

FTIR analysis of pyrolyzed LLDPE and polystyrene microparticles and their chemical reaction mechanism completed with computational bibliometric literature review to support sustainable development goals (SDGs)

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ABSTRACT

The purpose of this study was to determine the chemical compound content of polystyrene and linear low-density Density Polyethylene (LLDPE) microparticles after the pyrolysis process analyzed by

Fourier Transform Infrared (FTIR). The pyrolysis was done by decomposing 307.6 g of a mixture of LLDPE particles (sizes of 5000 μm) and polystyrene particles (sizes of 3000 μm) with a ratio of 1:1 for 180 min at a temperature in the range of 120-190°C in the absence of air using a closed batch reactor (length x width x height = 14.4 x 17.3 x 24 cm). The reactor had outlets connected to condensers (cooled at 24°C). The condensers were set in series, with condenser 1 directly connected to the reactor and condenser 2 positioned at the outlet of condenser 1. The pyrolysis result in the first condenser was a brownish-yellow

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KEYWORDS

FTIR, LLDPE, Plastic, Polystyrene, Pyrolysis

liquid (15 mL) with a strong odor. The second condenser produced a yellow liquid (2 mL) and a distinctive odor. After the pyrolysis, the reactor contained a brown solid (residue). Different chemical compositions were detected. The sample from condenser 1 contained C=C ethylene bonds, C=C styrene aromatics, and C-H long-chain alkanes, whereas the second condenser contained -OH bond (like water). Further, when the samples were compared with pure LLDPE and Polystyrene, there was no C=C bond. This pyrolysis process showed two reactions: the end chain cracking and random cracking. This study brings ideas in the pyrolysis of plastic wastes, supporting current issues in the sustainable development goals (SDGs).

INTRODUCTION

Currently, various methods can be used to proceed with waste from plastic. Some people proposed the use of alternative plastic, such as bioplastic (Consebit et al. 2022; Duruin et al. 2022; Basnur et al. 2024). Other researchers give ideas for reusing, and recycling plastic (Soegoto et al. 2021), or even giving regulations (Setyani et al. 2023). Some people proposed the use of alternative plastics, such as methods that convert plastic waste into lower-quality raw materials (Syamsiro 2015), and methods of making paving blocks from plastic waste (Azham et al. 2023). Some methods for solving plastic issues are mechanical shredding methods for transforming plastic into small pieces to make it easy for further processes (Rukiah 2018; Nurprasetyo et al. 2017). Other methods for decomposing plastic into simple fractions are pyrolysis with high heating (Kaminsky et al. 2005; Pebrianti and Salamah 2021), and processing methods using chemical reactions to modify the structure of plastic and change it into a valuable product (Raquez et al. 2013). Pyrolysis decomposes plastic into simple fractions with high heating (Liestiono et al. 2017; Hanif et al. 2016). The pyrolysis method is the thermochemical decomposition of a substance into a more useful product, in the absence of oxygen as a fixed oxidizer. Pyrolysis can produce renewable fuels and other valuable products that can be useful for everyday life (Mangala and Putra 2019; Subagyono et al. 2021; Jamilatun et al. 2022; Jelita et al. 2023; Mutolib et al. 2023; Jamilatun et al. 2023; Rahmat et al. 2023). Here, the purpose of this study was to determine the chemical compound content of polystyrene and linear low-density polyethylene (LLDPE) microparticles after the pyrolysis process analyzed by Fourier Transform Infrared (FTIR). LLDPE and polystyrene were selected because they are the most used plastics.

- (i) LLDPE is a linear polymer with a fairly significant number of short-chain branching. In general, LLDPE is made from the copolymerization of ethylene with short chains of alpha-olefins (1-butene, 1-hexane, 1-octene, and so on). LLDPE is used as a coating

packaging, shampoo packaging, cooking oil packaging, and crackle bags. LLDPE is a type of synthetic plastic that is non-biodegradable or cannot be degraded by microorganisms. Thus, this causes environmental problems. LLDPE plastic production per year at PT. Chandra Asri Petrochemical and Lotte Chemical Titan Nusantara are around 400.000 tons/year.

- (ii) Polystyrene *Styrofoam* is a type of plastic that is very lightweight, rigid, and translucent, a material that is easily brittle and cheap. It is made from styrene (vinyl benzene) monomer. Styrofoam packaging is used as a protective wrap for a product. However, based on data from the Indonesian Statistics (Badan Pusat Statistik (BPS)) regarding Indonesia's Environmental Statistics in 2018, plastic waste in Indonesia reached 65.2 million tons per year. The sustainable use of polystyrene styrofoam raises a new problem, the accumulation of waste in the environment.

Research on LLDPE and polystyrene has been well-documented. Here, in short, we analyzed the pyrolysis of mixed plastic (a combination of LLDPE and polystyrene). We decomposed 307.6 g of a mix of LLDPE particles (sizes of 5000 μm) and polystyrene particles (sizes of 3000 μm) with a ratio of 1:1 for 180 min at a temperature in the range of 120-190°C in the absence of air. This research had an impact on processed plastic waste using pyrolysis and understood the functional groups of pyrolysis components. Novelty in this study is pyrolyzing LLDPE and Polystyrene without using catalysts and using a simple set of tools made from materials available in the market to make sure that the process can be easily scaled up. This study brings ideas in the pyrolyzing of plastic waste, supporting current issues in the sustainable development goals (SDGs).

