Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 09 September-2026, Page No.- 11366 - 11376
DOI: 10.47191/etj/v11i09.01, I.F. – 8.595

Production of Liquid Fuel from South Sumatra Remilling Rubber Waste through TiO_2-Catalyzed Cracking: Effects of Temperature and Catalyst Loading on Fuel Characteristics

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ABSTRACT: This study investigated the effects of reaction temperature and TiO_2 catalyst loading on the production yield and fuel properties of liquid fuel derived from remilling rubber latex waste through catalytic cracking. Experiments were conducted at temperatures of 300, 350, and 400°C using catalyst loadings of 33.7, 37.5, and 41.2 g for 60 minutes under a pressure of 70 psi. The liquid products were characterized in terms of yield, density, viscosity, flash point, calorific value, cetane number, and functional groups using Fourier Transform Infrared (FTIR) spectroscopy. The results demonstrated that both reaction temperature and catalyst loading significantly influenced product yield and fuel characteristics. The highest liquid fuel yield of 38.04% was obtained at 350°C with a catalyst loading of 41.2 g. The resulting fuel exhibited densities ranging from 0.8156 to 0.8628 g/mL, viscosities from 0.86 to 0.95 mm^2/s, flash points between 30.6 and 36.2°C, and a maximum calorific value of 41.337 MJ/kg, which is comparable to that of commercial diesel fuel. FTIR analysis confirmed the predominance of aliphatic $–CH_2–$ and $–CH_3$ functional groups, indicating the formation of alkane fractions through the cleavage of polyisoprene chains. The cetane number reached 51.1, suggesting favorable combustion quality and compliance with the typical range of commercial diesel fuels. These findings indicate that remilling rubber latex waste has considerable potential as a sustainable alternative energy resource for liquid fuel production.

KEYWORDS: catalytic cracking; remilling rubber latex waste; TiO_2 catalyst; liquid fuel; waste-to-energy; cetane number.

1. INTRODUCTION

The increasing demand for energy driven by industrialization, transportation, and urbanization has led to higher consumption of fossil fuels, depletion of energy reserves, and increased CO_2 emissions and environmental pollution (Ibrahim Abbas Abdullah Abbas Amer et al., 2025; Jiannan Wang et al., 2024; Pham Xuan Hoa et al., 2024; Tailon Martins et al., 2021). Therefore, the development of waste-based alternative energy has become a promising solution for supporting sustainable energy systems and promoting a circular economy (Nisa Aslan et al., 2025; Nazim Forid et al., 2024; Paul H. Brunner et al., 2024; Konstantinos Moustakas et al., 2023).

Thermochemical conversion of waste into liquid fuel can reduce waste volume while producing economically valuable products (Naveen Chandra Joshi et al., 2024; Rajendran Nandhini et al., 2022; Ren-Xuan Yang et al., 2022; Mohammed B. Al Rayaan et al., 2021). Remilling rubber latex waste is rich in hydrocarbons derived from cis-1,4-polyisoprene, making it a potential feedstock for conversion into liquid fuel. However, this waste is still frequently disposed of or burned without further utilization (Siwarote Boonrasri et al., 2026; Lidya D. Kasmiarno et al., 2024).

Pyrolysis and catalytic cracking can produce light hydrocarbon fractions similar to diesel and kerosene. Among these processes, catalytic cracking is considered more effective because the presence of a catalyst can improve product selectivity and fuel quality (Petr Straka et al., 2023; David John et al., 2021; Hussain Gulab et al., 2021). Titanium dioxide (TiO_2) is regarded as a promising catalyst due to its high thermal stability and catalytic activity, which can enhance product yield and reduce residue formation (Mohammed Ismael et al., 2024; Takumi Watanabe et al., 2023). Operating temperature and catalyst loading play important roles in determining product distribution, with the optimal operating range for hydrocarbon-based waste generally reported to be 300–400°C (Premkumar et al., 2024; Rismawati Rasyid et al., 2024; Takumi Watanabe et al., 2023)

Based on these considerations, this study aims to analyze the effects of reaction temperature and TiO_2 catalyst loading on the production of liquid fuel from remilling rubber latex waste through catalytic cracking. This research is expected to support the development of environmentally friendly and sustainable waste-to-energy technology.

