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# Production of Liquid Fuel from Motorcycle Used Tire via Pyrolysis: Effect of Temperature on Yield and Calorific Value

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**ABSTRACT**: The continuous accumulation of used tires has raised serious environmental concerns due to their non-biodegradable nature. Pyrolysis offers a promising thermal conversion method to transform used tires into alternative energy sources. This study investigates the pyrolysis of used motorcycle tires, cut into 1 x 1 cm pieces, under atmospheric pressure at various temperatures ranging from 400°C to 750°C, using 500 grams of tire material for each run. The tar and char yields were collected, and the calorific values of the liquid product were analyzed. The optimum operating condition was found at 700°C, yielding 276.56 g of tar and 184.55 g of char after 2 hours and 35 minutes of reaction. The highest calorific value obtained was 39.98 MJ/kg. Although the liquid fuel produced exhibits significant energy content, its calorific value remains lower than that of conventional fuels used in vehicles. This indicates the potential of tire-derived oil as a supplementary fuel, with further improvement needed in quality and performance.

**Keywords:** used motorcycle tire; tar; pyrolysis; calorific value

## 1. Introduction

Used motorcycle tires are one type of solid waste that is difficult to decompose naturally and increases in number along with the growth of the automotive industry. According to Wik and Dave (2009) tire rubber consists of 40-60% polymer rubber, reinforcing agents such as carbon black (20-35%), aromatic extender oil (15-20%), additive vulcanization materials (4%, for example zinc oxide, benzothiazole and its derivatives), antioxidants (1%), and small amounts of processing aids (<1%, such as plasticizers and softeners). This makes used tires difficult to decompose and poses a serious environmental risk. Physical recycling efforts, such as vulcanization or shredding into rubber powder, have proven unable to manage this waste completely (Gao et al., 2022). Therefore, pyrolysis technology has emerged as a superior solution because it can convert used tires into high-value energy and material products. Notably, Setyoningrum et al. (2018) demonstrated that pyrolytic char can be further processed into activated carbon, adding value to the overall waste conversion process.

The pyrolysis process is a thermal decomposition process that occurs without oxygen, producing three main products: pyrolysis oil, gas, and char. Pyrolysis oil has a calorific value comparable to that of other fuels. The density and calorific value of various types of fuel are presented in Table 1.

**Table 1.** Density and Calorific Value of Various Fuels

| Fuel Type | Density (kg/m$^3$) | Calorific Value (MJ/kg) | Source |
|---|---|---|---|
| Scrap Tyre Oil | 965 | 41.5 | Islam, (2004) |
| Waste Paper Oil | 1205 | 13.19 | |
| Oily Condensate from Waste Plastic | 905 | 43.5 | |
| Fast Diesel | 780 | 45.46 | |
| Diesel | 827* | 45.18 | |
| Heavy Fuel Oil | 980* | 42.43 | |
| Rice Husk | 970-1040 | 0.86-2.17 | Hidayat (2009) |

The potential of waste tire pyrolysis oil (WTPO) as an alternative fuel for diesel engines depends on the development of effective waste management systems (Dewang et al., 2025). Proximate and ultimate analyses, as well as the low heating value of used tires, are listed in Table 2 (Wang et al., 2023). In a related study, Fan et al. (2025), found that the contents of volatiles and fixed carbon, as well as the C/H ratio, are relatively high, while the ash content is relatively low. Used tire pyrolysis oil has a high calorific value (38-45 MJ/kg) and contains aromatic and aliphatic hydrocarbon compounds similar to those found in fossil fuels (Zhang et al., 2021).

