

WASTE-TO-ENERGY TECHNOLOGIES AND APPLICATIONS

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ABSTRACTS

Waste-to-Energy (WtE) technologies have emerged as an important component of modern waste management and sustainable energy systems because they enable waste materials to be converted into useful forms of energy while reducing dependence on conventional disposal methods. Rapid urbanization, population growth, industrial development, and changing consumption patterns have increased the generation of municipal solid waste (MSW), creating significant environmental and public-health challenges. At the same time, many waste streams contain substantial amounts of organic matter and combustible materials that can be recovered as electricity, heat, biogas, syngas, bio-oil, and other useful products. Recent research identifies several major WtE pathways, including incineration, anaerobic digestion, gasification, pyrolysis, landfill-gas recovery, hydrothermal processes, and refuse-derived fuel systems.) This research examines the major WtE technologies and their applications from technical, environmental, economic, and sustainability perspectives. The study uses a systematic review approach based on recent scholarly literature published mainly between 2023 and 2026. Particular attention is given to technology selection, energy recovery, emissions, resource recovery, waste characteristics, circular-economy principles, and applications in municipal, agricultural, industrial, and food-waste management. The literature indicates that no single technology is universally appropriate because the performance of WtE systems depends on waste composition, moisture content, calorific value, source separation, infrastructure, financial conditions, and environmental regulations. Anaerobic digestion is particularly relevant for wet and organic-rich waste, whereas thermal technologies can be more suitable for combustible fractions and prepared refuse-derived fuel. Recent studies also emphasize integrated systems that combine material recycling, biological treatment, thermal conversion, energy recovery, and residue utilization.

KEYWORDS: *Waste-to-Energy, Municipal Solid Waste, Anaerobic Digestion, Incineration, Gasification, Pyrolysis, Biogas, Renewable Energy, Waste Management, Circular Economy, Energy Recovery, Sustainable Development.*

INTRODUCTION

Waste generation has become one of the major environmental challenges associated with population growth, urbanization, industrialization, and changing patterns of consumption. Municipal solid waste includes food residues, paper, plastics, textiles, wood, packaging materials, garden waste, and numerous other materials generated by households, commercial activities, institutions, and industries. When these materials are inadequately collected, transported, treated, or disposed of, they can contribute to air pollution, water contamination, soil degradation, greenhouse-gas emissions, unpleasant odors, disease transmission, and loss of potentially valuable resources. Recent research emphasizes that increasing waste generation requires management strategies that move beyond conventional disposal and instead promote resource recovery and circular-economy approaches. Waste-to-Energy refers broadly to processes through which waste materials are converted into usable energy. Depending on the technology and waste stream, the recovered energy may appear as electricity, steam, heat, biogas, biomethane, syngas, bio-oil, or other energy carriers. WtE

therefore represents an intersection between waste management and energy production. Instead of treating waste solely as a material requiring disposal, WtE approaches waste as a potential resource. Recent reviews identify incineration, gasification, pyrolysis, anaerobic digestion, landfill-gas recovery, hydrothermal processes, and refuse-derived fuel as important pathways for recovering energy from different waste streams. The importance of WtE has increased because traditional landfilling presents several long-term environmental challenges. Organic waste deposited in landfills can undergo anaerobic decomposition and produce methane, a potent greenhouse gas. Landfills can also require substantial land resources and may generate leachate that requires careful management. Capturing landfill gas and using it for electricity or heat can recover some energy from waste that has already been landfilled. However, landfill-gas recovery is generally considered a recovery option for existing or unavoidable landfilled waste rather than a replacement for source reduction, reuse, recycling, and other higher-priority waste-management practices. Recent research continues to emphasize the importance of integrating WtE into the waste-management hierarchy rather than treating energy recovery as an isolated solution.

Incineration is one of the most established WtE technologies. In a conventional waste-incineration facility, combustible waste is burned under controlled conditions, generating heat that can be transferred to water to produce steam and electricity. Combined heat and power systems can also supply useful thermal energy to industrial facilities or district-heating networks. One major advantage of incineration is its ability to substantially reduce the volume of residual waste requiring final disposal. However, modern incineration requires sophisticated air-pollution-control systems because combustion can generate particulate matter, nitrogen oxides, acidic gases, heavy-metal-containing residues, and other pollutants if the process is not properly controlled. Recent research continues to examine combustion performance, emissions, residues, and integration with other waste-management systems. Anaerobic digestion represents another important WtE pathway, especially for biodegradable and wet organic materials. In anaerobic digestion, microorganisms decompose organic matter in the absence of oxygen and produce biogas, which is mainly composed of methane and carbon dioxide. Biogas can be used to generate electricity and heat or upgraded to biomethane for use as a fuel. Digestate, the remaining material after digestion, may also have potential for nutrient recovery or agricultural applications when it meets appropriate quality and safety requirements. Food waste is particularly relevant because its high organic content can make biological treatment attractive. A recent review indicates that food waste can be transformed into biogas and subsequently used for electricity, heat, or fuel production, supporting both waste reduction and circular-economy objectives

