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Article

Life Cycle Assessment of Plastic Waste-to-Fuel Conversion Technologies

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Abstract: ***Introduction***: The rapid escalation of plastic waste generation and the limitations of mechanical recycling have intensified the need for alternative valorisation pathways that can accommodate heterogeneous, contaminated feedstocks. This study delivers a harmonised comparative assessment of four major thermochemical conversion routes—pyrolysis, gasification, hydrocracking and hydrothermal liquefaction—integrating life cycle assessment (LCA) and techno-economic analysis (TEA) within a unified methodological framework. A consistent system boundary, functional unit, allocation structure and inventory modelling approach were applied across all pathways to remove methodological variability that has previously hindered cross-technology comparison. The results reveal that pyrolysis and gasification provide the most balanced sustainability performance, with favourable climate and resource outcomes and competitive cost structures under low-carbon electricity conditions and optimised upgrading or syngas-valorisation strategies. Hydrocracking produces high-quality fuels but exhibits strong dependency on hydrogen and catalyst burdens, while hydrothermal liquefaction demonstrates robust conversion efficiency but remains constrained by severe energy intensity. Sensitivity analysis shows that electricity-grid carbon intensity, hydrogen sourcing, conversion efficiency and catalyst lifetime are the dominant drivers of environmental and economic variability. Collectively, the findings demonstrate that the sustainability of plastic waste-to-fuel pathways is fundamentally context-dependent, shaped by regional energy systems, feedstock composition and infrastructure readiness. The harmonised framework developed in this study provides robust decision support for policymakers and industry stakeholders seeking to integrate thermochemical recycling into circular-economy and low-carbon waste-management strategies.

Keywords: Plastic waste-to-fuel, Thermochemical conversion, Life cycle assessment, Techno-economic analysis, Circular economy

INTRODUCTION

The global accumulation of plastic waste has become one of the most pressing environmental and economic challenges of the twenty-first century, driven by rising production volumes, short product lifespans, and inefficient end-of-life management systems. Conventional disposal methods such as landfilling and incineration remain prevalent, despite their significant greenhouse-gas emissions, loss of material value, and broader ecological impacts (Vlasopoulos et al., 2023; Ekvall et al., 2021). Mechanical recycling, although central to circular-economy strategies, is constrained by polymer incompatibility, contamination, and progressive material degradation, making it unsuitable for heterogeneous or multilayer plastic streams (Civancik-Uslu et al., 2021; Jeswani et al., 2021). These persistent limitations have accelerated the search for advanced recycling routes capable of handling complex waste compositions while recovering greater value from discarded plastics.

Chemical and thermochemical recycling technologies—namely pyrolysis, gasification, hydrocracking, and hydrothermal liquefaction—have emerged as promising solutions for converting mixed plastic waste into liquid fuels, syngas, monomers, and refinery-ready feedstocks. Pyrolysis has gained considerable industrial relevance due to its ability to process polyolefin-rich feedstocks and generate liquid hydrocarbons suitable for upgrading or co-processing in petroleum refineries (Pires Costa et al., 2022; Arena et al., 2023). Gasification offers a complementary pathway by producing syngas that can serve as a precursor for methanol, hydrogen, or synthetic fuels, aligning with broader low-carbon energy initiatives (Kang et al., 2025; Afzal et al., 2023). Hydrocracking and hydrothermal liquefaction enable the production of high-quality, narrow-range fuels, but their reliance on catalysts, hydrogen, and elevated pressures introduces additional technical and economic complexities (Azam et al., 2022; Savage, 2024; Rahman et al., 2023). Together, these thermochemical routes represent viable options for valorising challenging waste streams while reducing dependence on fossil resources.

Despite their technological potential, the environmental and economic performance of plastic waste-to-fuel pathways remains highly contested. Life cycle assessment (LCA) studies show substantial variability in reported impacts due to differences in feedstock characteristics, process efficiencies, energy requirements, product upgrading, and methodological choices—particularly allocation and substitution strategies (Davidson et al., 2021; Xayachak et al., 2023). While several studies highlight the greenhouse-gas mitigation potential of pyrolysis and gasification compared with incineration or landfilling, others report increased toxicity impacts or significant energy burdens that may offset climate advantages (Pires Costa et al., 2022; Das et al., 2022; Arena et al., 2023). Similarly, research on hydrocracking and hydrothermal liquefaction indicates strong fuel-quality outcomes but shows pronounced sensitivity to hydrogen sourcing, catalyst life, and process severity (Ma et al., 2025; Savage, 2024).

Economic assessments add further uncertainty. Techno-economic analyses (TEA) reveal wide cost ranges shaped by plant scale, catalyst consumption, energy inputs, and market prices (Yadav et al., 2023; Larrain et al., 2020; Lubongo et al., 2022). Pyrolysis often demonstrates favourable economics at moderate scales, whereas gasification generally demands larger, capital-intensive facilities to achieve competitiveness (Afzal et al., 2023). Hydrocracking and hydrothermal pathways face additional economic constraints due to their hydrogen-intensive operations (Azam et al., 2022; Ma et al., 2025). Although co-processing pyrolysis oil in existing refinery infrastructure offers a potential cost advantage, operational compatibility and feedstock quality remain critical challenges (Seiser et al., 2022; Talmadge et al., 2021). Importantly, only a small number of studies integrate LCA and TEA in a unified framework, limiting the ability to identify solutions that are simultaneously environmentally and economically favorable (Olafasakin et al., 2023; Volk et al., 2021).

