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Research Paper

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

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Abstract

Currently, pyrolysis is the primary choice for addressing the significant problems caused by plastic waste. Temperature and catalysts are the main parameters in pyrolysis. However, using catalysts can become a serious problem when scaling up production capacity, as the process can become more complex and expensive due to the high cost of catalysts. Without a catalyst, the required pyrolysis temperature must be sufficiently high to achieve high-quality pyrolytic fuel oil. In this work, plastic grocery bag is pyrolyzed followed by distillation to produce a liquid similar to conventional fuel, called distillate plastic fuel. Non-catalyst and low-temperature pyrolysis was performed at a single temperature of 350 °C, followed by distillation at temperatures of 250 °C and 350 °C to determine the effect of distillation temperature on the chemical properties of the obtained distilled fuel. Elemental and composition analyses were conducted using the GCMS method. Results indicated that the chemical properties and composition of distilled plastic fuel are similar to diesel fuel with a heating value of approximately 43.362 to 44.364 MJ/kg.

Keywords: Plastic; Pyrolysis; Distillation; Distillate oil

1. Introduction

Plastic is often used in various daily activities, especially for food and beverage containers, industrial packaging, medical healthcare, etc. However, plastic waste, the discarded plastic materials that are no longer in use and have been thrown away or disposed of, has a significant adverse impact on the environment [1]. Plastic bags become the most widely used on a daily activity. This type of plastic is single-use, and because of that, the amount of plastic bag waste generated is abundant. Plastic bags are often not recycled properly, so many end up in landfills or scattered in the environment causing environmental pollution, which has a significant impact on the food chain [2].

To overcome the negative impact of plastic bag waste, those efforts are needed; to reduce the overall use of single-use plastics, recycle plastics more efficiently, and support innovation in developing environmentally friendly plastic substitutes. In addition, awareness of the importance of properly reducing, recycling, and disposing of plastic is also essential for individuals, companies, and governments. The government has a very important interest in regulating the use and solution of plastic waste problems through regulations [3].

Traditionally, plastic waste is burned to provide heat for steam generation. The generated steam has high thermal energy and can be used to power turbine blades to produce electricity for the local grids [4]. In addition to generating steam for electricity, combustion heat can also be stored for heating and other purposes [5]. However, in general terms, the energy recovery efficiency from the direct combustion of plastic waste is just about 10% [6]. This is usually influenced by the methods of combustion used by using conventional burning methods. A simple experiment has proven that combustion efficiency can be improved by using a model of a combustion chamber with internal air distribution [7]. Analytically, the use of an incinerator with two levels of combustion instead of a single combustion can also improve combustion efficiency [8]. Moreover, the direct burning of plastic waste without complete combustion releases a lot of toxicant substances, fly ash as well as greenhouse gases which increase the effects of climate change [9].

Instead of burning, pyrolysis can be considered another way to solve the plastic waste problem [10]. The pyrolysis process involves heating organic/inorganic matter in oxygen-free conditions and breaking molecules into various products including fuels, gases, and solid residues [11]–[15]. From the studied literature, the pyrolysis process is one of the methods that is considered potential to solve the problem of plastic waste by converting it into a useful energy source [16]. Therefore, further research and development of environmentally friendly technologies are key in implementing pyrolysis methods effectively. Single feedstock pyrolysis or even though co-pyrolysis with other feedstock can be a good choice to convert plastic wastes into alternative fuels [17].

The quality of plastic pyrolysis products is highly dependent on the temperature used. The operating temperature can control and optimize pyrolysis products such as pyrolysis oil, gas, or other chemicals, in a more efficient and economical way [18]. Pyrolysis is usually performed at temperatures between 300 and 900 °C [19]. Below the temperature of 300 °C, pyrolysis is categorized as low-temperature [20]. Above a temperature of 500 °C, the pyrolysis process is categorized as high-temperature. Pyrolysis requires energy; high-temperature pyrolysis requires a lot of energy compared to low-temperature pyrolysis. The researchers said that there is an optimal pyrolysis temperature to produce the maximum product, namely pyrolysis at medium temperatures between 500 °C to 600 °C. This process offers a balance between pyrolysis oil, gas, and biochar, making it a good choice for applications that require a combination of these products.

