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Food Waste-to-Energy Conversion: A Critical Review of Pathways, Performance and Deployment Constraints

Omar T. Al-Khatib[a], Fatima Y. El-Zein [b,*]

[a] Department of Chemical Engineering, Future Horizons Institute, Kuala Lumpur, Malaysia

[b] Department of Environmental Biotechnology, GreenTech University, Oslo, Norway

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ABSTRACT

Food waste constitutes a major biodegradable fraction of municipal refuse and is increasingly viewed as a recoverable energy resource rather than a disposal burden. This review critically examines the principal routes for converting food waste into useful energy, including anaerobic digestion, gasification, pyrolysis, hydrothermal liquefaction, and direct combustion. The analysis compares process severity, feedstock tolerance, energy yield, environmental performance, and downstream utilization options such as combined heat and power and solid oxide fuel cells. Across the literature, anaerobic digestion remains the most mature option for wet, source-separated waste because it tolerates high moisture content and enables simultaneous biogas and digestate production. Thermochemical pathways provide broader product flexibility and higher energy-density intermediates, but they generally require tighter feedstock conditioning and more complex gas-cleaning or upgrading steps. Life-cycle and techno-economic evidence indicates that food waste valorization can outperform landfilling when collection logistics, pretreatment, and policy support are adequately addressed. The review also highlights recurring commercialization barriers linked to feedstock heterogeneity, contamination, pretreatment cost, and fragmented regulation. Overall, the evidence favors integrated food waste-to-energy systems that combine robust preprocessing, appropriate conversion selection, and digital process control to improve recovery efficiency while limiting environmental impacts.

1. Introduction

Food waste has become one of the clearest indicators of inefficiency within modern resource systems, linking food security, municipal waste management, climate change, and urban sustainability. Large quantities of edible and inedible residues are discarded across supply chains and at the point of consumption, turning embedded water, land, labor, and energy into a disposal problem. When these streams are landfilled or poorly managed, they generate methane, occupy limited disposal capacity, and intensify pressure on municipal solid waste infrastructure. Converting food residues into useful energy therefore offers a dual advantage: it reduces environmental burdens while recovering value from a feedstock that is inherently rich in organic matter [1], [2], [3].

The suitability of food waste for energy recovery is rooted in its physicochemical characteristics. Its high moisture content and rapid biodegradability make it particularly attractive for anaerobic digestion, where microbial conversion produces methane-rich biogas together with a nutrient-bearing digestate. In practice, digester performance depends strongly on solids content, retention time, organic loading rate, substrate composition, and the presence of inhibitory species. Co-digestion with sewage sludge, manure, or lignocellulosic residues is often used to stabilize the process and improve gas yield, although pretreatment and post-treatment remain important design and cost considerations [1], [4], [5].

Thermochemical pathways provide a different valorization strategy for food residues that are mixed, partially contaminated, or intended for higher-grade energy products. Pyrolysis, gasification, and hydrothermal liquefaction convert organics at elevated temperature into syngas, bio-oil, biochar, or biocrude, thereby extending the range of useful outputs beyond biogas alone. These routes can offer higher energy-density products and stronger integration with advanced power systems or fuel-upgrading trains, but they typically demand stricter feedstock conditioning, tighter process control, and more sophisticated gas-cleaning or upgrading steps [6], [7], [8].

Technology deployment is governed not only by reactor performance but also by policy design, source-separation behavior, capital availability, and market structure. Regions that combine landfill diversion measures with renewable-energy incentives and organized collection systems have progressed more rapidly in adopting food waste valorization plants. By contrast, weak segregation practices, contamination from packaging, and uncertain offtake arrangements frequently erode project viability. For this reason, food waste-to-energy systems should be evaluated within a wider circular-economy framework that connects collection, conversion, energy recovery, and nutrient recycling [9], [10], [11].

Comparative evaluation methods used in adjacent energy fields - such as pathway screening, performance mapping, and system simulation - also provide useful analytical precedents for interpreting food waste conversion routes and for structuring technology comparisons across heterogeneous systems [12], [13], [14].