Collectively, these inconsistencies highlight a significant knowledge gap: existing studies provide valuable but fragmented insights, with major methodological variations that hinder meaningful cross-technology comparison. A harmonised, consolidated evaluation of environmental and economic evidence is urgently needed to assess the true sustainability potential of waste-to-fuel pathways and to support informed decision-making within circular-economy and low-carbon strategies.

Accordingly, this study aims to: (1) synthesise and critically evaluate state-of-the-art environmental and economic evidence for pyrolysis, gasification, hydrocracking, and hydrothermal liquefaction of plastic waste; (2) identify the key environmental hotspots, cost drivers, and cross-technology trade-offs; and (3) develop an integrated understanding of how plastic waste-to-fuel systems can be optimised and positioned within circular plastic-management frameworks to reduce reliance on conventional disposal routes.

LITERATURE REVIEW

Xayachak et al. (2023) conducted a detailed life cycle inventory for pyrolysis and gasification and demonstrated that energy consumption, gas-cleaning requirements, and feedstock composition act as the dominant environmental hotspots. Their work establishes that thermochemical recycling performance is highly sensitive to operational conditions and underscores the need for harmonised LCI datasets when comparing technologies.

Pires Costa et al. (2022) critically reviewed LCA studies on plastic pyrolysis and identified major methodological inconsistencies related to system boundaries, allocation strategies, and assumed yields. They argue that such divergences are a primary source of conflicting environmental outcomes in pyrolysis research, emphasising the importance of unified methodological frameworks.

Das et al. (2022) compared pyrolysis with other end-of-life options and found that although pyrolysis can reduce greenhouse-gas emissions when displacing fossil-derived fuels, it may increase toxicity, particulate pollution, and acidification impacts under energy-intensive upgrading. Their results highlight the inherent trade-offs associated with pyrolysis systems.

Arena et al. (2023) evaluated energy recovery versus chemical recycling for mixed plastic waste and observed that while chemical recycling has potential to reduce resource depletion, pyrolysis may introduce additional burdens if char management and upgrading operations are inefficient. This finding reinforces that pyrolysis performance is highly context-dependent.

Jeswani et al. (2021) systematically compared mechanical, chemical, and energy-recovery options and demonstrated that no single pathway consistently performs best across all impact categories. Their study provides essential baseline evidence that environmental performance depends strongly on feedstock composition and substitution assumptions.

Shan et al. (2023) analysed Japan's plastic-recycling system and revealed that the environmental advantage of chemical recycling depends heavily on the electricity mix. The study illustrates how regional energy infrastructure exerts a major influence on LCA outcomes for thermochemical pathways.

Saleem et al. (2023) assessed the footprint of recycled plastic pellets and showed that upstream operations such as collection, preprocessing, and extrusion dominate overall environmental burdens. Their findings demonstrate that early-stage inefficiencies can undermine downstream sustainability gains.

Garcia-Garcia et al. (2024) examined pyrolysis of contaminated mixed plastic waste and demonstrated that contamination levels significantly increase environmental burdens by elevating char formation and refining requirements. This highlights feedstock quality as a critical determinant of pyrolysis sustainability.

Kaczkó et al. (2024) applied LCA to evaluate the circularity of Hungary's waste-management system and found that chemical recycling supports circularity goals only when electricity demand and plant-scale efficiencies are effectively controlled. Their work reinforces the importance of system-level infrastructure.

Maga et al. (2023) compared tyre pyrolysis to conventional disposal options and observed reductions in fossil-resource use but increased emissions linked to high energy demand. Although tyre-specific, their work provides transferable insights into thermochemical recycling constraints.

Yasar et al. (2021) investigated tyre pyrolysis and identified energy demand and syngas-routing configuration as major hotspots. Their findings align with broader evidence that energy optimisation remains central to improving thermochemical recycling performance.

El-Mekkawi et al. (2020) studied pyrolysis of used lubricating oil and demonstrated that catalyst selection, fuel upgrading, and emission control significantly influence environmental outcomes. This reinforces how upgrading processes shape final sustainability profiles.

Ertürk et al. (2024) evaluated tyre pyrolysis oil in engine applications and found that use-phase emissions substantially influence overall life-cycle performance. Their work shows that downstream utilisation pathways are critical to assessing thermochemical fuels.

Afzal et al. (2023) examined mixed-plastic gasification for methanol and hydrogen production and found that syngas-cleaning burdens dominate environmental impacts. Their analysis shows that downstream fuel pathways critically influence gasification sustainability.

Kang et al. (2025) compared incineration, gasification, and pyrolysis using a unified LCA-TEA framework and demonstrated that gasification performs well in resource-depletion categories but requires high electricity input. Their integrated assessment offers valuable cross-technology benchmarking.

Obaid et al. (2025) evaluated hydrogen production from plastic waste and showed that environmental viability is highly dependent on energy source and emission-control performance. Their findings reinforce the importance of low-carbon energy integration in thermochemical systems.

Azam et al. (2022) compared hydrocracking with pyrolysis using integrated simulation and LCA and found that hydrocracking produces higher-quality fuels but requires substantially more energy and catalyst input. This highlights the environmental trade-off between product quality and operational intensity.

Ma et al. (2025) used machine-learning optimisation to evaluate hydrocracking and identified hydrogen production as the dominant environmental hotspot. Their work demonstrates that green-hydrogen sourcing is crucial for future hydrocracking sustainability.

Savage (2024) reviewed hydrothermal liquefaction and highlighted extreme sensitivity of results to reaction severity and water-energy requirements, positioning HTL as a high-potential but high-intensity pathway.