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The effect of temperature on the pyrolysis can optimize the distribution of biochar, bio-oil, and gas products. Previous work on bamboo waste pyrolysis has shown that optimal bio-oil yield occurs at 500 °C, followed by thermal degradation at higher temperatures due to secondary cracking (Mufandi et al., 2025). Addy Rachmat et al. (2007) investigated the effect of pyrolysis temperature (250–550 °C) on the liquid products from used rubber tires under vacuum and $N_2$ atmospheres, finding the highest yield at 350 °C (42.86%) in vacuum and 500 °C (50.14%) in $N_2$. The lowest viscosity and activation energy occurred at 400 °C and 300 °C, respectively, with calorific values peaking at 44.12 kJ/g (vacuum) and 46.32 kJ/g ($N_2$). The simulation at various temperatures, Cao et al. (2023) found that at 500°C, the highest tire-derived oil was obtained, the gas amount increased, and the char decreased with increasing temperature. Jaya et al. (2023) reported high tar and char yields from Fuso Canter truck tire pyrolysis at temperatures ranging from 500 to 800 °C, analyzing the products via GC-MS and ASTM D240 calorimetry. While previous studies have explored the influence of temperature under different atmospheres, both with and without $N_2$, this study focuses on atmospheric pressure conditions for practical and scalable applications.

**Table 2.** Proximate and Ultimate Analyses of Used Tire. $^a$Air dried basis; $^b$Dry basis after heating at 105 ± 5 °C for 24 h; calculated by mass balance

| **Proximate analysis (wt. %)$^a$** | |
|---|---|
| Moisture | 2.67 |
| 2.67 | 21.61 |
| Ash | 21.61 |
| Volatile matter | 59.22 |
| Fixed carbon | 16.50 |
| **Ultimate analysis (wt. %)$^b$** | |
| C | 69.50 |
| H | 7.02 |
| N | 0.39 |
| S | 1.37 |
| O$^c$ | 21.72 |
| **Low heating value (MJ/kg)** | 30.20 |

## 2. Materials and Methods

In this study, the material was used motorcycle tire (UMT). This study comprises several stages of the process, including material preparation, pyrolysis, and determination of calorific value. Used motorcycle tire was cut into pieces measuring 1 cm x 1 cm. The rubber was then weighed and placed into the pyrolysis reactor.

### 2.1. Experimental Procedure

The used motorcycle tire (UMT) pyrolysis experiment setup is shown in Figure 1. The pyrolysis process is carried out through several stages as follows: first, the pyrolysis equipment to be used is checked. After that, the raw material is weighed at 500 grams and placed into the pyrolysis tube. Next, the heater is turned on and the temperature is set at 400°C using a Thermocouple unit.

After that, the cooling water tap is opened to support the pyrolysis process. After the process is complete, the liquid product (tar) and solid product (char) are weighed to determine the weight of the pyrolysis results. This process is then repeated with the same weight of raw material at atmospheric pressure and varying temperatures of 400°C, 450°C, 500°C, 550°C, 600°C, 650°C, 700°C, and 750°C. All samples are taken until the tar no longer drips. After all samples are obtained, an analysis is conducted on each sample to evaluate the results.

Temperature was selected as the primary variable in this study due to its critical and direct influence on product distribution during pyrolysis, as widely acknowledged in the related literature. This focused approach also allows for a more straightforward interpretation of thermal behavior, particularly under atmospheric conditions relevant to practical, scalable pyrolysis applications.

