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Transforming Bubble Wrap and Packaging Plastic Waste into Valuable Fuel Resources

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ABSTRACT

This study aimed to investigate the potential of plastic waste, specifically bubble wrap and packaging plastic, as a fuel source through pyrolysis process. The samples were analyzed using FTIR and GC-MS. The results showed that both samples contained alkanes and alkenes, with hydrocarbon fractions like those found in gasoline, kerosene, and diesel fuel. The pyrolysis process resulted in hydrocarbon fractions ranging from light to heavy fractions. The bubble wrap sample showed the highest percentage of hydrocarbon fraction in the kerosene range (C10–C13), with an area of 19.23%. In contrast, the packaging plastic sample showed the highest percentage of hydrocarbon fraction in the diesel range (C14–C20), with an area percentage of 19.67%. The calorific value of the pyrolysis products was also determined, with the bubble wrap sample having a higher value than that of gasoline, while the packaging plastic sample had a value close to that of kerosene. The results of this study suggest that plastic waste has the potential to be converted into fuel, which can contribute to sustainable development by reducing dependence on fossil fuels and reducing plastic waste. However, further refinement of the pyrolysis products is needed to meet commercial fuel standards.

Keywords: plastic waste, pyrolysis, fuel, hydrocarbons, calorific value.

INTRODUCTION

The increasingly complex consumption needs of the population and the limited capacity of waste storage facilities can lead to waste generation and various waste compositions (Sharma et al., 2020). The coronavirus disease 2019 pandemic started to spread in Indonesia in March 2020. As a result, the government implemented large-scale social restrictions (PSBB) under Regulation No. 9 of 2020 from the Ministry of Health. This meant many activities, such as worship, schooling, working, and shopping, was done from home (Beck & Hensher, 2020). The pandemic increased online shopping through e-commerce applications, resulting in more plastic waste from packaging materials (Vanapalli et al., 2021). One solution to this issue is to convert plastic waste into energy through thermal processes such as pyrolysis, gasification, and incineration (Cudjoe & Wang, 2022). Pyrolysis technology has a strong advantage when it comes to processing packaging materials because it can convert plastic waste into valuable products (Peng et al., 2022). This process involves heating the plastic waste in the absence of oxygen, causing it to break down into gas and liquid fractions, such as oil, and solid residue (Kunwar et al., 2016).

Compared to other waste-to-energy technologies, pyrolysis has the advantage of being able to handle a wide range of feedstocks, including mixed plastic waste, which is difficult to recycle through other means (Davidson et al., 2021). Additionally, the pyrolysis process can generate high-quality oil that can be used as a fuel in various industries, including transportation and manufacturing (Wright et al., 2010). Packaging materials, such as bubble wrap and plastic packaging, are a significant contributor to plastic waste pollution, and finding sustainable ways to manage this waste is critical to reducing its impact on the environment. By using pyrolysis technology to convert packaging materials into valuable fuel resources, we can not only reduce the amount of plastic waste in landfills and oceans but also reduce our dependence on fossil fuels and move towards a more sustainable future.

Improper management of package waste can lead to an increase in waste generation. Plastic packaging materials such as plastic bags and bubble wrap are widely used in bookstores, electronic stores, souvenir shops, and cosmetic stores (Arora et al., 2022). The study of the potential recycling of plastic packaging materials, such as plastic bags and bubble wrap, is crucial for several reasons. Firstly, these materials are widely used in many industries, such as retail, electronic, cosmetic, and souvenir stores, and their disposal can lead to a significant increase in waste generation. Improper management of plastic packaging waste can harm the environment, including waterways, soil, and air pollution. Therefore, finding ways to recycle these materials can significantly reduce the waste generated and mitigate their harmful environmental effects. Secondly, studying the potential recycling of plastic packaging materials is crucial in limited landfill capacity (Suryawan et al., 2023). As the population grows and consumption patterns become more complex, the waste generated increases. Landfills are becoming increasingly limited and costly, and finding alternative waste management options is necessary. Recycling plastic packaging materials can not only reduce the amount of waste going to landfills but also provide a valuable source of raw materials for new products. Finally, recycling plastic packaging materials can contribute to achieving renewable energy targets set by governments (Suryawan et al., 2022; Zahra et al., 2022). Conversion of plastic waste to energy can be essential to achieve the government's renewable energy targets (Budiarto & Surjosatyo, 2021; Raharjo et al., 2022). For instance, the Indonesian government has targeted achieving a 23% renewable energy mix by 2025 and a 31% mix by 2050. The conversion of plastic waste to energy through pyrolysis can significantly contribute to achieving these targets. In conclusion, studying the potential recycling of plastic packaging materials is crucial for mitigating the negative impact of waste on the environment, reducing reliance on limited landfill capacity, and contributing to achieving renewable energy targets set by governments. The state of the art for this study is that several locations in Indonesia, such as Jakarta, have already implemented pyrolysis technology in waste management to convert plastic waste into fuel. However, the city of Surakarta, which is the research location, does not yet have this technology. The last research gap for this study is the lack of a comprehensive waste management system that includes using pyrolysis technology for plastic packaging waste in Indonesia (Abidah et al., 2021; Fatimah et al., 2020).