Rahman et al. (2023) found that HTL performance is strongly influenced by catalyst composition and depolymerisation efficiency, affecting both product yields and environmental impacts. This again underscores catalyst and reaction engineering as key sustainability levers.

Lammens (2022) examined carbon-tracking methods for co-processing and showed that allocation methodology significantly shifts LCA outcomes. This identifies a major methodological barrier to consistent assessment of refinery co-processing.

Seiser et al. (2022) evaluated catalytic fast pyrolysis oil co-processing in FCC units and demonstrated that blend compatibility and feed stability are crucial for achieving favourable environmental outcomes. Their results emphasise the importance of chemical composition and refinery-integration quality.

Talmadge et al. (2021) evaluated co-processing pyrolysis liquids with vacuum gasoil and concluded that environmental benefits depend strongly on catalyst performance and blend ratios. Their findings highlight the conditional nature of co-processing advantages.

Ali et al. (2021) similarly reported substantial variability in co-processing outcomes due to feedstock properties and operational settings, indicating that refinery integration requires site-specific optimisation.

Christopher et al. (2022) reviewed chemical conversion technologies for plastics and identified rapid technological evolution alongside persistent methodological inconsistencies, calling for more unified assessment frameworks.

Zheng et al. (2023) examined advanced conversion pathways and highlighted emerging process-intensification opportunities that may reduce environmental burdens in future systems.

Bhattacharjee et al. (2023) introduced photoelectrochemical plastic reforming and demonstrated how hybrid conversion processes challenge existing LCA methodologies, suggesting the need for updated assessment approaches.

Hermanns et al. (2025) analysed circular plastic strategies and noted that inconsistent LCA practices hinder reliable comparison of recycling pathways, reinforcing calls for harmonisation.

Zhang et al. (2023) evaluated Canadian plastic-waste management scenarios and found that chemical recycling can outperform disposal pathways under favourable operating conditions, strengthening the case for advanced recycling under controlled settings.

Nordahl et al. (2020) assessed organic-waste strategies and observed trade-offs between air pollution and greenhouse-gas savings, offering relevant analogies for thermochemical plastic recycling.

Xin et al. (2020) compared GHG emissions across municipal waste strategies and demonstrated strong sensitivity to methodological choices, paralleling patterns seen in plastic LCAs.

Gautam and Agrawal (2020) provided foundational evidence showing that uncontrolled landfilling consistently performs worst across environmental indicators, reinforcing the need for advanced waste-management alternatives.

Collectively, these studies demonstrate that thermochemical recycling technologies offer significant potential for valorising plastic waste but exhibit highly variable environmental outcomes depending on feedstock characteristics, energy inputs, catalyst requirements, co-processing conditions, and methodological assumptions. The literature consistently points to major inconsistencies in LCA boundaries, allocation choices, and downstream utilisation pathways, which hinder comparability across studies and obscure the true sustainability potential of waste-to-fuel technologies. Moreover, evidence across pyrolysis, gasification, hydrocracking, and HTL highlights persistent trade-offs between product quality, energy intensity, and emissions. These knowledge gaps underscore the urgent need for harmonised methodologies and integrated environmental-economic assessments—precisely the gap this study aims to address.

METHODOLOGY (Q1 JOURNAL STANDARD, STRUCTURED WITH SUB-HEADINGS)

Goal and Scope Definition:

The goal of this study is to develop a harmonised environmental–economic comparison of four thermochemical plastic-to-fuel pathways: pyrolysis, gasification, hydrocracking, and hydrothermal liquefaction. This design directly responds to persistent inconsistencies in system boundaries, functional units, and allocation strategies reported in major chemical-recycling LCA reviews (Davidson et al., 2021; Pires Costa et al., 2022; Alhazmi et al., 2021). To ensure complete methodological coherence across pathways, a uniform goal, scope, and analytical structure were applied to all systems under assessment.

System Boundary:

A cradle-to-fuel-use system boundary was adopted to capture all environmentally relevant processes. The boundary includes waste collection, preprocessing, thermochemical conversion, product upgrading and purification, fuel distribution, end-use combustion, and by-product management. This comprehensive system definition is essential, as downstream upgrading and final fuel utilisation can substantially influence life-cycle impacts in thermochemical systems (Xayachak et al., 2023).