2. MATERIALS AND METHODS

Preparation of Rubber Waste

Remilling rubber latex waste was cleaned, dried, cut into pieces of approximately 2–3 cm, and then crushed using a crusher to obtain a uniform particle size of 1–3 mm. Particle size reduction increases the contact surface area between the feedstock, heat, and catalyst, thereby enhancing heat transfer, thermal decomposition, and temperature uniformity within the reactor. This process accelerates the reaction rate and improves the liquid fuel yield. The prepared samples were stored in sealed containers to prevent contamination and moisture absorption prior to the catalytic cracking process.

Catalytic Cracking

A total of 1,000 g of remilling rubber latex waste was fed into a pyrolysis reactor, followed by the addition of TiO_2 catalyst at loadings of 33.7, 37.5, and 41.2 g. The mixture was homogenized, and the reactor was tightly sealed. The catalytic cracking process was then carried out at a pressure of 70 psi for 60 minutes at reaction temperatures of 300, 350, and 400°C.

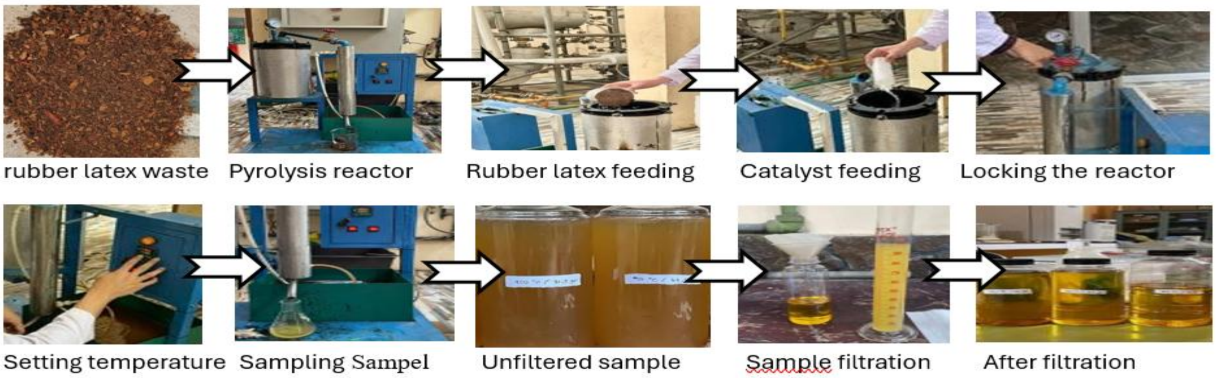

Figure 1. Catalytic cracking preparation and research flow diagram.

3. RESULTS AND DISCUSSION

Chemical Characterization and Elemental Analysis of Remilling Rubber Latex Waste

In this study, rubber latex waste was processed through catalytic cracking using a catalyst, and the resulting cracking products were characterized to determine their physical and chemical properties, including FTIR spectra, density, viscosity, flash point, cetane number (CN), and calorific value.

Functional Group Characterization of the Cracking Product Using FTIR

Fourier Transform Infrared (FTIR) analysis was conducted to identify the functional groups and hydrocarbon characteristics of the products obtained from the catalytic cracking of remilling rubber latex waste. The analysis was performed on the sample with the highest yield, obtained at 350°C with 41.2 g of catalyst, which produced a yield of 38.04%. In Figure 2, the FTIR results revealed absorption peaks at 2,947 cm^{-1} and 2,930 cm^{-1}, indicating the presence of $–CH_2–$ and $–CH_3$ groups. These peaks suggest the formation of aliphatic hydrocarbons, such as alkanes or alkyl compounds, resulting from the cleavage of polyisoprene chains during the cracking process. This indicates that the liquid product has characteristics similar to hydrocarbon-based fuels. Absorption bands in the range of 2,850–2,950 cm^{-1} are characterized as C–H stretching vibrations in alkane compounds derived from the pyrolysis of biomass and polymeric waste (Arslan Khan et al., 2026; Yi Zhang et al., 2025; Krishnaraj Janarthanan et al., 2022).

