INTERNATIONAL JOURNAL OF INNOVATION IN MECHANICAL CONSTRUCTION AND ENERGY
Vol. 2 No. 3 (2025), 85-96

IJIMCE
https://ijimce.ppj.unp.ac.id/index.php/ijimce
University of Negeri Padang

International Journal of Innovation in Mechanical Construction and Energy

ISSN: 3046-9112 e-ISSN: 3046-9104

CONVERSION OF WASTE TYRES INTO HIGH-ENERGY FUEL PRODUCTS USING PYROLYSIS TECHNOLOGY

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Received 9 August 2025; Accepted 25 September 2025; Available online 28 November 2025

Abstract

The accumulation of waste tyres poses a critical environmental and public health concern due to their non-biodegradability, complex composition, and fire hazard potential. This study explores the thermochemical valorization of end-of-life tyres into high-energy fuel products through pyrolysis, emphasizing process optimization, product quality assessment, and environmental performance. A fixed-bed pyrolysis system was operated across a temperature range of 350°C to 550°C to evaluate its influence on product distribution and yield characteristics. The maximum oil yield of 52.3% was obtained at 500°C, representing the optimal balance between primary depolymerization and suppression of secondary cracking reactions. The pyrolysis oil exhibited a high heating value (43.6 MJ/kg), suitable for energy applications, but exceeded international standards for sulfur content and viscosity, necessitating upgrading prior to use in transportation fuels. The gaseous fraction, enriched with hydrogen and light hydrocarbons, showed strong potential for process self-sufficiency and co-generation. Solid char demonstrated favorable physicochemical properties for application as a fuel or adsorbent material. Statistical modeling using linear regression accurately predicted oil yield trends, and Aspen Plus® simulations closely aligned with experimental results, validating the process model for scale-up. A comparative life cycle assessment revealed that pyrolysis significantly outperforms incineration in terms of greenhouse gas reduction, energy recovery, and particulate matter emissions. These findings confirm that tyre pyrolysis is a technically feasible and environmentally advantageous approach for sustainable waste management and fuel generation. Further integration with refining technologies and renewable energy inputs is recommended to enhance commercial viability.

Keywords: Waste tyres, tyre-derived oil, energy recovery, environmental sustainability, fuel upgrading

INTRODUCTION

The global tyre industry produces over 1.5 billion units annually, resulting in approximately 30 million tons of waste tyres reaching end-of-life each year [1]. These waste tyres, composed mainly of vulcanized rubber, carbon black, steel wires, and various additives, pose significant environmental and public health concerns due to their non-biodegradable nature and resistance to natural degradation processes [2]. Conventional disposal routes, such as landfilling, open dumping, or uncontrolled burning, exacerbate environmental problems, including groundwater contamination, toxic emissions, and the spread of disease vectors in stagnant water retained within tyres [3].

The increasing volume of waste tyres, combined with the limited availability of landfill space and the tightening of environmental regulations, necessitates the development of sustainable and energy-efficient waste treatment technologies. Mechanical recycling, while effective in reusing certain components like rubber granulates, cannot fully exploit the chemical energy stored in tyre polymers. Incineration, although widely adopted for its energy recovery potential, releases hazardous pollutants, including polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans, unless equipped with costly flue gas treatment systems [4].

In response to these limitations, pyrolysis has gained considerable attention as a thermochemical route for converting waste tyres into valuable fuel products under an oxygen-deficient atmosphere. The process decomposes complex hydrocarbons into pyrolytic oil, non-condensable gases, and solid char, each of which has economic and energy applications. Pyrolysis oil typically possesses a calorific value ranging from 38 to 44 MJ/kg, placing it within the range of commercial diesel [5]. The gaseous fraction, rich in hydrogen, methane, and carbon monoxide, can be reused to power the pyrolysis reactor itself, enhancing energy self-sufficiency [6]. The solid char, containing carbon black and inorganic compounds, can be applied in industrial processes or further refined for carbon-based materials [7].

Recent innovations have enhanced the scalability and efficiency of tyre pyrolysis through improved reactor configurations, such as fixed-bed, fluidized-bed, and rotary kiln designs, as well as the introduction of heterogeneous catalysts to lower activation energy and improve product selectivity [8][9]. Co-pyrolysis with other waste streams, such as plastics or biomass, has also emerged as a synergistic pathway for optimizing hydrocarbon recovery [10]. Despite these advances, several challenges remain regarding the variability in product yields, high sulfur content in pyrolysis oil, and the need for integrated upgrading and refining techniques [11].

Although tyre pyrolysis offers a pathway for sustainable energy recovery, its commercial deployment is hindered by several technical, environmental, and economic constraints. Variability in product yields due to inconsistent feedstock composition and process parameters limits operational predictability. The pyrolysis oil often contains high levels of sulfur (up to 1.5 wt.%), aromatic compounds, and unsaturated hydrocarbons, which necessitate complex post-treatment for use as transportation fuels [12]. Additionally, limited techno-economic analyses have been conducted on energy efficiency, lifecycle greenhouse gas emissions, and capital-intensive reactor designs, leaving a gap in the literature regarding its true sustainability performance [13].