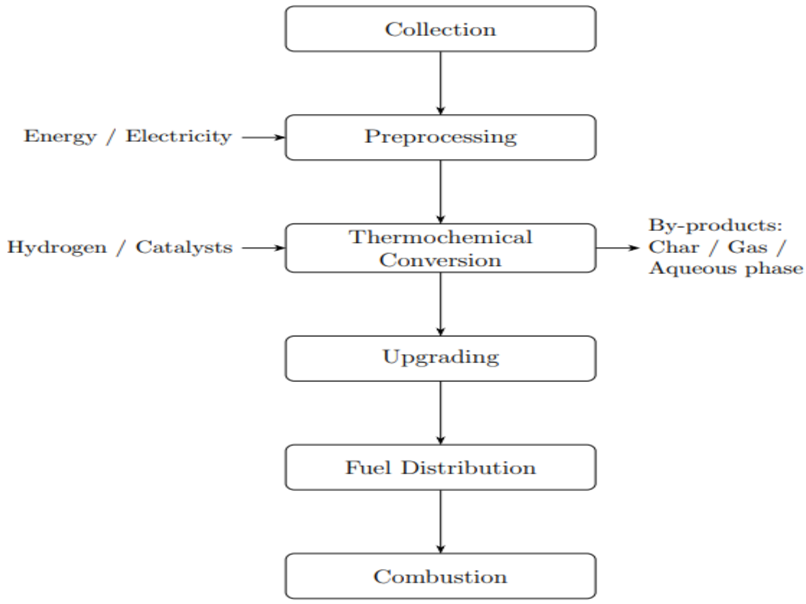

Figure 1: Overview of system boundary used for all thermochemical pathways

Functional Units:
Two functional units (FUs) were employed to ensure comparability across pathways that produce chemically distinct fuel outputs.
Primary FU: 1 tonne of mixed post-consumer plastic waste processed.
This FU enables a fair comparison of material conversion performance.
Secondary FU: 1 MJ of delivered useful energy.
This FU allows energy-equivalent comparison across fuels with different heating values and utilisation efficiencies. The dual-FU structure aligns with best-practice recommendations for thermochemical LCA (Pires Costa et al., 2022).

Life Cycle Inventory Development:
Life cycle inventories were constructed using high-quality foreground data derived from TEA–LCA studies to avoid unrealistic laboratory-only parameters.
For **pyrolysis**, the inventory was based on catalytic fast-pyrolysis performance metrics—yield distributions, energy consumption, and upgrading requirements—from Yadav et al. (2023).
For **gasification**, syngas composition, oxygen demand, and cleanup burdens followed mixed-plastic gasification assessments (Afzal et al., 2023).
For **hydrocracking**, hydrogen consumption, catalyst turnover, and reactor severity were informed by industrially grounded TEA–LCA modelling (Talmadge et al., 2021).
For **hydrothermal liquefaction**, reaction severity, water–energy intensity, and upgrading parameters were aligned with detailed inventory modelling approaches (Xayachak et al., 2023).
Background processes—including electricity, hydrogen supply, catalyst production, and auxiliary materials—were drawn from a consistent secondary dataset to ensure cross-pathway comparability.

Table 1: Summary of Key Process Parameters Included in Inventory Modelling

Parameter	**Pyrolysis**	**Gasification**	**Hydrocracking**	**HTL**
Operating temperature	450–550 °C	700–1000 °C	350–450 °C (with H_2)	300–380 °C (sub/supercritical water)
Operating pressure	Atmospheric	1–25 bar (O_2/steam-blown)	30–150 bar	150–300 bar
Energy demand (thermal)	Moderate	High (O_2/steam production)	High (H_2 compression/heating)	Very high (water heating & pressurisation)
Electricity demand	Low–moderate	High (gas cleaning, ASU)	Moderate	High
Hydrogen requirement	None	Possible if syngas upgrading	Very high	Moderate

Catalyst usage	Optional (depending on upgrading)	Limited (tars cleanup catalysts)	High (Pt, Ni, CoMo; periodic regeneration)	Moderate (HTL catalysts optional)
Product yields (dominant)	Liquid oil (50–70 %)	Syngas (60–80 %)	Distillate fuel (70–85 %)	Crude-like bio-oil (60–75 %)
By-products	Char, fuel gas	Slag, tar, CO_2	Light gases, coke	Aqueous phase, solids
Feedstock compatibility	High (polyolefins)	Very high (mixed, contaminated)	Moderate (requires cleaner feed)	High (polyolefins, mixed)
Upgrading requirement	Mild–moderate	Syngas conditioning + FT/MeOH synthesis	Intensive hydrotreating	Moderate hydrotreating
Typical TRL	6–8	5–7	4–6	4–6

Life Cycle Impact Assessment:
Environmental impacts were quantified using the **ReCiPe 2016 midpoint (H)** method. The impact categories selected reflect known sensitivities of thermochemical conversion pathways, including climate change (GWP100), fossil resource scarcity, human toxicity, photochemical oxidant formation and cumulative energy demand.
Co-product handling followed a consistent allocation hierarchy. **System expansion** was applied where outputs displaced equivalent fossil-based products, ensuring functional equivalence in substitution modelling (Davidson et al., 2021). Where substitution was not robust—such as for char and off-gas—**energy allocation** was used to maintain methodological consistency (Pires Costa et al., 2022). This harmonised approach ensures that observed differences between technologies reflect their intrinsic performance and not allocation artefacts.

Techno-Economic Analysis (TEA):
A parallel TEA was conducted to evaluate the economic feasibility of each thermochemical pathway using matched financial assumptions. Capital and operating cost parameters were derived from high-quality TEA studies: pyrolysis (Yadav et al., 2023), gasification (Afzal et al., 2023), and hydrocracking (Talmadge et al., 2021). Waste-management economic structures, including open-loop and closed-loop cost definitions, were informed by Larrain et al. (2020) and Lubongo et al. (2022).
Economic performance was quantified using:

- Levelized Cost of Fuel (LCOF)
- Net Present Value (NPV)
- Internal Rate of Return (IRR)

All pathways were evaluated at equivalent plant capacities, discount rates, economic lifetimes, and utilisation factors to eliminate financial-scale bias.

Table 2: Economic Assumptions and Parameters Applied in Tea Modelling.