This study aims to analyze the hydrocarbon fractions and calorific values of two types of plastic waste, bubble wrap and packaging plastic, through the pyrolysis process. The results of this study provide insights into the potential of plastic waste as a source of fuel and energy, as well as the chemical composition of plastic waste and the potential environmental impacts of its disposal. The findings of this study can help develop strategies for waste management and recycling of plastic waste, as well as in identifying opportunities for alternative energy sources. Additionally, this study contributes to the body of knowledge on plastic waste's chemical composition and properties, which can be used as a basis for further research and development of new waste management and recycling technologies.

METHOD

Study location

Surakarta, also known as Solo, is in Central Java, Indonesia. The city has a population of approximately 550,000 and is known for its cultural and historical significance and its thriving economy. As with many rapidly developing cities in Indonesia, Surakarta faces a growing plastic waste problem. This significant amount of plastic waste presents a critical environmental and public health issue for the city.

Furthermore, Surakarta's location and economic development make it an ideal candidate for a case study on transforming plastic waste into valuable fuel resources. The city is strategically located near major transportation hubs and is a hub for trade, industry, and services. This economic activity generates significant amounts of waste, including plastic waste. Additionally, Surakarta has shown a commitment to sustainable development, as evidenced by the city's adoption of a Low Carbon City Action Plan in 2016 (Hasyimi & Azizalrahman, 2021). The plan aims to reduce greenhouse gas emissions by promoting renewable energy, energy efficiency, and waste management practices. By studying Surakarta's plastic waste management practices and exploring the potential for transforming plastic waste into fuel resources, researchers can provide valuable insights into sustainable waste management practices that can be applied in other cities facing similar challenges.

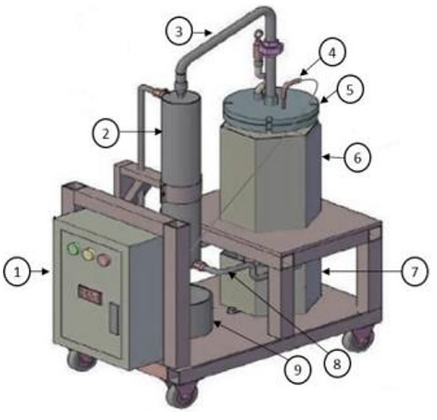
Pyrolysis processing

The raw material used in this pyrolysis process study is consumer plastic packaging materials. The sample preparation stage is carried out before the pyrolysis process is shredding. The used sample is clean from dirt, so washing and drying are not necessary. Shredding is carried out using a shredding machine with a size of 1–1.5 cm. The shredding process aims to facilitate the pyrolysis process and the entry of samples into the reactor. The pyrolysis process on bubble wrap plastic is duplicated, while in the plastic packaging sample, it is done in a single process. The pyrolysis operation uses a batch-type reactor with electric heating fuel that requires a power of 3,500 watts. The pyrolysis reactor is stainless steel cylinder-shaped with a height of 50 cm and a diameter of 30 cm (Figure 1). The reactor has a hole fitted with a 20 mm stainless steel pipe connected to a glass condenser. Here are the steps of the pyrolysis operation:

1. Weigh the plastic waste with a scale.
2. Prepare clean water to fill the condenser.
3. Put the plastic waste into the reactor and then close it.
4. Insert a thermocouple into the reactor to measure the heating temperature.
5. Install the connecting pipe between the reactor and the condenser.
6. Turn on the water pump to flow into the condenser.
7. Turn on the reactor connected to electricity and adjust the heating temperature.
8. Prepare a measuring cup to collect the pyrolysis oil.
9. Weigh and measure the volume of the pyrolysis oil obtained.

