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Gap Analysis of WtE Technologies for Tropical MSW: A Systematic Review and Development Direction of Waste Heat Recovery-Based Hybrid Architectures

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Abstract. The management of tropical Municipal Solid Waste (MSW) with extreme moisture content (>60%) presents a fatal thermodynamic challenge for conventional waste-to-energy (WtE) facilities. The “wet waste penalty” phenomenon in stand-alone incineration systems triggers massive latent heat absorption, resulting in systemic inefficiency and high exergy destruction wasted through the flue gas stack. This paper presents a targeted systematic review of the primary literature to dissect the research gap between the potential of thermochemical technologies and their rational implementation in developing nations. Analysis confirms that advanced technologies face irrational capital expenditure (CAPEX), while stand-alone systems approach asymptotic efficiency limits. As a resolution, this study proposes a retrofitting-based hybrid architecture for incineration-pyrolysis that utilizes the flue gas recovery route (200°C–300°C). This sensible heat extraction fully subsidizes the pyrolysis reactor's activation energy without interfering with the main steam cycle (zero steam bleeding). This hybrid integration effectively recycles exergy destruction, boosting overall thermal efficiency and providing a dual output of baseload electricity and high-density hydrocarbons, making it a realistic energy-circularity transition scheme for existing WtE infrastructure.
Keywords**.** Waste-to-Energy, wet waste penalty, exergy destruction, hybrid system, flue gas recovery

1. Introduction

The transition to a circular economy heavily relies on Waste-to-Energy (WtE) thermochemical conversion to simultaneously reduce waste volume and generate power (Tamba & Sujastika, 2024; Winanti et al., 2022). However, replicating developed-nation WtE infrastructure in tropical developing regions frequently encounters fatal operational failures due to extreme Municipal Solid Waste (MSW) moisture levels (>60%) (Agatha et al., 2024). This high-moisture profile degrades the Lower Heating Value (LHV) below self-sustaining combustion thresholds, triggering a severe "wet waste penalty" (Chaerul & Ridho, 2025; Febijanto et al., 2024). Consequently, conventional incinerators operate as inefficient drying facilities; high-grade thermal energy is squandered as latent heat for moisture evaporation rather than producing mechanical turbine work, causing massive exergy destruction and entropy generation within the flue gas and condenser (Winanti et al., 2022; Yang et al., 2018).

To circumvent these limitations, advanced alternatives such as pyrolysis recovering the plastic fraction into bio-oil and syngas and plasma gasification have emerged (Chen et al., 2014; Kasiński & Dębowski,

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2024). Yet, contemporary literature reveals a stark techno-economic polarization. While these advanced technologies achieve near-perfect exergy conversion, their exorbitant capital and operational expenditures (CAPEX/OPEX) render them economically irrational for developing cities (Zafar et al., 2024). Conversely, mature conventional incineration infrastructures remain locked in profound thermal inefficiency (Febijanto et al., 2024). This dichotomy exposes a critical gap between theoretical stand-alone thermal advancements and practical, field-viable implementation (Caiardi et al., 2022).

Addressing these operational voids, this review systematically evaluates the WtE evolutionary trajectory to pinpoint the intersection of thermodynamic efficiency and economic realism (Cui et al., 2024). By critically assessing the top five WtE conversion routes against thermal performance and local implementation rationality (Purwanta et al., 2022; Zafar et al., 2024), this study proposes a paradigm-shifting strategic framework: a retrofitting-based incineration-pyrolysis hybrid architecture. This integrated approach is formulated as the most viable resolution to salvage destructed exergy, optimize thermal circularity, and bridge the techno-economic gap in existing WtE facilities.

2. Methods

This review paper adopts a targeted systematic review framework to dissect the evolutionary trajectory of WtE technologies and identify operational anomalies occurring in developing countries (Cui et al., 2024). Unlike conventional bibliometric reviews that rely on large volumes, this study employs a strictly filtered, purposive sampling technique to select primary literature. The inclusion criteria were specifically limited to literature evaluating single-system thermodynamic parameters, extreme-moisture waste characteristics (>60%), and the prospects of implementing waste heat recovery cycles in existing WtE infrastructures.