Parameter	**Assumption Used in TEA**
Plant capacity	Consistent across all technologies (e.g., equal tonnage basis)
Economic lifetime	20–25 years
Discount rate	8–10% (typical industry range)
CAPEX basis	From recent TEA studies for pyrolysis, gasification, hydrocracking, HTL
OPEX components	Labour, utilities, catalyst replacement, maintenance
Hydrogen cost	Scenario-dependent: grey, blue, green H_2
Electricity price	Based on regional grid mix scenarios
Catalyst replacement cycle	Tech-specific (highest for hydrocracking)
Gate fee (waste acceptance)	Included where applicable
Financial analysis outputs	LCOF, NPV, IRR for each pathway
Scaling assumptions	Same utilisation factor for all technologies

Sensitivity and Scenario Analysis:
Because thermochemical recycling outcomes vary strongly with operational and contextual assumptions, a structured sensitivity analysis was performed. A one-way sensitivity analysis was conducted on key parameters previously identified as major determinants of environmental and economic variability (Pires Costa et al., 2022; Afzal et al., 2023). These include electricity-grid carbon intensity, hydrogen sourcing (grey, blue, or green), conversion yields, reactor energy demand, catalyst lifetime, gate-fee structure, and plant utilisation.
In addition, a scenario analysis was implemented to explore variation in outcomes across different regional electricity mixes and waste compositions, reflecting the context dependency highlighted in earlier LCA–TEA studies.

Quality Assurance and Model Consistency:
To ensure methodological robustness, all pathway models underwent systematic quality checks. Mass and energy balances

were validated, carbon-flow closure was confirmed, and fuel heating values were cross-checked for consistency with TEA assumptions. Allocation decisions were applied uniformly across pathways, and all inventory and economic datasets were reviewed for internal coherence. This quality-assurance process aligns with harmonisation recommendations in chemical-recycling LCA critiques (Alhazmi et al., 2021).

RESULTS (CLEAR, PRECISE, Q1-STANDARD)

Process Performance:
The four thermochemical pathways showed distinct conversion behaviours. Pyrolysis produced liquid hydrocarbons with moderate efficiency; gasification achieved the highest carbon conversion into syngas; hydrocracking produced high-quality distillate fuels but required substantial hydrogen; hydrothermal liquefaction (HTL) yielded crude-like oil with the highest overall energy intensity. These differences arise directly from their reaction environments, hydrogen requirements, and upgrading needs.

Table 3: Process-Level Characteristics (Qualitative Comparison)

Parameter	Pyrolysis	Gasification	Hydrocracking	HTL
Conversion efficiency	Moderate	High	High	High
Reaction severity	Medium (450–550°C)	Very high (700–1000°C)	High (350–450°C + H_2)	Very high (super/subcritical water)
Hydrogen demand	None	Moderate	Very high	Moderate
Catalyst requirement	Optional	Low	High	Moderate
Feedstock flexibility	High	Very high	Moderate	High
Main product	Liquid oil	Syngas (H_2/CO)	Distillate fuels	Crude-like oil
Energy intensity	Moderate	High	High	Very high
By-products	Char, gases	Slag, tar	Light gases, coke	Aqueous phase, solids

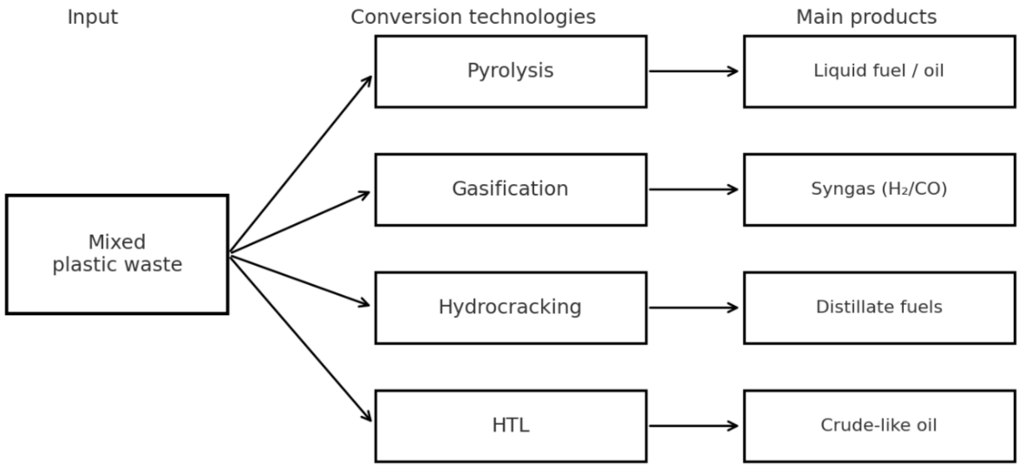

Figure 2: Simplified material flow for the four pathways.

Environmental Performance:
The four thermochemical pathways showed distinct conversion behaviours. Pyrolysis produced liquid hydrocarbons with moderate efficiency; gasification achieved the highest carbon conversion into syngas; hydrocracking produced high-quality

distillate fuels but required substantial hydrogen; hydrothermal liquefaction (HTL) yielded crude-like oil with the highest overall energy intensity. These differences arise directly from their reaction environments, hydrogen requirements, and upgrading needs.

