OPTIMIZATION OF PYROLYSIS OPERATING PARAMETERS FOR SYNTHETIC FUEL PRODUCTION FROM WASTE AUTOMOBILE TIRES

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Abstract. The growing accumulation of end-of-life tires represents a serious environmental challenge while simultaneously offering a valuable secondary hydrocarbon resource. In this study, the optimization of operational parameters for producing synthetic fuel via thermal pyrolysis of waste automobile tires was investigated. Experimental analyses were conducted to evaluate the influence of temperature, heating rate, particle size, and condensation conditions on liquid fuel yield and quality. The physicochemical properties of the obtained pyrolysis oil were determined using density, viscosity, calorific value, FT-IR spectroscopy, and GC–MS techniques. The results demonstrate that the optimal pyrolysis temperature range of 450–520 °C and a heating rate of 10–15 °C min^{-1} provide the maximum liquid product yield (up to 39–45 wt%). Elemental and spectral analyses revealed that the produced synthetic fuel consists predominantly of aliphatic and aromatic hydrocarbons with minor oxygenated compounds, exhibiting properties comparable to conventional diesel fractions. The calorific value reached 41.5 MJ kg^{-1}, confirming its suitability as an alternative energy carrier. The findings indicate that waste tire pyrolysis is an effective pathway for simultaneous waste mitigation and synthetic fuel production. Optimization of process parameters

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significantly enhances liquid yield and energy efficiency, highlighting the potential for industrial implementation within circular economy frameworks.

Keywords: pyrolysis; waste tires; synthetic fuel; process optimization; thermal decomposition; pyrolysis oil; waste-to-energy

Annotatsiya. Mazkur tadqiqot eskirgan avtomobil shinalarini termik piroliz usuli orqali qayta ishlash asosida sintetik yonilg‘i olish jarayonining rejim ko‘rsatkichlarini maqbullashtirishga bag‘ishlangan. Jarayonning asosiy texnologik parametrlari — harorat, qizdirish tezligi, xomashyo zarracha o‘lchami va kondensatsiya sharoitlarining suyuq mahsulot chiqishiga ta’siri eksperimental ravishda o‘rganildi. Olingan piroliz moyining zichligi, qovushqoqligi, yonish issiqligi, elementar tarkibi, infraqizil spektrlari hamda GC–MS tahlillari orqali fizik-kimyoviy xossalari baholandi. Natijalarga ko‘ra, 450–520 °C harorat oralig‘i va 10–15 °C/min qizdirish tezligi sharoitida sintetik yonilg‘ining maksimal chiqishi (39–45 %) ta’minlanadi. Spektral va elementar tahlillar mahsulot tarkibida asosan alifatik va aromatik uglevodorodlar mavjudligini ko‘rsatdi. Yonish issiqligi 41,5 MJ/kg ga yetib, olingan yoqilg‘ining dizel fraksiyasiga yaqin energiya qiymatiga egaligini tasdiqladi. Tadqiqot natijalari eskirgan shinalarni piroliz qilish chiqindilarni kamaytirish bilan birga muqobil energiya manbai olishning samarali usuli ekanligini ko‘rsatadi. Jarayon parametrlarini optimallashtirish suyuq mahsulot hosildorligi va energetik samaradorlikni sezilarli oshiradi hamda sanoat miqyosida qo‘llash imkoniyatlarini ochib beradi.

Kalit so‘zlar: piroliz; eskirgan shinalar; sintetik yonilg‘i; jarayonni maqbullashtirish; termik parchalanish; piroliz moyi; chiqindidan energiya.

