

Research Paper

Catalyst-Free Pyrolysis of Mixed Tyres and Plastic Waste for Heavy Fuel-Oil Production with Distillation

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🌐 <https://doi.org/10.31603/ae.13098>

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Abstract

Article Info

Submitted:

28/01/2025

Revised:

09/07/2025

Accepted:

17/08/2025

Online first:

27/08/2025

Waste from used tires and plastics poses a significant environmental challenge due to their non-biodegradable nature. These materials take hundreds to thousands of years to decompose naturally. Every year, plastic and tire waste increase in correlation with population growth and vehicle usage. This waste management is frequently insufficient, resulting in significant adverse effects on human society. One of the effective solutions to the environmental challenges posed by used tires and plastic waste is converting them into crude oil and solid char using pyrolysis technology without a catalyst. This process is a thermochemical decomposition that occurs at high temperatures without oxygen. Pyrolysis breaks down the complex chemical structure of plastics and tires into simpler, valuable components. After being cut into small pieces of 3 cm to 5 cm, the feedstock was placed into a pyrolyzer, with each batch weighing 500 grams, to produce pyrolytic liquid oil and char. The pyrolysis temperature was set at 350 °C for all experiments, with a heating rate of 10 °C/min and a holding time of 90 minutes. The process was followed by distillation at two different temperatures, 250 °C and 350 °C, with a heating rate of 10 °C/min. This distillation process separated the pyrolytic oil based on its boiling points to obtain distillate liquid oil. Two types of distillate liquid oil were produced and analyzed using gas chromatography and mass spectrometry to determine their chemical composition and compounds. It was found that both distillate oils contained similar organic compounds, primarily consisting of complex mixtures of C12–C31 hydrocarbons, which are typical of heavy fuel oils. The heating value of both distillate oils was 31.26 MJ/kg. Additionally, the residual char produced during the process had a calorific value of 21.73 MJ/kg, indicating its potential use as a solid fuel. These properties demonstrate the potential of the products to substitute conventional fuels for heavy machinery or industrial boilers. This study confirms that used tires and plastic waste can be converted into heavy fuel oils, offering great potential as alternative energy sources.

Keywords: Waste plastic; Pyrolysis; Distillation; Heavy fuel; Char

1. Introduction

Technological developments and world population growth lead to a drastic increase in energy needs. In addition, the decrease in primary energy sources and the persistence of carbon emissions pose significant challenges. Therefore,

all nations, including Indonesia, are striving to explore alternative energy sources to fulfill their commitment to achieving net-zero emissions by 2060 [1]. On the other hand, population growth has led to increased waste generation from households, industries, hospitals, offices, and



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hotels, alongside biomass waste. The unmanaged waste can be classified as organic or inorganic. Particular concern arises from the severe impact of inorganic waste, primarily plastics, which persist in the environment for hundreds of years [2]. Unlike biomass, which can be processed through gasification to produce gaseous fuel [3], [4], [5], plastic waste and automotive waste, such as tires, significantly harm the environment if improperly managed. Rather than being discarded, plastic waste can be converted into liquid fuel, as it is derived from fossil fuels [6], [7], [8].

Heavy fuel oil (HFO), or marine diesel, is obtained from distilling crude oil at a boiling temperature between 350 °C and 500 °C. It has a higher viscosity than diesel, with a typical heating value of around 40.9 MJ/kg and a flash point exceeding 60 °C [9]. Heavy fuel oil can also be produced from alternative sources, such as plastic waste and used tires, through thermal conversion processes [9]. Heavy fuel oil can also be produced from alternative sources, such as plastic waste and used tires, through thermal conversion processes [10]. Heavy fuel oil is a liquid fuel composed of various hydrocarbon molecules, primarily derived from heavier and more complex fractions of crude oil. These hydrocarbons are characterized by long, branched carbon chains with many carbon atoms.

Research has shown that pyrolysis of individual plastics can produce a high liquid yield of over 80 wt.%, with a calorific value of approximately 40 MJ/kg [11]. Similarly, liquid oil derived from waste tires has an even higher calorific value, around 42.70 MJ/kg [12]. Additionally, there are opportunities to reduce waste and generate an alternative energy source by converting waste tires and plastic into liquid fuel. Many studies have shown that tire and plastic waste streams have significant potential to be converted into fuel oil through pyrolysis or thermal processing [13], [14]. Oil produced from the pyrolysis of plastics has a higher calorific value than wood-based oil and is comparable to conventional diesel. The conversion of tires and plastic waste into fuel oil presents several advantages, including reducing environmental pollution and decreasing reliance on fossil fuels. However, individual pyrolysis of these waste streams generates toxic gases and emissions [15]. Moreover, pyrolyzing plastic waste alone is

inefficient and costly, as it requires sorting from mixed waste and additional treatment to address contamination from other materials. Therefore, co-pyrolysis is more efficient and effective for rubber tires and plastic waste.

