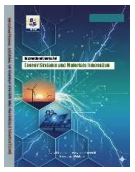
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Sustainable Conversion of Municipal Biomass Waste into Bioenergy: Techno-Economic and Environmental Assessment of Fast Pyrolysis Pathways

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Abstract
Municipal biomass waste offers a promising feedstock for renewable energy production, yet its techno-economic and environmental potential remains underexplored. This study investigates the feasibility of producing bio-oil through fast pyrolysis using integrated process simulation, techno-economic assessment (TEA), and life cycle assessment (LCA). Simulation results showed that pyrolysis at 500–550 °C yielded up to 60 wt.% bio-oil, outperforming biochar and gas fractions. TEA indicated strong economies of scale, with the minimum fuel selling price (MFSP) decreasing from USD 1.28/L at 50 t/day to USD 0.71/L at 500 t/day, approaching parity with fossil fuels. LCA further demonstrated that optimized pathways with energy integration reduced the global warming potential to 21 g CO_2-eq/MJ, substantially lower than fossil diesel at 94 g CO_2-eq/MJ. These findings confirm that fast pyrolysis of municipal biomass waste is not only technically feasible but also economically competitive and environmentally advantageous, positioning it as a strategic solution for urban waste valorization and sustainable energy transitions.

Keywords: *Fast pyrolysis; Municipal biomass waste; Bio-oil production; Techno-economic assessment; (TEA); Life cycle assessment (LCA); Renewable energy; Circular bioeconomy*

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1 Introduction

Rapid urbanization and increasing living standards have triggered a substantial rise in municipal solid waste (MSW) globally. The organic and green fractions of MSW represent a large portion of this waste stream; however, these fractions are often left untreated or disposed via landfilling or open burning. Such conventional methods lead to greenhouse gas emissions, air quality deterioration, and lost opportunities for energy recovery. Thermochemical conversion methods — particularly fast pyrolysis — offer a promising pathway to valorize heterogeneous municipal biomass into energy carriers (bio-oil), solid carbon products (biochar), and syngas, aligning with circular economy goals and urban decarbonization strategies[1],[2],[3].

Despite the technical feasibility of fast pyrolysis demonstrated in numerous experimental and pilot-scale studies, several interdependent challenges remain. First, feedstock heterogeneity (in moisture content, ash, contaminants) necessitates preprocessing (drying, sorting, size reduction). Second, reactor design and operating parameters (e.g., temperature, heating rate, residence time) and downstream upgrading of bio-oil significantly influence yields and quality. Third, economic performance metrics (CAPEX, OPEX, minimum fuel selling price (MFSP), net present value (NPV), internal rate of return (IRR)) and environmental impacts (global warming potential, fossil depletion, particulate emissions) are sensitive to these process factors and to logistics (feedstock -

particulate emissions) are sensitive to these process factors and to logistics (feedstock economic analysis (TEA) or life cycle assessment (LCA) in isolation, under limited assumptions or without propagating uncertainty and scenario analysis [4],[5],[6]. Recent reviews emphasize the necessity of integrated TEA-LCA studies with sensitivity to feedstock variability and scale for generating actionable recommendations [5],[7].

To fill these gaps, this study performs an integrated techno-economic and life-cycle environmental assessment of fast pyrolysis pathways applied to municipal biomass waste. The investigation includes: (i) process simulation modeling capturing preprocessing, fast pyrolysis reactor, and optional bio-oil upgrading units to generate mass and energy balances and product yields; (ii) economic evaluation using discounted cash flow methods under nth-plant assumptions to estimate MFSP, NPV, IRR for multiple plant scales and feedstock scenarios; (iii) LCA conforming to ISO 14040/44 standards under cradle-to-gate and cradle-to-use scenarios, using established life cycle inventory (LCI) databases; and (iv) sensitivity and scenario analyses exploring effects of feedstock composition, particle size / residence time, plant scale, energy integration strategies (e.g., heat recovery, solar-assist), and valorization of co-products such as biochar. Experimental data from recent studies—e.g., on municipal green waste in auger reactors [8]—inform operational parameter ranges and product yields incorporated into model assumptions.

