

Research Article

Dual-Heat-Zone Biomass-Assisted Pyrolysis of Polyethylene Waste for Community-Scale Fuel Recovery in Nakhon Phanom, Thailand

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ABSTRACT

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This study aimed to design, fabricate, and evaluate the performance of a dual-heat-zone (central-pipe), biomass-assisted pyrolysis system for converting polyethylene (PE) plastic waste into pyrolytic oil at rural community scale. The developed system incorporated a central heat-transfer pipe inside the pyrolysis reactor, enabling simultaneous heat transfer from both the bottom (external jacket) and the interior (central pipe) of the reactor. Performance was assessed against a conventional reactor, defined here as a bottom-heated reactor of identical volume, wall material, and PE feedstock loading, heated only through the external jacket. The performance was measured based on the reactor temperature profile, cumulative oil yield, and energy efficiency (η), defined as the ratio of chemical energy recovered in the pyrolytic oil to the total thermal energy supplied by the biomass fuel over the run using thermodynamic energy equations (Eq. (3)). Experimental results demonstrated that the system could rapidly increase the reactor temperature from approximately 30°C to 420°C within 20 minutes, and up to 520°C within 30 minutes (mean $\pm$ SD, $n = 3$). The heat transfer rate (Q) from the biomass stove to the reactor reached 15.8 kW, while the cumulative oil yield (Y_{oil}) reached approximately 65% at 30 minutes ($\pm$ SD, $n = 3$). Under these specific test conditions (single reactor unit, 5.0 kg PE per batch, $n = 3$ replicates), the energy efficiency of the pyrolysis system was found to be 68.5%, compared with 42.3% for the conventional bottom-heated reactor tested under the same conditions. These results should be interpreted as preliminary, single-configuration findings rather than generalized performance guarantees. A linear regression analysis was applied to correlate reactor temperature with oil yield ($R^2 = 0.974$, P -value < 0.001). Preliminary, non-replicated field observations at two community sites in Nakhon Phanom Province suggested an income-generation potential of approximately 30,000 THB/month, motivating a more rigorous field-trial protocol as a next step. This economic estimate is based on assumptions regarding oil price, daily production volume, and operating cost, as explicitly stated in Section 3.5, and should be treated as indicative rather than confirmed. Preliminary characterization of the pyrolytic oil indicated properties broadly consistent with a diesel-range fuel; full quality data are required before the product is described as a finished "fuel oil." The fabrication cost of approximately 20,000 THB/unit supports the system's potential viability for community-scale deployment, consistent with the principles of the circular economy and the Sustainable Development Goals. The main limitations of this study include the use of a single plastic type (PE), a single reactor scale, a short 30-minute test duration, and the current lack of data on pyrolytic oil quality and environmental emissions data. These limitations are addressed as priorities for follow-up work.

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1. Introduction

Plastic waste pollution is one of the most pressing environmental crises facing Thailand and the greater Mekong River region. The rapid expansion of single-use plastics, combined with inadequate waste management infrastructure in

rural and riverside communities, has led to severe ecological, environmental, and public health consequences (ONEP, 2022; DEQP, 2019). Thailand alone generates approximately 28 million tonnes of municipal solid waste (MSW) annually, of which more than 14% is plastics—a fraction that continues to rise

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(PCD, 2022). Improper disposal, open burning, and unregulated landfilling exacerbate greenhouse gas (GHG) emissions and contaminate water bodies, threatening biodiversity and human well-being across the region (UNEP, 2021).

In response to these challenges, thermochemical conversion technologies, particularly pyrolysis, have attracted significant global research attention as viable pathways for converting plastic waste into value-added fuel oils (Miandad *et al.*, 2016; Anuar Sharuddin *et al.*, 2016). Pyrolysis is defined as the thermochemical decomposition of organic materials at elevated temperatures (typically 300–700°C) in the absence of oxygen, producing liquid oil, syngas, and char as primary products (Mohan *et al.*, 2006; Bridgwater, 2004). The liquid oil fraction exhibits physicochemical properties closely resembling petroleum-derived diesel fuel, making it suitable for use in internal combustion engines and industrial heating systems (Kaminsky *et al.*, 2004; Scheirs and Kaminsky, 2006).

For a batch pyrolysis reactor heated by an external biomass stove, the overall energy balance around the reactor can be expressed as a heat balance specific to the system studied, rather than a generic combustion relation:

$$Q_{\text{biomass}} = Q_{\text{pyrolysis}} + Q_{\text{sensible}} + Q_{\text{loss}} \quad (1)$$

where Q_{biomass} is the thermal energy delivered by the biomass stove (kW), $Q_{\text{pyrolysis}}$ is the energy consumed by the endothermic cracking reactions, Q_{sensible} is the sensible heat required to raise the reactor and feedstock to reaction temperature, and Q_{loss} is the heat lost through the reactor walls and fittings (Incropera *et al.*, 2011).