Co-pyrolysis of used tires and plastic waste has been shown to enhance efficiency and improve the quality of the final products through several synergistic mechanisms [16]. This process enhances the quality of liquid fuels, offering an alternative to reduce dependence on fossil fuels [17]. Due to their high carbon content, calorific value, and volatile matter, waste polymer materials are suitable feedstocks for pyrolysis to produce crude oil and solid char, as illustrated in Figure 1. The characteristics of waste rubber tires and plastic differ, leading to variations in the pyrolysis process and the resulting products. However, limited information is available on low-temperature laboratory experiments of the co-pyrolysis of waste tires and plastic. Miranda *et al.* [18] and Hu *et al.* [19] conducted kinetic studies on pyrolysis mixtures of waste tires and plastic. Their findings on the co-pyrolysis of waste rubber tires and plastics indicate that positive interactions enhance the crude oil quality. However, the interactions between different plastics and tires remain poorly understood, primarily due to variations in their decomposition mechanisms, particularly at different pyrolysis temperatures. Researchers generally agreed that higher temperatures produce pyrolytic plastic oil with higher heating values.

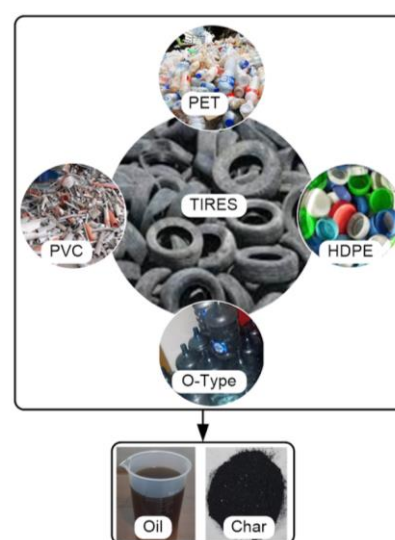


Figure 1. Tires and plastic wastes that are potentially used for heavy fuel oil and solid char production

This study addresses the issue by focusing on the low-temperature co-pyrolysis of waste rubber tires and four types of waste plastics: high-density polyethylene, polyethylene terephthalate, polyvinyl chloride, and polycarbonate. The experimental approach aims to investigate their thermo-decomposition characteristics and interaction effects. The pyrolysis characteristics and product distribution were analyzed using GC-MS to evaluate the products' properties, interaction effects, and composition. The work aims to provide a theoretical foundation for applying co-pyrolysis in processing these waste materials.

2. Methods

2.1. Materials

The feedstock used in this study consisted of a waste tire (WT) and four types of waste plastic: high-density polyethylene (HDPE) from bottle caps, polyethylene terephthalate (PET) from bottles, polyvinyl chloride (PVC) from plumbing materials, and O-type plastic made of polycarbonate from large water jug waste, as shown in Figure 2. These materials were gathered from various points around the research site, where they had accumulated as waste. Before being fed into the reactor, the feedstocks were chopped into particle sizes ranging between 30 and 50 mm and dried in sunlight to reduce moisture content. In this study, proximate and ultimate analyses were not carried out. The author assumed that the characteristics of used tires and plastic waste are consistent worldwide.

Consequently, the author refers to one of the researchers who has conducted a study on the use of rubber tires and plastic materials, as shown in Table 1 and Table 2.

2.2. Research Stages

The pyrolysis process was conducted using a lab-scale fixed-bed pyrolyzer with a volume of approximately 5 L. The pyrolyzer was heated by an LPG combustor, where the temperature was adjusted using a gas valve regulator and was monitored through an analog temperature sensor. 3 kg of feedstock was put into the pyrolyzer and gradually heated to the desired temperature of approximately 350 °C at a heating rate of 10 °C/min. Once the target temperature was reached, the process was maintained for 90 minutes. The vapor generated by the pyrolyzer was subjected to condensation via a condenser, leading to the collection of pyrolytic oil. Meanwhile, non-condensable gases were released into the atmosphere. The residue remaining in the reactor was identified as carbon black or char. Upon completion of the pyrolysis experiment, the



Figure 2. Feedstock used in this study

Table 1. Physical properties of rubber waste tires [20]

Elemental analysis (wt. %)		Proximate analysis (wt. %)		HHV (MJ/kg)
C	90.38	Ash	6.91	38.58
H	6.30	Volatile	67.6	
N	0.65	Moisture	1.81	
S	2.11	Fixed carbon	23.6	
O	0.56			

Table 2. Physical properties of plastic waste [21], [22]

Type of Plastic	Proximate analysis (%.wt)				Ultimate analysis (%.wt)					Cl	HHV (MJ/kg)
	M	FC	V	A	C	H	S	N	O		
PET	0.535	10.47	89.29	0.01	64.1	3.7	2.1	-	-	-	28.2
HDPE	0	0.02	99.19	0.79	86.5	15.1	0.25	-	-	-	45.4
PVC	0.77	5.745	94.26	0.09	38.53	5.04	0.176	0.013	0.00	56.25	22.73
O	0.065	1.18	98.42	0.5	-	-	-	-	-	-	-

weights of the liquid and solid products were measured and recorded. Subsequently, the process continued with distillation to refine and purify the pyrolytic oil. The distillate pyrolytic oil and char were then analyzed by the gas chromatography/mass spectrometry (GCMS) method to determine the chemical content and compounds of the obtained pyrolytic oil.