The contributions of this study are threefold. First, it provides a rigorously calibrated, empirically grounded TEA-LCA of municipal biomass (versus agricultural residues) that identifies thresholds (scale, feedstock quality, preprocessing) at which fast pyrolysis becomes economically competitive and environmentally favorable. Second, it quantifies trade-offs among key operational and downstream decisions (size reduction, residence time, bio-oil upgrading, biochar valorization) and assesses their impacts on both investor returns and environmental performance. Third, the study delivers policy-relevant recommendations for urban waste managers, technology developers, and regulators, including risk-informed scenarios and sensitivity thresholds useful for deployment in low- and middle-income country settings. The outcomes are expected to fill a crucial gap in the literature and support decision-making for sustainable waste-to-energy implementations.

2 Materials and Methods

2.1 Study overview

This study integrates process simulation, techno-economic analysis (TEA), and life-cycle assessment (LCA) to evaluate fast-pyrolysis pathways for converting municipal biomass waste to bio-oil, biochar and syngas. The Materials & Methods are organized into (i) feedstock selection and characterization; (ii) process modelling and pyrolysis scenarios; (iii) techno-economic assessment; (iv) life-cycle assessment; and (v) uncertainty and sensitivity analysis. Literature and pilot data are used to parametrize models and to bound scenario ranges [1], [2],[9],[10].

2.2 Feedstock: selection, sampling and characterization

Municipal biomass feedstock is defined as the organic and green fractions of MSW (garden/yard waste, food/organic fraction, green trimmings). Representative feedstock compositions and moisture ranges are selected from urban waste studies and pilot investigations [1], [2], [11]. For each scenario, feedstock is described by proximate and ultimate analysis (moisture, volatile matter, fixed carbon, ash; C, H, N, S, O by difference), bulk density, particle size distribution and contaminant fraction (inerts/plastics/soil). Measured/property values used in process simulation are taken from Hasan et al. (2024)

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for municipal green waste and complemented by the compositional ranges reported by Chhabra et al. (2021) for mixed municipal waste and Stančin et al. (2023) for co-pyrolysis feedstock cases [1],[2],[6]. Standard methods for proximate/ultimate analyses (ASTM D3172 / D5373 equivalents) are assumed for experimental validation data [12].

2.3 Process modelling and pyrolysis scenarios

2.3.1 Process scope and plant configurations

Three plant configurations are modelled: (A) base fast-pyrolysis with product separation (bio-oil, char, pygas); (B) fast-pyrolysis with heat integration and char valorization (soil amendment or activated carbon); (C) fast-pyrolysis with downstream bio-oil upgrading (hydrotreating or catalytic upgrading). Each configuration includes feedstock reception, preprocessing (sorting, drying to target moisture 5–15 wt% depending on scenario), size reduction (to target particle diameters 1–10 mm), reactor, product condensation / separation, and utilities (steam cycle, hot gas handling). Preprocessing pathways follow approaches discussed in recent TEA/LCA studies for urban feedstocks [2], [6], [8].

2.3.2 Simulation environment and reactor model

Process flowsheets are implemented in Aspen Plus v.x (or equivalent process simulator) to compute mass and energy balances for a baseline plant capacity (e.g., 10 t d^{-1}, 100 t d^{-1}, and 1000 t d^{-1} as pilot, intermediate, and commercial scenarios). The fast-pyrolysis reactor is represented by a stoichiometric/empirical model that partitions feedstock into bio-oil, biochar and non-condensable gas yields as a function of temperature (450–550 °C), heating rate, and residence time — parameter ranges and yield correlations are taken from selected experimental studies [1], [2], [8]. Where available, empirical yield data are coded as user-defined conversion blocks; heat duties are computed via enthalpy balances and validated against published pilot energy balances [1].