Data analysis

The yield percentage is the ratio between the output product and the amount of material initially used in the process. The yield percentage calculation in this study describes the efficiency value of the pyrolysis product. The pyrolysis product, in the form of oil and residue, is weighed and compared to the weight of the initial raw material to obtain the yield percentage. The yield percentage



1. Temperature controller
2. Condenser
3. Reactor and condenser connecting pipe
4. Thermocouple
5. Reactor cover
6. Combustion chamber
7. Condenser water container
8. Water pump hose
9. Pyrolysis oil container

Figure 1. Pyrolysis reactor

of liquid, solid, and gaseous products can be calculated using the following equations:

$$Yliquid\ (\%w/w) = (MLP/MPS) \times 100 \quad (1)$$

where: MLP – mass of liquid product, MPS – mass of plastic sample.

$$Ysolid\ (\%w/w) = (MSP/MPS) \times 100 \quad (2)$$

where: MSP – mass of solid product, MPS –mass of plastic sample.

$$Ygas\ (\%w/w) = 100 - (Yliquid(wt\%) + Ysolid(wt\%)) \quad (3)$$

The functional group analysis in this study serves to identify the compounds in the pyrolysis oil. The analysis is conducted using Fourier transform infrared (FTIR) spectroscopy. The sample is cut and adjusted with the available spectrum. The spectrum is recorded using a spectrophotometer at room temperature. The data obtained are in the form of a spectrum image between wave numbers and transmission so that the functional groups in the sample can be identified. The results of the analysis can be read using the FTIR region table.

The chemical composition of the pyrolysis oil is obtained from gas chromatography-mass spectroscopy (GC-MS) analysis. The results of the chemical composition analysis can be used to determine the potential of pyrolysis oil as a fuel. A liquid sample of 1 μl is injected into the GC-MS for 35.24 minutes. Each peak in the chromatogram is evaluated using the Wiley database. Next, the chemical compound components from the GC-MS analysis are identified using the PubChem database.

The analysis of the calorific value of fuel aims to obtain data on the amount of heat energy that can be released by fuel in a combustion process (Almu, et al., 2014). The calorific value data in this study can be used to determine the characteristics of the pyrolysis oil. The calorific value measurement can be conducted using a bomb calorimeter, which measures the amount of heat released in the complete combustion of a fuel. The combustion reaction inside the bomb calorimeter will generate heat, which water will absorb so that no heat is released into the environment.

RESULT AND DISCUSSION

The pyrolysis process uses plastic packaging materials such as bubble wrap and packaging plastic, low-density polyethylene (LDPE). Bubble wrap is a black plastic material with air bubbles on its surface, commonly used to pack fragile items, electronics, and items sensitive to impact. Meanwhile, packaging plastic is a clear and transparent plastic for wrapping goods. LDPE plastic has more branches, resulting in weaker intermolecular strength, and reduced hardness and strength. These LDPE properties make it easier for the pyrolysis cracking process. In this study, the packaging plastic is thermally processed using pyrolysis technology. This technology is chosen because it can process non-recyclable waste and produce gas, liquid, and solid products with economic value.

TGA is used to determine the decomposition point of the sample, which is indicated by a decrease in material weight due to heat, thus providing a reference for the pyrolysis temperature. Through TGA, the onset and endset temperatures can be determined. The onset temperature is when the decomposition reaction begins at a specific temperature, causing the material weight to decrease. Meanwhile, the end set temperature is the point at which the decomposition reaction ends, and the midpoint temperature is the peak of the reaction (Sari et al., 2022). The TGA results for LDPE plastic samples can be seen in Figure 2. The bubble wrap and packaging plastic used in pyrolysis were LDPE plastic materials.

Figure 2 shows that at a temperature of 440.48°C, there is a decrease in sample weight, which is called the onset temperature point. The degradation reaction of LDPE plastic sample ends at the endset temperature point of 470.67°C, indicated by the continuous mass line. The maximum weight loss occurs at the peak temperature (midpoint) of 455.51°C. This pyrolysis study uses an operating temperature of 430°C, which is the initial breakage temperature of LDPE polymer molecular bonds. Meanwhile, in the study by Xu and Schrader (2022), the LDPE plastic degradation temperature was found to be 350–500°C, with an onset temperature of 448°C, the peak temperature of 485°C, and endset temperature of 505°C, which resulted in less than 5% residue. The experiment's results indicate that temperatures above 400°C can be used for efficient pyrolysis processes. The maximum capacity of the laboratory-scale reactor used is 300 grams. The first procedure in the pyrolysis process is to weigh each sample's mass to determine the weight that will undergo pyrolysis. The prepared bubble