3. Results and Discussion

3.1. Characteristics of Pyrolytic Oil Product

Figure 3 illustrates the images that visualize the product resulting from the pyrolysis of waste tyres and four types of plastic waste. Figure 3a shows the crude pyrolytic oil product pyrolyzed at 350 °C. This oil appears blackish due to the presence of rubber and other substances like carbon black from tires [23]. Figure 3b depicts distillate oil at 250 °C and 350 °C. This distillate oil tends to have a deep black color caused by the carbon black content of the tires. Distillation oil tends to be cleaner and purer than crude pyrolysis oil because the impurities and heavy fractions have been separated. Gas chromatography and mass spectrometry analysis were conducted to identify the mixture of organic compounds present. These compounds are typical components of heavy fuel oil and include aliphatic and aromatic hydrocarbons. Distilled oil can be used as fuel for heavy machinery, industrial boilers, or power plants. In addition, it can also be further processed to produce chemical products or fuels with higher specifications.

Figure 3c shows the charcoal or solid residue. The charcoal produced from the pyrolysis of tires and plastics will likely contain high amounts of carbon and some inorganic residues such as ash. The presence of carbon black in tires also contributes to the carbon content in this charcoal. In addition to being used as a fuel, charcoal from pyrolysis can serve various other purposes, such as raw material for producing activated carbon, as

an adsorbent material, or as a mixed material in the construction industry. Given their properties and calorific value, charcoal residues derived from the pyrolysis of scrap tires and plastics have the potential to serve as an alternative to conventional fuels in industrial applications. This presents a sustainable and efficient method for waste management.

3.2. Pyrolytic Oil

The distillate oil obtained in this work was a dark oil of hydrocarbons of different natures, such as aromatics, alkanes, esters, and others. In addition, the presence of sulfur-containing compounds was also remarkable. The distillate oil was analyzed using GC–MS techniques to determine its chemical content. Table 3 shows the ultimate analyses of the obtained distillate oil at two different temperatures and their heating values. It can be seen that the carbon content is above 80 wt.%. Furthermore, the pyrolysis temperature increased carbon content and decreased hydrogen content, both of which are consistent with the previously discussed aromatization effects induced by temperature. The oxygen content is increased as the temperature is raised. However, the sulfur content was not detected in this study. It can also be seen that the heating value of distillate oil decreased slightly with temperature. This is due to the fact that the hydrogen content value decreases with temperature. Research conducted by Lopez *et al.* [24] on the pyrolysis of waste tires has shown that the hydrogen content decreases with temperature.

Figure 4 shows the chromatography test result of the distillate oil at 250 °C. The x-axis represents the acquisition time in minutes. Conversely, the y-axis indicates the counts or intensity, typically associated with the concentration of compounds eluting from the chromatographic column at a specific time. The peaks at particular retention times (5.891, 14.091, 22.217, 47.333, and 73.974 min)