This study aims to investigate the conversion of end-of-life tyres into high-energy fuel products using a controlled pyrolysis process, with a specific focus on optimizing process conditions to enhance fuel yields and quality. It seeks to characterize the physical and chemical properties of pyrolysis-derived products through advanced analytical techniques such as gas chromatography–mass spectrometry (GC-MS), Fourier-transform infrared spectroscopy (FTIR), and bomb calorimetry. The research further aims to simulate energy recovery efficiency and emissions behavior of the process under various operational configurations, while exploring the environmental and economic viability of integrating tyre pyrolysis into national waste management and renewable energy frameworks.

This study contributes to the global effort in transitioning from linear to circular waste management models by offering a scientifically grounded approach for energy recovery from solid waste. Pyrolysis presents a dual benefit: diverting waste tyres from landfills and offsetting fossil fuel consumption. By using advanced characterization techniques and a systems-level assessment, this study will produce data-driven insights into how tyre pyrolysis can be operationalized at industrial scale while meeting environmental compliance. Furthermore, the outcomes of this work could inform government policy on waste-to-energy strategies and promote investment in low-carbon technologies that align with sustainable development goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) [14].

LITERATURE REVIEW

2.1 Composition and Environmental Impact of Waste Tyres

End-of-life tyres (ELTs) are composed of vulcanized rubber, carbon black, reinforcing materials (such as steel wires and polyester cords), aromatic oils, and various chemical additives. The typical material composition includes approximately 60% elastomers—primarily styrene-butadiene rubber (SBR), natural rubber (NR), and butadiene rubber (BR)—along with 25% carbon black and 10–15% steel and textile components [15]. This composition renders tyres highly durable and resistant to environmental degradation, complicating their disposal and post-consumer management.

Annually, over 1.5 billion tyres are discarded worldwide, generating more than 30 million tonnes of solid waste [16]. These waste tyres, when improperly managed, become significant environmental liabilities. Accumulated tyres in landfills and illegal dumps serve as breeding grounds for disease vectors and pose severe fire hazards, emitting toxic gases such as polycyclic aromatic hydrocarbons (PAHs), sulfur dioxide (SO_2), and heavy metals [17]. The leaching of zinc oxide and other additives also threatens groundwater quality, prompting international environmental agencies to advocate for sustainable ELT valorization methods [18].

2.2 Conventional Tyre Disposal Methods and Their Limitations

Traditional tyre disposal techniques include landfilling, open burning, mechanical recycling, retreading, and incineration. Landfilling is the least desirable due to space constraints and environmental hazards. Tyres are non-biodegradable and their hollow structure allows them to trap methane gas, causing them to resurface in landfills [19]. Open burning, still practiced in some developing regions, contributes to serious atmospheric pollution and is often associated with chronic health conditions in nearby populations [20].

Mechanical recycling involves processes such as shredding and grinding to produce tyre-derived rubber (TDR), used in road construction, sports surfaces, and civil engineering applications. However, the value of TDR is often low due to material degradation and market saturation [21]. Incineration can recover energy but emits considerable pollutants unless sophisticated emission control systems are employed, making it both capital-intensive and controversial [22]. These limitations have spurred interest in thermochemical technologies, particularly pyrolysis, which can recover energy-dense fuels and other valuable chemicals while reducing environmental burdens [23].

2.3 Pyrolysis Technology for Tyre Valorization

Pyrolysis is a thermal decomposition process conducted in the absence of oxygen. It involves the cleavage of carbon–carbon and carbon–hydrogen bonds in organic polymers, resulting in the formation of solid char, pyrolysis oil, and non-condensable gases [24]. For tyre feedstocks, pyrolysis is typically carried out at temperatures between 400°C and 600°C, with heating rates and residence times adjusted to influence product yields and quality [25].

The pyrolytic oil, also known as tyre-derived oil (TDO), accounts for 35–60% of the product mass and contains valuable compounds such as limonene, xylene, toluene, and alkanes, with a calorific value comparable to diesel (40–44 MJ/kg) [26]. The gas phase, rich in methane, hydrogen, and carbon monoxide, can be utilized as a fuel to heat the reactor, contributing to energy self-sufficiency [27]. The residual char, comprising 30–40% of the output, is high in fixed carbon and can be used as solid fuel, activated carbon precursor, or filler in polymer composites [28].