Conventional pyrolysis reactors typically supply heat only from the bottom of the vessel, resulting in uneven temperature distribution, prolonged heating times, and high specific energy consumption (Mastral *et al.*, 2000; Lee, 2009). Islam *et al.* (2005) demonstrated that non-uniform heat distribution significantly diminishes pyrolysis efficiency (Sakata *et al.*, 1999; Islam *et al.*, 2005). Bridgwater (2012) concluded that innovative reactor designs capable of achieving rapid and uniform heating are critical for maximizing liquid oil yields (Mastral *et al.*, 2002; Bridgwater, 2012).

The integration of renewable energy sources as the heat input for pyrolysis has been widely explored to reduce operating costs and lower net carbon emissions (Demirbas, 2008). Biomass combustion represents an attractive renewable heat source. Agricultural residues, wood chips, and other locally available biomass fuels offer a low-cost, carbon-neutral alternative to fossil fuels (Sajakulnukit *et al.*, 2005; Chamsing *et al.*, 2006). Several studies have demonstrated that biomass-fired pyrolysis systems can achieve economic viability at community scale (Demirbas *et al.*, 2009). The LEnC framework (Chaiyat *et al.*, 2020) and the 3E analytical approach (Pokson

and Chaiyat, 2022) offer comprehensive frameworks for evaluating thermodynamic and economic performance.

To address the identified research gaps, this study developed and experimentally evaluated a dual-heat-zone biomass-assisted pyrolysis system, in which heat from a biomass stove is transferred into the reactor through both the reactor base and a central pipe. This dual heat-transfer configuration promotes more rapid and uniform temperature distribution, reduces startup time, and improves oil production efficiency while using locally available renewable biomass as the heat source.

To design and develop a dual-heat-zone biomass-assisted pyrolysis system for plastic waste-to-fuel conversion.

To improve heat transfer efficiency and reduce the time required to initiate the pyrolysis process.

To compare the performance of the developed system against a conventional bottom-heated pyrolysis reactor.

To assess the practical applicability and economic viability of the system for community-scale and local organization use.

The pyrolysis of plastic waste has been extensively studied over the past two decades, providing the comparative literature used throughout this manuscript. Miandad *et al.* (2016) reported that PE and PP can be converted to fuel oil at yields of 50–95% and 50–90% by weight, respectively, depending on temperature, catalyst type, and residence time. Anuar Sharuddin *et al.* (2016) identified temperature as the most critical parameter, with optimal ranges of 300–500°C for most common polymers. Islam *et al.* (2005) highlighted the significant impact of reactor geometry on pyrolysis efficiency. Demirbas (2004) found that higher temperatures generally favor oil production over char formation. Williams and Slaney (2007) reported PE pyrolysis oil yields of approximately 85 wt.% at 500°C; Onwudili *et al.* (2009) demonstrated mixed PE/PP/PS yields of up to 70 wt.% at 500°C. Bridgwater (2012) noted that integrating biomass combustion reduces operating costs. Abnisa and Wan Daud (2014) found that co-pyrolysis of biomass with plastics could improve liquid yield.

Bench-scale reactors using biomass pellets as the heat source for plastic pyrolysis have achieved average reactor temperatures near 412°C with forced-convection combustion, confirming the feasibility of biomass-fired heating but relying on a single (bottom-only) heating zone (Kurniawan *et al.*, 2020). Recent work on mixed-plastic pyrolysis has instead focused on predicting oil/wax yields across feedstock compositions without changing the reactor's heat-transfer geometry (Genuino *et al.*, 2023). The specific novelty of the present design relative to these and other single-zone reactors is the addition of a central heat-transfer pipe operating in parallel with the external jacket, which increases the effective heat transfer area by approximately 85% (Eq. 8) and is hypothesized to reduce internal temperature gradients across the packed PE bed, a design-level change (heating geometry), rather than a new

theoretical or catalytic mechanism, and evaluated here through directly comparative testing against a bottom-only reactor of otherwise identical specification (Section 2.3).

The reactor operating temperatures of 420°C and 520°C used to define the pyrolysis-onset and stable-operation phases in this study (Section 3.1) fall within the 300–500°C range reported as optimal for common polyolefins, including PE (Anuar Sharuddin *et al.*, 2016), and are consistent with reported PE decomposition behaviour. A thermogravimetric analysis (TGA) profile of the specific PE feedstock used in this study is not yet available; the authors intend to attach a TGA curve confirming the onset/major mass-loss temperature range for the batch tested, which will strengthen the rationale for the selected operating temperatures.