MATERIALS AND METHODS

The tools used in this study included a rectangular reactor (length = 14.4 cm, width = 17.3 cm, and height = 24 cm) combined with condensers (cylindrical cans with a diameter of 15 cm and height of 20 cm), an aluminum pipe with a diameter of 8 mm (length = 25 cm), an aluminum pipe with a diameter of 12 mm (length = 39 cm), glue, dextone glue, gas stoves, regulators, LPG gas (as the combustion sources), holding bottles, pipettes, thermocouples, scales, a water container, and FTIR using Shimadzu 8400 instrument. The materials used are pure polystyrene styrofoam and LLDPE particles (307.6 g), water, and plasticine. In this study, we used styrofoam polystyrene and LLDPE particles shown in **Table 1**. The sample used was a mix of the two particles as 307.6 g (in ratio 1:1).

Table 1: Characteristics of Particle LLDPE and Styrofoam Polystyrene

Sample	Shape	Color	Size (μm)
LLDPE Particles	Rounded flat	White (clear)	5000
Styrofoam Polystyrene	Rounded ball	White	3000

The process flow diagram of the process is presented in **Figure 1a**. The pyrolysis process used Liquid Petroleum Gas (LPG) as the heat source. The system was a closed batch reactor, where the reactor was connected to an aluminum pipe that served as the gas flow medium. During the pyrolysis, the gas flowed through the aluminum pipe and was condensed in two condensers. The gas condensed in the condenser when its temperature was lower than the temperature of the gas in the reactor. Inside the condenser, the gas condenses into a liquid. The liquid was

collected in the liquid storage. Meanwhile, the combustion residue from pyrolysis (exhaust gas) was collected in the gas storage (blurring gas). Then, **Figure 1b** shows the flow chart pyrolysis process. Pyrolysis was conducted by heating 307.6 g of a mixture of polystyrene styrofoam and LLDPE microparticles (in ratio 1:1) in the reactor at a temperature in the range of 120-190°C for 180 minutes. Every 15 minutes, the reactor temperature was periodically checked using a thermocouple (see **Figure 2**). The vapor/gas produced from the

heating process was directed into two condensers connected by an aluminum pipe. The cooling process occurs in condenser 1 and condenser 2, resulting in liquids with different characteristics. The sample characterization was performed using a Shimadzu 8400 FTIR instrument. This analysis was conducted to determine the functional group structure present in the condenser sample.