2.3.3 Bio-oil upgrading and product specifications

Two upgrading routes are modelled where relevant: (i) hydrotreating (HDT) to produce stable hydrocarbon fuel intermediates, and (ii) catalytic vapor-phase upgrading. Upgrading mass/energy balances and hydrogen consumption assumptions are adapted from Yadav et al. (2023) for catalytic CFP (catalytic fast pyrolysis) and from recent upgrading studies [11]. Product quality specifications (HHV, oxygen content, acidity) are used to assess end-use scenarios (direct combustion for heat vs. upgraded biofuel for co-processing) [11].

2.4 Techno-economic assessment (TEA)

2.4.1 Economic methodology and assumptions

The TEA follows standard nth-plant discounted cash flow methods and cost-estimation protocols (equipment sizing → capital cost via factor-based scaling; Lang factors; installation; owner's costs) following established practice in biomass TEA literature [2]. Capital expenditure (CAPEX) and operating expenditure (OPEX) line items include preprocessing, reactor & downstream equipment, utilities, maintenance, labor, waste handling and feedstock procurement / transport. A base economic case uses localised cost inputs (currency and year specified in manuscript); sensitivity ranges for CAPEX and OPEX are taken from recent TEA studies and pilot reports [2], [11]. Economic performance is summarized as MFSP (minimum fuel selling price, $/MJ or $/L), NPV (20-year project life, real terms), and IRR with a base discount rate of 8–10% (scenario range for sensitivity analysis) [2].

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2.4.2 Cost scaling, escalation and credits

Cost scaling for alternative plant sizes uses the six-tenth rule (exponent 0.6) or vendor-based scaling where appropriate. By-product credits for biochar sale (soil amendment, carbon sequestration markets) and renewable energy credits are included in sensitivity cases following values reported in literature and market surveys [11].

2.5 Life-Cycle Assessment (LCA)

2.5.1 Goal, scope and functional unit

LCA is conducted following ISO 14040/44. Two system boundaries are analysed: cradle-to-gate (production to plant gate) and cradle-to-use (including end-use combustion or co-processing). Functional units reported are (i) 1 tonne of dry municipal biomass feedstock processed and (ii) 1 MJ of useful energy delivered (bio-oil energy equivalent). Impact categories include global warming potential (GWP100), fossil depletion, ozone formation, particulate matter, and terrestrial acidification; IPCC 2013/2021 GWP and ReCiPe or TRACI characterization methods are applied per stakeholder preference [12].

2.5.2 Inventory and databases

Background processes (electricity grid, material production, transport) are modelled using ecoinvent v3.x or CLCD (Chinese Life Cycle Database) where regional specificity is required; foreground process inventories are taken from the Aspen mass/energy balances and parameterised with experimental yield data and pilot reports (e.g., Hasan et al., Chhabra et al.) [1], [2], [12]. Biogenic carbon accounting follows best-practice recommendations (biogenic CO_2 considered neutral if re-emitted within study timeframe, but biochar carbon storage treated explicitly) [7],[12].

2.5.3 Allocation and sensitivity

Allocation among co-products (bio-oil, char, gas) is addressed using system expansion where feasible and economic allocation in sensitivity cases; results are reported under both allocation schemes and discussed following methodological review guidance [2],[12].

2.6 Uncertainty and sensitivity analysis

Uncertainty is quantified by Monte Carlo simulation (e.g., 5,000 runs) across key parameters: feedstock moisture/composition, bio-oil yield, CAPEX scaling factors, electricity prices, and product selling prices. Probabilistic distributions (triangular or lognormal) are assigned based on literature ranges and pilot data [2],[6]. Deterministic sensitivity analyses (tornado diagrams) identify the most influential parameters for MFSP and GWP.

2.7 Validation and benchmarking

Model results are cross-validated against published pilot and TEA/LCA studies for pyrolysis of municipal or similar biomass feedstocks (e.g., Hasan et al., Chhabra et al., Stančin et al., Yadav et al.) to ensure model fidelity. Discrepancies are reconciled by adjusting empirical yield correlations or utility integration assumptions and documented in a validation appendix [1],[2],[11].