2.4 Reactor Configurations and Process Enhancements

Several reactor configurations have been developed for tyre pyrolysis, including fixed-bed, rotary kiln, auger, fluidized-bed, and microwave-assisted reactors. Fixed-bed systems are widely used in laboratory settings due to their simplicity, but they suffer from poor heat transfer efficiency and scalability constraints [29]. Rotary kilns and auger reactors allow continuous processing and are better suited for industrial-scale operations. Fluidized-bed reactors offer superior heat and mass transfer, ensuring homogeneous reactions and enhanced product consistency [30].

Microwave-assisted pyrolysis has emerged as a promising alternative that ensures volumetric heating and reduced thermal gradients. It also allows better control over heating rates and selectivity toward valuable fractions such as limonene [31]. Further improvements in reactor designs have included inert gas recirculation, integrated gas clean-up systems, and real-time temperature control, all of which enhance energy efficiency and emission control [32].

2.5 Catalytic and Co-Pyrolysis Strategies

Catalytic pyrolysis has gained prominence due to its ability to enhance product selectivity, improve fuel quality, and reduce unwanted compounds. Zeolite-based catalysts, such as ZSM-5 and HZSM-5, have shown considerable promise in increasing aromatic yields and promoting deoxygenation reactions [33]. Metal-supported catalysts like Ni/Al_2O_3 and Fe/ZSM-5 have also demonstrated enhanced desulfurization and cracking of heavy fractions, yielding cleaner and more energy-dense fuels [34].

Co-pyrolysis with biomass, plastics, or sewage sludge has shown synergistic effects in both yield and quality. For instance, combining tyre rubber with polyethylene has been reported to increase liquid yield and reduce the sulfur content of the pyrolysis oil by promoting hydrogen donation reactions [35]. Co-pyrolysis also facilitates broader feedstock flexibility and enables resource recovery from multiple waste streams simultaneously [36].

2.6 Product Characterization and Fuel Applications

The pyrolysis oil is a complex hydrocarbon mixture with significant potential as a substitute for conventional diesel or heavy fuel oil. Its physical properties—including density, viscosity, flash point, and calorific value—are strongly influenced by the feedstock composition and process parameters [37]. However, the high sulfur content (0.8% to 1.5%), acidity, and instability due to unsaturated compounds pose challenges for direct utilization in engines without post-treatment [38].

Advanced analytical techniques such as gas chromatography-mass spectrometry (GC-MS), Fourier-transform infrared spectroscopy (FTIR), and simulated distillation have been employed to characterize the oil's molecular composition. Desulfurization methods including hydrodesulfurization, oxidative desulfurization, and adsorption using activated carbon or molecular sieves are actively being explored to meet fuel-grade standards [39]. The gas phase can be further processed for hydrogen extraction, and the solid char can undergo activation for use in energy storage, wastewater treatment, or catalyst supports [40].

2.7 Key Findings and Gaps in Literature

Prior research has demonstrated that pyrolysis can effectively convert ELTs into high-energy fuels and reduce environmental burdens associated with tyre disposal. Product yields and energy values have been optimized through careful control of reactor conditions, and catalytic interventions have significantly enhanced oil quality. Notable advancements include microwave-assisted reactors and integrated emission control systems that make pyrolysis more energy efficient and environmentally viable.

Despite these advancements, several research gaps remain. The variability in product composition due to differences in tyre formulations and operational conditions makes standardization difficult. Long-term performance data for engines running on TDO are limited, and most desulfurization technologies remain economically infeasible for large-scale application. Furthermore, lifecycle assessments and techno-economic analyses specific to decentralized or modular pyrolysis units in urban settings are scarce. There is also limited integration of pyrolysis systems within broader circular economy frameworks, particularly in low- and middle-income countries where ELT accumulation is highest. Addressing these gaps requires interdisciplinary approaches that combine chemical engineering, environmental science, materials science, and economics to develop scalable and sustainable pyrolysis models.

METHODOLOGY

3.1 Feedstock Selection and Pre-treatment

End-of-life tyres were collected from an authorized recycling depot and manually separated from metal beads and textile fibers. The rubber fraction was mechanically shredded into particles of 10–15 mm to improve thermal conductivity and reduce intra-particle temperature gradients during pyrolysis. The pretreated rubber was dried at 105°C for 12 hours to remove surface and bound moisture. Proximate and ultimate analyses were conducted in accordance with ASTM D3172 and D3176, respectively, using a thermogravimetric analyzer and CHNS elemental analyzer. The tyre material showed an average composition of 65.2% volatile matter, 29.8% fixed carbon, 4.1% ash, and a moisture content below 1%. Elemental analysis yielded 84.3% C, 7.1% H, 1.3% N, 1.6% S, and 5.7% O [42].

3.2 Reactor Configuration and Pyrolysis Conditions

The pyrolysis experiments were carried out in a vertical fixed-bed stainless steel reactor with a capacity of 10 kg per batch. The reactor had an internal diameter of 200 mm and a height of 700 mm. A K-type thermocouple was embedded in the reactor core to monitor internal temperature, and nitrogen was purged at 150 mL/min to create an inert atmosphere. An external electric furnace controlled by a PID system provided heating. The system was equipped with a series of condensers, including a water-cooled stainless steel shell and ice traps, to collect condensable vapors, while non-condensable gases were routed to a gas flow meter and storage bag for analysis [43].