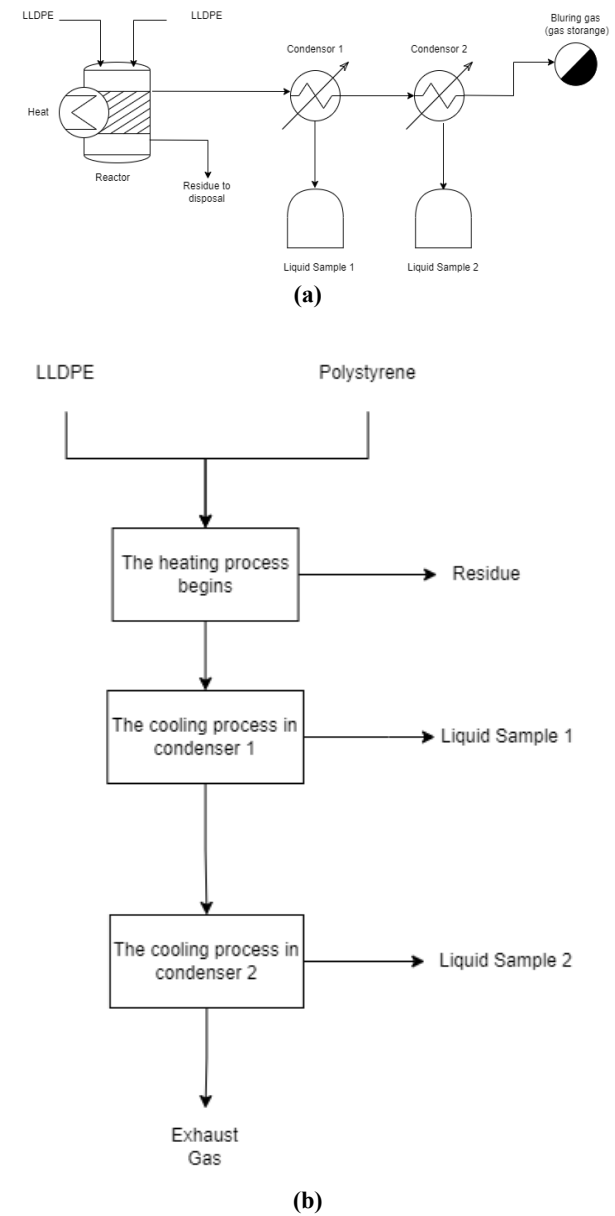


Figure 1: (a) Process flow diagram pyrolysis; (b) Pyrolysis flowchart

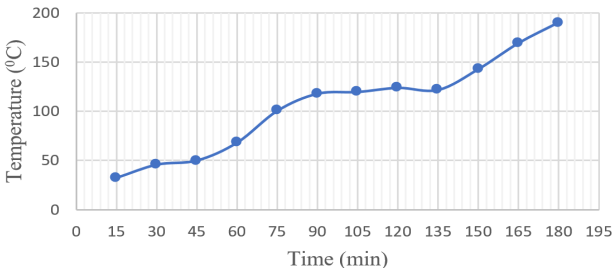


Figure 2: Temperature over during the pyrolysis process

RESULTS AND DISCUSSION

Research on LLDPE and polystyrene has been well-documented (see Figures 3 and 4, respectively). The research on this matter has attracted the attention of researchers (analyzed from bibliometric analysis in the Scopus database), showing the increasing number of research time by time. Detailed information regarding bibliometric analysis is reported elsewhere (Azizah et al. 2021; Al Husaeni et al. 2022). Bibliometric analysis is one of the excellent methods to understand current research trends, as reported elsewhere (Muktiarni et al. 2023; Muktiarni et al. 2024; Nandiyanto et al. 2023a; Nandiyanto et al. 2023b; Nandiyanto et al. 2023c; Nandiyanto et al. 2024; Rachmat et al. 2024; Nandiyanto et al. 2023d). Table 2 shows some previous studies that report related to plastic waste processing using the pyrolysis method. Figures 3 and 4 present the bibliometric analysis based on the Scopus database. Detailed information regarding the use of bibliometrics is shown elsewhere (Al Husaeni et al. 2022). The results showed an increasing number of publications relating to polystyrene waste management, indicating that the current studies have attracted researchers. The number of publications was found in the last five years (2019–2024). This study was done using the specific keywords ("polystyrene waste and styrofoam" as well as "LLDPE waste") in the Publish or Perish software, with a maximum number of article searches of 500 articles. We can find there is an increased number of publications from year to year, as well as identify the focus point in the research. Based on the VOSviewer results, six groups were generated, and these groups are indicated by colored circles. The size and smallness of the circle slide depend on how often the term appears. The more often such a term appears in scientific journals correlates to the larger the circle size.

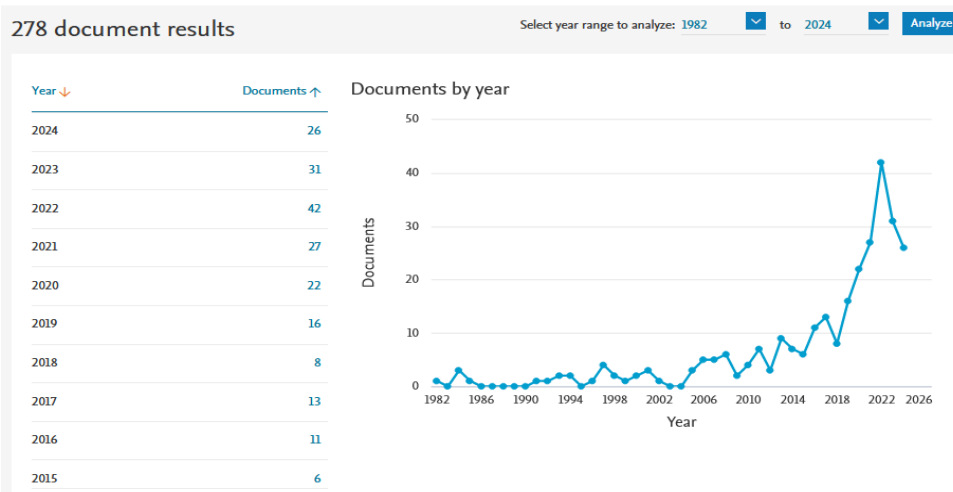


Figure 3: Previous studies on “LLDPE waste” from the Scopus database taken on May 2024

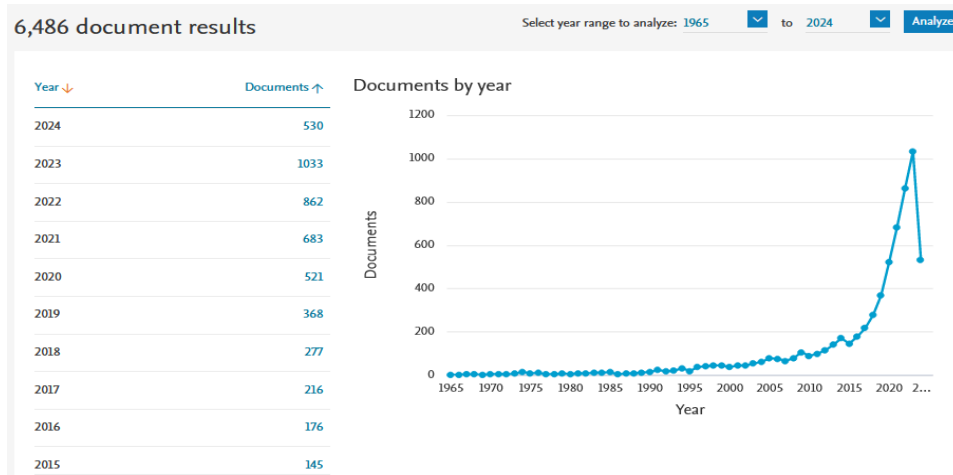


Figure 4: Previous studies on “polystyrene waste” from the Scopus database taken on May 2024