When the pyrolysis temperature is raised, i.e. the temperature above 600 °C will produce abundant gas, relatively clean oil, and a little biochar. This process is very efficient in producing gas that can be used as fuel or chemical raw materials but requires a lot of energy to reach high temperatures. Researchers say that pyrolysis at high temperatures is suitable for applications that require high-quality gas and oil products.

Pyrolysis can be performed with or without a catalyst. Catalyst-free pyrolysis is a simpler method and does not require any additional ingredients to speed up or direct the reaction. Although this process can reduce the volume of waste and produce useful products, the quality and efficiency of the resulting products may be less optimal compared to pyrolysis using catalysts. This process remains useful in waste management, energy production, and agricultural applications, especially when cost and complexity are important considerations.

Pyrolysis with catalysts can indeed improve process efficiency and direct the formation of desired products, such as pyrolysis oil or high-quality gases. Catalysts help speed up reactions, reduce tar formation, and allow for better control of the final product. While there are advantages in terms of product efficiency and quality, the use of catalysts also requires cost and maintenance considerations [21]. Overall, while catalytic pyrolysis offers advantages in terms of increased efficiency and product selectivity, these drawbacks need to be considered in process planning and implementation, especially for large-scale or commercial applications.

Many studies have tried to replace or mix synthetic fuels with conventional fuels, either biodiesel [22] or other fuels. Pyrolysis plastic fuel can also be used directly or mixed with gasoline or diesel fuel to drive internal combustion engines. However, researchers found that the emissions produced are still quite significant, especially at NOx levels [23]. So most researchers still use other additives in fuel to reduce emissions [24]. Engines may need to be adjusted to optimize the combustion of plastic fuels to reduce emissions, as these fuels may have different combustion properties compared to gasoline or diesel.

In this study, pyrolysis at low temperatures without the use of catalysts was carried out to explore the potential and limitations of a simpler and more economical process. The low temperature was chosen because according to the TGA, plastic has been graded starting at a temperature of 300 °C. In addition, low-temperature plastic pyrolysis produces more liquid and requires less energy than pyrolysis at high temperatures. In addition, low-temperature pyrolysis avoids the formation of uncondensed harmful gases and solid residues such as carbon black. Therefore, the main goal of this study is to understand the characteristics of pyrolytic plastic fuel, analyze the possibilities of large-scale production of plastic oils, and find practical applications for such products. The main objectives include cost reduction and evaluation of pyrolysis oil based on hydrocarbon composition and heating value.

2. Methods

Plastic waste from grocery bags used in this study was collected from various sources such as landfills, recycling facilities, and community donations. The plastic used is a type of low-density polyethylene (LDPE) derived from plastic used as shopping bags, because of its homogeneous nature and easy to find. The collected plastic waste is then cleaned of contaminants such as dirt and labels, dried in the open air, and directly used without chopping. Before the pyrolysis process, plastic sample was analyzed to determine their chemical composition.

For proximation and ultimate analysis, literature using similar plastics as research materials is used [25]. This analysis includes the determination of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) content. This data is important to calculate the Higher Heating Value (HHV) of the distillate products produced. Elemental analysis is performed using the CHNS/O elemental analysis method.

The pyrolysis process is carried out using a batch reactor made of square-shaped stainless steel with a capacity of about 5 kg of raw materials. This reactor is equipped with a condenser to condense pyrolysis vapor into pyrolysis liquid. The schematic of the pyrolysis system is shown in Figure 3. Approximately 2 kg of plastic samples are fed into the reactor. The reactor is heated at a heating rate of 10 °C per minute using an LPG burner, from room temperature to 350 °C, so that the cracking or pyrolysis process occurs, and the pyrolysis products are collected in the condenser tank. This process is carried out with a retention time of about 90 minutes. Pyrolysis products in the form of liquids and residues are collected in condensers and pyrolysis units.