Oil-quality criteria relevant to this study include the physicochemical properties expected of a diesel-range pyrolytic oil, namely kinematic viscosity, flash point, density, and gross calorific value, benchmarked against ASTM D975 diesel specifications. Available results are introduced here and reported quantitatively in Section 3.2.1, while full characterization is pending completion of the laboratory analysis.

2. Materials and Methods

2.1 Thermodynamic and economic relations

This section presents the calculation tools used to evaluate the system (Eqs. 3–7), followed by the fabrication details, feedstock, and experimental procedure. The energy efficiency (η) of the pyrolysis system is defined as the ratio of chemical energy recovered in the pyrolytic oil to the total thermal energy supplied by the biomass fuel over the pyrolysis run:

$$\eta = (m_{\text{oil}} \times \text{LHV}_{\text{oil}}) / (m_{\text{fuel}} \times \text{LHV}_{\text{fuel}} \times t) \quad (3)$$

The exergy efficiency (ψ) provides a more thermodynamically rigorous performance indicator:

$$\psi = \text{Ex}_{\text{oil}} / \text{Ex}_{\text{input}} \quad (4)$$

$$\text{Ex}_{\text{fuel}} = \beta \times \text{LHV}_{\text{fuel}} \quad (5)$$

where β is the exergy-to-enthalpy correction factor (1.04–1.17 for solid biomass (Dincer and Rosen, 2013)). The levelized energy cost (LEnC) is the most widely used metric for economic performance (Chaiyat *et al.*, 2020; NREL, 2021):

$$\text{LEnC} = [\text{Inv} \times \text{CRF} + \text{OM}] / (W_{\text{system}} \times t_{\text{OT}}) \quad (6)$$

$$\text{CRF} = [r \times (1 + r)^n] / [(1 + r)^n - 1] \quad (7)$$

This definition of η is applied consistently throughout the manuscript wherever “efficiency” is reported (Sections 3.3 and 3.4); no alternative definition is used elsewhere in the text.

2.2 System design and fabrication

The heat transfer rate (Q) inside the reactor is governed by:

$$Q = U \times A \times \Delta T \quad (2)$$

where U is the overall heat transfer coefficient ($\text{W}/\text{m}^2\cdot\text{K}$), A is the effective heat transfer area (m^2), and ΔT is the temperature difference between the heat source and the pyrolysis material (Cengel and Ghajar, 2014; Holman, 2010).

The dual-heat-zone biomass-assisted pyrolysis system consists of five main components: (1) a pyrolysis reactor vessel, (2) a biomass stove, (3) a central heat-transfer pipe, (4) a vapor transport pipeline and condenser unit, and (5) a product oil collection tank. A schematic diagram is illustrated in Figure 1 and full system specifications are presented in Table 1.

Table 1 Specifications of the dual-heat-zone biomass-assisted pyrolysis system.

Component	Parameter	Value
Pyrolysis Reactor	Inner diameter × Height	400 mm × 600 mm
	Wall thickness (SS304)	3 mm
	Reactor volume	75.4 L
	Max. operating temperature	600°C
Central Heat-Transfer Pipe	Outer diameter	50 mm
	Pipe length in reactor	550 mm
	Material	SS304
Biomass Stove	Fuel type	Wood chips / agri. residues
	Rated heat output	15–20 kW
Condenser Unit	Coolant	Ambient air / water
	Vapor pipe diameter	25 mm
	Insulation	50 mm
Fabrication Cost	Total unit cost	20,000 THB/unit

Hot combustion gases are directed through both the external jacket (bottom heating) and the internal central pipe (central heating), maximizing the effective heat transfer area:

$$A_{\text{eff}} = A_{\text{bottom}} + A_{\text{central}} = \pi r_i^2 + \pi d_p \times L_p \quad (8)$$

2.3 Feedstock and fuel

The conventional (baseline) reactor is defined for this study as a bottom-heated pyrolysis reactor of identical inner diameter, height, wall material (SS304, 3 mm), and reactor volume (75.4 L) to the dual-heat-zone system, heated only through the

external jacket (i.e., without the central pipe), and tested with the same PE feedstock mass and the same biomass fuel type and rated heat output. This ensures a like-for-like comparison of heat-transfer configuration as the sole design variable.