Gasification and pyrolysis are thermochemical technologies that differ from conventional combustion. Gasification converts carbon-containing materials under controlled conditions with limited oxygen or another gasifying agent, producing a combustible gas known as syngas. Depending on its composition and treatment, syngas can be used for heat, electricity, or as an intermediate for chemical and fuel production. Pyrolysis occurs in the absence or

near-absence of oxygen and produces products such as gases, liquid bio-oil or pyrolysis oil, and carbon-rich solid residues. These technologies can potentially produce valuable products, but their successful operation requires appropriate feedstock preparation, moisture control, process optimization, and management of contaminants. Recent studies comparing WtE technologies emphasize that technology selection should consider technical, environmental, economic, and social factors simultaneously. Hydrothermal technologies are also receiving increasing research attention. Hydrothermal carbonization can process wet feedstocks without requiring the same degree of drying that some conventional thermal processes require. It can generate carbon-rich solid products and potentially facilitate energy and material recovery. Hydrothermal liquefaction is another developing pathway for converting wet organic feedstocks into energy-rich liquid products. These technologies remain context-dependent, and their practical application depends on feedstock characteristics, process conditions, capital requirements, product markets, and environmental performance.

The environmental performance of WtE cannot be assessed simply by measuring the amount of electricity produced. A comprehensive evaluation should consider the complete life cycle of the system, including collection, transportation, preprocessing, conversion, energy generation, emissions, residue management, recycling interactions, and avoided landfill impacts. Life Cycle Assessment (LCA) is therefore frequently used to evaluate environmental consequences across different WtE pathways. A 2024 study combining bibliometric analysis and LCA found that gasification and incineration can have different environmental profiles across impact categories, demonstrating the importance of evaluating WtE technologies according to specific environmental indicators and local conditions. Economic factors are equally important. WtE plants can require significant investment in waste-processing equipment, boilers, turbines, gas-cleaning systems, anaerobic digesters, gas-upgrading units, storage infrastructure, and residue-management facilities. Thanasi-Boçe, M., & Hoxha, J. (2025) Elroraded on Operational costs can also be affected by waste collection, transportation, labor, maintenance, energy prices, tipping fees, regulatory requirements, and markets for recovered products.

Recent systematic research indicates that economic feasibility is strongly influenced by factors such as tipping-fee structures, electricity tariffs, carbon pricing, and local policy conditions. WtE technologies are particularly relevant for developing countries, where waste collection systems may be incomplete and waste streams can contain large organic fractions and high moisture levels. In such settings, technology imported directly from another country may not perform as expected because waste composition, infrastructure, energy prices, financing, regulations, and technical capacity differ. Research on lower- and lower-middle-income regions emphasizes that technology feasibility must be evaluated according to regional conditions rather than assuming that a single technology is suitable everywhere. For countries such as Pakistan, WtE presents potential opportunities in rapidly growing urban areas where municipal waste management and energy requirements are both important concerns. Organic municipal waste, agricultural residues, food waste, sewage-related organic

materials, and selected combustible waste fractions could potentially provide feedstocks for different energy-recovery systems. However, successful implementation requires reliable waste collection, source segregation, appropriate feedstock characterization, environmental monitoring, skilled technical personnel, financing mechanisms, and clear regulatory standards.

Another important aspect of WtE is residue management Thanasi-Boçe, M., & Hoxha, J. (2025) THAT eXPLAINED. Thermal technologies do not eliminate all material; they generate bottom ash, fly ash, char, or other residues depending on the process. Thanasi-Boçe, M., & Hoxha, J. (2025).found that Revealed that Some WtE residues may contain metals or other contaminants and therefore require appropriate treatment before reuse. A 2023 review examined the beneficial use of WtE residues in construction applications and highlighted the importance of environmental standards, leaching controls, and contaminant management. Potential applications include aggregate substitution, cement-related materials, asphalt and pavement materials, embankment fill, bricks, and lightweight construction products, provided that environmental requirements are satisfied. The relationship between WtE and the circular economy is also significant. A circular economy seeks to retain the value of materials and resources for as long as possible while reducing waste and environmental impacts. WtE should therefore generally be considered alongside prevention, reuse, recycling, composting, material recovery, and other resource-conservation measures. For example, recyclable metals can be recovered before thermal treatment, while biodegradable waste can be directed to anaerobic digestion. Residual non-recyclable materials can then be considered for thermal energy recovery where appropriate.