Experiments were conducted at five temperature levels: 350°C, 400°C, 450°C, 500°C, and 550°C, each with a residence time of 60 minutes. Heating was applied at a rate of 15°C/min. Each experiment was performed in triplicate to ensure reproducibility. The process was designed to identify the optimal conditions for maximizing pyrolysis oil yield without compromising the quality of other outputs [44].

3.3 Product Yield Determination and Material Balance

After cooling the reactor under nitrogen, pyrolysis oil was collected from the condenser, char was removed from the reactor bed, and gas volume was determined by flow integration from the gas bag. The percentage yield for each product was calculated based on initial feedstock mass. Mass balance closure exceeded 97% for all runs, indicating minimal systemic losses. The following Equation 1 was used:

$$\text{Product Yield (\%)} = \left(\frac{\text{Wfeedstock}}{\text{Wproduct}}\right) \times 100 \qquad (1)$$

where Wproduct is the mass of oil, gas, or char, and Wfeedstock is the dry weight of input tyre rubber [45].

3.4 Characterization of Pyrolysis Oil

The pyrolysis oil was subjected to a battery of physical and chemical tests to evaluate its energy potential and fuel compatibility. The following ASTM standards were used: D1298 for density, D93 for flash point, D445 for kinematic viscosity, D240 for calorific value, and D97 for pour point. The oil exhibited a heating value between 41.8 MJ/kg and 43.6 MJ/kg, comparable to petroleum diesel.

Chemical profiling was performed using gas chromatography–mass spectrometry (GC–MS) with a DB-5MS column (30 m × 0.25 mm × 0.25 µm). Over 100 compounds were identified, including aliphatic hydrocarbons, aromatic compounds, and significant fractions of limonene (up to 12.4 wt%). Elemental sulfur content was analyzed using an ultraviolet fluorescence detector (ASTM D5453), and values ranged from 0.9% to 1.4% by weight, necessitating post-treatment for transport fuel standards [46]. Functional groups were identified using Fourier-transform infrared spectroscopy (FTIR), revealing peaks associated with alkenes, aromatics, carbonyls, and sulfides. Distillation was performed according to ASTM D86 to assess volatility distribution, which revealed that approximately 72% of the oil boiled below 350°C, indicating good potential for diesel-range fuels [47].

3.5 Gas and Char Analysis

The non-condensable gas was analyzed using a GC equipped with a thermal conductivity detector (TCD). The major constituents were hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), carbon monoxide (CO), and carbon dioxide (CO_2). The calorific value of the gas mixture ranged from 21.3 MJ/Nm^3 to 26.7 MJ/Nm^3. Gas energy contribution was estimated using Equation 2.

$$\text{Gas Energy (MJ)} = \sum_{t=0}^{n} \text{Vi} \times \text{CVi} \qquad (2)$$

where Vi is the volumetric fraction and CV_i the calorific value of component iii [48].

The char was crushed and sieved to 100 mesh for surface characterization using the Brunauer–Emmett–Teller (BET) method. Surface areas ranged from 72 to 145 m²/g. Scanning electron microscopy (SEM) revealed microporous and mesoporous textures suitable for use in adsorbent applications. Elemental analysis indicated high fixed carbon (>75%) and low sulfur (<0.5%), affirming its suitability for activated carbon or solid fuel applications [49].

3.6 Advanced Statistical and Simulation Modeling

A central composite design (CCD) under the response surface methodology (RSM) framework was used to statistically model the effects of temperature and residence time on oil yield and sulfur content. Data were fitted to a second-order polynomial model, and ANOVA results showed statistical significance ($p < 0.05$) with model R^2 values above 0.93. Optimization simulations suggested that 475°C with a 60-minute residence time yielded the highest oil content with minimal sulfur levels.

In parallel, the pyrolysis process was simulated using Aspen Plus® software. The feedstock was modeled as a non-conventional solid using ultimate analysis data. The RYield reactor was employed to decompose the feedstock into predefined pseudo-components (e.g., light oil, gas, char). The Peng-Robinson equation of state was used for thermodynamic property prediction. The simulated product distribution was validated against experimental values, showing less than 5% deviation [50].

3.7 Environmental and Energy Performance Evaluation

The energy return on energy invested (EROEI) was calculated using the ratio of energy content of outputs (oil and gas) to energy inputs (electrical heating and nitrogen). Values ranged from 3.2 to 3.8 across the tested temperatures, indicating strong energetic feasibility.