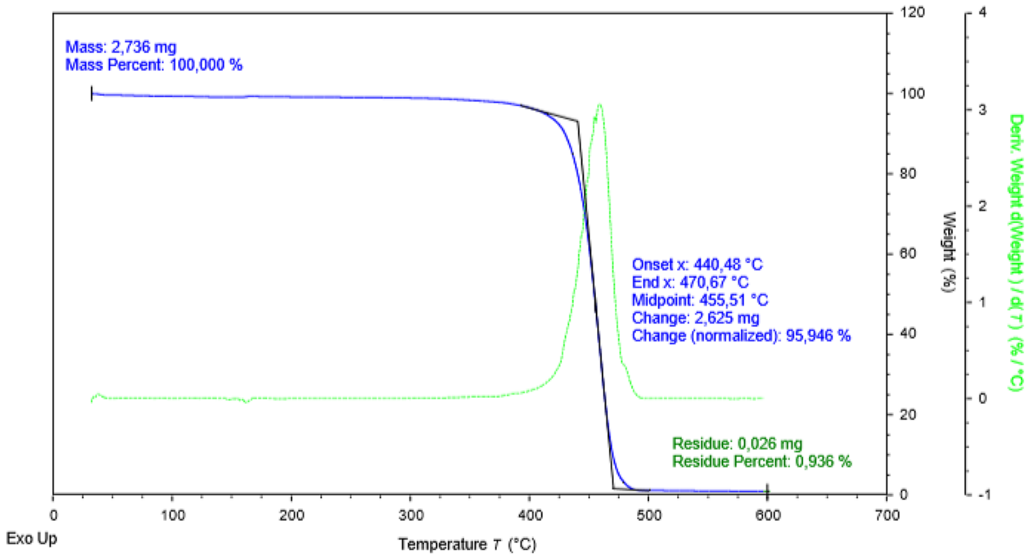


Figure 2. Thermogravimetric analysis test results

wrap and packaging plastic are weighed using the scales, each weighing 105 grams and 250 grams, respectively.

In this pyrolysis process, a batch-type reactor is used because it can be operated without catalysts and produce more liquid products. The first stage of the pyrolysis operation is to directly feed the prepared raw material into the reactor equipped with a thermocouple to determine the operating temperature. Next, the water pump in the condenser is turned on to cool the pyrolysis gas. The pyrolysis operation is carried out at atmospheric pressure with a temperature of 430°C. The pyrolysis products are gas, residue, and oil. Pyrolysis gas is a non-condensable gas. The final residue product in the form of charcoal will be left in the reactor. Meanwhile, the liquid product resulting from condensation is the main product in the pyrolysis process. Pyrolysis is stopped when the liquid product no longer drips. The next step is to measure the volume and weigh the oil product. After the reactor cools down, the residue is removed from the pyrolysis reactor and weighed. The liquid pyrolysis product needs to be tested to determine the potential fuel value of the sample and to determine the quality of the product. The tests include functional group analysis using Fourier transform infrared instruments, compound separation using gas chromatography-mass spectroscopy instruments, calorific value tests, flash point tests, and pour point tests.

The pyrolysis process using bubble wrap plastic as the raw material requires an operating time of 150 minutes. At a temperature of 343°C, thick smoke begins to form and passes through the pipe toward the condenser, where it is rapidly cooled, allowing the pyrolysis gas to condense into a liquid phase. The resulting liquid product drips into a collection bottle at an operating temperature of 430°C after being heated for 1 hour. In this pyrolysis process, a significant amount of liquid product is observed at the beginning of the operation, which gradually decreases and eventually stops at the end. This indicates that the longer the operating time and the higher the pyrolysis temperature, the lower the mass of plastic (Bow et al., 2019). Meanwhile, the pyrolysis process using packaging plastic as the raw material requires an operating time of 180 minutes. Thick smoke condensed through the condenser is formed after 120 minutes of operation. At minute 137, with a temperature of 437°C, 23 ml of liquid product in oil has been obtained, but no additional liquid product is obtained until the end of the pyrolysis process.

The plastic bubble wrap processing results in 105 grams of raw material, producing 72 ml of oil with a mass of 40 grams and 5 grams of residue. As shown in Figure 3a, the bubble wrap plastic oil is yellowish-brown, and the residue obtained is charcoal. On the other hand, a 250-gram plastic packaging sample can produce 23 ml of oil with a mass of 20.94 grams and a residue of 130 grams. Figure 3b shows that the color of the oil from the packaging plastic is almost the same as that of the bubble wrap oil. The residue from the packaging plastic is wax, which is a soft deposit like wax. The following is the pyrolysis product yield, as seen in Table 1.