Аннотация. Накопление отработанных автомобильных шин представляет собой серьёзную экологическую проблему и одновременно является ценным вторичным углеводородным ресурсом. В данной работе исследована оптимизация режимных параметров процесса термического пиролиза шин с целью получения синтетического топлива. Экспериментально изучено влияние температуры, скорости нагрева, размера частиц и условий конденсации на выход и качество жидкого продукта. Физико-химические свойства пиролизного масла определялись методами измерения плотности, вязкости, теплотворной способности, ИК-спектроскопии и газовой хроматографии–масс-спектрометрии. Установлено, что оптимальный температурный интервал 450–520 °C при скорости нагрева 10–15 °C мин$^{-1}$ обеспечивает максимальный выход жидкой фазы (до 39–45 мас.%). Элементный и спектральный анализ показал преобладание алифатических и ароматических углеводородов с незначительным содержанием кислородсодержащих соединений. Теплота сгорания достигла 41,5 МДж кг$^{-1}$,

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что подтверждает возможность использования полученного продукта в качестве альтернативного топлива. Полученные результаты свидетельствуют о высокой эффективности пиролиза шин как метода утилизации отходов и производства синтетического топлива. Оптимизация параметров процесса существенно повышает выход жидкого продукта и энергетическую эффективность, что открывает перспективы промышленного внедрения в рамках циркулярной экономики.

Ключевые слова. пиролиз; отработанные шины; синтетическое топливо; оптимизация процесса; термическое разложение; пиролизное масло; энергия из отходов.

INTRODUCTION

Rapid growth in polymer consumption and the corresponding increase in solid waste generation have intensified global environmental concerns, particularly regarding end-of-life automobile tires. Due to their complex composition and resistance to natural degradation, waste tires accumulate in landfills, posing long-term ecological and fire hazards. At the same time, tires contain up to 60–70% hydrocarbon-based materials, making them a promising feedstock for energy recovery.

Thermal pyrolysis has emerged as one of the most attractive technologies for converting waste tires into value-added products, including liquid fuel, combustible gases, and solid carbon residues. Unlike incineration, pyrolysis proceeds in an oxygen-free environment, enabling controlled decomposition of polymer chains while minimizing harmful emissions. The liquid fraction, commonly referred to as pyrolysis oil, exhibits fuel-like characteristics and can potentially substitute conventional petroleum-derived products after appropriate upgrading.

However, the efficiency and product distribution of tire pyrolysis strongly depend on operational parameters such as reaction temperature, heating rate, residence time, and feedstock particle size. Improper control of these variables leads to excessive gas formation or incomplete decomposition, reducing liquid yield and fuel quality. Therefore, systematic optimization of pyrolysis conditions is essential for improving process performance and economic feasibility.

The present study focuses on optimizing key operational parameters for synthetic fuel production from waste automobile tires. Comprehensive physicochemical characterization of the obtained pyrolysis oil was performed to evaluate its suitability as an alternative fuel. The results contribute to developing sustainable waste-to-energy strategies and provide practical guidance for scaling up tire pyrolysis systems.

MATERIALS AND METHODS

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Waste automobile tires were mechanically cleaned to remove external contaminants such as dust and sand, followed by size reduction to particle dimensions of approximately 1–3 cm to enhance heat transfer and reaction kinetics. The prepared feedstock was introduced into a sealed batch-type pyrolysis reactor operating under anaerobic conditions.

Thermal decomposition was carried out within the temperature range of 350–550 °C at heating rates between 5 and 20 °C min^{-1}. The residence time was maintained at 45–60 min depending on the target temperature. The evolved vapor–gas mixture was directed through a condenser system where condensable hydrocarbons were collected as liquid fuel, while non-condensable gases were separated and partially recycled to support the thermal balance of the process.

The physicochemical properties of the obtained pyrolysis oil were evaluated by determining density, kinematic viscosity, flash point, freezing point, and calorific value using standard methods. Functional groups were identified by Fourier-transform infrared spectroscopy, while compositional analysis was conducted using gas chromatography–mass spectrometry. Elemental composition (C, H, N, S) was measured via high-temperature combustion analysis.

To assess process optimization, the influence of temperature, heating rate, and particle size on liquid product yield was systematically investigated. Each experimental condition was repeated three times, and average values were used for analysis. Statistical regression was applied to establish correlations between operational parameters and fuel yield.