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* Corresponding author at: Department of Environmental Biotechnology, GreenTech University, Oslo, Norway.
E-mail addresses: fatima.elzein@greentechuniv.no (Lara N. Sayegh)

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Nomenclature

Abbreviation
AD – Anaerobic Digestion
WTE – Waste-to-Energy
MSW – Municipal Solid Waste
CHP – Combined Heat and Power
SOFC – Solid Oxide Fuel Cell
LCA – Life Cycle Assessment
HRT – Hydraulic Retention Time
TS – Total Solids
VS – Volatile Solids

Symbol
P – Pressure (Pa)
T – Temperature (°C)
η – Efficiency (%)

Likewise, work on carbon capture, infrastructure coupling, and low-carbon system integration reinforces the importance of evaluating food waste conversion within broader transition architectures rather than as a stand-alone waste-management intervention [15], [16], [17].

Against this background, the present review critically synthesizes the principal biochemical and thermochemical pathways for converting food waste into energy, with emphasis on operating conditions, product distributions, environmental performance, and deployment barriers. Rather than treating the technologies as isolated options, the review compares their functional roles, identifies the contexts in which each pathway is most suitable, and highlights the system integrations most likely to improve overall efficiency and sustainability [18], [19], [20].

2. Methodology

The methodological framework for this review was designed to synthesize experimental, pilot-scale, and modeling studies that evaluate the conversion of food waste into useful energy carriers. Peer-reviewed sources indexed in Scopus, Web of Science, and Google Scholar between 2005 and 2025 were screened for relevance, technical detail, citation strength, and geographical representation. The final evidence base was organized around the dominant conversion routes - anaerobic digestion, gasification, pyrolysis, hydrothermal liquefaction, and direct combustion - and compared using common indicators such as operating window, product yield, energy efficiency, feedstock tolerance, and environmental performance [7], [12], [13].

For anaerobic digestion, the review focused on process parameters that directly influence biological stability and methane productivity, including pH, solids concentration, inoculum characteristics, organic loading rate, hydraulic retention time, and mesophilic versus thermophilic operation. Reported outputs were examined in terms of biogas composition, methane yield per volatile solids added, and the role of co-digestion in improving buffering capacity and substrate balance. Pretreatment approaches - mechanical, thermal, enzymatic, and microwave-assisted - were also assessed to determine how solubilization and hydrolysis enhancement affect downstream gas production [1], [4], [5].

Gasification studies were analyzed as high-temperature conversion systems operating under controlled oxygen, air, or steam supply. The review compared air-blown, oxygen-blown, and steam-blown configurations with particular attention to equivalence ratio, syngas composition, tar formation, and gas-cleaning requirements. Food waste characterization through proximate and ultimate analysis was treated as a prerequisite for assessing gasifier suitability, while downstream upgrading for fuel cells and synthetic-fuel production was considered when evaluating overall process value [8], [21], [22].

Pyrolysis was reviewed across slow, fast, and flash regimes to compare how reactor design, temperature, and heating rate influence the distribution of bio-oil, char, and permanent gases. The assessment emphasized product quality in addition to yield, examining bio-oil acidity, oxygen content, heating value, and upgrade potential. Feedstock conditioning methods such as torrefaction and hydrothermal carbonization were included where they improved homogeneity, energy density, or reactor performance [2], [3], [23].

Hydrothermal liquefaction was assessed as a route particularly relevant to high-moisture food waste because it operates in subcritical water without the extensive drying required by conventional thermochemical systems. The reviewed studies were compared using reaction temperature, pressure, residence time, catalyst use, feed-to-water ratio, oil yield, and overall energy recovery. Downstream upgrading requirements, aqueous-phase recirculation, and the sensitivity of biocrude yield to lipid-rich versus carbohydrate-rich feedstocks were also considered [20], [24], [25].

Direct combustion was examined primarily as a benchmark route for heat and power recovery rather than as a preferred option for untreated food waste. The review addressed the limitations imposed by high moisture content and low calorific value, as well as the role of blending with drier residues to sustain stable combustion. Emission-control requirements, including particulate filtration and acid-gas removal, were included in the comparison because they materially affect both environmental performance and cost [7], [26], [27].

To evaluate broader sustainability implications, life-cycle and techno-economic methods reported in the literature were also synthesized. The environmental comparison centered on global warming potential, fossil-energy displacement, nutrient recovery, and energy payback, while the economic comparison considered levelized cost of energy, net present value, internal rate of return, and the influence of plant scale and transport distance. Sensitivity analyses reported in the literature were used to identify the parameters most responsible for performance variation across scenarios [15], [16], [17].