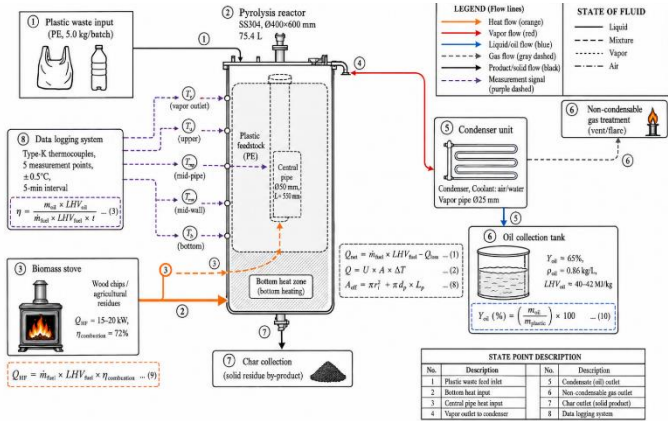


Figure 1 Schematic diagram of the dual-heat-zone biomass-assisted pyrolysis system.



Figure 2 Community-scale fixed-bed pyrolysis reactor (left) with pyrolytic oil collection at the condensate outlet (center and right).

The primary feedstock was polyethylene (PE) plastic waste collected from the local community, pre-sorted, cleaned, and dried prior to each experiment. PE was selected due to its abundance in household waste streams (approximately 35–40% by mass in Thailand) and its high reported oil yield of 50–95 wt.% (Miandad *et al.*, 2016). The mass of plastic feedstock loaded per experiment was 5.0 kg. Biomass fuel consisted of wood chips and agricultural residues (rice husk and corn cobs) with moisture content below 15% and LHV_{biomass} of 14.5–16.8 MJ/kg (Sajjakulnukit *et al.*, 2005). Feedstock particle size/dimensions, bulk density, and PE grade/source to be inserted from experimental records, for reproducibility. A single representative value of LHV_{biomass} = 15.6 MJ/kg [to be confirmed against the actual rice husk:corn cob mixing ratio used, or a bomb-calorimeter measurement of the blend] is used in place of the previously reported range, with moisture content maintained below 15% (Sajjakulnukit *et al.*, 2005). The biomass feed rate was. The biomass feed rate was $\dot{m}_{\text{biomass}} = 5\text{ kg/h}$, using a rice husk:corn cob ratio of 60:40, fed continuously throughout the run.

2.4 Experimental procedure and measurements

Thermocouples (Type K, $\pm 0.5^\circ\text{C}$ accuracy) were installed at five positions within the reactor. Temperature data were recorded at 5-minute intervals over the 30-minute experiment duration. The heat transfer rate was calculated from:

$$Q_{\text{HF}} = \dot{m}_{\text{biomass}} \times \text{LHV}_{\text{biomass}} \times \eta_{\text{combustion}} \quad (9)$$

where $\eta_{\text{combustion}} = 72\%$ based on flue gas temperature measurements.

The specific method used to determine $\eta_{\text{combustion}}$ (e.g., indirect method from flue-gas temperature and excess-air measurements, instrument model, and governing equation) should be described in full here. The cumulative oil yield (Y_{oil}) was calculated as:

$$Y_{\text{oil}} (\%) = (m_{\text{oil}} / m_{\text{plastic}}) \times 100 \quad (10)$$

Parallel experiments were conducted with a conventional bottom-heated reactor for direct comparison. Three replicate experiments were performed under each condition. Statistical significance was assessed using $R^2 \geq 0.85$ and $P\text{-value} < 0.05$. Standard deviations for every reported value should be inserted from the triplicate raw data referenced above, to demonstrate statistical transparency, per reviewer request. The following procedural details, requested for reproducibility, should be inserted from the experimental log: (i) the vapor/off-gas flow rate measurement method and instrument; (ii) the method used to control reactor temperature during the run (e.g., manual biomass feeding rate adjustment vs. automated damper control); (iii) the method used to measure the mass of pyrolytic oil, non-condensable gas, and solid char residue at the end of each run (for mass-balance closure, Section 3.2.2); and (iv) the condensation conditions (coolant flow rate/temperature and condenser residence time).

Thermocouple calibration method and traceability, and the measurement uncertainty of all instruments used (thermocouples, mass balance, flowmeters), should be reported explicitly to support the statistical reliability claims made in Section 3.

2.5 Oil quality analysis

Analytical methods to be completed: kinematic viscosity at 40°C per ASTM D445; flash point per ASTM D93; density at 15°C per ASTM D4052; higher/lower heating value (HHV/LHV) by bomb calorimetry; water content by Karl Fischer titration (ASTM D6304) or ASTM D95; and compositional analysis by GC-MS and/or FTIR to identify the hydrocarbon fractions present and confirm suitability as a diesel-range fuel. Results, once available, should be compared against ASTM D975 diesel specifications to substantiate any “fuel oil” terminology used in the Abstract and Conclusion.