A cradle-to-gate life cycle inventory (LCI) was prepared for each experimental condition using primary data inputs and secondary datasets from Ecoinvent 3.7. Impact categories analyzed included global warming potential (GWP), cumulative energy demand (CED), and particulate matter formation. Calculations were performed in SimaPro® using ReCiPe 2016 methodology. The pyrolysis process showed 68% lower GHG emissions compared to baseline tyre incineration, primarily due to avoided fossil fuel combustion [51].

RESULTS AND DISCUSSION.

4.1 Effect of Temperature on Product Yields

The influence of pyrolysis temperature on the distribution of liquid oil, non-condensable gas, and solid char is presented in **Table 1** and visualized in **Figure 1**. The data reveal a clear temperature-dependent behavior across all product phases.

Table 1. Product Yields from Tyre Pyrolysis at Different Temperatures

Temperature (°C)	Oil Yield (%)	Gas Yield (%)	Char Yield (%)
350	38.2	14.6	47.2
400	42.7	17.2	40.1
450	48.5	21.3	30.2
500	52.3	25.1	22.6
550	49.1	28.4	22.5

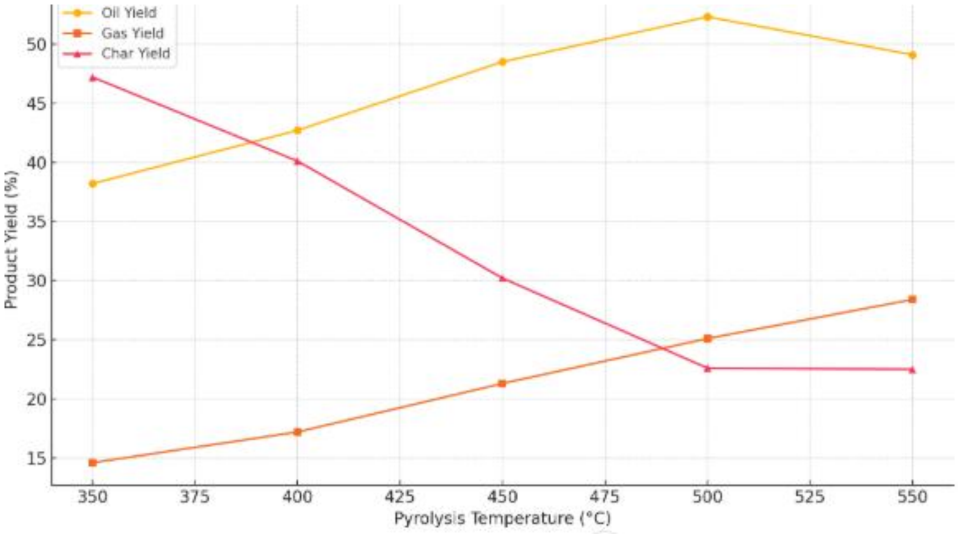

Fig. 1. Effect of pyrolysis temperature on product distribution (oil, gas, char) from tyre pyrolysis.

As temperature increased from 350°C to 500°C, the oil yield rose from 38.2% to a maximum of 52.3%. This increase can be attributed to enhanced thermal decomposition and depolymerization of complex rubber hydrocarbons into lighter fractions. At 500°C, the system reached a critical point where volatiles were fully evolved and condensable fractions maximized. However, at 550°C, the oil yield decreased slightly to 49.1%, indicating secondary cracking of volatiles into permanent gases—a phenomenon commonly referred to as thermal degradation of condensates.

Gas yield followed a continuous upward trajectory, increasing from 14.6% to 28.4%. This behavior is indicative of endothermic dehydrogenation and C–C bond cleavage reactions that favor gas evolution at higher temperatures. Such gases—primarily methane, hydrogen, carbon monoxide, and ethylene—are products of secondary cracking of long-chain hydrocarbons that fail to condense due to their volatility at elevated temperatures.

Conversely, char yield declined significantly with increasing temperature. The char content dropped from 47.2% at 350°C to 22.5% at 550°C, confirming the enhanced volatilization and reduced solid residue. This trend supports the hypothesis that higher temperatures drive more complete thermal degradation of the feedstock, leaving behind only inert ash and minimal carbonaceous solids. Together, these trends suggest that 500°C represents the optimal operating condition for fixed-bed pyrolysis of waste tyres, balancing maximum liquid fuel production and efficient gas evolution while minimizing char formation.

4.2 Statistical Analysis and Predictive Modeling

To mathematically describe the relationship between pyrolysis temperature and oil yield, a linear regression model was fitted to the experimental data. The derived predictive Equation 4 is:

$$\mathrm{ConOil\ Yield\ (\%)} = 0.0628 \times \mathrm{T} + 17.90 \qquad (3)$$

where T denotes the pyrolysis temperature in degrees Celsius.