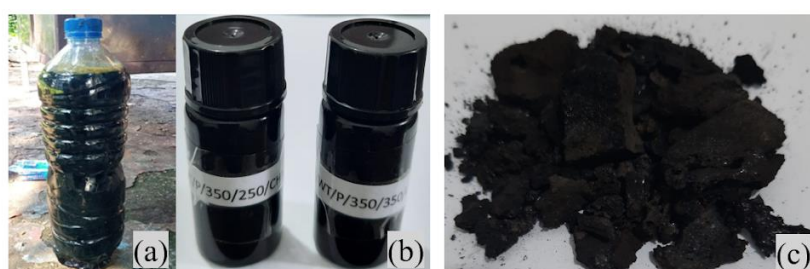


Figure 3. (a) Pyrolytic oil, (b) Distillate oil, (c) Pyrolytic Char

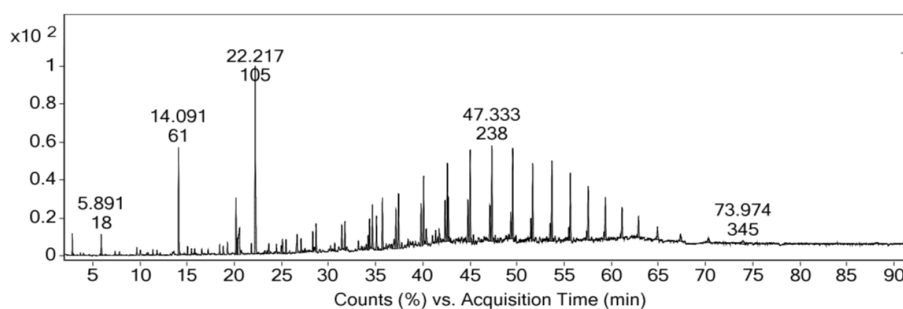


Figure 4. Gas chromatogram of the pyrolytic oil products distillate at 250 °C

Table 3. The chemical content of the distillate pyrolytic oil

Elemental analysis (wt. %)	Distillation Temperature	
	250 (°C)	350 (°C)
C	80.9400	81.0770
H	9.9218	9.6529
O	8.963	9.0949
N	0.1752	0.1752
S	n.a.	n.a.
Cl	n.a.	n.a.
HHV (MJ/kg)	31.26	31.12

indicate different compounds detected by the chromatographic system. Each peak corresponds to a compound eluting from the column and being detected. Each peak on the chromatogram corresponds to a different compound in the sample. Higher peaks signify a greater abundance of compounds in the sample.

3.3. GC-MS Analysis of Crude PPO

The crude PPO was investigated, and most of the compounds that were reported were identified. The carbon number distribution and Table 4 represent the identification and distribution of the compounds. It was observed that the amount of alkane and alkenes was dependent on the concentration of organic compounds. Analysis of the carbon number distribution revealed that about 35.41% of the oil comprises C6-C9 compounds. In contrast, compounds with carbon chains ranging from C10 to C14 account for roughly 48.40%. A similar finding has also been documented in existing literature [15].

Table 4 shows that a mixture of used tires and four types of plastic can serve as an alternative energy source through a pyrolysis process followed by distillation to produce liquid fuel. Meanwhile, Figure 5 illustrates the distribution of chemical carbon content at two different

temperatures, 250 °C and 350 °C. The graph shows an increase in carbon content with rising temperature across all categories, both light and heavy carbon. The most significant increase occurred in compounds with more than 16 carbon atoms ($C > 16$), where the carbon content rose sharply by 25% compared to molecules with 1-11 carbon atoms (C1-C11) and 12-16 carbon atoms (C12-C16). This indicates that higher temperatures tend to increase the number of chemical compounds with more carbon atoms. Elevated temperatures create more favorable conditions for chemical reactions that generate compounds with a higher number of carbon atoms. This occurs through increased reaction rates, molecular reorganization, shifts in thermodynamic equilibrium, and other factors that enhance molecular interactions, resulting in the formation of these compounds.

3.4. Product Char

Table 5 presents the results of the proximate analysis conducted by several researchers on various biomass or solid fuel samples. The study includes moisture content, ash content, volatile matter, fixed carbon, and calorific value. The moisture content values varied depending on the

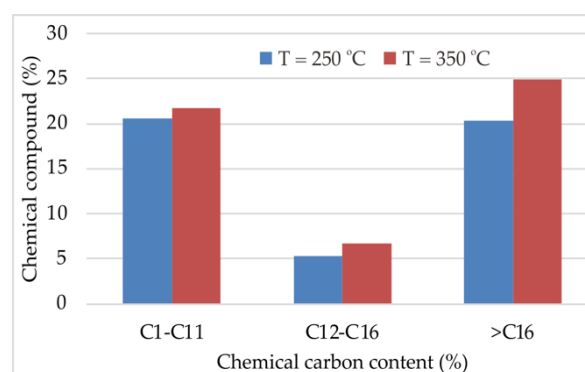


Figure 5. Effect of distillation temperature on the distillate chemical compounds

Table 4. Chemical compounds identified by Mass Spectrometry in distillate oil from mixed waste tires (WT) and PET/HDPE/PVC/Other-type plastics at 250 °C and 350 °C

