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Research Article

Analysis of Hydrocarbon Distribution in Polypropylene Plastic Pyrolysis Products as an Alternative Fuel

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ABSTRACT

This study investigated the liquid product obtained from the pyrolysis of polypropylene plastic waste and evaluated its hydrocarbon distribution for alternative fuel potential. Pyrolysis was conducted in a batch reactor under an inert atmosphere with electric heating. The process yielded 75.93% liquid oil, 20.09% non-condensable gas, and 3.98% solid residue, indicating efficient depolymerization into condensable compounds. Fourier transform infrared spectroscopy confirmed that the oil was dominated by aliphatic hydrocarbons with clear unsaturation. Gas chromatography–mass spectrometry showed that the liquid consisted mainly of alkenes (37.87%), followed by alcohols (25.22%), cyclic hydrocarbons (10.39%), and alkanes (3.92%). The high liquid yield and fuel-range hydrocarbon profile demonstrate that polypropylene waste pyrolysis can generate a fuel-like mixture, representing a promising route for plastic-to-fuel conversion.

Keywords: Plastic waste, Pyrolysis, Polypropylene, Alternative Fuel.

1. INTRODUCTION

The growing global production and consumption of plastic materials have resulted in an alarming increase in plastic waste, presenting a significant environmental challenge [1]. In 2020, Indonesia alone generated approximately 32.82 million tons of plastic waste, a figure that is expected to rise in the coming years as demand for plastic products continues to grow [2]. Among the various types of plastic waste, polypropylene (PP) stands out due to its widespread use in packaging, textiles, and consumer goods [3]. Unfortunately, the characteristics that make plastic so versatile, its durability, low cost, and resistance to degradation, also contribute to its persistence in the environment, where it can take hundreds of years to break down [4]. This non-biodegradable nature of plastics leads to their accumulation in landfills, rivers, oceans, and other ecosystems, severely impacting wildlife and disrupting natural habitats [5]. Plastic waste poses a grave threat to the environment, particularly in aquatic ecosystems, where it entangles marine life and introduces harmful microplastics into the food chain. Additionally, the improper disposal of plastic materials through incineration releases toxic chemicals, including carcinogenic dioxins and furans, further exacerbating air pollution and contributing to health hazards for both humans and animals [6]. The vast scale of plastic pollution, coupled with the limited effectiveness of traditional waste management methods, underscores the urgent need for sustainable solutions to address the growing plastic crisis and mitigate its environmental impact [7].

The growing challenge of plastic waste management has spurred the exploration of alternative solutions that not only address the environmental impact but also provide valuable outputs. Traditional recycling methods often face limitations due to the complexity and contamination of plastic waste, while landfilling and incineration contribute to long-term environmental degradation. In this context, pyrolysis has emerged as a promising method to convert plastic waste into useful products such as liquid hydrocarbons, gas, and solid residues[8]. Pyrolysis is a thermochemical process that breaks down plastics at high temperatures in the absence of oxygen, yielding products that can be further refined and utilized as fuels[9]. This process helps mitigate the environmental burden of plastic waste by reducing its volume and converting it into energy-rich compounds. Furthermore, the need for alternative energy sources is growing, driven by the global dependence on fossil fuels and the associated environmental concerns, such as greenhouse gas emissions and resource depletion [10].

The conversion of plastic waste into fuel via pyrolysis presents a dual solution, it not only tackles plastic pollution but also helps address the increasing demand for renewable energy sources[11], [12]. The pyrolysis process can be optimized through various methods, including catalytic pyrolysis, which enhances the yield of high-quality fuels and reduces the energy required for conversion. In particular, the use of catalysts like zeolites or biochar can significantly improve the conversion of plastic into liquid hydrocarbons, such as gasoline and diesel, which can be directly used in engines. By transforming plastic waste into liquid fuels, pyrolysis offers a sustainable solution for energy production while reducing the harmful environmental effects of plastic waste. Compared to direct plastic combustion, pyrolysis has clear advantages, including lower emissions and improved energy efficiency [13].