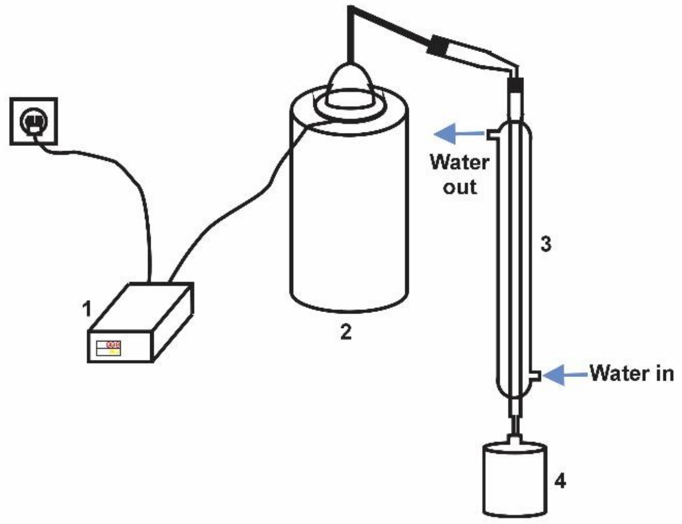

**Figure 1**. Schematic diagram of the pyrolysis experimental setup: (1) thermocouple, (2) furnace, (3) condenser, (4) tar sample.

### 2.2. Analysis Method

### 2.2.1 Determination of Calorific Value

A calorimeter is a device used to measure energy transferred as heat. The adiabatic bomb calorimeter is the most common device for determining $\Delta U$. The determination of the calorific value of liquid products from WTP in this study follows the principles outlined in ASTM D240, which specifies the use of an adiabatic bomb calorimeter for measuring the gross heat of combustion of hydrocarbon-based liquid fuels. The process begins in a fixed-volume vessel called the ‘bomb’. The bomb is immersed in a stirred water bath, and the entire apparatus is the calorimeter. The calorimeter is also immersed in the outer water bath. The temperature change ($\Delta T$) of the calorimeter is directly proportional to the heat energy ($q_V$) released or absorbed during the reaction. By measuring $\Delta T$, we can calculate $q_V$ and subsequently determine $\Delta U$. To convert $\Delta T$ into $q_V$, the calorimeter must be calibrated using a process with a known energy output. This calibration establishes the calorimeter constant (C), which links the observed temperature change to the actual heat transfer (Atkins & de Paula, 2009). Corrections for auxiliary combustion components such as ignition wires and threads, are applied, consistent with the ASTM method (ASTM D240-19).

$$Q = C.\Delta T \tag{1}$$

The determination of the heat of combustion of liquid products from pyrolysis is carried out using a bomb calorimeter. Liquid products from each temperature variation are put into a Bunsen burner and weighed. After that, the Bunsen burner containing the liquid product is placed in a Bunsen burner, and $O_2$ gas is passed through it. Furthermore, the Bunsen burner is protected from burning by covering it with a cylindrical tube containing water. The heat generated from the combustion of the Bunsen burner will cause the temperature to increase. During the combustion process, the water must be stirred continuously so that the heat is evenly distributed. When the Bunsen burner is extinguished, the increase in water temperature on the thermometer is recorded, and the Bunsen burner is left to return to its original temperature. To find out the calorific value (heat transfer) of the fuel, it is calculated using the formula:

$$Q = \frac{Qt}{m} \tag{2}$$

$$Q = \frac{Qc-(Qb+Qk)}{m} \tag{3}$$

$$Q = \frac{[C_c.(T_2-T_1)]-[(m_b.L_b)+(m_k.L_k)]}{m} \tag{4}$$

where:
Q = calorific value (calories/g)
Qt = corrected heat (calories)
m = mass of fuel burned (grams)
Qc = total heat (calories)
Qb = heat of yarn (calories)
Qk = heat of wire (calories)
mb = mass of yarn (grams)
Lb = specific heat of yarn (calories/g.K)
mk = mass of wire (grams)
Lk = specific heat of wire (calories/g.(K)
$T_2$ = temperature after reaction (K)
$T_1$ = temperature before reaction (K)
Cc = heat capacity of the calorimeter (calories/K)

The capacity of the calorimeter can be measured by burning a standard substance (Benzoic Acid) whose ΔU is known. $M_{benzoicacid} . \Delta U_{benzoic\ acid} = Cc.(T_2-T_1)$, where $\Delta U_{benzoic\ acid} = -6318$ calories/g

### 2.2.1 Product Distribution

Product distribution states the amount of phases, namely liquid and solid, produced during the pyrolysis process by determining the percentage of each phase.