RESEARCH OBJECTIVES

1. To examine the major Waste-to-Energy technologies and their applications in converting municipal, agricultural, industrial, and organic waste into electricity, heat, biogas, syngas, biofuels, and other useful energy products.
2. To evaluate the environmental, technical, and economic implications of Waste-to-Energy technologies, particularly in relation to greenhouse-gas emissions, waste-volume reduction, energy recovery, residue management, operational requirements, and economic feasibility.
3. To identify opportunities and challenges associated with the sustainable implementation of Waste-to-Energy systems, with particular attention to waste characteristics, source segregation, technological selection, circular-economy principles, environmental regulations, and future technological development

RESEARCH QUESTIONS

1. What are the major Waste-to-Energy technologies, and how are they applied to different types of waste?

2. What are the major technical, environmental, and economic benefits and challenges associated with Waste-to-Energy technologies?
3. What strategies can improve the sustainable implementation and efficiency of Waste-to-Energy systems within modern waste-management and circular-economy frameworks?

LITERATURE REVIEW

Recent literature presents Waste-to-Energy as a multidisciplinary field combining waste management, renewable and alternative energy production, environmental engineering, chemical engineering, biotechnology, economics, and sustainability. Chicaiza-Ortiz et al. (2024) examined WtE technologies for municipal solid waste management through bibliometric analysis and life-cycle assessment and reported that WtE can produce electricity, heat, and chemical products while requiring careful consideration of environmental performance and waste pretreatment. Their analysis also demonstrated the increasing research interest in gasification, incineration, pyrolysis, and other conversion pathways. A 2023 overview of sustainable energy generation from MSW identified incineration, pyrolysis, anaerobic digestion, and landfill-gas recovery as important energy-recovery routes and emphasized that technology selection should be matched with waste characteristics. Thanasi-Boçe, M., & Hoxha, J. (2025). THAT FOUND This is particularly important because municipal waste is heterogeneous, meaning that its moisture content, organic fraction, plastics, paper, metals, and other components can vary substantially between locations and seasons. Recent comparative research has consequently emphasized multi-criteria assessment rather than relying exclusively on energy-generation capacity. Incineration remains one of the most widely discussed WtE technologies because it can process large quantities of combustible waste while simultaneously reducing waste volume and producing heat and electricity.

Modern plants use boilers, turbines, heat-recovery systems, and air-pollution-control equipment to improve energy recovery and manage emissions. However, incineration requires appropriate feedstock quality and advanced pollution-control infrastructure. The 2026 critical review of municipal solid-waste incineration focuses on process performance, emissions, residues, and system integration, reflecting the continuing importance of improving combustion efficiency while managing environmental impacts. Recent literature also emphasizes the importance of recovering useful materials from combustion residues rather than treating ash solely as a disposal problem. Anaerobic digestion is particularly important for food waste, agricultural residues, sewage-related organic materials, and other biodegradable feedstocks. During digestion, microorganisms convert organic matter into biogas. The methane component can be combusted in engines or turbines to generate electricity and heat, or upgraded to biomethane. Digestate may also provide nutrients where quality and contamination requirements are met. Recent research on food waste confirms the potential of anaerobic digestion for producing biogas and reducing landfill use.) However,

successful digestion depends on factors such as feedstock composition, pH, temperature, organic loading rate, retention time, moisture, microbial stability, and contaminant levels. Gasification has received increasing attention because it can convert carbonaceous materials into syngas under oxygen-limited conditions. Syngas may be combusted for heat and electricity or further processed into chemicals and fuels. Gasification can offer opportunities for efficient resource recovery, but tar formation, feedstock variability, contamination, gas cleaning, and system complexity remain important technical issues. The 2024 LCA-based research by Chicaiza-Ortiz et al. found that gasification performed favorably across several environmental parameters in their specific comparative assessment, while also emphasizing the need for improved sorting, pretreatment, and valorization strategies.