Catalytic cracking resulted in the predominance of aliphatic hydrocarbon groups due to the thermocatalytic cleavage of carbon chains (Valentin R. Atlasov et al., 2025; Yi Hao et al., 2025; Bablu Alawa et al., 2023; Bin Chen et al., 2023). Peaks observed in the region of 2,920–2,950 cm^{-1} indicate the formation of light alkanes (Nathawat Unsomsri et al., 2026; Wu Li et al., 2020). Muhammad Rafique et al. (2023) explained that TiO_2 catalysts enhance the formation of short-chain hydrocarbons, as indicated by the presence of $–CH_2–$ and $–CH_3$ groups. Similarly, Bablu Alawa et al. (2023), Pamreishang Kasar et al. (2022), and Shahriar Bin Rasul et al. (2021) reported that the dominance of aliphatic functional groups in FTIR spectra reflects the successful conversion of feedstock through cracking into liquid fuel resembling commercial fuels.

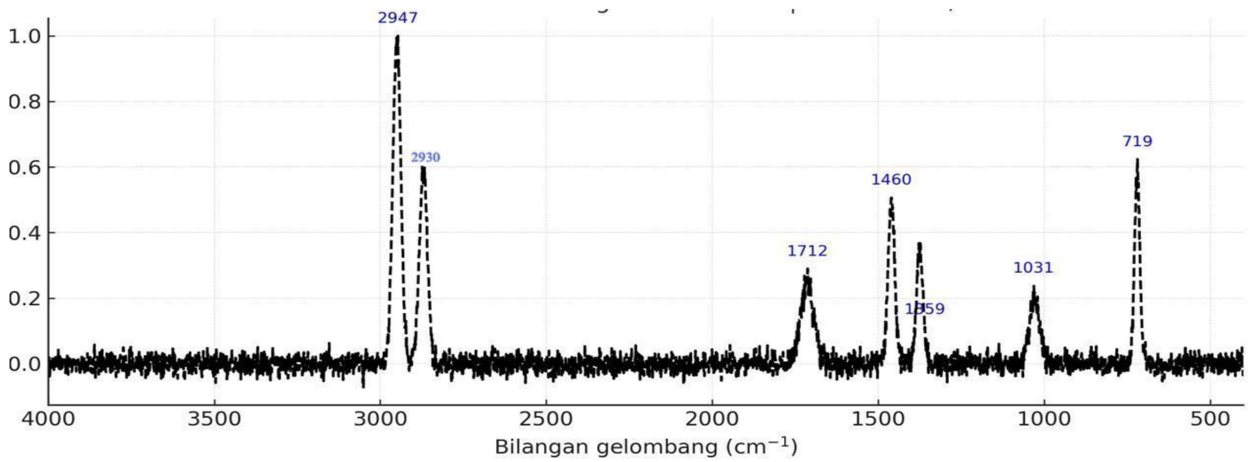

Figure 2. FTIR spectrum of the liquid fuel produced from catalytic cracking.

Effects of Catalytic Cracking Operating Parameters Using TiO_2 Catalyst

Effects of Temperature and Catalyst Loading on Yield

The results showed that operating temperature and TiO_2 catalyst loading significantly affected the yield and characteristics of liquid fuel produced from the catalytic cracking of remilling rubber latex waste (Figure 3). The highest liquid yield of 38.04% was obtained at 350°C with a catalyst loading of 41.2 g, whereas the lowest yield of 4.82% was recorded at 300°C with a catalyst loading of 33.7 g. These findings indicate that temperature and catalyst loading control the effectiveness of hydrocarbon decomposition during the cracking process (Supawan Vichaphund et al., 2025; Ravindra Kumar et al., 2024). Increased yield at 350°C indicates an optimum condition, in which the thermal energy is sufficient to break complex hydrocarbon chains into lighter fractions without causing excessive secondary decomposition, thereby enhancing liquid product formation (Oratepin Arjharnwong et al., 2025). The optimum temperature range for catalytic cracking of hydrocarbon-based waste is generally observed between 300 and 400°C. At 300°C, the cracking process is not yet optimal, due to insufficient available thermal energy, resulting in the predominance of heavier hydrocarbon fractions (Zaid et al., 2022). In contrast, the liquid yield decreases at 400°C, due to the increased formation of non-condensable gases, further cracking reactions, and coke formation, which reduce catalyst activity (Zaid et al., 2022).