Figure 3. Pyrolysis oil products from plastic bubble wrap (a) and plastic packaging (b)

Table 1 shows the percentage yield of various products obtained from the pyrolysis process of plastic bubble wrap and packaging plastic as raw materials. From the results, it can be observed that plastic bubble wrap produces a higher amount of uncondensed gas and lower residue compared to packaging plastic. Additionally, for the given weight of raw material (250 grams), the yield of oil is 8.4% for plastic bubble wrap and 52% for packaging plastic, indicating that packaging plastic produces more wax. These differences in product yield can be attributed to the mass of the raw material used. Low-mass raw materials have a higher gas phase and relatively low residues compared to high-mass materials due to faster heat transfer and easier spread (Rachmawati & Herumurti, 2015). These findings provide important insights into the optimization of pyrolysis processes for different types of plastic waste, which can be valuable in developing sustainable waste management solutions.

The results of the second experiment using a different reactor with a lower operating temperature of 300°C showed that the yield of oil increased to 50% while the yield of gas decreased to 46.29%, with only 3.71% of residue. This indicates that the yield of oil obtained decreases with increasing pyrolysis temperature. The decrease in oil yield as the operating temperature increases is attributed to more plastic being degraded into uncondensed gas. LDPE plastic has a branched chain that is easy to break (Sogancioglu et al., 2017), so more gas is formed than oil. This is consistent with the findings of previous research that oil yield decreases as the operating temperature increases (Alakowe, 2013). Therefore, it is important to optimize the operating temperature in pyrolysis to obtain the desired product yield.

Analysis of the liquid product using FTIR is used to identify the functional groups in the pyrolysis oil products. FTIR spectrophotometer is an interaction between molecules and electromagnetic radiation that can show the molecules in a sample at a certain wavelength. The presence of peaks or waves in the transmittance spectrum indicates that particles interact with infrared radiation. These peaks represent the elements bonded in the tested sample. FTIR measurements are possible for all solid, powder, liquid, and gas materials. The wavelength range used is between 600–4000 cm^{-1}. The results of the FTIR test with bubble wrap plastic and packaging plastic samples can be seen in Figure 4.

The sample analysis results using Fourier transform infrared spectrophotometer obtained an FTIR spectrum that shows peaks identified

Table 1. Pyrolysis results of plastic bubble wrap and plastic packaging

Type of plastic	Weight (gr)	Yliquid (%w/w)	Ysolid (%w/w)	Ygas (%w/w)
Plastic bubble wrap	105	38	4.7	57.3
Plastic packaging	250	8.4	52	39.6