The amount of condensed liquid product is determined by calculating the difference between the weight of the trapped liquid plus the solid residue and the initial plastic material used. Once the pyrolysis liquid is obtained, the separation of light and heavy molecules is carried out through the distillation process. Distillation was carried out at two different temperatures, namely 250 °C and 350 °C, producing two types of liquids that are thought to be similar to gasoline and diesel. To

Table 1. Proximate and ultimate analysis of the grocery bag plastic

Proximate analysis	Weight (%)	Ultimate analysis	Weight (%)
Moisture	0.15	Carbon	73.25
Volatile	94.48	Hydrogen	12.30
Ash	4.76	Nitrogen	0.02
Fixed carbon	0.61	Sulfur	0.49
		Oxygen	9.03

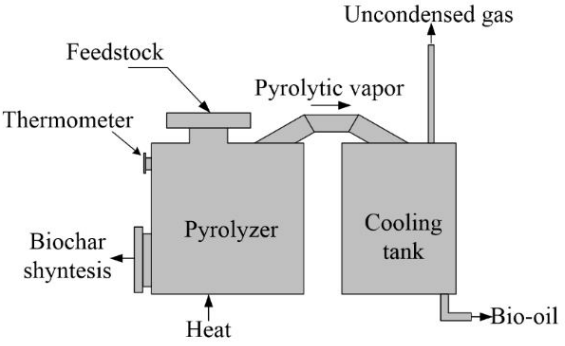

Figure 1. Schematic diagram of the system used

analyze the fraction of condensed distillate, gas chromatography combined with a mass spectrometer (GC-MS) is used. This analysis aims to determine the chemical components of the liquid products produced. In addition, elemental analysis is also carried out to determine the characteristics of the distillate products obtained. This data is then used to calculate the HHV of the distillate product using the Dulong equation.

3. Results and Discussion

Figure 2 presents images of two distillate plastic fuels, each with a different color, produced from the pyrolysis and subsequent distillation of grocery bag waste plastic. The figures depict the appearance of the distillate plastic fuel at two different temperatures: 250 °C in **Figure** 2a and 350 °C in **Figure** 2b. In **Figure** 2a, the fuel has orange color, indicating the presence of lighter hydrocarbons or a cleaner fraction of pyrolysis oil. This color suggests that the pyrolysis process was conducted under conditions favoring the production of more refined oil, possibly due to the lower temperature or a more controlled environment. In contrast, **Figure** 2b shows the fuel has dark or nearly black color, indicating the presence of heavier hydrocarbons or more complex, potentially contaminated pyrolysis products. The dark color suggests a higher concentration of carbon residues, tar, or other heavy fractions, typical of pyrolysis processes occurring at higher temperatures or under conditions that promote the breakdown of polymers into more complex molecules.

Table 2 shows data on the chemical composition and high heating value (HHV) of distillate at various distillation temperatures. The heating value is calculated using the formula recommended by Faisal et al. [26]. It can be seen that as the distillation temperature increases, the percentage of carbon and hydrogen tends to increase, while the percentage of oxygen decreases. HHV also increases to a temperature of 350°C, then decreases slightly at a temperature of 450°C. According to research conducted by Sorum et al. [27] plastic pyrolytic oil has the highest combustion value in the 42 to 47 MJ/kg.

Table 3 and **Table 4** display mass spectrometry graphs that illustrate the concentration of components (wt%) in the examined samples based on their covered area. The peaks on the graphs represent the relative concentrations of various chemicals within the samples. High peaks indicate a dominant component, suggesting that it is the primary ingredient or has the highest concentration in the mixture. In contrast, smaller peaks, especially those spread over shorter retention periods, suggest the presence of a wider range of chemicals, each at lower concentrations.

The graphs illustrate how the characteristics of the samples change with varying temperatures, revealing that the samples are composed of multiple distinct chemicals. This complexity suggests that the samples contain numerous components that are separated and detected through the spectrometry technique. Compounds with longer retention times (closer to 30 minutes) exhibit stronger interactions with the chromatography columns, which may indicate differences in polarity or molecular size compared to those that appear earlier.