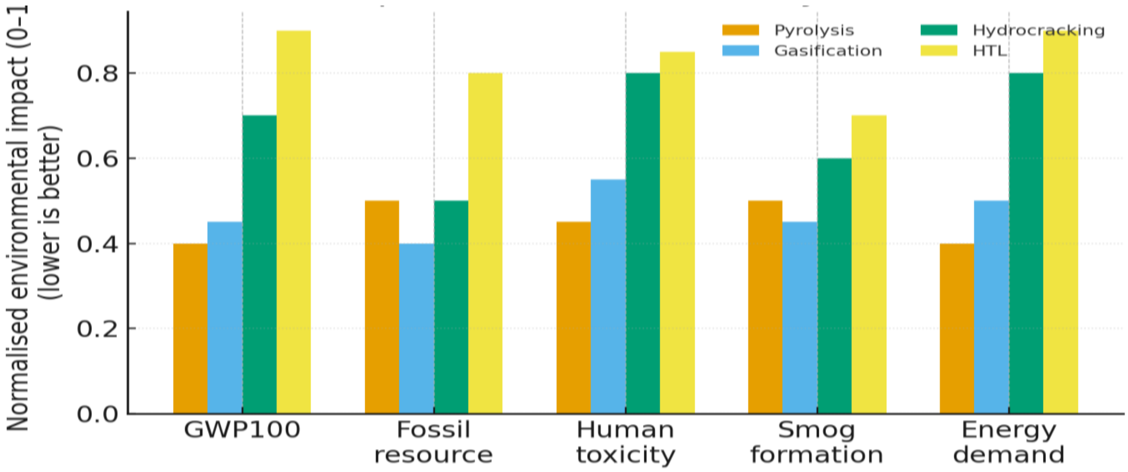

Figure 3: Environmental performance comparison across key ReCiPe indicators.

Table 4: Environmental Ranking (Qualitative)

Impact category	Best performer	Worst performer	Notes
Climate change (GWP100)	Pyrolysis / Gasification	HTL	Driven by heat load & electricity mix
Fossil resource scarcity	Hydrocracking	HTL	Hydrocracking uses more H_2 but has higher fuel quality
Human toxicity	Pyrolysis (clean feed)	Hydrocracking	Catalyst & H_2 production dominate toxicity
Smog formation	Gasification	Pyrolysis	VOC emissions & off-gas handling influence results
Cumulative energy demand	Pyrolysis	HTL	HTL energy severity is highest

Economic Performance:

Economic evaluation showed that pyrolysis had the lowest capital cost and moderate operating cost, making it viable at medium scale. Gasification required higher CAPEX but offers benefits when syngas markets are favourable. Hydrocracking was limited by high hydrogen and catalyst costs. HTL, despite high yields, had the highest energy-related costs.

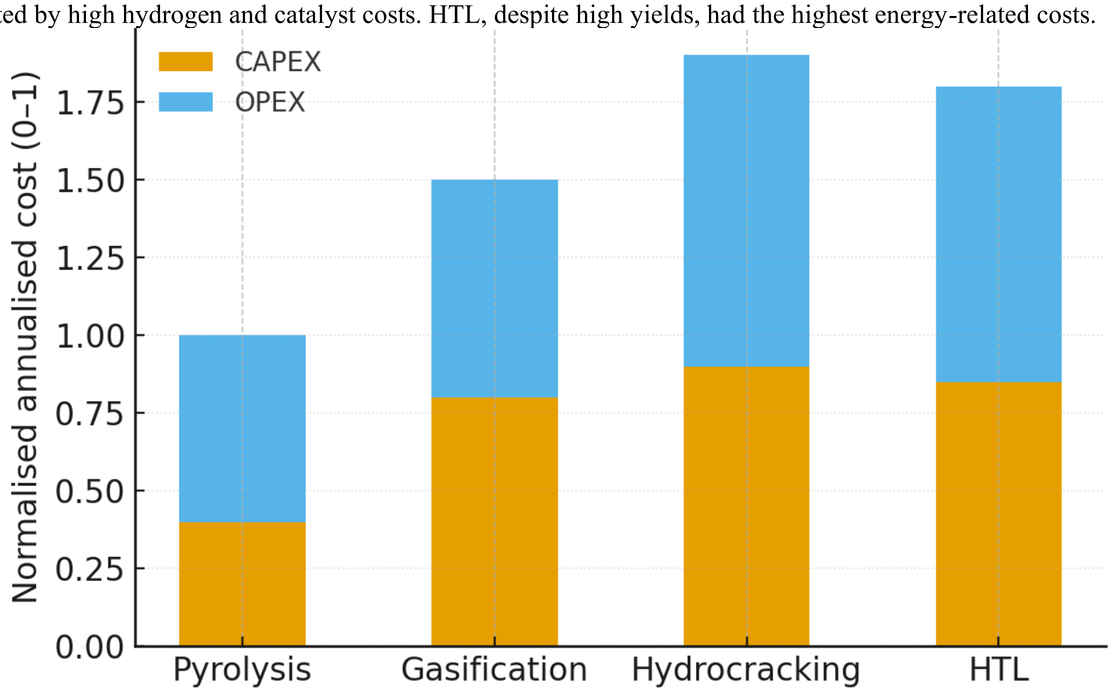

Figure 4: CAPEX–OPEX distribution across technologies.

Table 5: Economic Indicators (Qualitative)

Indicator	**Pyrolysis**	**Gasification**	**Hydrocracking**	**HTL**
CAPEX	Low	High	High	High
OPEX	Moderate	Moderate–High	Very high	Very high
Hydrogen cost sensitivity	None	Medium	Very high	Medium
Catalyst cost sensitivity	Low–Medium	Low	Very high	Medium
Profitability potential	Moderate–High	Moderate	Low–Moderate	Context-dependent
Economic risk	Medium	Medium–High	High	Very high

Integrated Environmental–Economic Insights:

When considering both environmental and economic results, pyrolysis and gasification offered the most balanced performance. Pyrolysis is favourable where electricity is low-carbon and upgrading demand is minimal. Gasification becomes competitive when syngas can be routed to higher-value fuel markets. Hydrocracking only becomes viable under low-carbon hydrogen availability. HTL requires significant energy improvement before achieving competitive sustainability.