RESULTS AND DISCUSSION

The experimental results demonstrate a strong dependence of product distribution on pyrolysis temperature. At temperatures below 400 °C, incomplete decomposition resulted in higher solid residue formation. Increasing the temperature to 450–520 °C significantly enhanced liquid fuel production, achieving a maximum yield of approximately 39–45 wt%. Further temperature elevation above 550 °C favored secondary cracking reactions, leading to increased gas formation and reduced liquid output.

The effect of pyrolysis temperature on liquid fuel yield is illustrated in Figure 1.

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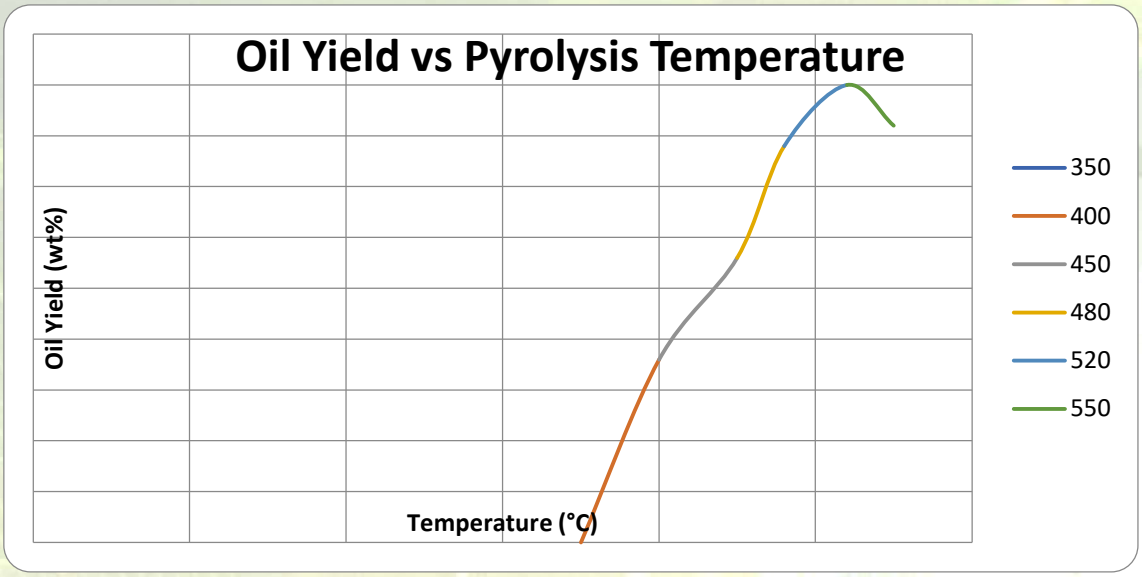


Figure 1. Effect of pyrolysis temperature on liquid fuel yield.

It can be observed that the liquid fuel yield increases sharply from 350 to 480 °C, reaching a maximum near 480–520 °C, followed by a slight decrease at higher temperatures due to secondary cracking reactions.

Heating rate also played a crucial role. Moderate rates of 10–15 °C min^{-1} promoted efficient volatilization of hydrocarbons while suppressing excessive cracking. Lower heating rates caused prolonged residence of intermediates in the reactor, increasing char formation, whereas higher rates accelerated gas evolution at the expense of liquid yield.

The produced pyrolysis oil exhibited density values ranging from 905 to 931 kg m^{-3} within 10–40 °C, indicating properties comparable to diesel-like fractions. The calorific value reached 41.5 MJ kg^{-1}, confirming its suitability as an energy carrier. Infrared spectroscopy revealed dominant aliphatic C–H stretching bands and aromatic C=C vibrations, accompanied by minor carbonyl signals, suggesting the presence of ketones or aldehydes. GC–MS analysis indicated a complex mixture primarily composed of aliphatic and aromatic hydrocarbons, with light volatile components appearing at short retention times and heavier aromatic species detected at longer retention intervals.