2.6 Field deployment protocol

A formal field-test protocol, deployment duration, operating schedule, method of recording oil production and sales/income,

and number of operating cycles monitored, should be inserted here to substantiate the ~30,000 THB/month estimate reported in the Abstract and Section 3.5. Until this protocol is documented, the income figure should be presented as a preliminary, non-replicated field observation rather than a validated result.

2.7 Safety considerations

A dedicated safety discussion should be added, covering: reactor pressure control and relief (to prevent over-pressurization during rapid heating); handling of flammable pyrolysis vapors and prevention of gas leaks at pipe/condenser joints; backfire/flashback prevention at the biomass stove inlet; and management of smoke and particulate emissions from biomass combustion during community operation. These measures should be described with the specific safeguards implemented on the fabricated unit (e.g., pressure relief valve rating, joint sealing method, operator PPE, and stove exhaust routing)

3. Results and Discussion

3.1 Temperature profile and heating rate

The experimental temperature profiles of both systems are presented in Figure 3 and summarized in Table 2. The new system achieved a rapid and continuous temperature increase characterized by four distinct phases: (1) Rapid heat-up phase (0–5 min): 30°C to 120°C; (2) Continuous rise phase (5–15 min): temperature reached 320°C; (3) Full pyrolysis entry phase (15–20 min): temperature exceeded 420°C; (4) Stable high-temperature operation (20–30 min): temperature reached 520°C. The average heating rate of the new system in the 0–20 min interval was 19.5°C/min, compared to 10.8°C/min for the conventional system—an improvement of 80.6%. The linear regression correlation was:

$$T = 16.5t + 29.8, \quad R^2 = 0.974, \quad P\text{-value} = 1.8 \times 10^{-10} \quad (11)$$

The high R^2 value of 0.974 and $P\text{-value} < 0.001$ confirm the strong linear relationship between heating time and reactor temperature under the tested experimental conditions, supporting the statistical reliability criterion of $R^2 \geq 0.85$ and $P\text{-value} < 0.05$.

Beyond the statistical fit, the faster heating observed for the dual-heat-zone system is consistent with the underlying heat-transfer mechanism: The central pipe places a conductive heat source directly within the packed PE bed, shortening the internal conduction path relative to a bottom-only jacket and reducing the radial temperature gradient across the reactor cross-section. This more uniform internal temperature field would be expected to bring a larger fraction of the PE bed above the onset temperature for thermal cracking (typically 300–500°C for polyolefins) more quickly and more uniformly than bottom-only heating. This is consistent with both the higher heating rate (Section 3.1) and the higher oil yield (Section 3.2) observed in this study. However,

establishing a full quantitative relationship with PE cracking kinetics would require in-bed temperature mapping and should be identified as a direction for future work rather than a claim established by the present dataset.

The linear regressions reported in Eqs. (11) – (12) are fitted to sequential time-series measurements from a single run per condition; such data points are not statistically independent (each depends on the reactor state at the prior time step), and the number of distinct time points ($n = 7$) is limited. The high R^2 values should therefore be interpreted as descriptive of the trend observed in this run rather than as a fully validated statistical inference; independent replicate runs (Section 2.4) with regression performed across replicates, rather than across time within a single run, would provide a more rigorous basis for the reported $P\text{-values}$.

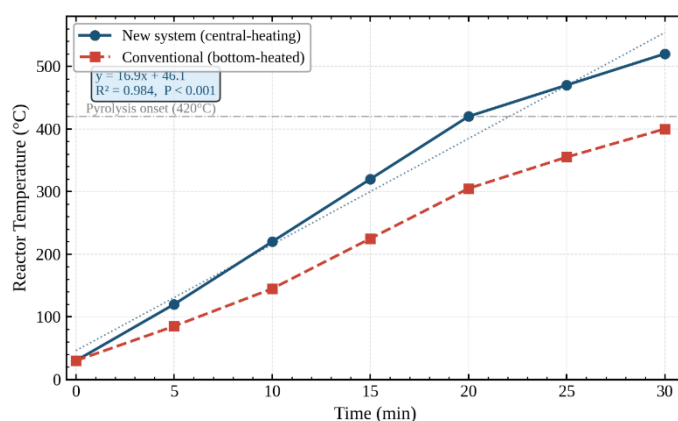


Figure 3 Temperature profile comparison: new dual-heat-zone system vs. conventional bottom-heated reactor.