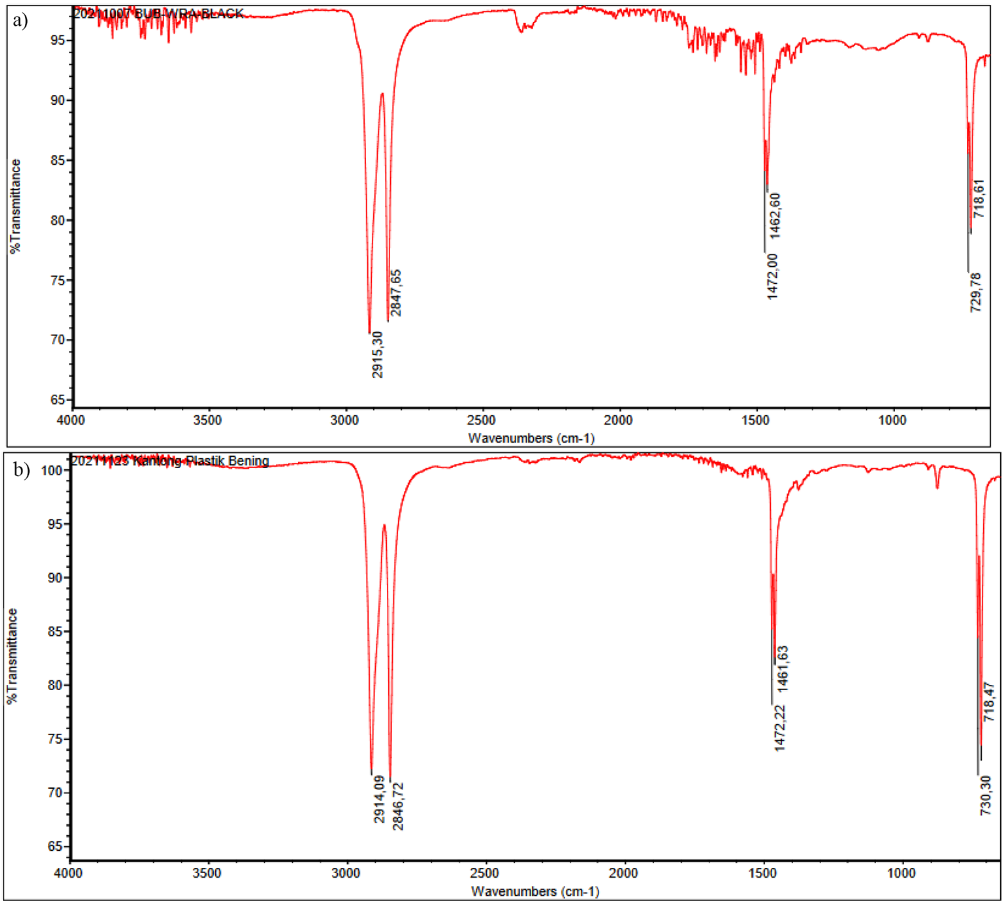


Figure 4. FTIR spectrophotometric test results for plastic oil bubble wrap (a) and plastic packaging (b)

by the instrument. In general, there are 6 dominant peaks as shown in Figure 4a. The absorption peak is in the wavelength scale range. The first and second peaks located at the wavelength of 2915.30 and 2847.65 cm^{-1} are C-H bonds of alkane groups. The third and fourth peaks, with a wavelength of 1472.0 and 1462.60 cm^{-1} are C-H bonds of alkane groups. The fifth and sixth peaks are at wavelengths of 729.78 and 718.61 cm^{-1}, respectively, as C=C bonds of alkena groups. The FTIR analysis results of the plastic packaging oil sample shown in Figure 4.9 also showed 6 dominant peaks. The first peak obtained at a wavelength of 2914.09 and 2846.72 cm^{-1} was identified as C-H bonds of alkane groups. At the same time, the third and fourth peaks at a wavelength of 1472.22 and 1461.63 cm^{-1} are C-H bonds of alkane functional groups. The wavelength of 730.30 and 718.47 cm^{-1} on the fifth and sixth peaks, respectively, corresponds to the C=C bonds of alkena groups. The infrared spectrum generated from the pyrolysis process of bubble wrap plastic and plastic packaging is dominated by alkane and alkena functional groups. The peak also shows the aliphatic structure in the oil at 1640 cm-1 as C=C bonds of alkena groups. Bonds at peaks 1470 and 1365 cm^{-1} are due to the stretching of C-H bonds of alkane groups. The C=C bond with a wavelength of 909 cm^{-1} is identified as an alkena group (Yan et al., 2015). Based on the test results obtained, the FTIR spectrum shows that both solid and liquid samples of LDPE plastic are dominated by alkane and alkena functional groups.

Based on the GC-MS analysis results presented various components of compounds contained in the plastic bubble wrap pyrolysis product sample were obtained. Generally, the GC-MS analysis results were dominated by hydrocarbon compounds, which accounted for 50.69% of the total area, while the remaining 49.31% were alcohol and ether compounds that were easily flammable. There were 5 compounds with the highest percent area. The first compound, with an area of 44.37%, was 3,5,9-trioxa-4-phosphahene-icosan-1-aminium,4-hydroxy-N,N,N-trimethyl-10-oxo-7-[(1-oxododecyl)oxy]-, hydroxide, inner salt, 4-oxide, which has a molecular formula of C32H64NO8P and is not a hydrocarbon compound. The second compound had an area of 6.82%, which was 1-methyl-2-octylcyclopropane with a molecular formula of $C_{12}H_{24}$. The third compound was 1-heptyl-2-methylcyclopropane with a molecular formula of C11H22 and an area of 6.51%. The fourth compound was 2,6,10,14-tetramethylheptadecane with an area of 5.96%, with a molecular formula of C21H44. The fifth compound had an area of 5.82%, 5-tetradecene with a molecular formula of C14H28.