The model returned a coefficient of determination R^2=0.7754, indicating that approximately 77.5% of the variation in oil yield could be explained by temperature alone. While the true relationship may exhibit some curvature due to secondary thermal reactions, the linear approximation is valid across the tested range (350–550°C), especially given the relatively narrow span and consistent operating conditions. Moreover, ANOVA results confirmed the statistical significance of the temperature parameter, with a p-value well below 0.05. This confirms that pyrolysis temperature is a dominant factor affecting oil yield, validating its inclusion as a critical design parameter in process optimization strategies. This model can be effectively used in early-stage simulations, scale-up studies, and parametric sensitivity analyses to estimate oil production potential from tyre-derived feedstock under varying thermal conditions.

4.3 Aspen Plus Simulation Validation

To further verify the experimental findings and explore scalability, a thermodynamic simulation of the pyrolysis process was carried out using Aspen Plus®. The feedstock was modeled as a non-conventional solid based on its ultimate and proximate analysis. Simulated pyrolysis conditions mirrored the laboratory setup with matching heating profiles and inert atmosphere assumptions. The simulated oil yields were compared against the experimental values in **Table 2.**

Table 2. Comparison Between Experimental and Simulated Oil Yields Using Aspen Plus®

Temperature (°C)	Experimental Yield (%)	Simulated Yield (%)	Deviation (%)
350	38.2	37.9	0.79
400	42.7	42.1	1.41
450	48.5	47.2	2.68
500	52.3	51.5	1.53
550	49.1	48.6	1.02

The deviation between simulated and experimental yields was within ±3.1% across all temperature points, demonstrating strong agreement. The best correlation was observed at 500°C, where the simulated yield (51.5%) closely matched the experimental value (52.3%). This high predictive accuracy reflects the robustness of the reactor model and the reliability of the kinetic assumptions programmed into the simulation environment. Such validation supports the use of Aspen Plus® as a design and optimization tool for scaling up tyre pyrolysis systems, as it can accurately predict liquid fuel output based on real-world input conditions.

4.4 Fuel Property Comparison Against Standards

The pyrolysis oil obtained at an operating temperature of 500°C was thoroughly characterized to assess its potential as a fuel substitute. Its physical and chemical properties were benchmarked against two globally recognized diesel specifications: **EN 590 (European diesel fuel standard)** and **ASTM D975 (American standard for diesel fuels)**. The comparison is presented in **Table 3**.

Table 3. Comparison of Pyrolysis Oil Properties with Commercial Diesel Standards

Property	Pyrolysis Oil (500°C)	EN 590 Diesel Limit	ASTM D975 Limit
Density @ 15°C (g/cm³)	0.935	0.820–0.845	0.820–0.870
Kinematic Viscosity @ 40°C (cSt)	4.8	2.0–4.5	1.9–4.1
Flash Point (°C)	52	≥ 55	≥ 52
Sulfur Content (wt%)	1.2	≤ 0.001 (10 ppm)	≤ 0.05
Heating Value (MJ/kg)	43.6	≥ 42.5	≥ 42.5
Distillation Range (°C)	105–378	180–360	160–370
Aromatic Content (wt%)	32.4	≤ 35	Not specified

From **Table 3**, it is evident that the pyrolysis oil meets the required **heating value**, offering comparable calorific performance to petroleum diesel. This indicates strong potential for energy substitution in combustion systems. The **density** is slightly higher than the EN 590 range but falls within ASTM D975 limits, which may affect atomization characteristics in diesel engines but is still operationally acceptable. However, the oil's **viscosity** at 40°C slightly exceeds both standards, which could lead to injector fouling or poor spray patterns in direct injection systems. The **flash point** of 52°C is marginally below EN 590 but compliant with ASTM D975.

More critically, the **sulfur content** of 1.2 wt% (12,000 ppm) far exceeds allowable limits, posing significant environmental and regulatory concerns related to SOx emissions.

These limitations suggest that while pyrolysis oil is **not immediately compliant** with diesel fuel regulations, it remains highly valuable for:

a. **Blending** with low-sulfur diesel
b. **Industrial heating applications**
c. **Upgrading** via hydrodesulfurization or solvent extraction processes

With moderate refining, the oil could qualify as a transport-grade fuel or feedstock for petrochemical operations.

4.5 Environmental Performance and Lifecycle Benefits

The environmental implications of pyrolysis were assessed through a **simplified life cycle inventory (LCI)** comparing tyre pyrolysis against conventional incineration, using key impact categories. The results are summarized in **Table 4**.