Distillation Temperature					
250 °C			350 °C		
Chemical Name	Chemical Formula	Area (%)	Chemical Name	Formula	Area (%)
Aromatics					
Benzene	C ₆ H ₆	0.53	Benzene	C ₆ H ₆	0.64
Phenol	C ₆ H ₆ O	3.36	Phenol	C ₆ H ₆ O	3.53
Toluene	C ₇ H ₈	0.79	Toluene	C ₇ H ₈	0.92
Benzoic acid	C ₇ H ₆ O ₂	2.91	Benzoic acid	C ₇ H ₆ O ₂	3.51
Phenol, 4-ethyl	C ₈ H ₁₀ O	2.20	Phenol, 4-ethyl-	C ₈ H ₁₀ O	2.59
Methanol, oxo, benzoate	C ₈ H ₆ O ₃	0.60	p-Cumenol	C ₉ H ₁₂ O	9.16
Phenol, methyl ethyl	C ₉ H ₁₂ O	9.10	Phenol, 2-(1,1-dimethyl ethyl)-5-methyl-	C ₁₁ H ₁₆ O	1.38
Phenol, dimethyl ethyl, methyl	C ₁₁ H ₁₆ O	1.09	Naphthalene, 2-ethenyl-	C ₁₂ H ₁₀	0.64
Naphthalene, ethenyl	C ₁₂ H ₁₀	0.61			
Phenol, methyl, phenyl ethyl	C ₁₅ H ₁₆ O	2.47	Phenol, 4-(1-methyl-1-phenylmethyl)-	C ₁₅ H ₁₆ O	2.59
Alkanes					
Eiconase	C ₂₀ H ₄₂	4.65	Eicosane	C ₂₀ H ₄₂	4.46
Heneicosane	C ₂₁ H ₄₄	4.67	Heneicosane	C ₂₁ H ₄₄	4.27
			Docosane	C ₂₂ H ₄₆	4.22
2-Methylhexacosane	C ₂₇ H ₅₆	3.90	2-Methylhexacosane	C ₂₇ H ₅₆	3.53
Hentriacontane	C ₃₁ H ₆₄	4.03	Hentriacontane	C ₃₁ H ₆₄	4.01
Ester					
Carbonic acid, eicosyl, vinyl ester	C ₂₃ H ₄₄ O ₃	3.10	Carbonic acid, eicosyl vinyl ester	C ₂₃ H ₄₄ O ₃	3.10
Others					
Chloroacetic acid, tetradecyl ester	C ₁₆ H ₃₁ ClO ₂	2.22	Chloroacetic acid, dodecyl ester	C ₁₄ H ₂₇ ClO ₂	0.50
			Chloroacetic acid, tetradecyl ester	C ₁₆ H ₃₁ ClO ₂	2.12
			Acetic acid, chloro-, hexadecyl ester	C ₁₈ H ₃₅ ClO ₂	1.33

Table 5. Characteristics of the produced biochar compared to other research

Proximate analysis (wt.%)			
No	Content	[25]	This work
1	Moisture (%)	2.41	3.93
2	Ash (%)	0.16	2.52
3	Volatile (%)	1.40	17.8
4	Fixed carbon (%)	6.03	79.68
5	Heating value (MJ/kg)	8.84	21.73

sample and the drying method used by each researcher. The reported percentage of ash varies across different studies, potentially due to variations in material types and testing methodologies. The variations in study results suggest differences in the chemical composition of

the tested materials. Different fixed carbon values indicate variations in the kind of material and its energy content. Differences in calorific value between studies can be attributed to variations in material types and measurement methods. Selecting the appropriate fuel for a specific application requires considering all these parameters to ensure efficient and effective fuel use. Understanding each parameter in a proximate analysis allows us to determine the quality and suitability of materials for a wide range of energy and industrial applications.

Figure 6 shows the results of chromatogram testing of char products. This test is carried out to identify and measure the chemical components of charcoal products. Tests are carried out to ensure the quality, identification, and quantification of