Feedstock preparation, moisture content, temperature, heating rate, residence time, and product quality can strongly influence performance. Consequently, pyrolysis is generally more appropriate when waste streams can be sufficiently characterized and processed. Hydrothermal technologies provide additional options for wet organic waste. Hydrothermal carbonization can transform wet biomass into carbon-rich materials under elevated temperature and pressure, while hydrothermal liquefaction can produce energy-rich liquid products from suitable wet feedstocks. The recent WtE literature increasingly discusses these technologies as part of emerging systems, although their commercial application remains dependent on economic and technical conditions. The 2026 review of thermochemical WtE technologies includes hydrothermal carbonization alongside incineration, pyrolysis, and gasification and highlights opportunities for energy recovery and residue valorization as well as challenges such as capital cost and process complexity. RDF represents another approach to improving waste energy recovery. Instead of using mixed waste directly, combustible components can be separated, processed, and prepared into a more consistent fuel. . Li, X., Ren, B., Kou, X., Hou, Y., Buque, A. L., & Gao, F. (2024) THAT eXPLAINED The quality of RDF depends on the removal of undesirable materials, moisture reduction, particle-size control, and appropriate blending.

Recent research has examined advances in RDF preparation and combustion systems as part of low-carbon WtE development. RDF can potentially be used in dedicated WtE plants or selected industrial applications where suitable combustion and emissions-control systems are available. The environmental assessment of WtE is complex because benefits in one category can be accompanied by impacts in another. For example, energy recovery can avoid some fossil-fuel use, while thermal treatment can produce atmospheric emissions and solid residues. Similarly, anaerobic digestion can recover energy from food waste, but transportation, pretreatment, methane leakage, digestate management, and electricity-generation efficiency influence its overall environmental performance. Life-cycle assessment is therefore valuable because it evaluates multiple stages rather than focusing only on the conversion process. Recent systematic research recommends integrated techno-economic-environmental evaluation when assessing WtE systems. The economic literature indicates that WtE feasibility depends on more than the amount of energy produced. Capital

investment, operating costs, waste supply, gate or tipping fees, electricity prices, heat demand, subsidies, carbon policies, transportation distance, residue disposal costs, and recovered-material markets can all influence project viability. A technically successful plant may still face financial difficulties if the local waste supply is unreliable or if there is insufficient demand for its energy products. Therefore, feasibility studies should combine technical assessment with financial modelling and sensitivity analysis.

WtE residue management is another significant research area. Incineration and other thermal processes produce ash and other residues that may require stabilization and safe disposal or beneficial use. Tian et al. (2023) reviewed the potential use of WtE residues in civil engineering and noted applications involving aggregates, pavement materials, cement-related products, embankments, bricks, and lightweight construction materials. They also emphasized the importance of controlling heavy metals, dioxins/furans, leaching, and other environmental concerns before beneficial reuse. The literature also increasingly connects WtE with circular-economy principles. A sustainable system should prioritize waste prevention and material recovery before energy recovery of suitable residual fractions. Source segregation is therefore fundamental. Separating organic waste, recyclable materials, hazardous materials, and combustible residuals can improve feedstock quality and reduce contamination. Integrated systems can combine recycling, composting, anaerobic digestion, RDF production, thermal conversion, and residue recovery. Such integration can improve overall resource efficiency compared with relying on one technology alone.

METHODOLOGY

This study adopts a qualitative systematic literature-review approach to examine Waste-to-Energy technologies and their applications. The research is based on secondary information obtained from peer-reviewed journal articles, review papers, scientific publications, and recent scholarly literature published primarily from 2023 to 2026. The approach was selected because the purpose of the study is to synthesize existing knowledge concerning different WtE technologies, their applications, benefits, limitations, environmental effects, and sustainability potential rather than to conduct laboratory experiments. The review approach considers major technological categories including incineration, anaerobic digestion, gasification, pyrolysis, landfill-gas recovery, hydrothermal conversion, and refuse-derived fuel. Particular attention is given to studies that discuss energy recovery, emissions, life-cycle impacts, economic feasibility, waste characteristics, resource recovery, and circular-economy applications. Recent systematic studies demonstrate the usefulness of structured literature analysis for comparing WtE technologies across technical, environmental, economic, and social dimensions.