$$Y_{liquid\ product} = \frac{W\ liquid\ product}{W\ sample}\ x\ 100\ \% \tag{5}$$

$$Y_{solidproduct} = \frac{W\ remaining\ solid}{W\ sample}\ x\ 100\ \% \tag{6}$$

## 3. Results and Discussion

### 3.1. Tar Results

In this study, pyrolysis was conducted on 500 grams of used motorcycle tires with operating temperatures varying from 400 °C to 750 °C. The results of observations showed that the increase in temperature was directly proportional to the amount of tar (liquid product) produced until it reached the optimum point, as shown in Figure 1. At a temperature of 700 °C, the maximum result was 276.56 grams (55.31%) of tar after 2 hours and 35 minutes of reaction, as shown in Figure 2.

**Figure 2**. Tar Produced from UMT Pyrolysis

Kaminsky et al. (2001) and Kaminsky et al. (2009) reported that 27-57 wt.% of tire rubber pyrolysis oil could be obtained at temperature ranging from 550 to 780 °C in lab-scale, technical-scale, and pilot-scale using fluidized beds. The other research conducted at the same temperature by Li et al. (2004), yielded 43-45 wt.% oils using a rotary kiln reactor. Most pyrolysis oils were lower than this study, which was mainly due to the good mass and heat transfer achieved.

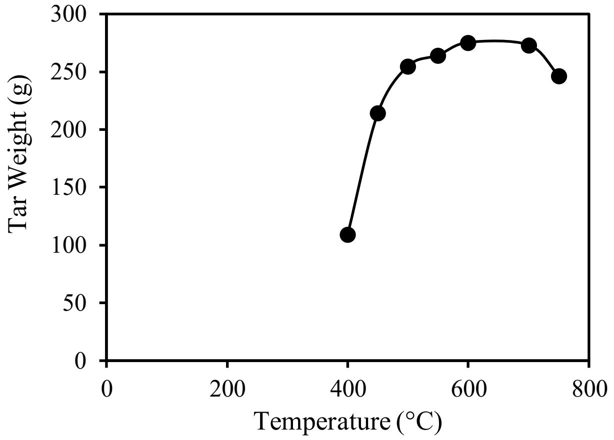

**Figure 3**. The Effect of Temperature on The Weight of The Tar Produced

At a temperature of 750 °C, there was a decrease in the amount of tar produced. This phenomenon is similar to the experiment by Choi et al. (2014), which indicates the occurrence of a secondary reaction where some volatile compounds undergo further decomposition into gases or high-molecular-weight compounds, causing an increase in the solid fraction and a decrease in the liquid fraction.