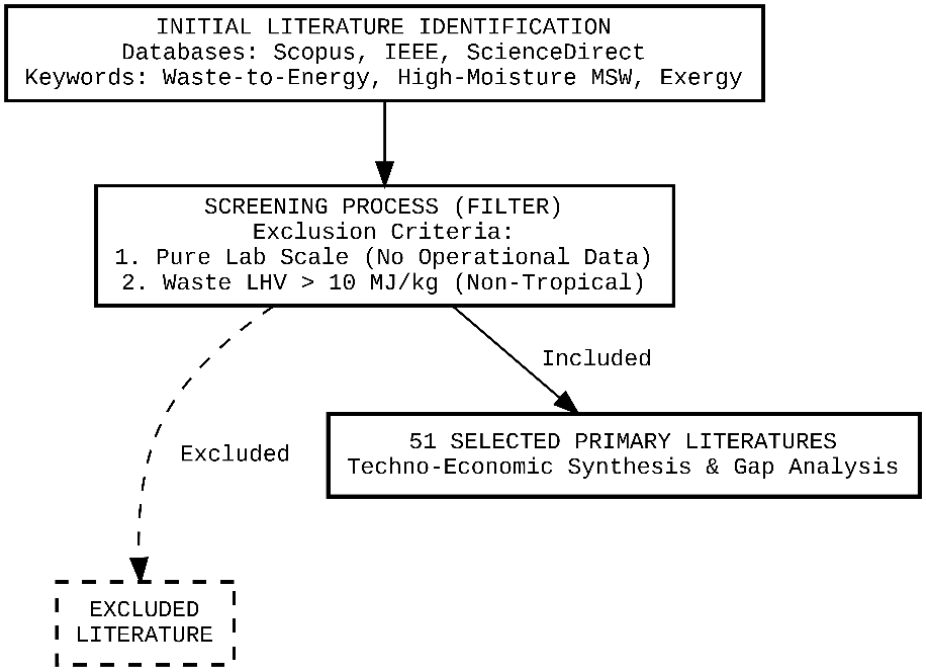


Fig. 1. Flowchart of literature selection.

The literature identification and selection process followed a rigorous multi-stage methodology to ensure a comprehensive synthesis of the WtE landscape. As illustrated in Fig. 1, the process advanced

from initial database identification through screening and eligibility phases, culminating in the final inclusion of 51 high-impact studies. This systematic filtration ensures that the subsequent thematic clustering and gap analysis are grounded in scientifically validated and relevant data, providing a robust foundation for the techno-economic evaluations presented in this study.

Table 1. Synthesis Matrix of Key Literatures and Gap Analysis

Thematic Landscape (Cluster)	Key References	Core Thermodynamic & Operational Arguments	Bridging Gap Findings
A. Operational Failure (Existing Facilities)	Winanti et al. (2022); Febijanto et al. (2024)	Inefficiency of wet waste combustion (>60% moisture); massive latent heat absorption.	High-temperature heat exergy is wasted in the stack (exergy destruction) and not reused.
B. Limits of Advanced Technologies (Stand-Alone)	Faisal et al. (2024); Martínez-Narro et al. (2023)	Superiority of pyrolysis kinetics in producing liquid hydrocarbons (bio-oil) and syngas.	Requires highly expensive external heating energy (OPEX) to maintain the oxygen-free reactor temperature.
C. Economic Irrationality of Advanced Technologies	Sesotyo et al. (2019); Kasinski & Debowski (2024)	Optimization of plasma gasification to achieve absolute efficiency and slag melting.	Too advanced; initial construction CAPEX is unfeasible for the scale of developing cities.
D. Hybrid Resolution & Heat Recovery	Yang et al.. (2018); Caiardi et al. (2022); Cui et al. (2024)	Modelling of cross-technology thermal integration and global WtE decarbonization trend analysis.	Conclusion: Heat recovery-based hybrid systems are the future solution bridging the weaknesses of the systems in Clusters A and B.