The need for sustainable plastic waste management has become a global priority as the environmental impacts of plastic accumulation intensify. Among the various methods available, pyrolysis stands out as an effective solution for converting plastic waste, particularly polypropylene (PP), into useful products. Pyrolysis is a thermochemical process that decomposes organic materials at high temperatures in the absence of oxygen, breaking long-chain hydrocarbons into smaller molecules. This process typically produces three primary products: liquid oil, gaseous compounds, and solid residues (char) [14]. The liquid oil produced during pyrolysis contains hydrocarbon compounds similar to gasoline and diesel, making it a promising alternative fuel source [15]. This process can significantly reduce the volume of plastic waste, while converting it into valuable fuels that can be used in internal combustion engines, thus contributing to energy sustainability. Moreover, pyrolysis provides an environmentally friendly alternative to traditional waste disposal methods such as landfilling and incineration, which can release harmful toxins into the environment [16].

The potential of polypropylene pyrolysis products as alternative fuels lies not only in their similarity to conventional fuels like gasoline and diesel but also in their relatively low environmental impact compared to fossil fuels. Pyrolytic oil derived from PP can be utilized in motor vehicles, offering a renewable energy option while addressing both plastic pollution and energy consumption. In fact, several studies have demonstrated that the fuel properties of pyrolytic oil are comparable to those of conventional fuels, making it a feasible substitute in internal combustion engines with minimal adjustments [16].

In this study, post-consumer polypropylene drinking-water cups are thermally degraded in a non-catalytic batch pyrolysis reactor at 450 °C to produce a liquid fuel fraction. The work characterizes the resulting pyrolysis oil through detailed GC–MS analysis to determine the distribution of hydrocarbon compound groups (such as alkanes, alkenes, and cyclic hydrocarbons), supported by FTIR spectra to identify the dominant functional groups. In addition, basic fuel-related properties of the liquid product are evaluated and interpreted in relation to its potential use as an alternative fuel. The findings are intended to provide practical insight into the feasibility of converting widely available PP cup waste into a usable liquid fuel using a relatively simple reactor configuration.

2. EXPERIMENTAL SECTION

2.1. Materials

The materials used in this study included post-consumer polypropylene (PP) plastic waste in the form of drinking-water cups, obtained from a local supplier (CV Citra Plastik, Sukoharjo, Indonesia). The PP waste was thoroughly cleaned and shredded into small, uniform pieces prior to use. Nitrogen gas (N_2), supplied by PT Samator (Indonesia), was employed to establish an inert atmosphere during the pyrolysis experiments to prevent combustion.

2.2. Instrumentation

The pyrolysis experiments were performed using a laboratory-scale batch pyrolysis reactor equipped with an electric heating furnace as the heat source. The reactor unit consisted of a stainless-steel pyrolysis chamber integrated with an electric heater, and the reaction temperature was monitored using a K-type thermocouple connected to a digital temperature controller and display. The generated vapors were routed through a vapor outlet to a water-cooled condenser, and the condensed liquid oil was collected in a receiving flask, while non-condensable gases were discharged through a separate gas outlet line. The chemical composition of the liquid pyrolysis oil was analyzed using Gas Chromatography–Mass Spectrometry (GC–MS, Shimadzu QP 2010 SE) and functional groups were identified by Fourier Transform Infrared Spectroscopy (FTIR, Shimadzu 8201 PC)[17].

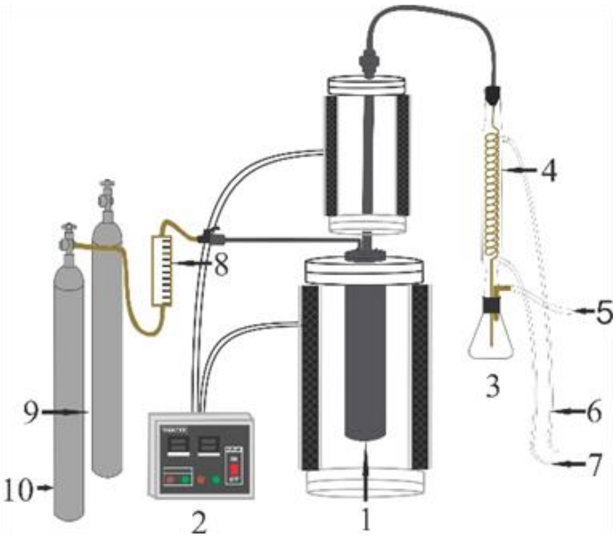

Figure. 1. Schematic diagram of the batch pyrolysis reactor

(1) Reactor, (2) Control panel, (3) Oil collector), (4) Condenser, (5) Outlet water,
(6) Inlet water, (7) gas collector, (8) Rotameter, (9) Nitrogen gas, (10) Hydrogen gas