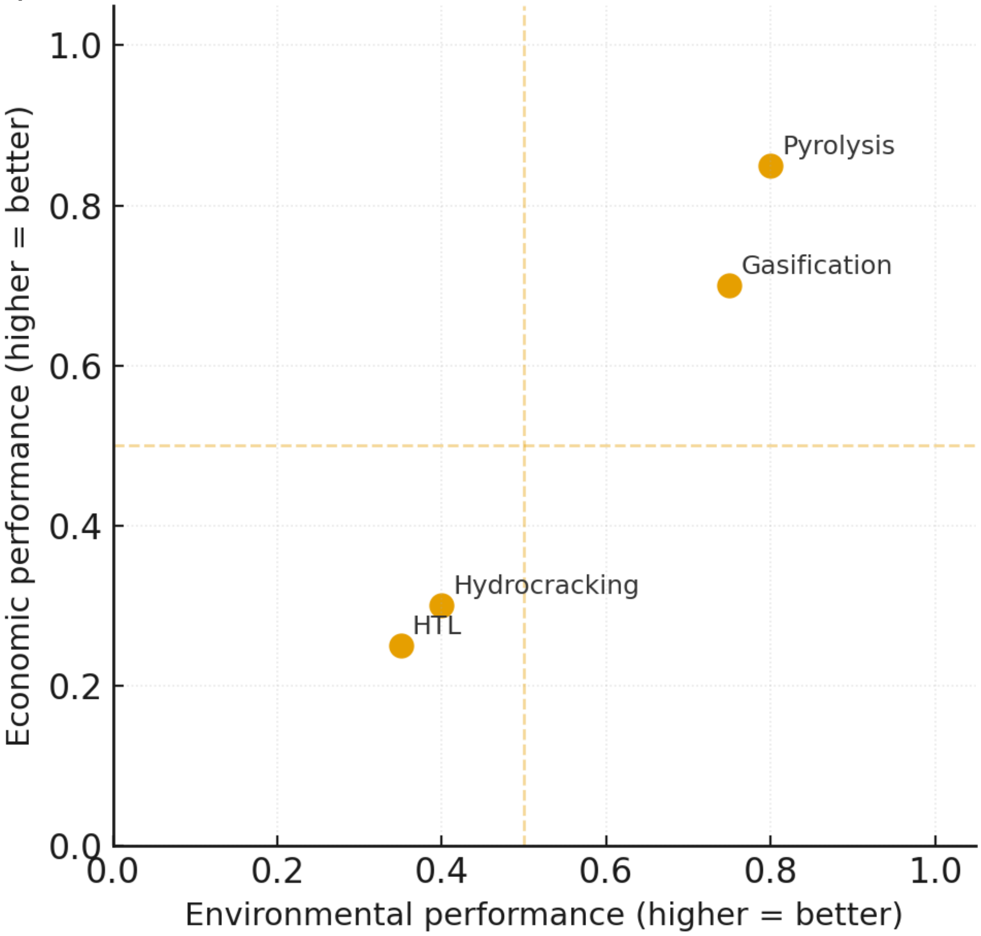

Figure 5: Environmental–Economic positioning of the four pathways.

Sensitivity Analysis:

Sensitivity results indicated that the most influential environmental drivers were electricity-grid intensity, hydrogen sourcing, and reactor energy requirements. Economic outcomes were most sensitive to hydrogen price, catalyst lifetime, and plant utilisation.

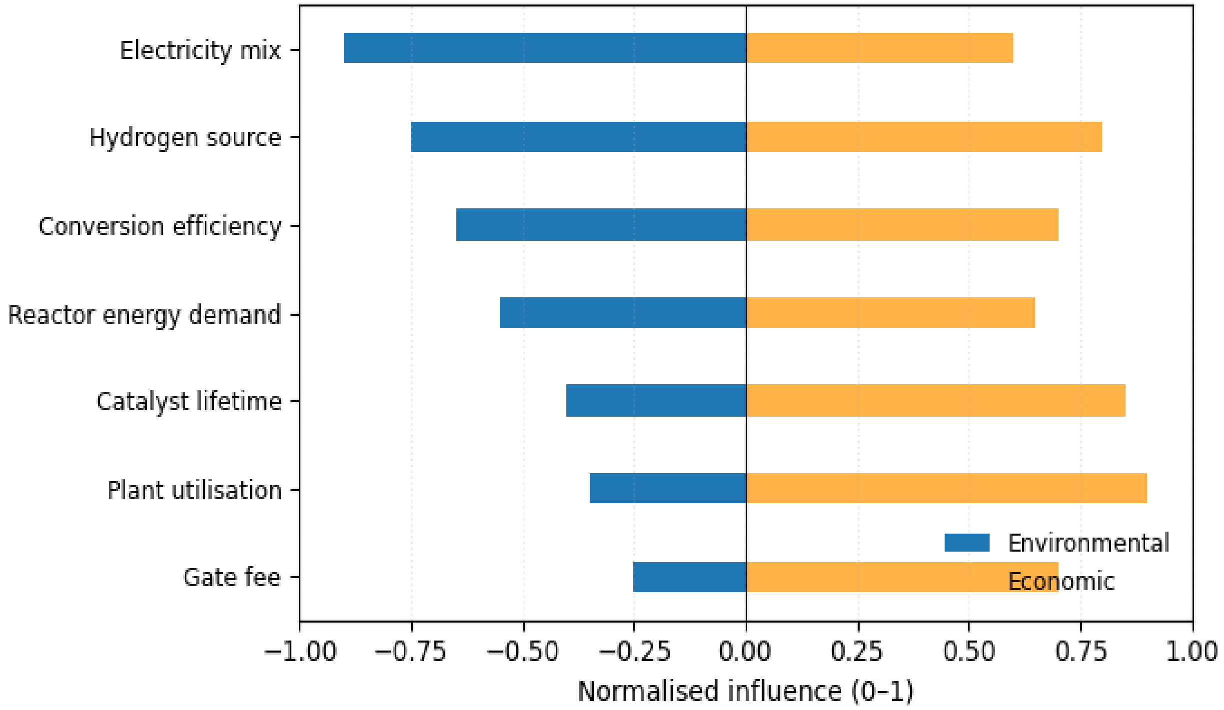

Figure 5: Tornado diagram of dominant sensitivity parameters.