As detailed in Table 1, this analytical synthesis explicitly delineates a critical research gap. The fundamental deficit lies not in inventing new technologies, but in the absence of integration designs capable of recycling sensible waste heat (e.g., incinerator flue gas) to fully subsidize secondary endothermic processes (e.g., pyrolysis). Mitigating this gratuitous exergy loss to the environment irrefutably justifies shifting the WtE development paradigm from inter-technology competition toward technological harmonization via hybrid architectures.

3. Results

The evolution of thermochemical-based WtE technologies is fundamentally divided into two main routes: total oxidation (incineration) and thermal degradation under anoxic conditions (pyrolysis and gasification) (Chen et al., 2014; Ungureanu et al., 2025). A review of operational case studies in developing countries reveals a chronic thermodynamic anomaly known as the Wet Waste Penalty. Tropical MSW characteristics with extreme moisture content (>60%) drastically degrade the adiabatic combustion temperature (Agatha et al., 2024; Winanti et al., 2022). The energy that should have been converted into mechanical work at the turbine is entirely absorbed as a parasitic heat load for the water evaporation phase. This condition triggers systemic thermal inefficiency and results in massive exergy destruction in the stack (flue gas) and the condenser (Chaerul & Ridho, 2025; Sesotyo et al., 2019).

Operational failures resulting from these thermodynamic limitations have disrupted the global research direction. The chronological analysis of the evaluated literature reveals a sharp paradigm shift. Prior to 2018, the literature landscape was dominated by technical optimization efforts on stand-alone systems, specifically mass-burn grate modifications to force the combustion of wet waste (Ram et al., 2021; Tamba & Sujastika, 2024). However, entering the 2022 to 2025 period, there was an exponential surge in publications examining integrated (hybrid) thermal architectures. This trend of disruption confirms the scientific consensus that stand-alone systems have reached their asymptotic efficiency limits.

Contemporary WtE research now revolves entirely around exergy recovery (Caiardi et al., 2022; Cui et al., 2024).

3.1. Evolution of annual publication trends

A chronological review of WtE literature reveals a definitive paradigm shift over the past decade. As illustrated in Fig. 2, pre-2018 research was heavily confined to evaluating single-technology operations, primarily focusing on emission mitigation and mechanical grate improvements for mass-burn incineration (Maulidayanti et al., 2024; Tamba & Sujastika, 2024). Conversely, the 2022–2025 timeframe exhibits an exponential surge in publications investigating integrated hybrid architectures (Cui et al., 2024; Yang et al., 2018). This trajectory signifies a robust scientific consensus: single-technology optimization has reached its asymptotic thermodynamic limits, effectively redirecting future WtE development toward aggressive exergy recovery via cross-technology integration (Caiardi et al., 2022; Kasiński & Dębowski, 2024).