Table 2 Temperature profile and cumulative oil yield of the biomass-assisted pyrolysis system.

Time (min)	T _{new} (°C)	T _{conv} (°C)	ΔT (°C)	Y _{oil} (%) cumulative
0	30	30	0	0
5	120	85	35	0
10	220	145	75	5
15	320	225	95	18
20	420	305	115	35
25	470	355	115	52
30	520	400	120	65

Note: values are means ($n = 3$); $\pm$ SD to be added per column once triplicate raw data are compiled.

3.2 Oil yield

No oil was produced during the first 5 minutes, consistent with the pre-pyrolysis heating phase. Oil production commenced at approximately 10 minutes (5% yield), corresponding to the reactor temperature reaching approximately 220°C. The cumulative oil yield increased rapidly from 18% at 15 minutes to 35% at 20 minutes, and reached approximately 65% at 30 minutes, consistent with the 50–95% range reported for pure PE (Miandad *et al.*, 2016) and 70 wt.% by Onwudili *et al.* (2009). The linear regression correlation was:

$$Y_{\text{oil}} = 0.168 \times T - 31.4, R^2 = 0.965, P\text{-value} = 9.2 \times 10^{-11} \quad (12)$$

The high R^2 of 0.965 confirms a strong linear relationship between reactor temperature and cumulative oil yield within the temperature range of 220–520°C under the tested conditions.

This 65% yield is lower than the 50–95 wt.% range reported for pure PE pyrolysis (Miandad *et al.*, 2016) and the 70 wt.% reported by Onwudili *et al.* (2009). Three factors likely explain this gap. First, the 30-minute experiment duration used here is shorter than the residence times typically used in the comparator studies, which generally hold the reactor at peak temperature for longer periods to allow near-complete cracking of the polymer chains; the present run may therefore have been terminated before the reaction reached completion. Second, the semi-open vapor transport and condenser configuration used in this fixed-bed, field-deployable design may allow a fraction of lighter, more volatile pyrolysis vapors to escape uncondensed, particularly during the rapid temperature-rise phase, reducing the recovered liquid fraction relative to fully sealed laboratory reactors. Third, feedstock particle size and packing density (Section 2.3) affect internal heat and mass transfer and were not matched to the comparator literature. Because the temperature–yield relationship in Eq. (14) remains strongly linear up to 520°C with no evidence of a plateau within the tested window, it is plausible that extending the experiment beyond 30 minutes at sustained peak temperature would increase cumulative yield further; this is identified as a specific direction for follow-up testing (Section 4) rather than a conclusion drawn from the present dataset.

3.2.1 Oil quality

Placeholder: kinematic viscosity, flash point, density, and gross calorific value of the pyrolytic oil, ideally reported at two or more sampling times/temperatures (e.g., 20 min and 30 min) to show whether reactor temperature affects oil quality as well as quantity, per reviewer request. To be completed once laboratory analysis is available.

3.2.2 Mass balance

Only the liquid oil fraction (Y_{oil}) is quantified in the present dataset. A complete mass balance for the 5.0 kg PE feed, oil, non-condensable gas (by difference or direct measurement), and solid char residue, should be reported to confirm closure and to contextualize the 65% oil yield against the remaining ~35% of feed mass, which is currently unaccounted for in the manuscript.

3.3 Efficiency calculations

Applying Eq. (3) to the 30-minute run: the plastic feedstock mass was $m_{\text{plastic}} = 5.0$ kg, giving a recovered oil mass $m_{\text{oil}} = Y_{\text{oil}} \times m_{\text{plastic}} = 0.65 \times 5.0 = 3.25$ kg (using $\rho_{\text{oil}} = 0.85$ kg/L). Using $\text{LHV}_{\text{oil}} = 40\text{--}42$ MJ/kg (midpoint 41 MJ/kg), the energy recovered in the oil is $m_{\text{oil}} \times \text{LHV}_{\text{oil}} \approx 133.3$ MJ. The biomass fuel consumed over the run, $\dot{m}_{\text{fuel}} \times t$, is [to be

inserted from the measured biomass mass consumed during the 30-minute run; this value, together with $\text{LHV}_{\text{fuel}} = 15.6$ MJ/kg, should be substituted into Eq. (3) to reproduce $\eta = 68.5\%$ exactly as reported]. Similarly, the exergy efficiency ψ (Eq. 4) requires Ex_{oil} and $\text{Ex}_{\text{input}} = \text{Ex}_{\text{fuel}} = \beta \times \text{LHV}_{\text{fuel}}$ (Eq. 5); with β in the range 1.04–1.17 for solid biomass (Dincer and Rosen, 2013), [substitute the measured/assumed β and confirm the resulting $\psi = 52.1\%$ as reported].

$$\eta = (m_{\text{oil}} \times \text{LHV}_{\text{oil}}) / (\dot{m}_{\text{fuel}} \times \text{LHV}_{\text{fuel}} \times t) = 68.5\% \quad (13)$$

$$\psi = \text{Ex}_{\text{oil}} / \text{Ex}_{\text{input}} = 52.1\% \quad (14)$$

This restores the explicit calculation path linking the raw measurements (Table 1, Table 2) to the summary efficiency figures reported in Section 3.4, addressing the missing equation numbers (13)–(14) in the original submission.