2.3. Procedure

Polypropylene (PP) plastic waste was first washed with distilled water to remove impurities and air dried. 20 g of PP was loaded into the batch pyrolysis reactor (Figure 1). Prior to heating, the reactor was tightly sealed and purged with nitrogen gas (N_2) for several minutes to ensure an inert atmosphere and to prevent oxidative degradation [18]. The reactor was then heated using an electric furnace from ambient temperature to the target pyrolysis temperature 450 ^{o}C at a controlled heating rate 20 ^{o}C.min^{-1}, and maintained at this temperature for a predetermined residence time 60 min. During the process, pyrolysis vapors passed through a water-cooled condenser, producing liquid oil that was collected in a receiving flask, while non-condensable gases were released through the gas outlet. After completion, the reactor was allowed to cool naturally to room temperature before solid residue (char) was removed and weighed. The product yields were calculated using Eqs. (1)–(3) [19].

$$Liquid\ product\ (wt\%) = \frac{weight\ of\ liquid\ product(g)}{weight\ of\ feed(g)\ -\ weight\ of\ residue(g)}\ x100 \quad (1)$$

$$Char\ (wt\%) = \frac{weight\ of\ residue(g)}{weight\ of\ feed(g)}\ x100 \quad (2)$$

$$Gas\ product\ (wt\%) = 100 - liquid\ product - residue \quad (3)$$

3. RESULTS AND DISCUSSION

3.1. Product Yield and Visual Characteristics

The product distribution from polypropylene (PP) waste pyrolysis at 450 ^{o}C for 1 h is shown in Figure 2. From an initial feed of 20.11 g, the process produced 15.27 g of condensed liquid oil, 0.80 g of solid residue (char), and 4.04 g of non-condensable gas. These correspond to yields of 75.93% liquid, 3.98% char, and 20.09% gas, respectively. The liquid fraction was clearly dominant, indicating efficient thermal depolymerization of PP into volatile hydrocarbons that readily condensed into oil. With a measured liquid density of 0.73 g mL^{-1}, the obtained oil volume was approximately 20.9 mL, suggesting that the product is rich in relatively light hydrocarbon compounds. The low char yield confirms that PP, as a polyolefin with negligible ash content, tends to volatilize almost completely rather than forming solid carbonaceous residue. Meanwhile, the formation of 20.09% gas indicates secondary cracking reactions at 450 °C, where part of the vapor phase further decomposed into permanent gases. This yield profile demonstrates that PP waste is a favorable feedstock for liquid fuel production via pyrolysis under the applied conditions.