Table 2: Previous studies on the Pyrolysis of LLDPE and Polystyrene

No	Author(s), year	Topic
1.	(Liestiono et al. 2017)	The results of the study obtained a lot of oil with an oil yield of 35.83% with a temperature increase rate of 6°C/min. The results of gas identification, are the most dominant are butene-type gases and physical property test results, the characteristics of plastic oils are close to those of fuel oil, especially kerosene.
2.	(Hanif et al. 2016)	This study uses GCMS to characterize the liquid products produced. The characterization results showed that the role of calibrated dolomite in reducing the percentage of aromatics and the absence of nitrogen led to the formation of nonhydrocarbon compounds in the product.
3.	(Bow 2018)	This study did not mix LDPE and PP into one pyrolysis process but was carried out separately.
4.	(Yuriandala et al. 2016)	The addition of aluminum-coated plastic for polystyrene pyrolysis accelerates the pyrolysis time at an optimal temperature of 450°C so that the aluminum-coated plastic acts as a catalyst.
5.	(Batutah et al. 2022)	This study used three types of plastic.
6.	(Nofendri and Haryanto 2021)	The results of the study were obtained that the oil produced according to the criteria and bids was used as fuel.
7.	(Hafeez et al. 2023)	This study describes the pyrolysis process in FBR reactors. Further studies show that the hydrocarbon (HC) range of diesel fuel (C ₁₀ -C ₁₉) is between 40 and 63% in the yield of pyrolysis oil obtained.
8.	(Al-Salem et al. 2021)	The results of the study showed that diesel-type hydrocarbons were the most abundant with the highest total amount for samples extracted from low-density polyethylene pyrolysis oil. The resulting oil is highly desirable and can be used as a fuel with a cetane number of 84. The oil in this study has a low aromatic content that is likely to be held back by the thermal cracking process in the fraction of the gas product. The flash point measured for the oil sample (80°C) corresponds to the market standard for diesel fuel.

9.	(Fan et al. 2021)	This study compares microwave pyrolysis stirred continuously and in batches. Hydrocarbons from continuous pyrolysis show a narrower distribution of carbon atoms. Up to 98.0% of hydrocarbons with gasoline content are obtained from a continuous system.
10.	(Dewi 2017)	The character shown by the oil from pyrolysis of PS plastic with temperatures of 400, 450, and 500°C is closer to the characteristics of gasoline. However, it does not have optimal conditions because the oil produced tends to be constant despite increasing temperatures.

The pyrolysis process of polystyrene and LLDPE particles was carried out for 180 min. **Figure 2** shows the temperature measurement results recorded with a thermocouple during the pyrolysis process. During the pyrolysis process, volatile matter evaporation occurred, and the decomposition of long chains of hydrocarbons into lower molecular weight compounds took place. The resulting pyrolyzed gases flow into the condenser and are cooled by water, allowing it to be condensed into a liquid. This liquid was collected in condenser 1 and condenser 2. The temperature measured in the reactor in the first 30 minutes was around 48.5°C, indicating that the plastic mixture was still in the process of melting. At 135 minutes, the temperature was 121.6°C. There was a decrease in temperature due to the transfer of heat into the reactor. Thus, heat was distributed to the reactor walls and moved to the surrounding environment.

The temperature begins to be stable between 75 to 135 minutes at a temperature of 120°C. After 150 minutes, there is a significant increase in temperature, leading to the complete decomposition of the substances in the sample. This is in line with the Arrhenius equation, stating that the higher temperature brings the greater value of the thermal decomposition constant. As a result, the pyrolysis rate increases, and the pyrolyzed gases are formed and condensed faster into liquid. From 150 to 180 minutes, the temperature continued to increase with the final temperature of 190.3°C. This temperature was close to the standard temperature of the system for plastic pyrolysis, which was at 200°C. Although the experimental temperature covers the actual melting point range of 100-115°C, it does not reach its decomposition temperature in the range of 220-250°C, resulting in the results that the pyrolysis in the reactor has not been completely decomposed.