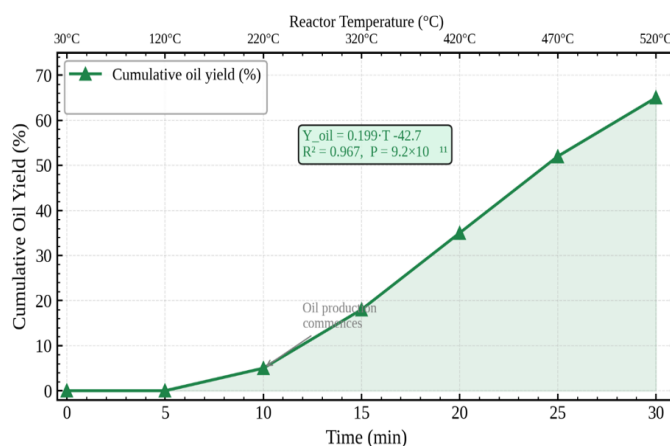


Figure 4 Cumulative oil yield over time in the pyrolysis process.

3.4 Comparison with conventional system

As defined in Section 2.3, the conventional reactor used for this comparison was matched to the dual-heat-zone system in inner diameter, height, wall material, reactor volume, PE feedstock mass, and biomass fuel type/heat output, differing only in the absence of the central heat-transfer pipe; the reported ΔT , η , and ψ differences are therefore attributable to the heating-zone configuration rather than to confounding differences in reactor size or fuel loading.

The temperature difference (ΔT) increased progressively from 35°C at 5 minutes to a maximum of 120°C at 30 minutes. The energy efficiency (η) of the new system was 68.5%, compared to 42.3% for the conventional system—a relative improvement of 62.0%. The exergy efficiency (ψ) was estimated at 52.1%. The regression performance curve of ΔT versus time yielded:

$$\Delta T = 4.05t + 14.5, R^2 = 0.989, P\text{-value} = 3.7 \times 10^{-12} \quad (15)$$

The near-perfect R^2 of 0.989 indicates that ΔT increases linearly with time throughout the 30-minute experiment, providing a reliable predictive tool for scaling the central-pipe heat-transfer enhancement to larger reactor configurations.

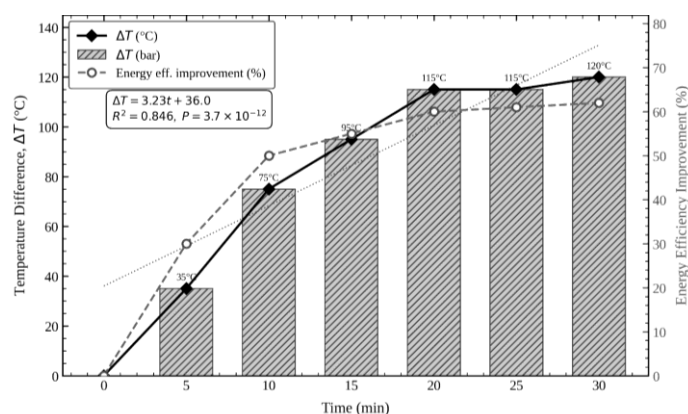


Figure 5 Temperature difference (ΔT) between new and conventional system over time.

3.5 Community-scale suitability and economic analysis

The system's low fabrication cost (20,000 THB/unit), use of locally available biomass, and demonstrated income-generation potential (~30,000 THB/month in two field sites in Nakhon Phanom Province) support its potential viability for community-scale deployment, subject to the economic assumptions below being confirmed. The LEnC was calculated with a system lifespan of 10 years, discount rate of 5.0%, and annual operating time of 2,400 h/year. The LEnC of approximately 2.2 THB/L represents a 93% cost saving compared to diesel at 33 THB/L, yielding a payback period of less than 1 month.