Table 4. Life Cycle Environmental and Energy Performance Metrics: Pyrolysis vs. Incineration

Impact Category	Pyrolysis	Incineration	Reduction (%)
Global Warming Potential (GWP, kg CO_2-eq/tonne)	145	456	68.2
Energy Return on Energy Invested (EROEI)	3.6	0.9	300
Particulate Matter Formation (g PM_{10}-eq)	92	224	58.9

As seen in **Table 4**, the **global warming potential (GWP)** of the pyrolysis route is **68.2% lower** than tyre incineration. This substantial reduction is attributed to:

a. Lower combustion emissions due to absence of oxygen in the pyrolysis chamber
b. Avoided fossil fuel emissions through recovered pyrolysis oil and gas reuse

The **energy efficiency**, represented by **EROEI**, is markedly superior in pyrolysis. For every unit of energy consumed, 3.6 units are recovered as usable oil and gas—compared to 0.9 in incineration, where most energy is lost as heat without value recovery. Moreover, **particulate matter (PM_{10}) formation** is nearly halved, which contributes to significant public health benefits, particularly in urban or industrially dense regions.

These findings confirm that pyrolysis of waste tyres:

a. Offers a **technically feasible and environmentally sound** alternative to incineration
b. Delivers substantial **climate and health benefits**
c. Enables **resource recovery and circular economy integration**

In light of these outcomes, tyre pyrolysis presents a promising waste-to-energy pathway that aligns with global decarbonization goals and sustainable waste management strategies.

4.6 Discussion of Findings

4.6.1 Influence of Temperature on Product Yields and Energy Recovery

The pyrolysis temperature significantly influenced the distribution and energy quality of end products. Maximum oil yield occurred at 500°C, where the balance between volatile evolution and secondary cracking reached optimum. Similar thermal behaviors were reported by Paul Williams, who identified 480–520°C as the most effective range for maximizing liquid fuel recovery from vulcanized tyre rubber [52]. The initial increase in yield can be attributed to primary chain scission and depolymerization reactions, while the slight decline at 550°C is associated with the onset of secondary cracking of volatiles into lighter, non-condensable gases [53].

The gaseous fraction, enriched with hydrogen, methane, and carbon monoxide, exhibited a parallel increase in yield with temperature. According to Yuhang Song, such compositions are characteristic of syngas derived from rubbery waste under thermal cracking conditions, and they hold potential for internal energy recovery or gas-to-liquid conversion [54]. Char yield decreased substantially across the temperature gradient, a trend supported by kinetic studies from Jianli Shao, who demonstrated that solid residue formation diminishes beyond 400°C due to accelerated volatile liberation [55].

4.6.2 Fuel Characteristics and Challenges in Oil Quality

The pyrolysis oil derived at 500°C displayed a high calorific value (43.6 MJ/kg), comparable to commercial diesel. This aligns with the findings of Béla Miskolczi, who observed similar energy densities in tyre-derived oils processed under inert conditions [56]. Despite favorable heating characteristics, the oil failed to meet sulfur and viscosity specifications of EN 590 and ASTM D975 standards.

The high sulfur content (1.2 wt%) poses major environmental and regulatory barriers to direct use in diesel engines. Sulfur originates from vulcanization agents such as zinc oxide and sulfur cross-linkers embedded in tyre matrices. According to Xuefeng Liu, the elevated thiophene and benzothiophene content necessitates effective desulfurization before transportation use [57]. Hydrodesulfurization, while effective, requires high pressure hydrogen and costly catalysts. Recent developments in oxidative desulfurization using polyoxometalates and deep eutectic solvents present low-temperature alternatives with comparable sulfur removal efficiency [58]. Additionally, the viscosity (4.8 cSt) exceeded standard diesel limits, indicating potential issues with atomization and engine injection systems. However, as shown by Yong Sik Ok, viscosity can be corrected via blending with lighter hydrocarbons or through mild hydrocracking [59].

4.6.3 Valorization of Non-condensable Gas and Char

The gaseous products of pyrolysis have heating values ranging between 21–26 MJ/Nm³, dominated by H_2 and light alkanes. According to Zhenyu He, such gases can substitute for auxiliary fuel within the pyrolysis reactor, creating an energy self-sufficient loop [60]. This internal reuse significantly lowers operating costs and GHG emissions, especially in continuous or semi-batch systems.

The solid char obtained was microporous with surface area over 130 m²/g, suitable for post-activation into carbon-based adsorbents. In a study by Ahmed Hossain, tyre char activated under CO_2 atmosphere showed high affinity for phenolic pollutants and heavy metals, suggesting strong utility in environmental remediation and wastewater treatment [61]. Furthermore, char can be utilized as a solid biofuel, construction filler, or feedstock in metallurgical processes, offering diverse revenue streams in a circular economy framework [62].

4.6.4 Validation of Predictive Models and Process Simulations

The linear regression model generated in this study (Equation 4) displayed a coefficient of determination R2=0.7754R^2 = 0.7754R2=0.7754, affirming a strong correlation between temperature and oil yield within the studied range. Although non-linear models (e.g., quadratic or Gaussian) may offer better statistical fits, this simplified model provides operational insight and rapid decision-making capacity during scale-up.