Figure 5 shows the photograph images of the samples. Initial conditions for polystyrene and LLDPE particles are shown in **Figures 5(a) and 5(b)**, respectively. **Table 3** shows the concluding results of the visual observation of liquids and residues from the pyrolysis of a mixture of polystyrene and LLDPE particles, in which sample 1 was from condenser 1 and

sample 2 was from condenser 2. **Table 3** was based on **Figures 5(c), 5(d), and 5(e)**. In the first condenser (see **Figure 5(c)**), a yellow-brown liquid of 15 mL was obtained, which was less clear with a strong odor. In the second condenser (see **Figure 5(d)**), a clear yellow liquid of 2 mL was obtained with a distinctive odor, along with brown residue solids (wax) with a volume of 25% from the reactor volume. There is a change in color from each sample coming from each condenser. A decrease in brown to yellow color concentration from residue to sample 2 was characterized by the degradation process of long chains of polymers into shorter hydrocarbon chains. The residue in the reactor was assumed to contain the longest hydrocarbon chain, indicating that the LLDPE and Polystyrene particles degrade into wax (see **Figure 5(e)**). Sample 1 was assumed to contain hydrocarbon chains shorter than the residue and longer than sample 2. To ensure the components contained in samples 1 and 2, FTIR analysis was carried out.

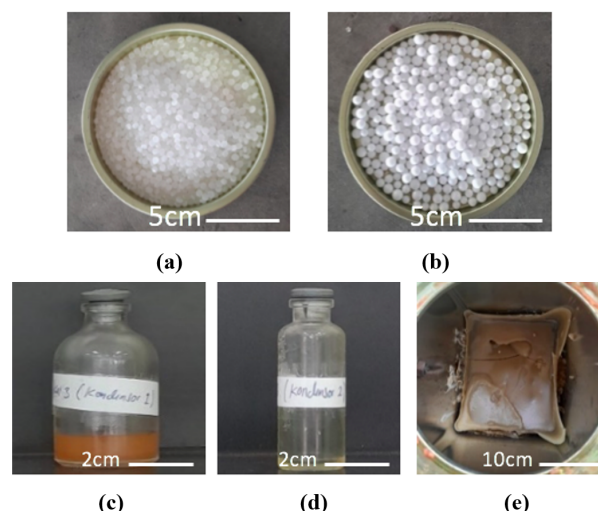


Figure 5: (a) LLDPE particles, (b) Styrofoam polystyrene, (c) Pyrolysis results from sample 1 in condenser 1; (d) Pyrolysis results from sample 2 in condenser 2; and (e) Residue inside the reactor

Table 3: Visual Observation Results of Pyrolysis Results

Sample	Form	Volume	Color	Clarity
1	Liquid	15 mL	Brownish-yellow	Lack of clarity
2	Liquid	2 mL	Yellow	Clear
Residue	Solids (wax)	-	Brown	-

Figure 6 shows the FTIR spectrum data of LLDPE, Polystyrene, water, sample 1, and sample 2. The x-axis expresses the wavenumber at 500-4000 cm^{-1} and the y-axis expresses the %transmitter at 20-100%. Based on the pyrolysis results of LLDPE and Polystyrene mixture, two samples were obtained by FTIR Shimadzu 8400 analysis. The data were compared with pure LLDPE, Polystyrene, and Water spectra without structural changes and impurities.

Based on **Figure 6**, sample 1 has 6 peaks indicating 6 functional groups have been identified. Based on wavenumber, a few peaks have a similarity to the raw materials. These similarities indicate that sample 1 has not decomposed completely which is characterized by the C-C bond breaking. Sample 2 has 2 peaks

and is similar to the water spectrum. Thus, we can assume that sample 2 contains water. Detailed information regarding how to read and interpret FTIR analysis is reported elsewhere (Nandiyanto et al. 2029; Nandiyanto et al. 2023e; Sukamto and Rahmat 2023; Obinna 2022).