RESEARCH DESIGN

The research uses a descriptive and systematic review research design. Relevant literature was organized according to technology type, feedstock, energy product, application,

environmental performance, technical requirements, economic considerations, and sustainability challenges. The design allows information from different studies to be compared and synthesized into a coherent framework. The analysis follows several stages: identification of relevant studies, screening of titles and abstracts, selection of studies according to relevance, extraction of major findings, categorization of technologies, comparison of applications, and synthesis of conclusions. The approach is consistent with recent WtE literature that uses systematic-review and PRISMA-oriented methodologies to organize evidence from large bodies of research. For example, a 2026 systematic review examined 87 peer-reviewed studies and evaluated multiple WtE technologies across technical, economic, and environmental dimensions

DATA ANALYSIS

The collected literature was analyzed through thematic content analysis and comparative synthesis. Information from selected studies was grouped into major themes, including technology characteristics, feedstock requirements, energy products, environmental impacts, economic conditions, operational challenges, residue management, and sustainability applications. Each WtE technology was examined according to its conversion mechanism and suitability for different waste streams. The analysis indicates that waste characteristics are one of the most important determinants of technology suitability. High-moisture organic waste is generally more compatible with biological processes such as anaerobic digestion, while relatively dry and combustible waste fractions can be appropriate for thermal conversion. Gasification and pyrolysis require controlled feedstock conditions and can be sensitive to moisture, contaminants, and heterogeneous composition. Incineration can handle broader waste mixtures but requires sophisticated combustion and emission-control systems. Recent comparative studies similarly demonstrate that WtE technologies should be assessed according to multiple technical, environmental, economic, and social criteria rather than energy output alone. The second component of the data analysis concerned environmental performance. The literature was examined for evidence concerning greenhouse-gas emissions, air pollutants, landfill diversion, energy substitution, residue generation, and resource recovery. LCA studies demonstrate that the environmental performance of WtE can vary substantially according to the technology, electricity mix, waste composition, plant efficiency, transportation, and residue treatment. Therefore, claims about the environmental superiority of a particular technology cannot be generalized without considering the system boundary and local conditions.

FINDINGS

The findings demonstrate that Waste-to-Energy technologies provide multiple pathways for converting waste into useful energy while reducing the quantity of waste requiring final disposal. Incineration remains an important technology for large-scale treatment of combustible municipal waste because it can reduce waste volume and recover heat for

electricity and thermal applications. However, its successful implementation requires reliable emission-control systems, trained personnel, continuous monitoring, and appropriate residue management. The findings further indicate that anaerobic digestion is particularly valuable for organic-rich waste streams such as food waste, agricultural residues, and selected biodegradable municipal waste. The process produces biogas that can be used for electricity, heat, or upgraded biomethane. Its application can simultaneously reduce organic waste disposal and recover energy. However, stable operation requires appropriate feedstock characteristics, biological control, contamination management, and effective digestate utilization. Gasification and pyrolysis have considerable potential for converting selected carbon-rich waste materials into energy-rich gases, liquids, and solid products. Gasification can produce syngas for energy applications, whereas pyrolysis can generate gas, liquid products, and carbon-rich solids. However, these technologies require appropriate preprocessing and process control. Feedstock heterogeneity, moisture, tar formation, contaminants, and high capital requirements remain important barriers. Recent research supports further technological development while emphasizing the need for integrated environmental and economic assessment. The findings also show that technology selection must be based on waste characteristics. No single WtE technology can be considered universally appropriate for every community.

CONCLUSION

Waste-to-Energy technologies provide an important opportunity to address two interconnected challenges: increasing waste generation and growing demand for sustainable energy. The reviewed literature demonstrates that waste can be converted into electricity, heat, biogas, syngas, fuels, and other useful products through technologies such as incineration, anaerobic digestion, gasification, pyrolysis, landfill-gas recovery, hydrothermal conversion, and RDF systems. These technologies can reduce the quantity of waste requiring disposal while recovering energy and, in some circumstances, valuable materials. However, WtE should not be regarded as a universal replacement for waste prevention, reuse, recycling, and other resource-conservation strategies. Its effectiveness depends strongly on local waste composition, moisture content, calorific value, source segregation, infrastructure, technical expertise, environmental regulations, financing, and energy markets. Recent research consistently demonstrates that technology selection should be based on a comprehensive evaluation of technical, environmental, economic, and social factors. Future WtE development should therefore emphasize integrated waste-management systems, improved source separation, advanced pretreatment, efficient energy recovery, strict emission control, life-cycle assessment, residue valorization, and circular-economy principles. Developing countries can potentially benefit from WtE, but implementation should be adapted to local waste characteristics, institutional capacity, financial conditions, and environmental requirements. Overall, WtE can become a useful component of sustainable waste management when it is carefully designed, scientifically evaluated, properly regulated, and integrated with broader resource-recovery strategies.

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