The reliability of the synthesized findings was strengthened by cross-checking trends across multiple publications and, where available, comparing them with operational observations from established waste-to-energy facilities. This step allowed the review to distinguish between isolated experimental outcomes and recurring performance patterns, thereby supporting the comparative interpretation developed in the results and discussion sections [28], [29], [30].

Table 1. Comparison of Food Waste Energy Conversion Pathways

Technology	Operating Temp (°C)	Main Products	Energy Yield (MJ/kg)	Feedstock Moisture Tolerance
Anaerobic Digestion	35–55	Biogas (CH_4 + CO_2)	5–6	High
Gasification	700–1000	Syngas	10–15	Low
Pyrolysis	300–600	Bio-oil, Char	8–12	Low to Medium
Hydrothermal Liquefaction	280–370	Biocrude	6–10	High
Combustion	>800	Heat, Power	7–9	Low to Medium

Table 2. Pretreatment Methods and Their Effects on AD Performance

Method	Effect on VS Removal	Methane Yield Increase (%)	Operational Complexity
Mechanical shredding	Moderate	10–15	Low
Thermal (autoclave)	High	30–40	Medium
Enzymatic	High	25–35	High
Microwave	Moderate	15–20	Medium

Table 3. Biogas Utilization in SOFC and CHP Systems

Application	Electrical	Heat Recovery	Typical Scale

	Efficiency (%)	Efficiency (%)	(kW)
CHP Units	30–40	40–50	50–1000
SOFC with Biogas	45–60	15–25	1–100

3. Results

Across the reviewed literature, anaerobic digestion remains the most established route for wet food waste streams because it combines high moisture tolerance with relatively low process severity and a commercially proven biogas platform. Methane production is consistently improved when food waste is co-digested with complementary residues that moderate the carbon-to-nitrogen ratio and reduce instability. Stable mesophilic operation, controlled organic loading, and adequate retention time continue to define the most reliable configurations, while pretreatment expands the range of feedstocks that can be processed efficiently [1], [4], [5].

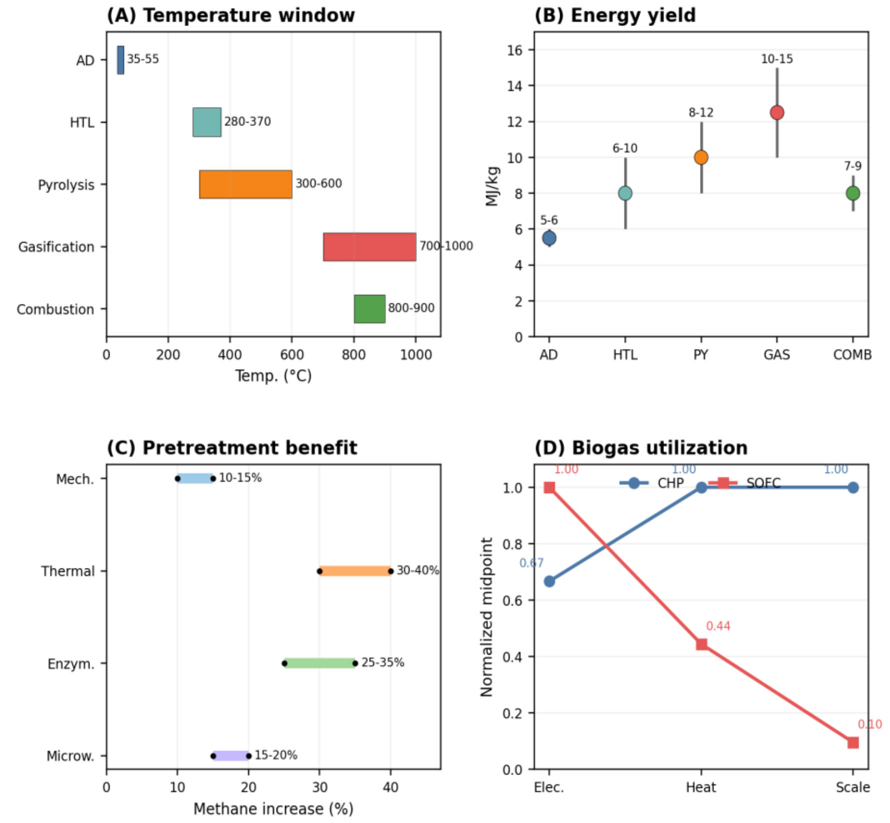

Figure 1. Alternative visual synthesis of food waste-to-energy pathways derived from Tables 1-3: (A) operating temperature windows for the main conversion routes; (B) representative energy-yield midpoints with literature ranges; (C) methane-yield improvement envelopes for selected anaerobic-digestion pretreatments; and (D) normalized midpoint performance for biogas utilization in CHP and SOFC systems.