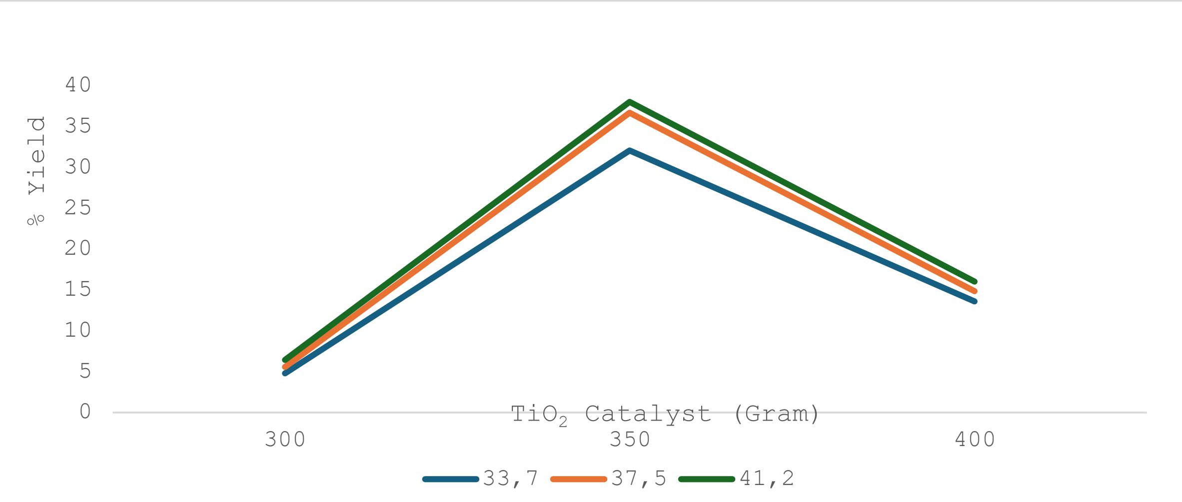

Figure 3. Effect of Temperature and TiO_2 Catalyst Loading on Pyrolysis Yield (%)

Increasing the TiO_2 catalyst loading increased the number of active sites, thereby accelerating the cleavage of hydrocarbon chains into lighter molecules (Kelvin A. Sanoja-Lopez et al., 2025; Ullas Krishnan et al., 2023; Xu Hou et al., 2017). TiO_2 has a large surface area, high thermal stability, and surface acidity that support cracking reactions and improve the selectivity of liquid fraction formation (Ullas Krishnan et al., 2023; Xu Hou et al., 2017). Ullas Krishnan et al. (2023) reported that the use of a catalyst can increase yield by more than 35% compared with non-catalytic pyrolysis. The high yield obtained in this study indicates the potential of remilling rubber latex waste as an alternative energy source, as its cis-1,4-polyisoprene content can be converted into short-chain hydrocarbons with high calorific value (Tannaz Alamfard et al.,2025; Amit Kumar et al., 2024). This finding also supports the concepts of waste-to-energy conversion and circular economy. Therefore, controlling the operating temperature and catalyst loading is essential to achieve optimum conversion, while minimizing gas formation and carbon residue.

Effects of Temperature and Catalyst Loading on Density

The density of the liquid fuel ranged from 0.8156 to 0.8628 g/mL (Figure 4), with the highest value obtained at 400°C and a catalyst loading of 41.2 g. This range is close to the density of commercial diesel fuel, which is approximately 0.82–0.86 g/mL.