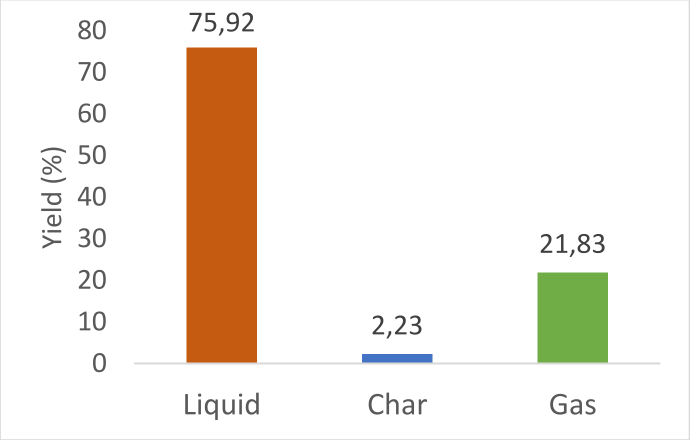

Figure 2. Product distribution

The liquid product obtained from the pyrolysis of polypropylene (PP) plastic waste at 450 °C for 1 h is shown in Figure 3. Visually, the condensate appears as a clear yellow amber oil with relatively good transparency, indicating a low amount of suspended solids. The oil showed a single-phase liquid without visible tar-like deposits, while a thin lighter layer at the bottom suggests the presence of lighter hydrocarbon fractions that separated during cooling. The formation of a bright, low-viscosity oil is consistent with the thermal cracking behavior of PP, which predominantly produces volatile aliphatic hydrocarbons in the gasoline diesel carbon range [4]. The appearance of the PP pyrolysis oil supports the yield results, confirming that the process effectively converted most of the PP feed into a liquid hydrocarbon-rich product with promising fuel characteristics prior to further chemical identification by FTIR and GC–MS

Figure. 3. Liquid Product from the pyrolysis of polypropylene plastic waste

3.2. Functional Group Identification

FTIR analysis of the liquid product from PP pyrolysis (Figure 4) shows that the oil is dominated by hydrocarbon functional groups, consistent with the polyolefin nature of polypropylene. A strong absorption at 2963 cm^{-1} corresponds to C-H stretching of sp^3 aliphatic groups ($-CH_3$/$-CH_2-$), indicating that the pyrolysis oil is rich in saturated hydrocarbon chains. This band is in good agreement with typical PP pyrolysis oils reported in the literature, where C-H sp^3 stretching appears around 2950 cm^{-1}. In addition, a weak peak at 3073 cm^{-1} is assigned to C-H stretching of sp^2 groups, suggesting the presence of unsaturated hydrocarbons. This interpretation is supported by the clear band at 1646 cm^{-1}, which is attributed to C=C stretching vibrations, confirming that olefinic/alkenic compounds were formed during chain scission reactions. Similar sp^2 C-H (3026 cm^{-1}) and C=C (1500–1600 cm^{-1}) signals were also observed in PP pyrolysis oil by [6] indicating olefin formation as a characteristic product of PP cracking. The absorption at 1452 cm^{-1} corresponds to C-H bending (scissoring) of aliphatic $-CH_2$/$-CH_3$, further confirming the dominance of paraffinic/olefinic hydrocarbons in the liquid fraction. Finally, the sharp peak at 889 cm^{-1} is associated with out-of-plane =C-H bending, a typical fingerprint of terminal alkenes, reinforcing that unsaturated hydrocarbons constitute an important portion of the product.

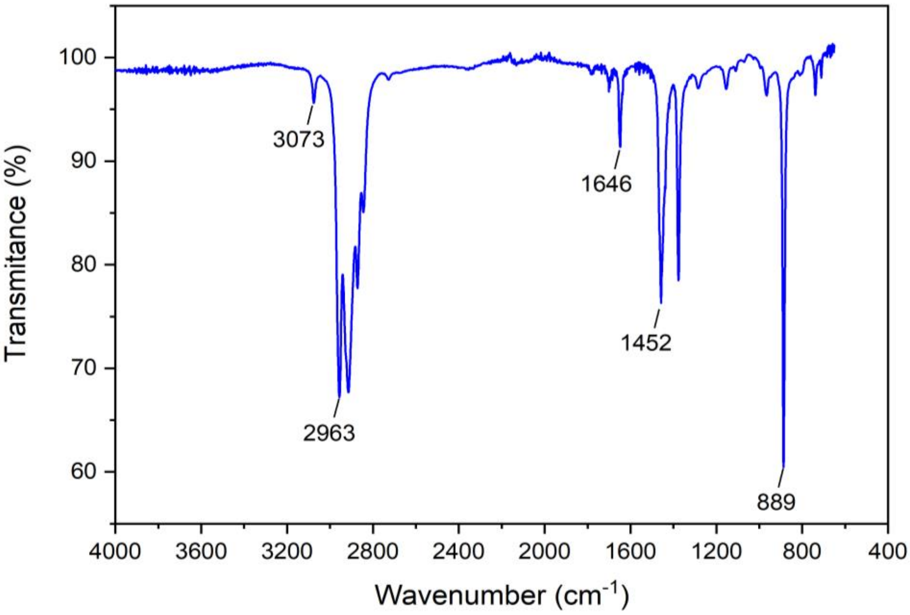

Figure 4. FTIR spectrum of liquid oil from pyrolysis of polypropylene (PP) plastic waste