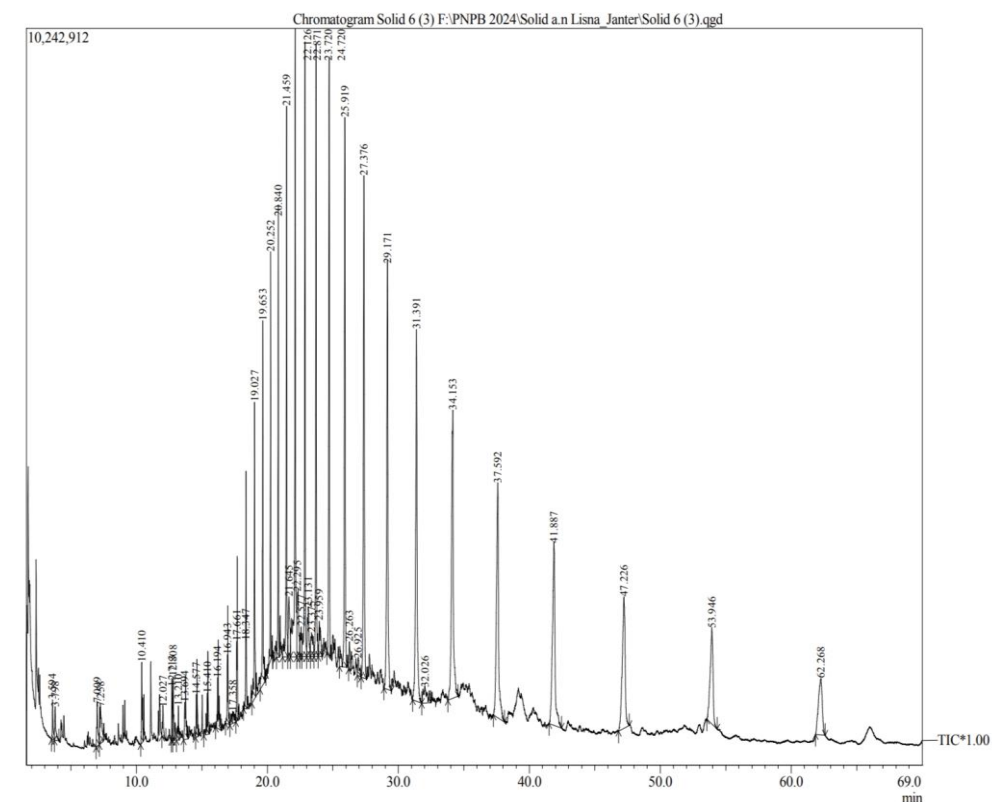


Figure 6. Mass Spectrometry of the char pyrolyzed at 350 °C

components in biochar product mixtures. This chromatogram provides detailed information about the various compounds present in the sample. The horizontal axis shows the retention time in minutes, representing when a compound passes through the chromatography column and reaches the detector. The time range on this chromatogram is from 0 to about 69 minutes. The vertical axis shown by the graphic peak indicates that the compounds are detected at that retention time. Each peak on the chromatogram represents a different compound in the sample. The peaks' height and area reflect the compound's relative amount in the sample. Taller peaks signify more plentiful compounds.

Table 6 displays the chemical components of charcoal constituents obtained at a pyrolysis temperature of 350 °C. This analysis aims to identify and measure the chemical composition of the resulting charcoal, which is essential for understanding its quality and potential use as an alternative fuel or for other industrial applications. Compounds such as tetratetracontane, benzene, and naphthalene, which are fuel elements, indicate that this charcoal has the potential to be used as an energy source. The toluene compound has the largest percentage

of area (23.14%), suggesting that toluene is one of the main components in the charcoal produced. Naphthalene compounds were detected in two different peaks with significant total areas (10.59% and 1.41%), indicating that naphthalene is also an important component. Additionally, aromatic compounds such as xylene, benzaldehyde, and benzene are present in smaller but still significant amounts, indicating the presence of various aromatic compounds in the charcoal.

4. Conclusion

This work aims to convert waste tires and plastic waste into valuable energy. The primary objective is to convert non-recyclable plastic waste and used tires into heavy fuel oil and charcoal through pyrolysis without a catalyst, followed by distillation. This process aims to reduce environmental impact and serve as an alternative to conventional fossil fuels. The resulting crude pyrolytic oil shows a blackish appearance due to carbon black in the tires. Distillation at 250 °C and 350 °C produces two types of distillate oils with similar characteristics, particularly regarding organic composition. These oils are a complex mixture of C12–C31 compounds, typical compo-

Table 6. Tentative Mass Spectrometry compound name of biochar products from co-pyrolysis mixed waste tires (WT) and PET/HDPE/PVC/Other-type plastics pyrolyzed at 350 °C

Peak No.	R. Time (min)	Area (%)	Compound Name
1	3.594	0.33	Benzene, ethyl
2	3.798	0.44	Benzene, 1,2-dimethyl
3	7.009	0.56	Octadecanoic acid, 3-hydroxy-, methyl ester
4	7.258	0.81	Phenol
5	10.410	0.71	Naphalene
6	12.027	0.35	Benzofuran, 2,3-dihydro-2-methyl
7	12.713	0.50	1,1'-Biphenyl
8	12.808	0.46	Tetradecane
9	13.210	0.34	Benzene
10	13.694	0.74	1-Tetradecanol
11	14.577	0.58	1-Hexadecene
12	15.410	0.72	9-Eicosene
13	16.194	0.86	1-Octadecanol
14	16.943	0.82	1-Octadecanol
15	17.358	0.37	Anthracene, 9-methyl-
16	17.661	1.11	1-Octadecanol
17	18.347	1.37	1-Tricosene
18	19.027	1.98	Docosane
19	19.653	2.41	Tricosane
20	20.252	2.14	Tetratetracontane
21	20.840	2.68	Tetratetracontane
22	21.459	3.62	Tetratetracontane
23	21.645	1.03	1-Hexacosene
24	22.126	5.82	Tetratetracontane
25	22.259	1.18	1-Eicosanol
26	22.577	0.45	Germacrane-A
27	22.871	4.60	Tetratetracontane
28	23.131	0.86	9,10 Dideutero octadecanal
29	23.375	0.56	Hexacosane, 9-octyl
30	23.720	4.75	Tetratetracontane
31	23.959	5.58	Tetratetracontane
32	24.720	4.85	Tetratetracontane
33	25.919	5.58	Tetratetracontane
34	26.263	0.32	Tetrapentacontane
35	25.925	0.32	Triacontane, 1-Bromo
36	27.376	5.66	Tetratetracontane
37	29.171	5.83	Tetratetracontane
38	31.391	6.11	Tetratetracontane
39	32.026	0.70	Tetratetracontane
40	34.153	6.18	Tetratetracontane
41	37.592	5.68	Tetratetracontane
42	41.887	5.27	Tetratetracontane
43	47.226	4.23	Tetratetracontane
44	53.946	3.07	Tetratetracontane
45	62.268	2.41	Tetratetracontane