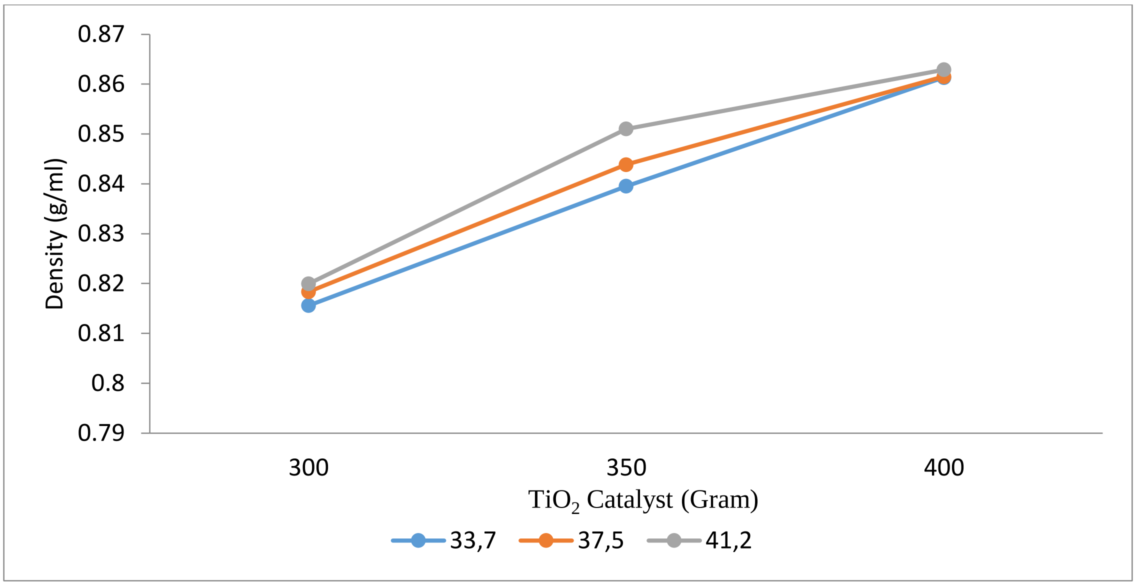

Figure 4. Effect of Temperature and TiO_2 Catalyst Loading on Density

Increased density at higher temperatures is influenced by the formation of heavier hydrocarbons, aromatic compounds, and carbonaceous residues, resulting from secondary reactions such as aromatization and repolymerization (Avinash R. Mali et al., 2023; Xiangbo Zhao et al., 2023; Haneen et al., 2022). High temperatures also promote the formation of non-condensable gases, leaving heavier fractions to remain condensed and thereby increasing the density of the product. As the addition of TiO_2 catalyst accelerates cracking reactions, excessive catalyst loading may promote the formation of polycyclic aromatic compounds and coke, which can also increase product density. Liquid fuel derived from rubber waste conversion contains a mixture of alkanes, alkenes, and aromatic hydrocarbons resembling conventional diesel fuel. TiO_2 demonstrates good catalytic performance by improving the selectivity of liquid fractions and enhancing fuel quality through the formation of aliphatic hydrocarbons (Jasmin Shah et al., 2008).

Effects of Temperature on Viscosity

The viscosity of the liquid fuel ranged from 0.86 to 0.95 mm²/s and tended to decrease as the operating temperature increased (Figure 5). This decrease in viscosity indicates that higher temperatures produce hydrocarbons with lower molecular weights and shorter carbon chains (Naif S et al., 2024; N. Miskolczi et al., 2024; Leilei Cheng et al., 2022; Widya Wijayanti et al., 2022). At lower temperatures, decomposition is incomplete, causing heavier fractions to dominate the product and increasing intermolecular forces and viscosity. Higher temperatures accelerate C–C bond cleavage, resulting in the formation of short-chain alkanes and alkenes with weaker intermolecular forces (Naif S et al., 2024; N. Miskolczi et al., 2024). Thus, viscosity is inversely related to operating temperature because the conversion of heavier fractions into lighter fractions increases with temperature.