The GC-MS results indicate the presence of alkenes, alkanes, alcohols, and other compounds with a carbon chain range of C_7-C_{38}. There were 9 alkene compounds with carbon chains ranging from C_7–C_{27}, which were methylcyclohexane (C_7H_{14}), pentylcyclopropane (C_8H_{16}), 1-heptyl-2-methylcyclopropane ($C_{11}H_{22}$), 1-methyl-2-octylcyclopropane ($C_{12}H_{24}$), 5-tetradecene ($C_{14}H_{28}$), 7-hexadecene ($C_{16}H_{32}$), 9-nonadecene ($C_{19}H_{38}$), 5-eicosene ($C_{20}H_{40}$), and 1-heptacosene ($C_{27}H_{54}$), with a total area of 30.69%. There were 8 alkane compounds with carbon chains ranging from C8-C20, consisting of heptane (C_7H_{16}), 2,4-dimethylhexane (C_8H_{18}), nonane (C_9H_{20}), decane ($C_{10}H_{22}$), dodecane ($C_{12}H_{26}$), 2,6,10,14-tetramethylheptadecane ($C_{21}H_{44}$), hexadecane ($C_{16}H_{34}$), and eicosane ($C_{20}H_{42}$), with a total area of 17.74%. Meanwhile, the alcohol compounds found in the sample were 10-pentadecanol ($C_{15}H_{30}O$) with a percentage of 1.11% and 1-hexadecanol ($C_{16}H_{34}O$) with a percentage of 1.77%. The component compounds found in a sample of plastic packaging pyrolysis product were analyzed by GC-MS. Hydrocarbons were the dominant compounds, comprising 50.54% of the total compounds, while the remaining 49.46% were alcohols and other derivative products. The compound with the highest percentage area was identified as 3,5,9-trioxa-4-phosphaheneicosan-1-aminium, 4-hydroxy-N,N,N-trimethyl-10-oxo-7-[(1-oxododecyl) oxy]-, hydroxide, inner salt, 4-oxide, which has a molecular formula of $C_{32}H_{64}NO_8P$ and an area of 42.79%. The second compound was 1-methyl-2-octylcyclopropane with a molecular formula of $C_{12}H_{24}$ and an area of 5.56%, while the third compound was 1-heptyl-2-methylcyclopropane with a molecular formula of $C_{11}H_{22}$ and an area of 5.25%. The fourth compound, with an area of 4.81%, was identified as 5-tetradecene with a molecular formula of $C_{14}H_{28}$. The fifth compound, with an area of 4.43%, was dodecane with a molecular formula of $C_{12}H_{26}$. All these compounds were hydrocarbons except for the one with the molecular formula of $C_{32}H_{64}NO_8P$.

The GC-MS results for the sample include alkanes, alkenes, alcohols, and other compounds with carbon chains ranging from C_7 to C_{32}. Ten alkanes with carbon chains ranging from C_7 to C_{13} were identified, including heptane (C_7H_{16}), octane (C_8H_{18}), nonane (C_9H_{20}), undecane ($C_{11}H_{24}$), dodecane ($C_{12}H_{26}$), tetradecene ($C_{14}H_{30}$), 2,6,11-trimethyl dodecane ($C_{15}H_{32}$), 6,9-dimethyl tetradecane ($C_{16}H_{34}$), 2-methyl octadecane ($C_{19}H_{40}$), and eicosane ($C_{20}H_{42}$), with a total area of 22.06%. Nine alkenes with carbon chains ranging from C_7 to C_{21} were also identified, including methylcyclohexane (C_7H_{14}), pentylcyclopropane (C_8H_{16}), 2,4-dimethyl-1-heptene (C_9H_{18}), 1-heptyl-2-methyl-cyclopropane ($C_{11}H_{22}$), 1-methyl-2-octyl-cyclopropane ($C_{12}H_{24}$), 5-tetradecene ($C_{14}H_{28}$), hexadecane ($C_{16}H_{32}$), 9-nonadecene ($C_{19}H_{38}$), and 10-heneicosene ($C_{21}H_{42}$), with a total area of 27.42%. The alcohol compounds found in the plastic packaging pyrolysis product were E-7-tetradecenol ($C_{14}H_{28}O$) at 0.4%, E-10-pentadecenol ($C_{15}H_{30}O$) at 0.7%, and 1-hexadecanol ($C_{16}H_{34}O$) at 3.86%.

The GC-MS analysis of the plastic bubble wrap and packaging samples showed that the main compounds were alkanes and alkenes, consistent with the FTIR results of both samples. Based on the chromatogram of the liquid sample obtained from pyrolysis, it was found that there were three types of hydrocarbon fractions. Gasoline has a hydrocarbon bond range of green naphtha (C_5–C_9), greenjet fuel (C_{10}–C_{13}) and green diesel (C_{14}–C_{20}) (Shalaby et al., 2015). Based on the hydrocarbon fractions contained in the sample, their similarity to fuel fractions can be seen in Table 2.

Table 2 shows that the hydrocarbon distribution is highly diverse, ranging from light to heavy carbon fractions. Based on these results, it can be seen that the bubble wrap plastic sample has the

Table 2. Area of hydrocarbon fraction

Type of plastic	% Area of hydrocarbon fraction		
	Gasoline (C_5-C_9)	Kerosene (C_{10}-C_{13})	Diesel fuel (C_{14}-C_{20})
Plastic bubble wrap	8.14	19.23	16.65
Plastic packaging	11.61	18.23	19.67

largest percentage of hydrocarbon fraction area in the kerosene fraction with a carbon range of C_{10}–C_{13}, amounting to 19.23%. This study obtained the same result as (Amoloye et al., 2013) research that the GC-MS analysis of LDPE plastic pyrolysis products showed that the largest hydrocarbon fraction was the kerosene fraction. Meanwhile, the plastic packaging sample has the largest percentage of fraction area in the solar fraction range of carbon fractions, namely C_{14}–C_{20}, with a percentage of 19.67%. Based on (Yan et al., 2015) research, LDPE plastic pyrolysis products are also dominated by alkane and alkene compounds with the largest hydrocarbon fraction being solar.