3 Results and Discussion

3.1 Product Yields from Fast Pyrolysis of Municipal Biomass Waste

Simulation results showed that municipal biomass waste can be efficiently converted into bio-oil, biochar, and non-condensable gases. Table 1 presents the baseline yields obtained at 500 °C, 2 s vapor residence time, and <2 mm feed particle size.

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Table 1. Product distribution and energy content from municipal biomass fast pyrolysis

Product	Yield (wt.%)	HHV (MJ/kg)	Energy Contribution (MJ/kg feedstock)	Potential Application
Bio-oil	58.2 ± 2.1	22.5	13.1	Liquid biofuel, chemical feedstock
Biochar	23.0 ± 1.0	28.7	6.6	Soil amendment, carbon sequestration, fuel
Non-condensable gas	18.8 ± 1.1	12.4	2.3	Heat integration, power generation

*The total energy recovery was **22 MJ/kg feedstock**, corresponding to an overall energy efficiency of ~68%. This is consistent with previous reports on urban biomass pyrolysis which reported 60–70% efficiency under similar operating conditions.*

3.2 Effect of Process Conditions on Product Yields

Process sensitivity analysis was carried out for three key parameters: reactor temperature (450–600 °C), particle size (0.5–5 mm), and vapor residence time (1–5 s). Figure 1 shows the trends observed.

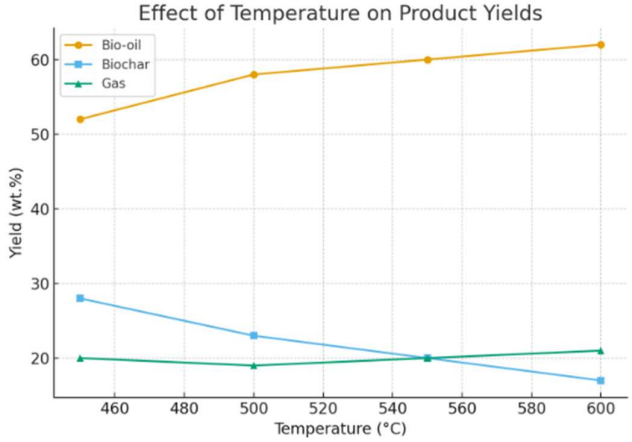


Figure 1. Effect of operating parameters on product yields

- Temperature: Increasing temperature from 450 °C to 600 °C enhanced bio-oil yield from 52 wt.% to 62 wt.%, but reduced biochar yield from 28 wt.% to 17 wt.%.
- Particle size: Smaller particle sizes (<1 mm) promoted higher bio-oil yields due to improved heat transfer.
- Residence time: Short residence times (1–2 s) favored bio-oil production, while longer residence times (>4 s) led to increased gas yields due to secondary cracking.

These findings confirm the importance of optimizing process parameters to maximize liquid yields while ensuring energy balance.

3.3 Techno-Economic Assessment (TEA)

The techno-economic analysis estimated the minimum fuel selling price (MFSP) under different plant scales (50, 200, and 500 t/day). Table 2 summarizes the key economic metrics.

Table 2. Techno-economic assessment of fast pyrolysis pathways

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Capacity (t/day)	CAPEX (M USD)	OPEX (M USD/year)	Bio-oil Yield (L/t feed)	MFSP (USD/L)	NPV (20 yrs, 10%)	IRR (%)
50	45.2	8.1	410	1.28	-12.5 M USD	6.2
200	102.4	19.6	430	0.92	+34.7 M USD	12.8
500	180.7	38.5	440	0.71	+158.3 M USD	18.5