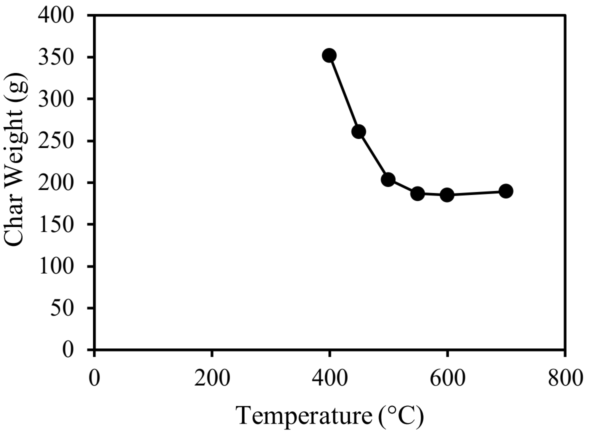

**Figure 4.** The Effect of Temperature on The Weight of The Char Produced

### 3.2. Calorific Value Analysis

The calorific value analysis of tar products shows an increasing trend as the process temperature increases. The highest calorific value is achieved at a temperature of 700 °C, resulting in 9520.98 cal/gram, equivalent to 39.98 MJ/kg, as shown in Figure 3. This value is almost equivalent to that of No. 2 diesel fuel, as defined by ASTM D975 (Zerin et al., 2025). After passing this temperature, the calorific value decreases slightly. This is likely due to the reduction of volatile hydrocarbon compounds that are condensed into light gases or undergo further degradation reactions that do not produce tar with high energy content. This change is in line with the principle of pyrolysis, which states that at high temperatures, liquid products tend to crack into gas or solid carbon residue. Yu (2007) separated pyrolysis into three parts: the metaplast part, primary pyrolysis, and secondary pyrolysis. Secondary reactions in tar result in processes such as crosslinking and decomposition of tar. Crosslinking will produce secondary charcoal, in the form of soot, while tar decomposition will produce secondary gas.

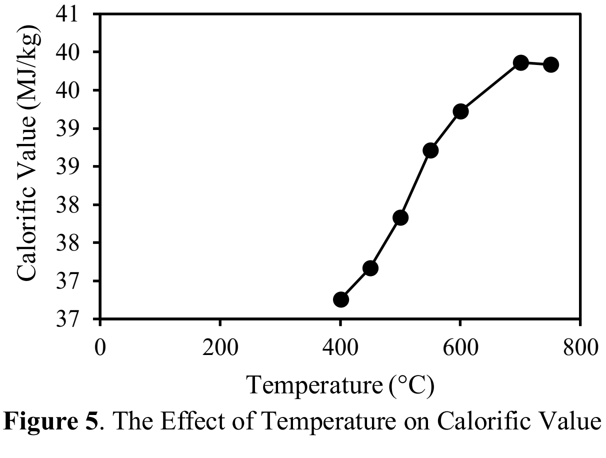

**Figure 5**. The Effect of Temperature on Calorific Value

Research by Zhang et al. (2021) indicates hat waste tire pyrolysis oil (WTPO) has a high energy content, however, it still requires purification due to presence of sulfur and nitrogen compounds, which limit its direct use as a fuel. These results align with the findings of various studies, which demonstrate that temperature control has a significant impact on pyrolysis outcomes. Supporting the calorific value produced in this study, Fajar et al. (2004) revealed that GC/MS analysis of UMT in organic phase has a high content of olefin and aromatic compounds, around 39.29% and 27.91%, respectively, indicating potential as a fuel substitute. Overall, pyrolysis not only offers a solution for sustainable waste management but also contributes to energy diversification by reusing previously wasted carbon-based resources.

### 3.3. Product Distribution

The distribution of pyrolysis products from used motorcycle tires varied significantly with temperature, as shown in Figures 2 and 3. As the temperature increased from 400 °C to 700 °C, the yield of liquid product (tar) consistently increased, reaching a maximum of 276.55 g (55.31%) at 700 °C. Conversely, the solid residue (char) decreased from 70.38% (351.90 g) at 400 °C to 36.91% (184.55 g) at 700 °C, as shown in Table 2, indicating more extensive thermal decomposition of the rubber matrix at higher temperatures. These results are consistent with other studies. Hossain et al. (2017) observed that the pyrolysis temperature from 320 to 440 °C raised the liquid yield to 39%.

The gas fraction, which was not directly measured but estimated by mass difference, remained relatively low up to 700 °C but increased sharply to 12.30% (61.5 g) at 750 °C. This increase indicates the occurrence of secondary cracking reactions, in which condensable volatiles are further decomposed into permanent gases, likely consisting of Co, $CO_2$, $CH_4$, and light hydrocarbons, as commonly observed in tire pyrolysis system. This finding is consistent with that of Ramirez Arias et al. (2022), which also emphasizes the role of secondary cracking, promoting the release of permanent gases at high temperatures or longer vapor residence times. Conesa et al. (2004) who observed that gas yield increased up to 62 wt.% and oil yields nearly disappeared at temperatures above 720 °C.