The graphic also demonstrates how distillation temperature significantly influences the chemical composition of the sample. As the distillation temperature increases, the retention time required for certain compounds also increases, suggesting that heavier hydrocarbon compounds need longer retention times and higher temperatures to separate from their parent substances. The prominent peaks at longer retention times indicate that these compounds are particularly abundant in the mixture and could be a primary focus for future research. The area under the high peaks, along with the numerous smaller peaks, suggests that while one or more compounds are dominant,

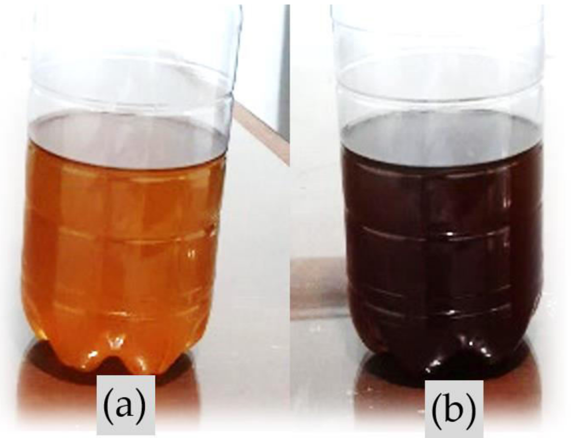

Figure 2. Physical properties of distillate plastic fuel at temperatures; (a) 250 °C, and (b) 350 °C

many others are present in smaller quantities. Further quantitative analysis can be conducted to determine the exact amounts of each substance.

Based on the spectrometry test, the sample contained a wide range of compounds at varying concentrations, with one or more dominant compounds corresponding to the distillation temperature. The complex composition and distribution of retention times demonstrated the effectiveness of the spectrometry test method in separating the sample components. This spectrometry graph reveals the chemical makeup of the material, allowing for the distinction between major and minor compounds based on retention time and peak height. These findings provide a foundation for further research, such as compound identification using retention time databases or confirmation of compound identity through mass spectrometry. Moving forward, the next steps could involve the identification of the principal molecule, absolute quantification using internal standards, or a detailed investigation of the secondary compounds present in the sample.

Table 3 and **Table 4** show the distribution of components contained in the test sample ranging from light hydrocarbon molecules to heavy hydrocarbons. This component distribution is in good agreement with the literature [28]–[30]. It can be seen that plastic distillation fuel contains a wide variety of hydrocarbon molecules. It can be seen that the distillation temperature has a great influence on the products produced because hydrocarbons have different saturation points. Light hydrocarbons evaporate at low temperatures while heavy hydrocarbons evaporate at high temperatures.

Table 2. Elemental composition of distillate oil

Distillation Temp (°C)	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	HHV (MJ/kg)
250	85.850	12.370	0.000	1.780	44.362
350	84.240	12.160	0.000	3.600	43.364