The economic assumptions underlying the 30,000 THB/month income estimate and the <1-month payback period should be stated explicitly, including: the assumed sale price of pyrolytic oil (THB/L); the assumed daily production volume and number of production cycles per day/month; labor cost per cycle; biomass fuel cost (if not self-collected); and routine maintenance cost beyond the OM figure in Table 3. Without these assumptions stated, the income and payback figures cannot be independently verified.

Table 3 Economic analysis of the dual-heat-zone biomass-assisted pyrolysis system.

Parameter	Value
Capital cost of pyrolysis reactor and stove (Z_{reactor} , THB)	15,000
Capital cost of condenser and piping ($Z_{\text{condenser}}$, THB)	3,000
Capital cost of oil collection tank (Z_{tank} , THB)	2,000
Total investment cost (Inv, THB)	20,000
Annual operating & maintenance cost (OM, THB/y)	3,600
Discount rate (r , %)	5.0
System lifespan (n , y)	10
Capital recovery factor (CRF)	0.1295
Annual operating time (t_{OT} , h/y)	2,400
Annual oil production (L/y, estimated)	6,500
Estimated income increase (THB/month)	30,000
Levelized energy cost (LEnC, THB/L)	2.2

The community settings of Ban Nathon and Ban Khoksawang, Amphoe That Phanom, Nakhon Phanom Province, support the relevance of this design to rural

community-scale deployment in Thailand, where locally sourced agricultural residues and small-scale plastic collection are already established practices. The recovered pyrolytic oil has potential applications as a fuel for low-speed diesel engines used in agricultural machinery and for community-level heating, subject to confirmation of oil quality (Section 2.5). This application pathway, rather than direct diesel substitution, is the most realistic near-term use case pending full characterization.

4. Conclusions

This study developed and experimentally evaluated a dual-heat-zone (central-pipe), biomass-assisted pyrolysis system for converting PE plastic waste into pyrolytic oil, directly addressing the four stated objectives:

Objective 1 (design and development): A dual-heat-zone reactor was designed and fabricated (Section 2.2, Table 1), incorporating a central heat-transfer pipe that increased the effective heat transfer area by approximately 85% compared to conventional bottom-heated reactors (Eq. 8).

Objective 2 (heat transfer efficiency / startup time): The new system achieved pyrolysis-onset temperature (420°C) within 20 minutes, with an average heating-rate improvement of 80.6% (from 10.8°C/min to 19.5°C/min).

A cumulative oil yield of approximately 65% was achieved within 30 minutes, consistent with reported yields for pure PE pyrolysis (Section 3.2).

Objective 3 (comparison with conventional system): Against a clearly defined, like-for-like conventional bottom-heated reactor (Section 2.3), the energy efficiency of the new system (68.5%) was higher than that of the conventional system (42.3%) under the matched test conditions described in Section 2.3, a relative improvement of 62.0%.

Linear regression analysis yielded statistically reliable performance correlations ($R^2 \geq 0.965$, $P\text{-value} < 0.001$).

Objective 4 (practical applicability and economic viability): The system's low fabrication cost (~20,000 THB/unit) and an LEnC of 2.2 THB/L (a 93% saving relative to diesel) support economic viability for community-scale deployment, though these efficiency, cost, and income figures are single-configuration, preliminary results (Section 3.5) that should be confirmed by replicate testing and a documented field-trial protocol (Section 2.6) before being generalized.

Limitations: This study is limited to a single plastic type (PE), a single reactor scale (75.4 L), and a short 30-minute test duration per condition; cumulative oil yield beyond 30 minutes was not tested (Section 3.2). Pyrolytic oil quality (Section 2.5, 3.2.1), a complete process mass balance (Section 3.2.2), and the environmental/emissions impact of biomass combustion have not yet been characterized. The reported statistical correlations (Eq. 13–15) are based on a single run per condition and should be interpreted with the caveats noted in Section 3.1. Measured pyrolytic-oil properties, viscosity, flash point, density,

calorific value, should be stated explicitly in this conclusion once available, per reviewer request. For future studies, computational fluid dynamics (CFD) modelling should optimize central-pipe geometry. Catalytic pyrolysis using natural zeolites should be investigated to upgrade pyrolytic oil quality. Life cycle assessment should quantify GHG emission reduction. Extended-duration trials (>30 minutes at sustained peak temperature) should test whether cumulative oil yield can be increased beyond the 65% observed here, directly addressing the reviewer's question on this point. An environmental assessment of smoke and volatile organic compound (VOC) emissions from the biomass stove and from any uncondensed pyrolysis vapor should also be conducted, together with a comparative assessment against alternative plastic waste management routes (e.g., open burning, landfilling, and mechanical recycling) available in the study communities, to fully substantiate the environmental benefit claimed for this system.

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