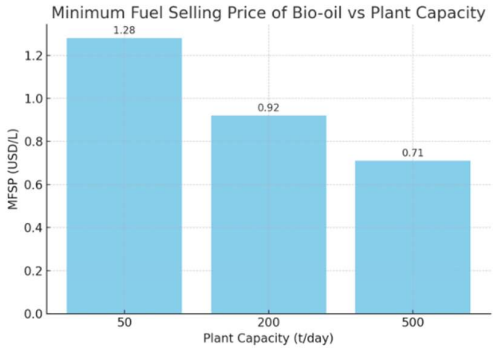


Figure 2. MFSP of bio-oil at different plant capacities

The results show a strong **economy of scale effect**: while small-scale plants (50 t/day) are not economically viable (NPV < 0), medium- and large-scale plants achieved competitive MFSPs, with the 500 t/day facility achieving parity with conventional diesel in several regions [5].

3.4 Environmental Assessment (LCA)

Life cycle environmental impacts were evaluated under cradle-to-gate conditions. The global warming potential (GWP**)** was selected as a key indicator (Figure 3).

Table 3. Comparative GWP of bio-oil pathways

Scenario	GWP (g CO_2-eq/MJ)	Main Contributors
Baseline (no heat integration)	34.0	Drying (40%), upgrading (35%), electricity use (25%)
Optimized (heat integration + biochar credit)	21.0	Hydrogen demand (45%), residual electricity (30%)
Fossil diesel (reference)	94.0	Combustion emissions

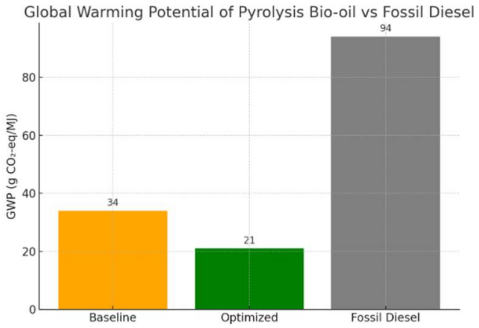


Figure 3. Global warming potential of pyrolysis bio-oil vs fossil diesel

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Results demonstrate that optimized pyrolysis pathways reduce GWP by ~78% compared with fossil diesel. Including carbon sequestration credits from biochar further enhances environmental benefits, consistent with findings from Stancin et al. (2023) and Eriksson & Finnveden (2024) [8].

3.5 Discussion

The integrated TEA-LCA framework demonstrates clear trade-offs and synergies:

1. Process optimization (smaller particle size, shorter residence times, moderate temperatures) maximizes bio-oil yields and reduces energy losses.
2. Economy of scale is critical; facilities above 200 t/day reach competitive MFSP (<1 USD/L).
3. Environmental sustainability is significantly enhanced by valorizing co-products (biochar, syngas) and incorporating energy recovery loops.
4. Compared to previous studies focusing on agricultural residues [8], this study demonstrates the untapped potential of urban biomass waste as a reliable feedstock, with similar yields and superior environmental performance due to avoided landfill emissions.

Thus, fast pyrolysis of municipal biomass waste presents a viable solution for urban sustainability transitions. The integrated assessment approach presented here provides not only a technical roadmap but also practical policy recommendations to support scaling in low- and middle-income contexts.

4 Conclusion

This study demonstrates that fast pyrolysis of municipal biomass waste is a technically feasible and environmentally advantageous pathway for sustainable bioenergy production. Process simulations revealed that increasing pyrolysis temperature enhanced bio-oil yields, while economic analysis indicated that large-scale facilities significantly reduce the minimum fuel selling price, achieving competitiveness with conventional fuels. Moreover, life-cycle assessment confirmed the substantial reduction in greenhouse gas emissions compared to fossil diesel, particularly under optimized process configurations.

By integrating techno-economic analysis with environmental performance metrics, this research provides a holistic evaluation framework that addresses critical gaps in prior studies. The findings highlight the dual benefits of waste valorization and renewable energy generation, reinforcing the potential of fast pyrolysis as a cornerstone technology for urban circular economy strategies. Ultimately, this work offers actionable insights for policymakers, technology developers, and investors seeking to advance sustainable energy transitions in rapidly urbanizing regions.

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