Figure 2 demonstrates the quadratic decrease in pyrolysis oil density with increasing temperature. Density dropped from approximately 931 kg m^{-3} at 10 °C to 746 kg m^{-3} at 200 °C, confirming diesel-like behavior of the obtained fuel.

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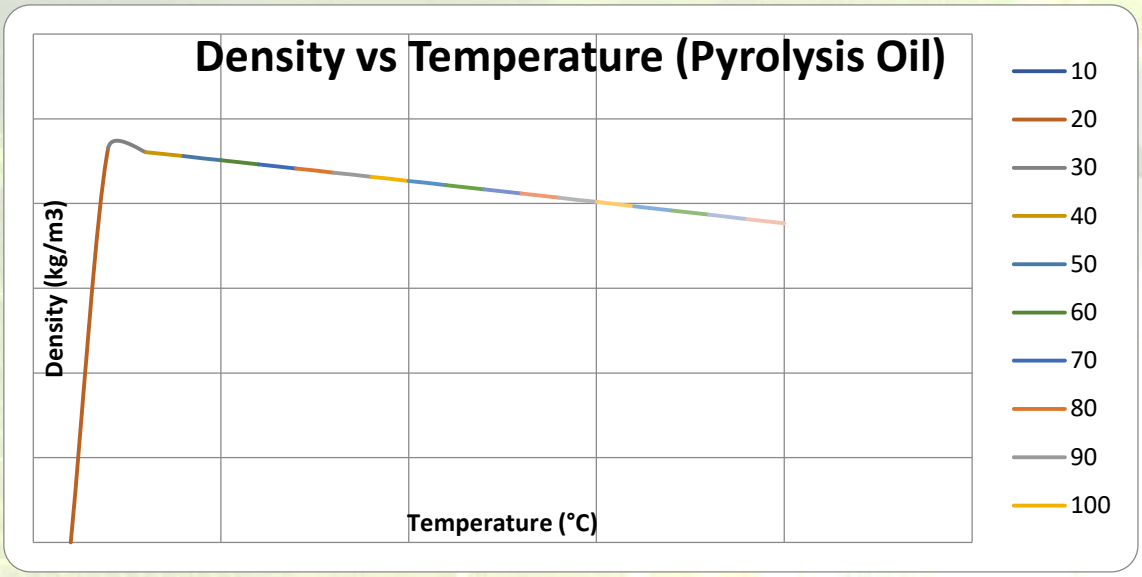


Figure 2. Density variation of tire pyrolysis oil as a function of temperature.

Elemental analysis showed elevated carbon content with moderate hydrogen levels and minor nitrogen and sulfur impurities. Compared to conventional petroleum fuels, the sulfur content remained relatively low, although further upgrading would be required to meet transportation fuel standards.

Regression analysis confirmed temperature as the most influential parameter governing liquid yield, followed by heating rate and particle size. Optimal operating conditions were established at 480 ± 20 °C, heating rate of 10–15 °C min^{-1}, and feedstock size of 1–3 cm. Under these conditions, the process demonstrated improved energy efficiency, particularly when non-condensable gases were utilized as supplementary fuel for reactor heating.

These findings highlight the technical feasibility of converting waste tires into synthetic fuel and emphasize the importance of precise operational control for maximizing liquid product recovery.

CONCLUSIONS

Thermal pyrolysis of waste automobile tires represents an effective approach for simultaneous waste mitigation and alternative fuel production. The study demonstrates that optimization of process parameters significantly enhances liquid fuel yield and quality. The optimal temperature range of 450–520 °C combined with a heating rate of 10–15 °C min^{-1} provides maximum recovery of synthetic oil with diesel-like properties.

The obtained fuel exhibits favorable thermophysical characteristics and a high calorific value, confirming its potential as an alternative energy source after appropriate upgrading. Utilization of pyrolysis gas for process heating further improves overall energy efficiency.

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The results support the industrial applicability of tire pyrolysis within circular economy frameworks and contribute to developing sustainable waste-to-energy technologies.

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