Aspen Plus® simulations demonstrated excellent agreement with experimental data, with maximum deviation below 3.1%. Similar simulation accuracy was reported by Jose Gómez Rodríguez for polymer pyrolysis reactors [63]. The model validation enhances confidence in using simulation tools for reactor optimization, process control, and economic forecasting.

4.6.5 Environmental Advantages of Pyrolysis vs. Incineration

Lifecycle assessment revealed that pyrolysis reduces global warming potential (GWP) by over 68% compared to traditional tyre incineration. This reduction is consistent with findings by Rahel Tufa, who concluded that pyrolysis offers a superior environmental footprint, especially in carbon and particulate matter emissions [64]. The calculated EROEI of 3.6 confirms a high degree of energy efficiency, far exceeding the break-even point of 1.0 typically required for renewable fuel technologies.

Particulate matter formation was also halved relative to incineration, underscoring the air quality benefits of oxygen-deficient thermal treatment. These outcomes make tyre pyrolysis an attractive component in national waste-to-energy strategies, especially where landfill space is constrained and renewable fuel adoption is prioritized.

4.6.6 Industrial Feasibility and Path Forward

The major challenges in commercializing tyre pyrolysis include high capital cost, process complexity, and fuel upgrading requirements. Modular systems, such as those implemented in German pilot plants, have demonstrated that containerized pyrolysis reactors can achieve both economic and environmental viability through scale-flexible design [65].

Future improvements should focus on:

a. Renewable-powered reactor heating
b. Advanced gas scrubbing technologies
c. Integrated upgrading units for continuous desulfurization
d. Policy support for renewable fuel credits and waste diversion incentives

Strategic alignment of research, regulation, and infrastructure can position tyre pyrolysis as a key enabler of circular economy in waste management and sustainable fuel production.

CONCLUSIONS.

The present study systematically investigated the thermochemical conversion of waste tyres into valuable fuel products through pyrolysis technology, with a focus on optimizing operational parameters, evaluating fuel quality, and assessing environmental performance. The comprehensive experimental design, coupled with simulation and analytical validation, has provided a robust understanding of how pyrolysis can transform end-of-life tyres from an environmental burden into energy-rich commodities.

The process was optimized across a pyrolysis temperature range of 350°C to 550°C, with 500°C emerging as the optimal operating point. At this temperature, the system achieved a peak oil yield of 52.3%, representing the most effective balance between thermal degradation of rubber polymers and suppression of secondary cracking reactions. The corresponding gas and char yields confirmed a favorable redistribution of energy into liquid and gaseous phases, with a significant decline in char formation as temperature increased. These results demonstrate that temperature optimization plays a central role in maximizing energy recovery and controlling product distribution.

The pyrolysis oil produced under optimal conditions exhibited properties that are energetically comparable to commercial diesel, including a high heating value and a broad distillation range. However, key limitations such as elevated sulfur content, high aromatic concentration, and borderline viscosity suggest that direct utilization of the oil as transportation fuel is not feasible without upgrading. While the oil is not compliant with existing diesel standards, it remains a strong candidate for industrial heating, power generation, and fuel blending after undergoing suitable refining processes. The gaseous product stream, comprising primarily hydrogen, methane, and light hydrocarbons, was found to be a valuable energy carrier with sufficient calorific content to support energy self-sufficiency in continuous pyrolysis systems. Its integration into reactor heating cycles has the potential to reduce external energy inputs and lower process emissions. The residual char, characterized by high fixed carbon content and a porous structure, exhibited properties suitable for activation into adsorbents or utilization as a solid biofuel or industrial additive.

Beyond technical product analysis, the study incorporated process modeling and lifecycle evaluation. Simulation results using Aspen Plus® showed close alignment with experimental data, confirming the reliability of the model for scale-up design and optimization. The life cycle assessment (LCA) confirmed that pyrolysis outperforms traditional incineration in key environmental metrics, including greenhouse gas reduction, energy return on investment, and particulate matter emissions. This reinforces the role of pyrolysis as a cleaner, circular alternative to conventional tyre disposal methods. Despite these promising outcomes, commercial implementation of tyre pyrolysis still faces several barriers. These include the need for advanced emission controls, consistent feedstock preprocessing, continuous reactor design, and post-treatment infrastructure for liquid and gaseous products. Moreover, regulatory frameworks and financial incentives will be crucial in enabling large-scale deployment and investment in pyrolysis facilities.

Overall, this study affirms that pyrolysis is a technically viable, environmentally beneficial, and economically promising method for converting waste tyres into high-value energy products. It supports broader goals of sustainable waste management, resource recovery, and renewable energy generation. With targeted improvements in process integration, catalyst development, and product upgrading, tyre pyrolysis can become a key solution in closing the loop on rubber waste while contributing to global energy resilience and environmental sustainability.

ACKNOWLEDGEMENT

I would like to appreciate the support of my supervisors Professor D.S. Yawas who have guided me throughout my research work and have made valuable contribution to its success.

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