nents of heavy fuel oils. Distilled oil has a calorific value of 31.26 MJ/kg, making it a potential candidate for conventional fuel substitution in heavy machinery or industrial boilers. The charcoal residue from the pyrolysis process has a calorific value of 21.73 MJ/kg, indicating its potential as an alternative solid fuel. These heavy

fuel oil and charcoal products from pyrolysis can be used.

Acknowledgements

The author sincerely thanks the Universitas Negeri Medan through the Institute for Research and Community Service, Universitas Negeri

Medan, for funding support through PNBPN Universitas Negeri Medan Fiscal Year 2024 under the Decree of the Rector of Universitas Negeri Medan No: 00299/UN33/KPT/2024. Two final-year diploma students, workshop employees, and research partners were also thanked for supporting this research.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

This work was funded by the Universitas Negeri Medan through the Institute for Research and Community Service.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

References

- [1] B. P. Resosudarmo, J. F. Rezki, and Y. Effendi, "Prospects of Energy Transition in Indonesia," *Bulletin of Indonesian Economic Studies*, vol. 59, no. 2, pp. 149–177, May 2023, doi: 10.1080/00074918.2023.2238336.
- [2] S. Dey, G. T. N. Veerendra, P. S. S. A. Babu, A. V. P. Manoj, and K. Nagarjuna, "Degradation of Plastics Waste and Its Effects on Biological Ecosystems: A Scientific Analysis and Comprehensive Review," *Biomedical Materials & Devices*, vol. 2, no. 1, pp. 70–112, Mar. 2024, doi: 10.1007/s44174-023-00085-w.
- [3] D. H. T. Prasetyo, A. Sanata, I. Sholahuddin, M. D. Nashrullah, H. Y. Nanlohy, and M. S. Panithasan, "Comprehensive analysis of tar reduction method in biomass gasification for clean energy production: A Review," *Mechanical Engineering for Society and Industry*, vol. 4, no. 3, pp. 556–569, Dec. 2024, doi: 10.31603/mesi.12712.
- [4] J. P. Simanjuntak, Lisyanto, E. Daryanto, and B. H. Tambunan, "Producer gas production of Indonesian biomass in fixed-bed downdraft gasifier as an alternative fuels for internal combustion engines," *Journal of Physics: Conference Series*, vol. 970, p. 012019, Mar. 2018, doi: 10.1088/1742-6596/970/1/012019.
- [5] S. Mujiarto, B. Sudarmanta, H. Fansuri, and A. R. Saleh, "Comparative Study of Municipal Solid Waste Fuel and Refuse Derived Fuel in the Gasification Process Using Multi Stage Downdraft Gasifier," *Automotive Experiences*, vol. 4, no. 2, pp. 97–103, Apr. 2021, doi: 10.31603/ae.4625.
- [6] J. P. Simanjuntak, M. Z. Zainon, N. W. B. M. Zulkifli, B. H. Tambunan, J. L. Sihombing, and R. Riduwan, "Development of an Innovative Thermal Cracking of Mixed-Plastic Waste Without Catalyst as an Alternative Fuel Source," *International Journal of Technology*, vol. 15, no. 5, p. 1539, Sep. 2024, doi: 10.14716/ijtech.v15i5.6905.
- [7] E. Daryanto and et al., "Potential of Grocery Bags Plastic Waste as a Fuel Substitute for Fossil-Based Fuels: A Characterization Study on the Non-Catalytic Low-Temperature Pyrolysis Process," *Automotive Experiences*, vol. 7, no. 3, pp. 450–459, Dec. 2024, doi: 10.31603/ae.12099.
- [8] M. Setiyo, Sunaryo, and M. L. Rochman, "Pyrolysis for plastic waste: Environmental goals vs business interests, which is more realistic?," *Mechanical Engineering for Society and Industry*, vol. 5, no. 1, pp. 1–4, 2025, doi: 10.31603/mesi.14149.
- [9] A. Fivga and I. Dimitriou, "Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment," *Energy*, vol. 149, pp. 865–874, Apr. 2018, doi: 10.1016/j.energy.2018.02.094.
- [10] M. Blazsó, "Composition of Liquid Fuels Derived from the Pyrolysis of Plastics," in *Feedstock Recycling and Pyrolysis of Waste Plastics*, Wiley, 2006, pp. 315–344. doi: 10.1002/0470021543.ch12.
- [11] J. D. Martínez, M. Lapuerta, R. García-Contreras, R. Murillo, and T. García, "Fuel Properties of Tire Pyrolysis Liquid and Its Blends with Diesel Fuel," *Energy & Fuels*, vol. 27, no. 6, pp. 3296–3305, Jun. 2013, doi: 10.1021/ef400602e.
- [12] C. Allouis, F. Beretta, and A. D'Alessio,