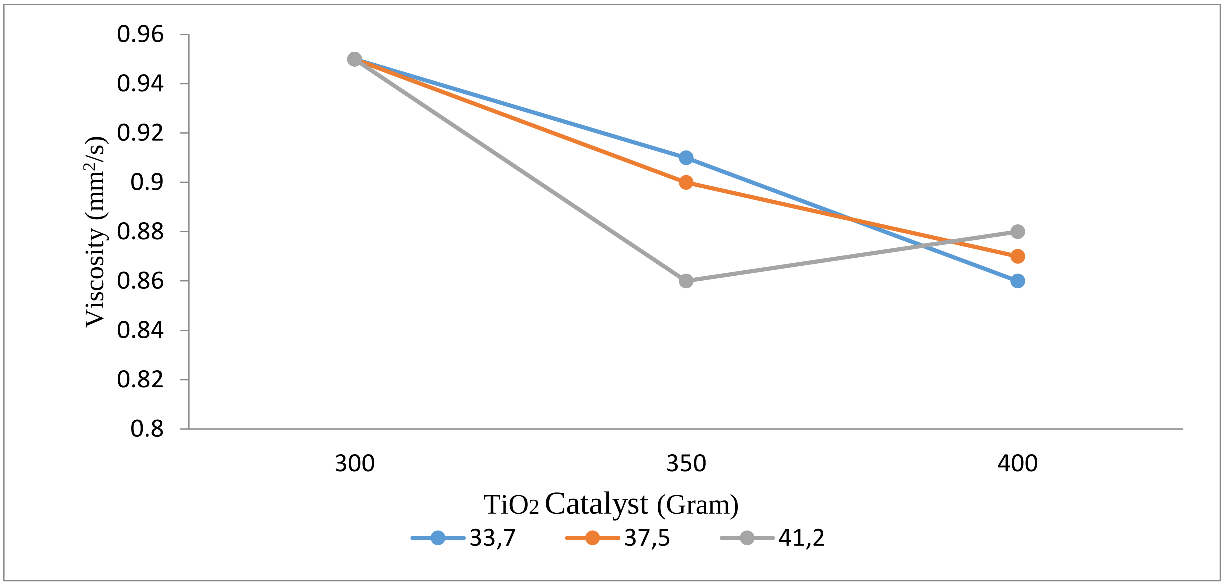

Figure 5. Effect of Temperature and TiO_2 Catalyst Loading on Viscosity

The use of TiO_2 catalyst also reduces viscosity by enhancing cracking activity on the catalyst surface (Naif S et al., 2024; N. Miskolczi et al., 2024). Metal oxide catalysts are known to improve the selectivity of light fraction formation compared with non-catalytic processes. The viscosity values obtained in this study were lower than those of commercial diesel fuel but still indicated good flow characteristics for an alternative fuel (Iman Nowrouzi et al., 2025). However, excessively low viscosity may reduce lubricity; therefore, upgrading or blending with conventional fuels may be required (Arkoudeas et al., 2014). Hydrocarbon distribution strongly affects viscosity: the predominance of short-chain alkanes lowers viscosity, whereas aromatic compounds and heavier hydrocarbons tend to increase it (Arkoudeas et al., 2014).

Effect of Temperature on Flash Point

The flash point of the liquid fuel ranged from 30.6 to 36.2°C, with the highest value obtained at 350°C and a TiO_2 catalyst loading of 41.2 g (Figure 6). The relatively low flash point indicates the predominance of highly volatile light hydrocarbon fractions, such as short-chain alkanes, alkenes, and light aromatic compounds. Higher operating temperatures accelerate the formation of light hydrocarbons, including methane, ethane, propane, and gasoline-range compounds, thereby reducing the flash point (Dianne et al., 2021). Excessively high cracking temperatures may reduce fuel stability due to the excessive formation of volatile fractions. Therefore, the flash point of liquid fuel derived from rubber waste is lower than that of commercial diesel.