3.3. Hydrocarbon Compound Distribution

The hydrocarbon composition of the PP pyrolysis oil identified by GC-MS is summarized in Table 1. The liquid product is dominated by C_9-C_{12} hydrocarbons, indicating that pyrolysis at 450 °C mainly cracked PP into light-to-middle fractions. The most abundant compound was 2,4-dimethyl-2-heptene (27.5%), followed by several branched and cyclic hydrocarbons such as 1,4-dimethylcyclohexane (5.68%), 5-ethyl-1-nonene (4.03%), and 3-octadecene (3.22%). In addition, a minor fraction of oxygenated compounds was detected, particularly alcohol derivatives such as 2-isopropyl-5-methyl-1-heptanol (7.85% and 5.83%) and several trimethylcyclohexyl methanol isomers (0.58-2.24%). These oxygenated signals likely originate from additives, contaminants, or secondary reactions during condensation, but their overall contribution remains much smaller than the hydrocarbon fraction, consistent with the FTIR profile showing hydrocarbon dominance [20].

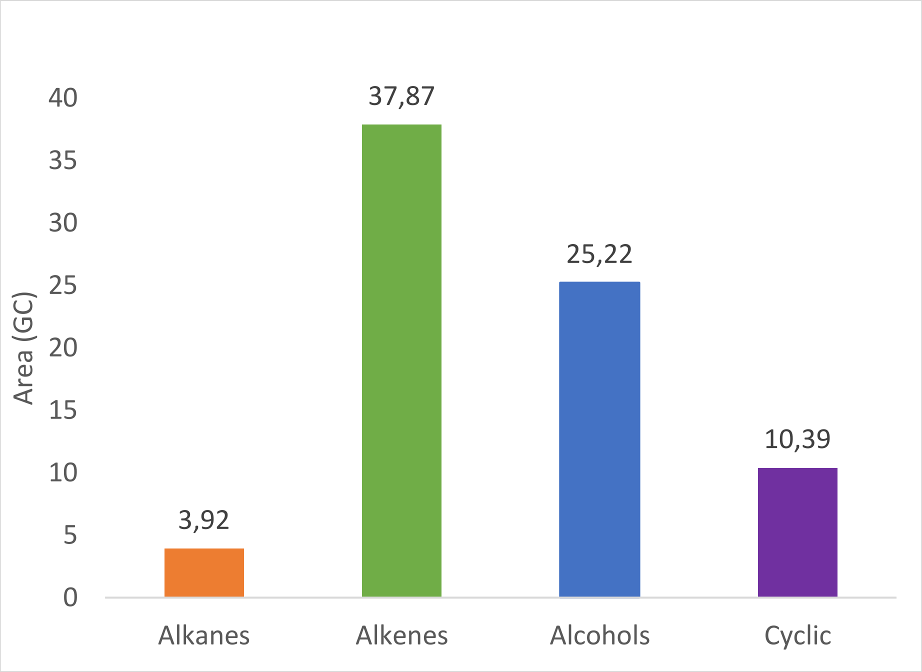

Figure 5. Distribution of hydrocarbon compound groups in the pyrolysis oil

The updated hydrocarbon compound groups distribution of the PP pyrolysis oil is shown in Figure 5. The composition is dominated by alkenes (37.87% GC area), followed by alcohols (25.22%), cyclic hydrocarbons (10.39%), and a relatively small fraction of alkanes (3.92%). The predominance of alkenes confirms that polypropylene cracking at 450 °C largely proceeds via random β-scission mechanisms that generate unsaturated olefinic fragments as primary products. This agrees well with the FTIR profile, which shows clear C=C stretching and sp^2 C–H bands, indicating substantial unsaturation in the liquid fraction. The very low alkane share suggests that hydrogen transfer reactions leading to saturation were limited under the applied non-catalytic conditions, so olefins remained the major products.