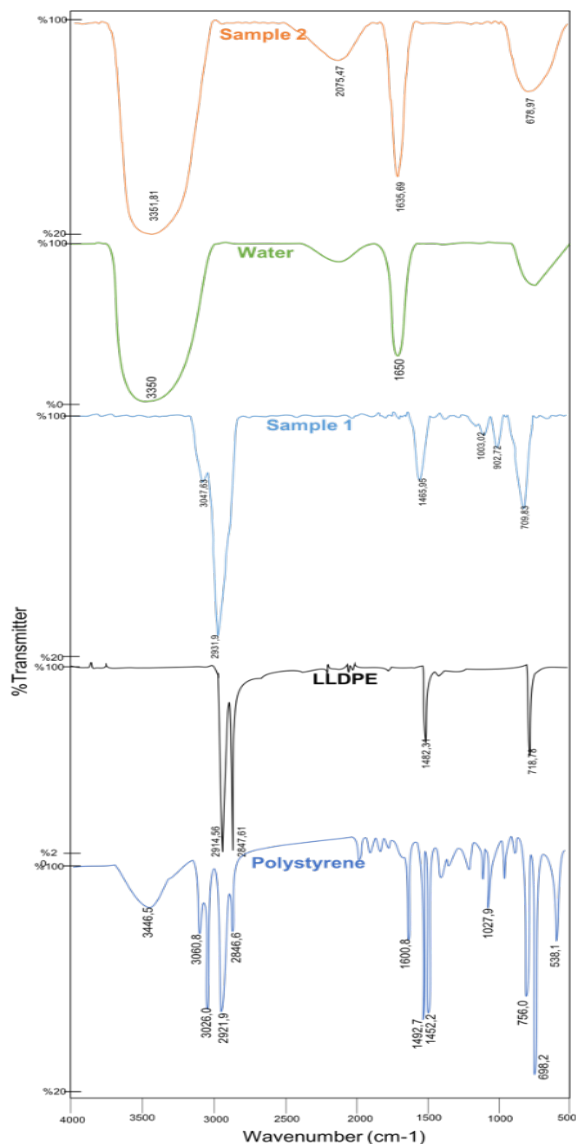


Figure 6: FTIR spectrum (a) Sample 2; (b) Water; (c) Sample 1; (d) Pure LLDPE; (e) Pure polystyrene

Table 4: Comparison of FTIR Data

No	FTIR (cm ⁻¹) peak					Functional Group
	Polystyrene	LLDPE	Sample 1	Sample 2	Water	
1	698.2	718	709.83	-	-	Methylene group (-CH ₂ -) bending for Alkane
2	-	-	-	-	-	Methylene group (-CH ₂ -) bending for Alkane
3	756	-	-	-	-	Methylene group (-CH ₂ -) bending for Alkane
4	-	-	902.72	-	-	Trans C-H out of a plane on Olefinic compound
5	-	-	1003.02	-	-	Trans C-H out of a plane on Olefinic compound
6	-	-	-	-	-	C-X with flour
7	1452.2	-	-	-	-	C=C-C Aromatic ring
8	-	1469	1465.95	-	-	C=C-C Aromatic ring
9	1492.7	-	-	-	-	C=C-C Aromatic ring
10	1600.8	-	-	-	-	C=C group conjugated
11	-	-	-	1635.69	1650	O-H from water Bending (Scissors)

Table 4 shows the comparison data of sample 1, sample 2, LLDPE, water, and Polystyrene wavenumber. Based on FTIR data, Polystyrene as raw material has peaked at a wavenumber of 3060.8 and 3026.0 cm⁻¹, indicating the aromatic C-H stretching vibrations. Then, three peaks at wavenumbers 1600.8, 1492.7, and 1452.2 cm⁻¹ are aromatic C=C stretching vibrations, indicating the presence of benzene rings. After that, peaks with wavenumbers 756.0 and 698.2 cm⁻¹ are associated with the bending vibration of the C-H outside plane, indicating that there is only one substituent on the benzene ring. The last peak with wavenumbers 2921.9 and 2848.6 cm⁻¹ indicates the presence of methylene (Hafeez et al. 2023). Meanwhile, LLDPE data shows that LLDPE consists of aliphatic long chains of alkanes at 2849 and 2916 cm⁻¹ and C=C bonds at 1469 cm⁻¹ (Al Salem et al. 2021).

No	FTIR (cm ⁻¹) peak					Functional Group
	Polystyrene	LLDPE	Sample 1	Sample 2	Water	
12	2848.6	2849	-	-	-	Asymmetric and Symmetric (-CH ₂ -) stretching on Long Chain Aliphatic Compound
13	2921.9	2916	2931.9	-	-	Asymmetric and Symmetric (-CH ₂ -) stretching on Long Chain Aliphatic Compound
14	3026	-	3047.63	-	-	H-C= olefinic bond
15	3060.8	-	-	-	-	Aromatic C-H stretching
16	3446.5	-	-	3351.81	3350	O-H from water Stretching

FTIR data resulted in the following points:

- (i) Sample 1 had six peaks with different wavenumbers. The first peak at wavenumber 3047.63 cm⁻¹ shows the absorption of sp² hydrogen bonds vibration that bonds to C=C olefin compounds. The second peak at wavenumber 2931.9 cm⁻¹ shows the absorption of sp² hydrogen bonds vibration that bonds to long chains of alkanes. These data show that sample 1 still has a long chain of alkanes. Then, the third peak at a wavenumber of 1465.95 cm⁻¹ is an aromatic C=C bond, indicating the presence of a side group which is styrene in the polymer chain or styrene compound resulting from polystyrene degradation through pyrolysis. Furthermore, the fourth peak with a wavenumber of 902.72 cm⁻¹ showed the absorption of C-H trans vibrations in olefin compounds. The fifth peak with a wavenumber of 709.83 cm⁻¹ indicates the presence of methylene bending/bending (-CH₂-) in long-chain alkanes. This proves that sample 1 contains C-H trans groups of olefin compounds, C=C bonds in ethylene and styrene, and long chains of alkanes. The formation of a double bond (C=C) indicates the breaking of the C-C bond of polystyrene and LLDPE during the pyrolysis process.

- (ii) Sample 2 had two peaks with different wavenumbers.