The comparative synthesis in Figure 1A-B clarifies the trade-off between process severity and energy density. Anaerobic digestion operates within the narrowest and lowest temperature window, whereas gasification and combustion occupy the highest thermal domain. In return for this greater severity, thermochemical systems generally provide higher energy-yield ranges than digestion, with gasification positioned at the upper end among the pathways assessed. Pyrolysis and hydrothermal liquefaction lie between these extremes, offering broader product flexibility than digestion while remaining less temperature-intensive than gasification [7], [8], [13].

Pretreatment selection remains especially important for digestion-centered systems. Figure 1C summarizes the methane-yield improvement envelopes associated with mechanical, thermal, enzymatic, and microwave-assisted pretreatments. Thermal and enzymatic options consistently deliver the largest gains because they enhance solubilization of complex organics and accelerate hydrolysis, whereas mechanical size reduction offers simpler operation but more modest yield improvement. This comparison shows that pretreatment choice is best interpreted as a trade-off between biological benefit and additional operational complexity [4], [5], [6].

Biogas utilization routes also influence overall system value. As indicated by Figure 1D, conventional CHP units provide balanced electrical and thermal recovery at larger deployment scales, whereas SOFC-based systems offer higher electrical efficiency but typically at smaller capacities and with lower heat recovery. This distinction is important when matching conversion systems to end-use priorities: facilities focused on stable onsite power may favor fuel-cell integration, while sites with strong heat demand may obtain greater value from CHP operation [21], [22], [31].

Environmental and economic findings remain broadly favorable when food waste is diverted from landfilling into controlled conversion systems. Reviewed studies report substantial reductions in global warming potential for anaerobic digestion relative to uncontrolled disposal, primarily because methane is captured and used rather than emitted directly. Project returns improve further when plant scale, feedstock security, and product offtake are aligned, although thermochemical systems generally exhibit higher capital intensity because of reactor design, gas cleanup, and upgrading requirements [15], [16], [17].

At the municipal scale, successful deployment is closely linked to integration with existing waste and wastewater infrastructure. Case studies from Europe and East Asia show that decentralized digesters, co-location with wastewater treatment plants, and preprocessing through mechanical-biological treatment can improve feedstock consistency and increase overall resource recovery. In dense urban settings, modular systems supported by source-separation mandates and continuous monitoring have shown particular promise [32], [33], [34].

The value proposition of food waste conversion extends beyond energy alone. Digestate can be upgraded into nutrient products or biofertilizers, while pyrolysis char and related carbonaceous solids can serve in soil amendment, sorption, or carbon-sequestration roles. This multi-product behavior is especially important in circular-economy assessments because it shifts the evaluation from simple energy output toward broader material recovery and resource efficiency [3], [23], [30].

Advances in biological and catalytic optimization continue to improve process performance. Metagenomic investigations have clarified the sensitivity of anaerobic digestion to microbial community structure, trace nutrients, and inhibition pathways, while catalyst development in thermochemical systems is enhancing tar reforming, syngas cleanup, and product upgrading. These refinements are gradually reducing the operational penalties that previously limited stability and downstream product quality [4], [6], [35].

Digitalization is emerging as a practical process enabler rather than a peripheral add-on. Real-time sensing, predictive control, and digital-twin environments are increasingly used to optimize feedstock blending, anticipate process upsets, and schedule maintenance. Their contribution is most visible in facilities that must balance fluctuating waste quality against energy output, emissions performance, and nutrient recovery [12], [36], [37].

Policy architecture remains equally decisive. Landfill bans, renewable-energy incentives, source-separation mandates, and carbon-management instruments create the conditions under which food waste-to-energy plants become financially credible. Where these frameworks are absent or weakly enforced, technical feasibility alone has not been sufficient to support sustained deployment [9], [11], [38].