Table 1. Hydrocarbon Compound Distribution

Retention time (min.)	Compound	Molecular Formula	GC Area (%)
2.1	C_9H_{18}	2,2-dimethyl-3-heptene	0.53
2.5	C_9H_{18}	1,3,5-trimethylcyclohexane	1.3
2.8	C_9H_{18}	2,4-dimethyl-2-heptene	27.5
3	C_9H_{18}	1,3,5-trimethylcyclohexene	2.72
3.4	C_9H_{16}	3,3,5-trimethylcyclohexene	0.69
4.2	C_9H_{16}	2,3,3-trimethylcyclohexane	1.5
4.9	$C_{10}H_{18}$	2,5-dimethyl-1,6-octadiene	1.13
8.23	$C_{11}H_{22}$	2-methyl-3-methylene-nonane	0.99
8.74	$C_{11}H_{24}$	2,6-dimethylnonane	0.68
8.89	$C_{11}H_{24}$	2,6-dimethylnonane	0.75
11.1	$C_{10}H_{20}$	1,4-dimethylcyclohexane	5.68
11.3	$C_{11}H_{22}$	5-ethyl-1-nonene	4.03
13.4	$C_{10}H_{20}O$	2,4,6-trimethylcyclohexyl methanol	2.24
13.5	$C_{10}H_{20}O$	2,4,6-trimethylcyclohexyl methanol	0.62
13.5	$C_{10}H_{20}O$	1,2,4-trimethylcyclohexyl methanol	0.58
17.8	$C_{11}H_{24}O$	2-isopropyl-5-methyl-1-heptanol	7.85
18	$C_{18}H_{36}$	3-octadecene	3.22
18.3	$C_{11}H_{24}O$	2-isopropyl-5-methyl-1-heptanol	5.83
19.7	$C_{10}H_{20}O$	2,4,6-trimethylcyclohexyl methanol	1.52
23.3	$C_{12}H_{24}$	4,6,8-trimethyl-1-nonene	1.46
23.9	$C_{14}H_{30}O$	2-hexyl-1-octanol	0.85
24.9	$C_{10}H_{20}O$	2,4,6-trimethylcyclohexyl methanol	1.20
28.0	$C_{18}H_{36}O$	1-octyl-2-decanol	1.40
28.6	$C_{18}H_{36}O$	2-hexyl-2-decanol	1.40
29.5	$C_{13}H_{24}O$	cyclodecanol methanol	1.05
32.2	$C_{24}H_{50}O$	2-decyl-1-tetradecanol	0.68

The presence of cyclic hydrocarbons (10.39%) indicates secondary cyclization and rearrangement reactions in the vapor phase, producing substituted cyclohexane/cyclohexene derivatives as also identified in Table 1[6]. A notable proportion of alcohols (25.22%) was detected, mainly consisting of branched aliphatic and cyclic alcohol derivatives. Since PP is a hydrocarbon polymer, oxygenated compounds in pyrolysis oils are commonly attributed to additives in the original plastic, trace impurities, or secondary oxidation during vapor condensation, and similar observations have been reported for plastic-derived oils in previous studies. From a fuel perspective, the dominance of olefins and the significant presence of light oxygenates suggest the oil is rich in gasoline-range molecules, but the relatively high alcohol content may influence polarity and stability; therefore, upgrading or blending may be required before direct fuel application [20].

4. CONCLUSION

Pyrolysis of polypropylene plastic waste at 450 °C for 1 h produced a dominant liquid fraction of 75.93%, with 20.09% non-condensable gas and 3.98% solid residue. FTIR confirmed that the oil was mainly composed of aliphatic hydrocarbons with clear C=C unsaturation, consistent with polypropylene cracking behavior. GC–MS showed that the product was dominated by alkenes (37.87%), followed by alcohols (25.22%), cyclic hydrocarbons (10.39%), and alkanes (3.92%), indicating a hydrocarbon profile largely within the fuel range and rich in gasoline-type olefinic compounds. These results demonstrate that polypropylene waste is highly suitable for conversion into liquid fuel via pyrolysis, although the high olefin content and the presence of oxygenated compounds suggest that upgrading or blending would be needed to improve stability and meet commercial fuel specifications.

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AUTHOR CONTRIBUTIONS

Mazlan performed the experimental work and contributed to drafting the manuscript, while Pranoto contributed to the study conception and manuscript revision. All authors have reviewed and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to the content of this work.

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