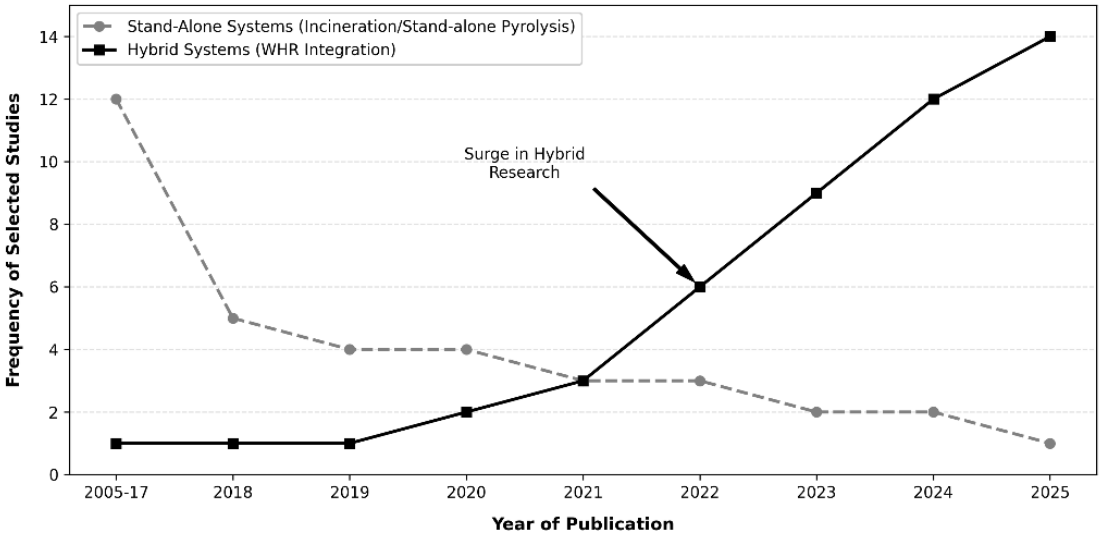


Fig. 2. Evolution of WtE Literature Focus Trend

3.2. Critical evaluation of top 5 WtE technologies

Evaluating dominant WtE technologies for high-moisture MSW reveals a stark contrast between theoretical potential and practical viability. Conventional incineration, despite its infrastructural maturity, suffers a severe "wet waste penalty," squandering high-grade energy as latent heat and sensible flue gas loss (Chaerul & Ridho, 2025; Febijanto et al., 2024). Conversely, stand-alone pyrolysis yields high-energy products, but its endothermic nature demands massive external heating, drastically inflating OPEX and penalizing net efficiency (Faisal et al., 2024; Purwanta et al., 2022). While conventional gasification offers superior emissions, its field scalability is persistently hindered by tar reforming complexities and extreme feed moisture sensitivity (Sudibyo et al., 2017; Ungureanu et al., 2025). Plasma gasification achieves maximum thermal conversion, yet its exorbitant CAPEX and massive parasitic electrical loads render it economically irrational for developing cities (Sesotyo et al., 2019; Zafar et al., 2024). Resolving these inherent deficits, the integrated hybrid architecture (incineration-pyrolysis) emerges as the optimal thermodynamic solution. By repurposing incineration waste heat to drive endothermic pyrolysis, this

symbiotic configuration eliminates secondary heating OPEX, salvages destructed exergy, and maximizes overall thermal efficiency through feasible plant retrofitting (Caiardi et al., 2022; Yang et al., 2018).

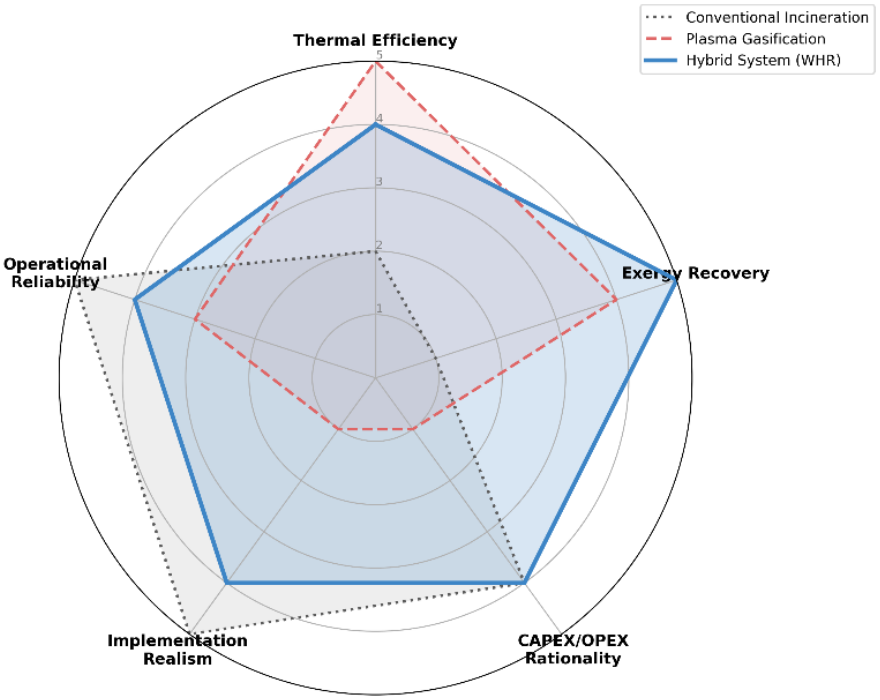


Fig. 3. Multicriteria analysis: WtE performance vs implementation realism.