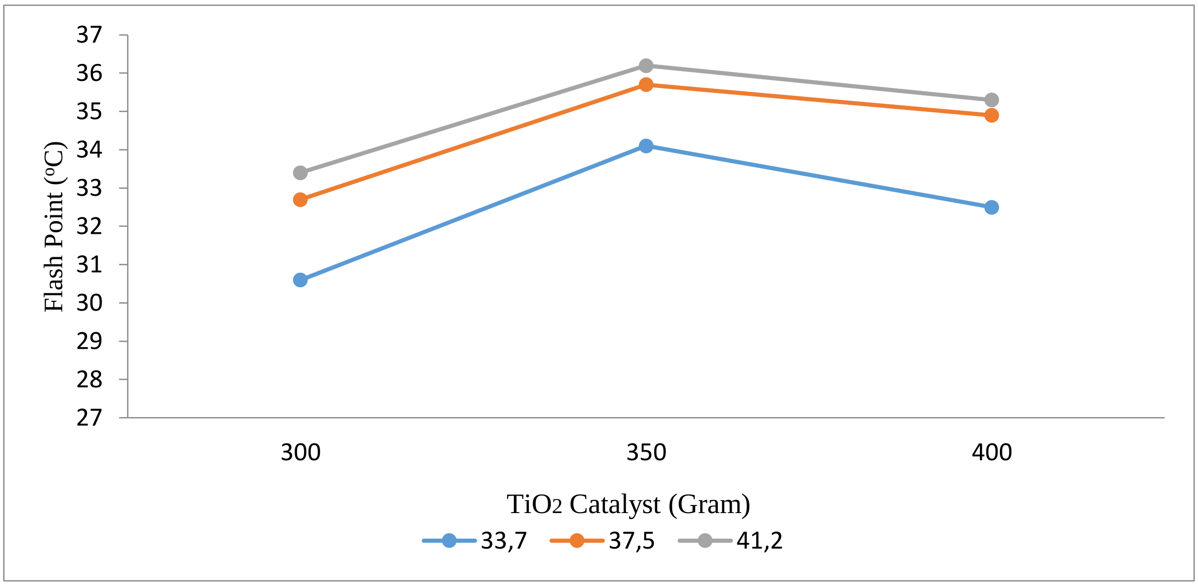

Figure 6. Effect of Temperature and TiO_2 Catalyst Loading on Flash Point

The addition of TiO_2 catalyst accelerates the formation of light fractions through catalytic activity on active sites, making the fuel more flammable (Omwoyo et al., 2023). The high surface area and surface acidity of TiO_2 support the formation of short-chain alkanes and alkenes and increase product volatility (Yue Wang et al., 2025; Fatemeh Ariaeinezhad et al., 2024;Marhaini et al.,2024). Ibhadebhunuele Gabriel Okoduwa et al. (2025) and Yanan Gan et al. (2011) stated that metal oxide catalysts can produce liquid fuels with good combustion characteristics and high volatility. Although the flash point of the product is lower than the standard value for commercial diesel fuel, the liquid product remains promising as an alternative fuel after upgrading and purification, such as distillation and separation of light fractions, to improve storage stability and safety.

Calorific Value

Calorific value is an important parameter for determining liquid fuel quality because it indicates the amount of energy released during complete combustion (Wan Nor et al., 2025; Ellisson et al., 2022). The results, shown in Figure 7, indicate that the highest calorific value was obtained at 350°C with a TiO_2 catalyst loading of 41.2 g, reaching 41.337 MJ/kg. This value is close to the range of commercial diesel fuel, which is approximately 42–46 MJ/kg (Zahira Yaakob et al., 2013). The high calorific value demonstrates that catalytic cracking of remilling rubber latex waste can produce hydrocarbons with high energy content.