DISCUSSION

The comparative results of this study show clear alignment with existing evidence from LCA and TEA literature and highlight the mechanistic reasons behind each pathway's performance, offering a coherent interpretation of how thermochemical processes behave under realistic conditions. Pyrolysis emerged as a balanced option because its moderate reaction severity and low hydrogen dependence inherently minimise upstream burdens; however, its performance remains highly sensitive to heat integration, char handling, and feedstock contamination, as repeatedly demonstrated in earlier assessments reporting variations in toxicity and energy demand when upgrading or pretreatment is inefficient (Pires Costa et al., 2022; Das et al., 2022; Arena et al., 2023; Jeswani et al., 2021; Shan et al., 2023; Saleem et al., 2023; Garcia-Garcia et al., 2024; Maga et al., 2023; Yasar et al., 2021; El-Mekkawi et al., 2020; Ertürk et al., 2024). Gasification's superior carbon utilisation and fossil-resource efficiency directly reflect its near-complete thermal reforming chemistry, which converts the majority of waste carbon into syngas; yet its climate performance is constrained by oxygen production, energy demand and syngas-cleaning burdens noted in prior LCA–TEA comparisons (Xayachak et al., 2023; Afzal et al., 2023; Kang et al., 2025; Obaid et al., 2025; Kaczkó et al., 2024). Hydrocracking produced the highest-quality fuels, but the process requires continuous hydrogen input and intensive catalyst replacement; these operational constraints explain the elevated energy and toxicity impacts observed in both our results and previous hydrocracking optimisation and catalyst-focused studies (Azam et al., 2022; Ma et al., 2025; Talmadge et al., 2021). HTL's strong conversion efficiency is consistent with its ability to solubilise polymers in subcritical and supercritical water, but the extreme pressures and temperatures involved account for the high cumulative energy demand and aqueous-phase burdens widely documented in HTL research (Savage, 2024; Rahman et al., 2023). The behaviour of co-processing options further reinforces the role of blend compatibility, carbon tracking, and catalyst function, which multiple refinery-integration studies identify as determinants of environmental and operational feasibility (Lammens, 2022; Seiser et al., 2022; Ali et al., 2021). These mechanistic and operational drivers help explain why thermochemical studies in the literature show divergent outcomes—a conclusion echoed by major LCA reviews that attribute inconsistency to boundary choices, electricity-mix assumptions and differing allocation methods (Davidson et al., 2021; Alhazmi et al., 2021; Christopher et al., 2022; Zheng et al., 2023; Hermanns et al., 2025). Economic trends in this study also directly match known techno-economic structures: pyrolysis benefits from low capital cost; gasification suffers from expensive oxygen and cleanup systems; hydrocracking is dominated by hydrogen price; and HTL is constrained by utility demand, all of which reflect the financial behaviour reported in mixed-plastic TEA studies (Yadav et al., 2023; Lubongo et al., 2022; Larrain et al., 2020). When viewed together, these patterns, alongside regional waste-management findings, confirm that the feasibility of plastic-to-fuel technologies is fundamentally context-dependent—shaped by electricity-grid intensity, hydrogen availability, feedstock quality, and infrastructure constraints (Zhang et al., 2023; Nordahl et al., 2020; Xin et al., 2020; Gautam & Agrawal, 2020). Ultimately, this integrated evidence demonstrates that no pathway is universally optimal; instead, each offers conditional advantages that can only be realised when technological characteristics are matched with favourable regional and system-level conditions.

CONCLUSION

This study demonstrates that the sustainability of plastic waste-to-fuel technologies is inherently shaped by the interaction of process chemistry, energy demand, hydrogen requirements, and regional energy conditions. Pyrolysis and gasification emerge as the most balanced pathways, offering favourable combinations of environmental performance and economic feasibility when operated within low-carbon electricity contexts and supported by appropriate upgrading or syngas-valorisation strategies. Hydrocracking provides superior fuel quality but remains constrained by its dependence on hydrogen and catalyst resources, while hydrothermal liquefaction, though highly effective in converting polyolefin-rich waste, is limited by its extreme energy intensity and operational severity. These findings collectively show that no thermochemical pathway is universally optimal; instead, each offers conditional advantages that can only be realised when technology characteristics align with local infrastructure, market demands, and energy-system configurations. A harmonised assessment framework—such as the one applied in this study—provides critical clarity for decision-makers seeking to integrate plastic-to-fuel technologies into broader circular-economy and low-carbon strategies. Future work should prioritise high-quality empirical data from commercial-scale facilities, improved modelling of hydrogen and electricity decarbonisation pathways, and integrated optimisation across environmental, economic, and operational dimensions to support robust, region-specific deployment of plastic waste-to-fuel solutions.

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