This pattern suggests that 700 °C is the optimal temperature for maximizing tar yield under the tested conditions. The optimal temperature found in this study aligns with results from bamboo pyrolysis, where oil yield peakes then declines at higher temperatures (Mufandi et al., 2025). Beyond this point, at 750 °C, the tar yield declined to 246.70 g (49.34%), likely due to secondary cracking reactions that converted condensable volatiles into permanent gases. The increased formation of gas and char at higher temperatures is consistent with previous reports (Hussain et al., 2017; Choi et al., 2014) on over-cracking during pyrolysis.

Therefore, careful temperature control is essential to optimize the product distribution and maximize the recovery of energy-rich liquid fuels from used tires. Although the calorific value of tar from UMT is still lower than that of conventional diesel, the results confirm that UMT has potential as a blended fuel source.

Furthermore, while temperature is a dominant factor, residence time also significantly affects product distribution through its kinetic influence on tar cracking reactions. At elevated temperatures, longer vapor residence times enhance secondary cracking, leading to increased permanent gas formation and reduced tar yield, as observed in the decline at 750 °C.

**Table 2.** Product Distribution. Notes: initial weight = 500 gram

| Temperature (°C) | Time (hour) | Product Distribution (%) | |
|---|---|---|---|
| | | Liquid Product | Solid Product |
| 400 | 6.47 | 21.85 | 70.38 |
| 450 | 5.02 | 42.85 | 52.13 |
| 500 | 3.42 | 50.99 | 40.67 |
| 550 | 3.35 | 52.87 | 37.85 |
| 600 | 3.30 | 54.64 | 37.36 |
| 650 | 3.05 | 55.09 | 37.01 |
| 700 | 2.35 | 55.31 | 36.91 |
| 750 | 2.32 | 49.34 | 38.36 |

Kinetic studies support this behavior. Ramirez Arias et al. (2022) found that the activation energy of tire pyrolysis varies between 40 and 119 kJ/mol, depending on the heating rate and particle size, which influences the reaction intensity. Miranda et al. (2013) also observed that extended residence time alters product pathways, especially at higher conversions. Notably, Conesa et al. (2004) revealed that extended vapor residence times (approximately 10 minutes) at high temperatures promote gas formation and suppress liquid yields, findings that align closely with our results.

Hence, future studies could benefit from examining the combined effect of temperature and vapor residence time, supported by detailed kinetic modelling and controlled heating rate experiments, to further elucidate the mechanisms governing product distribution and to refine pyrolysis process optimization.

## 4. Conclusions

This study highlights the potential of pyrolysis as an effective method for converting UMT into liquid fuel (tar) with a calorific value reaching up to 39.98 MJ/kg at 700 °C. The results indicate that temperature plays a significant role in influencing product distribution, with the highest liquid yield (55.31%) obtained under these conditions. These findings support the potential of UMT as an alternative or blended fuel source, contributing to circular economy initiatives and reducing reliance on fossil fuels.

Building on this foundation, future work may focus on exploring additional operational variables, such as heating rate, feedstock preparation, and residence time, to further enhance process performance. Chemical characterization using methods such as GC-MS, FTIR, and elemental analysis can provide valuable insight into the molecular composition and environmental profile of the fuel. Investigating catalytic upgrading techniques and evaluating the process at pilot scale would also contribute to a better understanding of its practical applicability and commercial viability. These directions represent promising avenues for expanding the role of UMT within the landscape of sustainable energy innovation.

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## Statement

During the preparation of this work, the authors used ChatGPT 4.0 in order to improve English language skills and proofread the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## CRediT authorship contribution statement

**Indah Retno Wulandary:** Writing – original draft, writing - review and editing, Visualization, Validation, Resources, Investigation, Formal analysis, Conceptualization.

**Yona Octavia:** Writing - review and editing, Visualization, Validation, Resources, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data used is confidential.

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