To visually elucidate this techno-economic trade-off, Fig. 3 maps the three contrasting technology profiles across fundamental indicators. Conventional incineration exhibits extreme asymmetry: while robust in operational reliability, its performance severely contracts on the thermodynamic efficiency axis due to the wet waste penalty. Conversely, plasma gasification presents an opposite anomaly, peaking in thermal efficiency but failing fatally on the cost feasibility and implementation realism axes. Bridging this polarization, the proposed WHR Hybrid System achieves the most optimal equilibrium. The dominant polygon area demonstrates that the hybrid architecture successfully replicates the high thermal efficiency of advanced technologies while preserving the economic rationality and retrofitting viability of conventional systems. Ultimately, this integrated heat recovery approach effectively breaks the historical trade-off between thermodynamic performance and real-world financial constraints.

Table 2. Techno-Economic Comparison Matrix of Top 5 WTE Technologies

Rank	WtE Technology Classification	Thermal Efficiency Performance	Economic & Operational Barriers (CAPEX/OPEX)	Implementation Realism (Developing Nations)
1	Conventional Incineration	Very Low (Due to parasitic water load)	Moderate (Physical infrastructure is generally already established)	Very High
2	Stand-alone Pyrolysis	Moderate (Highly temperature sensitive)	High (External fuel OPEX for heating)	Moderate
3	Conventional Gasification	Moderate to High	High (Complex tar purification system)	Low to Moderate
4	Plasma Gasification	Very High (Approaching Absolute)	Very High (Irrational initial CAPEX & plasma torch power)	Very Low (Too Advanced)
5	Hybrid System (WHR)	High (Exergy Recovery Optimization)	Low to Moderate (Based on Retrofitting Schemes)	Very High

3.3. Thermodynamic resolution: Research gap and hybrid system optimization

Overcoming the parasitic load of high-moisture tropical MSW requires a paradigm shift toward integrated architectures, as combustion chamber modifications alone are insufficient. The incineration-pyrolysis hybrid resolves this by repurposing waste thermal energy as driving enthalpy for secondary reactions (Liu & Liu, 2005; Yang et al., 2018). However, a critical gap persists between conceptual macro-modelling (Caiardi et al., 2022; Cui et al., 2024) and reactor-level realities, frequently overlooking the equilibrium reactor's sensitivity to wet waste fluctuations. Inadequate heating fails to trigger thermal cracking in the Gibbs reactor, burdening the system. This study bridges this void by demonstrating that waste heat recovery must be precisely calibrated against pyrolysis activation energy limits to ensure thermodynamic viability (Martínez-Narro et al., 2023; Yang et al., 2018).

Fundamentally, this architecture mitigates the massive exergy destruction endemic to conventional incinerators, which exhaust high-grade energy via 200°C–300°C flue gas (Chaerul & Ridho, 2025; Sesotyo et al., 2019). Instead of bleeding active steam from the Rankine cycle—which mathematically curtails turbine output—the proposed integration extracts sensible heat directly from the stack (Liu & Liu, 2005). Salvaging this "dead" exergy fully subsidizes the pyrolysis reactor's endothermic OPEX. Consequently, a mutually beneficial dual-output synergy emerges: the incinerator sustains baseload electrical generation without turbine curtailment, while the pyrolysis unit simultaneously degrades plastic polymers into superior energy-density secondary products (Faisal et al., 2024).