- "Structure of inorganic and carbonaceous particles emitted from heavy oil combustion," *Chemosphere*, vol. 51, no. 10, pp. 1091–1096, Jun. 2003, doi: 10.1016/S0045-6535(02)00714-2.
- [13] B. H. Tambunan, H. Ambarita, T. B. Sitorus, A. H. Sebayang, and A. Masudie, "An Overview of Physicochemical Properties and Engine Performance Using Rubber Seed Biodiesel–Plastic Pyrolysis Oil Blends in Diesel Engines," *Automotive Experiences*, vol. 6, no. 3, pp. 551–583, Nov. 2023, doi: 10.31603/ae.10136.
- [14] M. Venturelli, E. Falletta, C. Pirola, F. Ferrari, M. Milani, and L. Montorsi, "Experimental evaluation of the pyrolysis of plastic residues and waste tires," *Applied Energy*, vol. 323, p. 119583, Oct. 2022, doi: 10.1016/j.apenergy.2022.119583.
- [15] M. S. Qureshi *et al.*, "Pyrolysis of plastic waste: Opportunities and challenges," *Journal of Analytical and Applied Pyrolysis*, vol. 152, p. 104804, Nov. 2020, doi: 10.1016/j.jaap.2020.104804.
- [16] F. Abnisa and W. M. A. Wan Daud, "A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil," *Energy Conversion and Management*, vol. 87, pp. 71–85, Nov. 2014, doi: 10.1016/j.enconman.2014.07.007.
- [17] D. Li, S. Lei, G. Rajput, L. Zhong, W. Ma, and G. Chen, "Study on the co-pyrolysis of waste tires and plastics," *Energy*, vol. 226, p. 120381, Jul. 2021, doi: 10.1016/j.energy.2021.120381.
- [18] M. Miranda, I. Cabrita, F. Pinto, and I. Gulyurtlu, "Mixtures of rubber tyre and plastic wastes pyrolysis: A kinetic study," *Energy*, vol. 58, pp. 270–282, Sep. 2013, doi: 10.1016/j.energy.2013.06.033.
- [19] Q. Hu, Z. Tang, D. Yao, H. Yang, J. Shao, and H. Chen, "Thermal behavior, kinetics and gas evolution characteristics for the co-pyrolysis of real-world plastic and tyre wastes," *Journal of Cleaner Production*, vol. 260, p. 121102, Jul. 2020, doi: 10.1016/j.jclepro.2020.121102.
- [20] W.-C. Wang, C.-J. Bai, C.-T. Lin, and S. Prakash, "Alternative fuel produced from thermal pyrolysis of waste tires and its use in a DI diesel engine," *Applied Thermal Engineering*, vol. 93, pp. 330–338, Jan. 2016, doi: 10.1016/j.applthermaleng.2015.09.056.
- [21] S. D. Anuar Sharuddin, F. Abnisa, W. M. A. Wan Daud, and M. K. Aroua, "A review on pyrolysis of plastic wastes," *Energy Conversion and Management*, vol. 115, pp. 308–326, May 2016, doi: 10.1016/j.enconman.2016.02.037.
- [22] W. U. Eze, R. Umunakwe, H. C. Obasi, M. I. Ugbaja, C. C. Uche, and I. C. Madufor, "Plastics waste management: A review of pyrolysis technology," *Clean Technologies and Recycling*, vol. 1, no. 1, pp. 50–69, 2021, doi: 10.3934/ctr.2021003.
- [23] J. D. Martínez, N. Puy, R. Murillo, T. García, M. V. Navarro, and A. M. Mastral, "Waste tyre pyrolysis – A review," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 179–213, Jul. 2013, doi: 10.1016/j.rser.2013.02.038.
- [24] G. Lopez *et al.*, "Waste truck-tyre processing by flash pyrolysis in a conical spouted bed reactor," *Energy Conversion and Management*, vol. 142, pp. 523–532, Jun. 2017, doi: 10.1016/j.enconman.2017.03.051.
- [25] J. Jamradloedluk and C. Lertsatitthanakorn, "Characterization and Utilization of Char Derived from Fast Pyrolysis of Plastic Wastes," in *Procedia Engineering*, 2014, pp. 1437–1442. doi: 10.1016/j.proeng.2014.03.139.