The calorific value of the plastic bubble wrap pyrolysis product is 44.8 MJ/kg. This result is higher than the calorific value of gasoline fuel which has a calorific value of 44 MJ/kg. Meanwhile, the calorific value of the pyrolysis oil product from plastic packaging is 41.7 MJ/kg, which is close to the calorific value of kerosene fuel with a calorific value of 43.8 MJ/kg. Based on these results, it can be concluded that the pyrolysis oil product does not yet have the same standards as commercial fuel. This indicates that further purification is needed to obtain a standard value for commercial fuel. In the study by (Jaafar et al., 2022), the calorific value of LDPE plastic oil was found to be 47 MJ/kg. Meanwhile, in the study by (Al-Salem et al., 2022) using the same sample, the calorific value obtained was 45.9 MJ/kg. Based on the calorific value results obtained, LDPE plastic is considered to have a high calorific value and has the potential to be used as fuel.

Based on the study's results, several policy implications can be drawn. First, there is a need for stricter regulations and policies regarding the disposal of plastic waste, particularly for bubble wrap and packaging plastics. These regulations should encourage implementing more sustainable practices, such as recycling and upcycling, to reduce plastic waste in landfills and the environment. Additionally, the regulations should require manufacturers to use more environmentally friendly materials and packaging alternatives. Second, the study highlights the potential of plastic waste as an energy source. Governments and policymakers can consider incentivizing the development of technologies that can convert plastic waste into usable energy, such as fuel. This can provide a more sustainable solution to the growing energy demand while also addressing the issue of plastic waste.

Based on the findings of this study, there are some implications for the case study in Surakarta, Indonesia. As a city with a high population density and limited land area, Surakarta faces challenges in waste management, particularly in dealing with plastic waste. The study highlights the potential of pyrolysis technology to convert plastic waste into fuel, which could provide an alternative to fossil fuels and reduce plastic waste in the environment. Therefore, the Surakarta local government could consider promoting pyrolysis technology for plastic waste management and exploring the potential for producing fuel from plastic waste. Additionally, this study indicates that further research is needed to optimize pyrolysis technology for plastic waste management, particularly in improving fuel quality. The results suggest that the fuel produced from pyrolysis has a high calorific value but does not yet meet the same standards as commercial fuels. Therefore, future research could focus on developing methods to refine and upgrade the fuel produced from the pyrolysis, which could increase its value and usefulness as an energy source. The findings of this study provide valuable insights for the Surakarta local government to consider when formulating waste management policies and programs that promote sustainable development.

CONCLUSION

The results showed that both samples contained major compounds of alkanes and alkenes, with a distribution of hydrocarbons ranging from light to heavy fractions. The highest hydrocarbon fraction area in the bubble wrap sample was in the kerosene fraction (C_{10}–C_{13}), while the packaging plastic sample had the highest percentage in the diesel fraction (C_{14}–C_{20}). Furthermore, the calorific value of the pyrolysis product from bubble wrap was higher than that of gasoline. In contrast, the calorific value of the pyrolysis product from packaging plastic was found to be like that of kerosene. This study suggests that plastic waste can be a potential alternative fuel source. However, further research is necessary to refine the pyrolysis process and purification of the resulting fuel to meet the standard of commercial fuels. Moreover, the environmental impact of plastic waste as a fuel source must be evaluated thoroughly before considering it as a viable option. Nonetheless, this study contributes to the ongoing efforts to reduce plastic waste and find sustainable solutions to the energy crisis. This study supports sustainable development by exploring the potential of plastic waste as an energy source through pyrolysis. The results showed that plastic bubble wrap and packaging, commonly found in plastic waste, contain significant amounts of hydrocarbons that can be converted into fuel through pyrolysis. This offers an alternative to traditional fossil fuels and helps reduce environmental waste. Additionally, the study highlights the importance of further research and development to improve fuel quality through pyrolysis. The results showed that the fuel produced from plastic waste did not yet meet the standards of commercial fuels and required further purification. This emphasizes the need for continued innovation and investment in sustainable technologies to improve plastic waste management's efficiency and environmental impact.

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