The peak at the wavenumber of 3351.81 cm⁻¹ shows a stretching vibration of hydroxy groups (-OH) with a widened peak. The peak at the wavenumber of 1635.69 cm⁻¹ shows a scissor-type bending vibration of the hydroxyl group with a sharp peak. Meanwhile, if compared to FTIR for water spectra, sample 2 has similar spectral and wavenumber absorption forms, in which it has a stretching vibration of the hydroxyl group at a wavenumber of 3350 cm⁻¹ with a widened peak and scissor-type bending vibrations of the hydroxyl group at a wavelength of 1650 cm⁻¹ with a pointed/sharp shape. Therefore, the reaction that takes place during pyrolysis involves oxygen, informing the existence of some aerobics because it produces water molecules (Dewi 2017).

Figure 7 shows the proposed reaction from pyrolysis of LLDPE and Polystyrene. The reaction is a random cutting reaction that produces caramel brown wax. Further heating possibly produces gasoline and diesel or light hydrocarbons. In addition, there is a chain-end cutting reaction that produces monomers, such as styrene and ethylene. The oligomerization of monomers forms longer chains and the cyclization of oligomers forms aromatic hydrocarbons. The reaction mechanism is estimated according to the results of FTIR analysis as well as the physical properties of samples and residues.

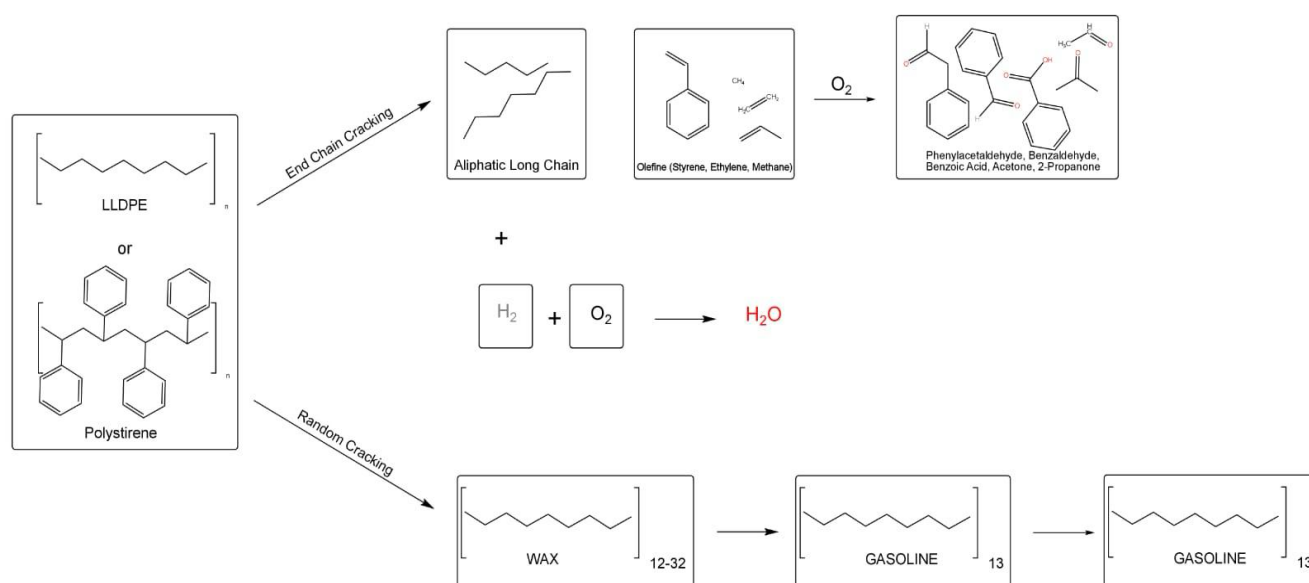


Figure 7: Plastic degradation reaction during pyrolysis

The presence of C=C bonds indicates the presence of ethylene and styrene, as well as methylene bonds in the long chain of

alkanes for sample 1. It indicates a radical polymer chain-breaking reaction at the end of the chain that produces hydrogen

gas, long-chain polymers, and olefin compounds in the form of styrene, ethylene, and propylene. This solving process is divided into several reactions:

- (i) **C-H Bond Termination. Reactions (1) and (2) in Figure 8** show that the C-C bending bonds in the LLDPE and Polystyrene chains begin to break due to high-temperature application during pyrolysis. This break causes the formation of hydrogen-free radicals at the points of breaking bonds. The hydrogen radicals bond together to form hydrogen gas, according to the following reaction (3),

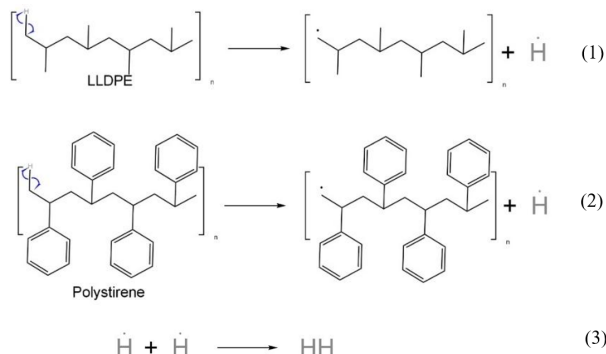


Figure 8: C-H bond termination

- (ii) **Formation of Double Bond C=C. Reactions (4) and (5) in Figure 9** show the release of hydrogen atoms at the end of the chain through a radical reaction causing the instability of the molecule. Thus, the C-C bond is broken and forms a C=C double bond by producing 2-propylene and styrene and a long polymer chain. In addition to the End Chain Cracking mechanism, there is also a Random Cracking reaction to produce wax characterized by the formation of residues in the form of brown solids according to Figure 5(e).