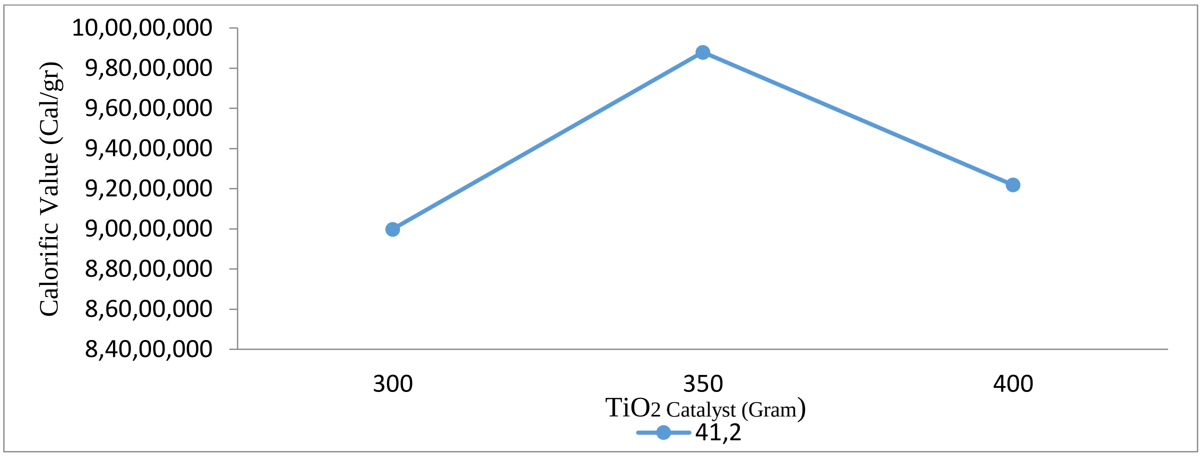

Figure 7. Effect of Temperature and TiO_2 Catalyst Loading on Calorific Value

The calorific value is influenced by the distribution of hydrocarbons formed during the cracking process, particularly alkanes and medium-chain hydrocarbons, which have higher combustion energy than oxygenated compounds or heavy fractions (Kalyan Vuchuru et al., 2023; Renbao Zhao et al., 2021). At 350°C, the cracking process occurred under optimum conditions, resulting in a balanced hydrocarbon distribution and promoting the formation of high-energy alkanes and alkenes. In contrast, low temperatures may lead to incomplete decomposition, whereas excessively high temperatures can promote further cracking into non-condensable gases, thereby reducing the calorific value of the liquid product (Hosta Ardhyananta et al., 2025; Bin Hua et al., 2024;Marhaini et al.,2024).

The use of TiO_2 catalyst increased the calorific value by accelerating the cleavage of polymer chains into short- and medium-chain hydrocarbons. Increasing the catalyst loading provides more active sites, making the cracking process more effective and promoting the formation of hydrocarbons with higher energy content (Hosta Ardhyananta et al., 2025; Tejas Ukarde, 2021). The surface acidity and thermal stability of TiO_2 support the formation of high-quality liquid fuel. Metal oxide catalysts are also known to increase the content of alkanes and aliphatic hydrocarbons, which contribute to higher calorific values (Siphumelele Majodina et al., 2026).

The high calorific value is also influenced by the characteristics of rubber waste, which is rich in carbon and hydrogen. The cis-1,4-polyisoprene structure enables the formation of hydrocarbons with a high H/C ratio, thereby increasing combustion energy (Camila Guajardo et al., 2025; Abhijit Bera et al., 2023). In addition, the low contents of water, oxygen, and carbon residue contribute to improving the energy quality of the liquid fuel (Leonardo Colelli et al., 2026). These results indicate that liquid fuel produced through catalytic cracking of remilling rubber latex waste has strong potential as an alternative energy source that supports waste-to-energy development and environmental pollution reduction.

Cetane Number Analysis

In Table 1, the liquid fuel sample had a cetane number of 51.1, as determined using a Cetane Octane Gasoline Analyzer. Cetane number is an important parameter for assessing diesel fuel quality because it reflects the ability of the fuel to ignite spontaneously after injection. A higher cetane number indicates shorter ignition delay, resulting in more complete and efficient combustion (Dunya Ahmed Khalaf et al., 2021). The cetane number of 51.1 indicates that the liquid fuel product has good combustion quality and falls within the typical range of commercial diesel fuel. A cetane number above 50 generally indicates more stable combustion, lower emissions, and better engine performance (Heng Wu et al., 2022). These findings suggest that the thermal conversion product of rubber waste has potential as an alternative fuel for diesel engine applications.

Table 1. Cetane number analysis results.

No.	Sample Name	Test Parameter	Test Method	Analysis Result
1.	Liquid fuel	Cetane number	Cetane Octane Gasoline Analyzer	51.1

4. CONCLUSION

The favorable operating conditions were achieved at a temperature of 350°C with the use of 41.2 g of TiO_2 catalyst, resulting in the highest yield of 38.04%. The liquid fuel produced exhibited characteristics comparable to those of commercial diesel fuel, with a density of 0.8448 g/mL, viscosity of 0.86–0.95 mm^2/s, flash point of 35.3°C, calorific value of 41.337 MJ/kg, and cetane number of 51.1.FTIR analysis revealed the predominance of aliphatic $–CH_2–$ and $–CH_3$ functional groups, indicating the cleavage of polyisoprene chains into alkane and alkyl fractions, as well as the effectiveness of TiO_2 in enhancing cracking activity and improving the selectivity of liquid product formation. The operating temperature and catalyst loading significantly influenced both the yield and physicochemical properties of the resulting liquid fuel.

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