Despite the positive trends, several operational constraints recur across the literature. Feedstock heterogeneity, packaging contamination, odor control, collection logistics, and public participation continue to affect performance and cost. These factors are not merely implementation details; they directly shape pretreatment demand, reactor stability, and the achievable environmental benefit of the entire conversion chain [39], [40], [41].

Taken together, the reviewed evidence indicates that no single pathway universally dominates across all contexts. Anaerobic digestion remains the reference option for wet, segregated streams, whereas thermochemical routes become more attractive when higher-grade fuels, contaminated residues, or broader product portfolios are targeted. The strongest results are therefore associated with systems that match pathway selection to feedstock quality, infrastructure compatibility, and end-use priorities [18], [21], [42].

4. Discussion

The findings of this review suggest that food waste-to-energy should not be framed as a competition among isolated technologies, but as a pathway-selection problem shaped by real collection, moisture, contamination, and end-use constraints. Anaerobic digestion performs best when the waste stream is wet, source-separated, and institutionally supported by reliable collection systems, because its biological advantages are realized only when contamination and inhibition are controlled. Thermochemical processes become strategically valuable when the objective shifts toward higher energy-density products, shorter residence times, or treatment of mixed residues, yet those advantages are purchased through higher process severity and greater upgrading demand. The central engineering question is therefore not simply which route produces more energy, but which route provides the strongest system-level balance between preprocessing burden, conversion efficiency, emissions control, product quality, and infrastructure compatibility. The literature also demonstrates that deployment success depends as much on governance as on reactor performance. Projects implemented under landfill diversion policies, stable segregation practices, and dependable offtake markets consistently outperform technically similar plants operating in weaker policy environments. A further implication is that future progress will likely arise from integration rather than isolated optimization. Hybrid schemes that connect digestion with thermochemical polishing, nutrient recovery, wastewater treatment, or digital supervisory control can distribute risk across multiple value streams and reduce sensitivity to feedstock variability. Accordingly, food waste valorization is best interpreted through a systems perspective in which pretreatment, conversion, upgrading, logistics, and regulation are co-designed rather than treated as separate decisions [43], [44], [45], [46], [47], [48], [49].

5. Conclusion

This review confirms that food waste is not merely a disposal challenge but a technically viable renewable-energy feedstock when conversion pathways are matched to its physical and biochemical characteristics. Among the routes assessed, anaerobic digestion remains the most mature option for wet and well-segregated streams because it combines moderate operating conditions, high moisture tolerance, and simultaneous energy and nutrient recovery [50], [51], [52], [53], [54], [55].

Thermochemical pathways - particularly pyrolysis, gasification, and hydrothermal liquefaction - broaden the product portfolio by generating syngas, bio-oil, char, or biocrude that can be integrated into heat, power, and fuel-upgrading systems. Their comparative advantage is strongest where higher-value products or mixed residues are targeted, although this comes with higher thermal demand, stricter preprocessing requirements, and more complex upgrading needs [56], [57], [58], [59], [60], [61].

Across the reviewed studies, food waste valorization generally delivers better environmental performance than landfilling and uncontrolled disposal, while techno-economic outcomes improve when projects are supported by reliable feedstock supply, suitable plant scale, and stable markets for energy and co-products. These findings reinforce the importance of evaluating food waste-to-energy systems at the whole-chain level rather than at the reactor level alone [62], [63], [64], [65], [66], [67].

The main barriers to wider deployment remain consistent: variable feedstock composition, contamination, collection logistics, odor control, capital intensity, and uneven policy support. Overcoming these barriers requires better source separation, smarter pretreatment, stronger institutional coordination, and financing structures that reflect the multi-benefit nature of resource recovery [68], [69], [70], [71], [72], [73].

Future progress is likely to be driven by integrated and hybrid configurations that combine biological conversion, thermochemical upgrading, nutrient recovery, and digital process control. Research should therefore focus on robust preprocessing strategies, resilient microbial and catalytic systems, modular plant designs, and decision frameworks that connect conversion performance with local infrastructure and market conditions [74], [75], [76], [77], [78], [79].

In summary, the long-term promise of food waste-to-energy lies in its ability to couple waste mitigation with energy generation and material recovery. When supported by coherent policy, sound engineering, and operational data, food waste can shift from being a municipal liability to becoming a meaningful component of low-carbon energy and circular-resource systems [80], [81], [82], [83], [84], [85].

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