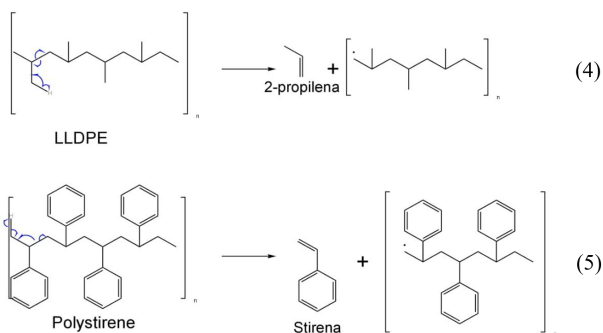


Figure 9: Formation of double bond C=C

Reactions (6) and (7) in Figure 10 show when the C-C bond in the middle chain breaks to form two long radical chains, these radical chains can react again to form various sizes of polymer chains.

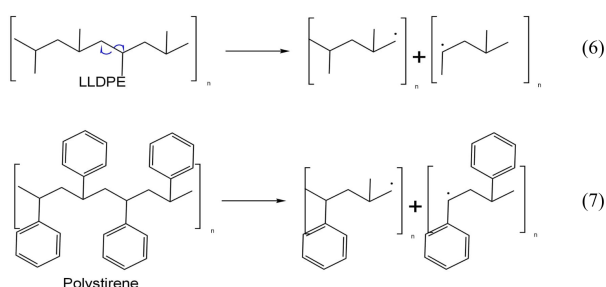


Figure 10: Further breakdown chemical reaction

Meanwhile, the reaction in sample 2 is formed because the system contains some aerobic conditions. Thus, the hydrogen that results from the break of C-H bonds reacts with oxygen, according to the following Reactions (8), (9), and (10) in Figure 11.

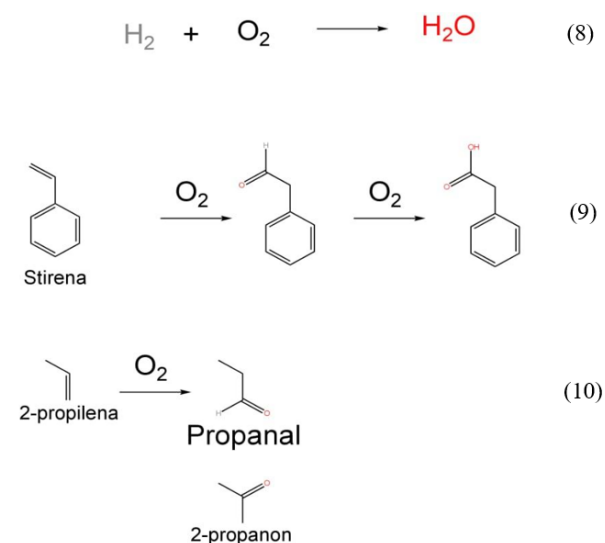


Figure 11: Further breakdown chemical reaction

If the system is in an aerobic condition, the styrene and 2-propylene transform into phenylacetaldehyde, benzaldehyde, benzoic acid, phenylacetic acid, propanal, and 2-propanone by oxidations even though in small amounts. Judging from the possible reaction mechanisms involved during pyrolysis, sample 1 contains long chains of alkanes, styrene, and 2-propylene, whereas sample 2 consists of water and very little phenylacetaldehyde, benzaldehyde, benzoic acid, phenylacetic acid, propanal, and 2-propanone.

Finally, the findings of this study are strongly aligned with the SDGs, particularly SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDGs 14-15 (Life Below Water and Life on Land). The catalyst-free pyrolysis process of LLDPE and polystyrene demonstrated in this research shows the potential of converting plastic waste into value-added products such as liquid fuels and solid wax, thereby reducing the volume of plastic ending up in the environment and lowering greenhouse gas emissions from open burning. This approach not only transforms waste into resources but also supports the transition towards a circular economy and environmentally friendly technologies that can be implemented at various scales, from local communities to industry, thus directly contributing to the achievement of these SDG targets. This study adds new information regarding SDGs as reported elsewhere (Basnur et al., 2024; Samsuri et al., 2025; Syahrudin et al., 2026).

CONCLUSION

This study was to determine the chemical compound content of polystyrene and LLDPE after the pyrolysis process was analyzed using FTIR. This research had an impact on processed plastic waste using pyrolysis and knew the functional groups of pyrolysis components. This study also supports current issues in the SDGs.

ACKNOWLEDGMENT

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

ABD Nandiyanto is the main contributor, supporting grant, and editing final manuscript. AS, SV, and FMTM are mainly doing experiments and writing the first draft. IK, TK, OF, and MRB are supporting and give advices for this research.

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