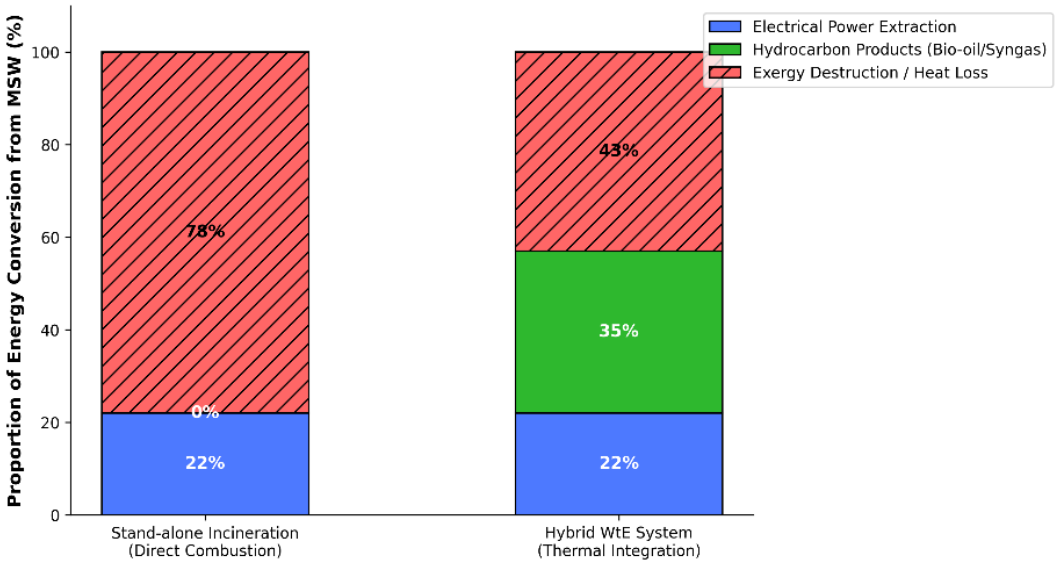


Fig. 4. Comparison of projected energy extraction efficiency alignment with future WtE development trends.

This dual-output mechanism significantly boosts the energy extraction efficiency per ton of MSW, surpassing the asymptotic limits that have long shackled stand-alone incineration. As illustrated in Fig. 4, this heat-recovery-based design stands at the forefront of the global WtE paradigm shift. While advanced technologies like plasma gasification prove economically irrational regarding CAPEX for developing nations (Zafar et al., 2024), this retrofitting-based hybrid system represents a highly realistic trajectory. Ultimately, future WtE development will focus on optimizing thermal circularity rather than inventing new stand-alone combustion methods. This architecture solidifies the postulate that energy efficiency in managing extreme-characteristic waste is achieved by harmonizing technologies to exploit every remaining joule of energy, rather than defying thermodynamic laws through forced external heating.

4. Conclusion

This study concludes that managing high-moisture municipal solid waste (>60%) in tropical regions necessitates a definitive paradigm shift from single-chamber incineration to integrated hybrid architectures. Conventional systems have reached their asymptotic efficiency limits, inherently crippled by the "wet waste penalty" that degrades combustion into an exergy-destroying water evaporation process. Conversely, advanced alternatives like plasma gasification remain economically irrational. The proposed incineration-pyrolysis hybrid system emerges as the most viable thermodynamic resolution. By extracting sensible heat from the stack flue gas (200°C–300°C) rather than resorting to steam bleeding, the architecture successfully recovers destructed exergy to completely subsidize the pyrolysis reactor's endothermic heating demands. This strictly calibrated integration yields high-density hydrocarbons (bio-oil and syngas) without intervening in the Rankine cycle, thereby keeping the turbine's electrical output at its maximum.

To bridge the gap between this theoretical thermodynamic equilibrium and commercial retrofitting, future investigations must advance towards dynamic predictive control. Developing robust thermal algorithms is essential to maintain isothermal reactor conditions against seasonal fluctuations in the raw

MSW heating value. Furthermore, integrating comprehensive Life Cycle Assessments (LCA) and Levelized Cost of Energy (LCOE) analyses will be critical. Quantifying the carbon footprint reduction from fossil fuel substitution and establishing post-retrofitting economic parameters will ultimately solidify this hybrid system as the backbone of circular-economy energy infrastructure in developing nations.

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