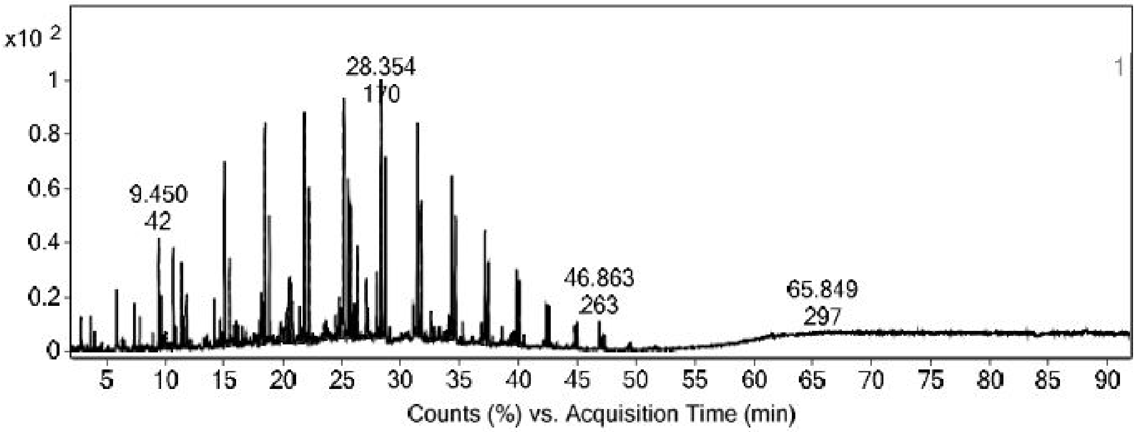

Figure 3. Mass spectrometry of grocery bags waste plastic distillation at 250 °C

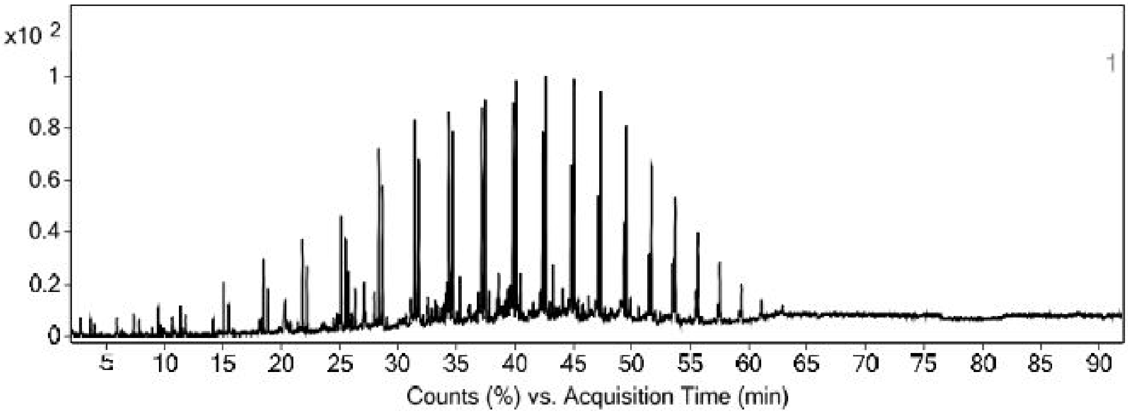

Figure 4. Mass spectrometry of grocery bags waste plastic distillation at 350 °C

Table 3. Mass spectrometry of distillate plastic fuel distillate at 250 °C

Area (%)	Component Name	Formula
0.83	Spiro[2,4]hepta-4,6-diene	C_7H_8
0.81	Cyclopentane, 1,2,3-trimethyl-, (1.alpha.,2.alpha.,3.beta.)-	C_8H_{16}
0.81	Ethylbenzene	C_8H_{10}
0.42	p-Xylene	C_8H_{10}
1.46	Styrene	C_8H_8
1.26	trans-2,4-Dimethylthiane, S,S-dioxide	$C_7H_{14}O_2S$
0.56	Cyclopentanone, 2-(1-methylpropyl)-	$C_9H_{16}O$
0.74	.alpha.-Methylstyrene	C_9H_{10}
0.26	1-Nonylcycloheptane	$C_{16}H_{32}$
2.81	Cyclodecane	$C_{10}H_{20}$
0.34	Chloroacetic acid, 10-undecenyl ester	$C_{13}H_{23}ClO_2$
0.73	trans-2-methyl-4-n-pentylthiane, S,S-dioxide	$C_{11}H_{22}O_2S$
3.58	1-Undecanol	$C_{11}H_{24}O$
0.28	Tetracyclo[5.3.0.0<2,6>.0<3,10>]deca-4,8-diene	$C_{10}H_{10}$
0.78	Benzoic acid	$C_7H_6O_2$
1.58	Heptanediamide, N,N'-di-benzoyloxy-	$C_{21}H_{22}N_2O_6$
1.44	Benzoic acid	$C_7H_6O_2$
0.89	Benzoic acid	$C_7H_6O_2$
0.68	Naphthalene	$C_{10}H_8$
0.64	9-Octadecyne	$C_{18}H_{34}$
3.88	1-Dodecanol	$C_{12}H_{26}O$
1.00	1,12-Tridecadiene	$C_{13}H_{24}$
4.60	n-Pentadecanol	$C_{15}H_{32}O$
1.46	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
4.86	1-Tetradecanol	$C_{14}H_{30}O$
0.59	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
4.45	n-Pentadecanol	$C_{15}H_{32}O$
2.70	Carbonic acid, decyl undecyl ester	$C_{22}H_{44}O_3$
0.25	Chloroacetic acid, pentadecyl ester	$C_{17}H_{33}ClO_2$
0.69	1-Decanol, 2-hexyl-	$C_{16}H_{34}O$
0.47	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
3.16	1-Hexadecanol	$C_{16}H_{34}O$
2.77	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.38	Benzene, 1,1'-(1,3-propanediyl)bis-	$C_{15}H_{16}$
0.43	1,19-Eicosadiene	$C_{20}H_{38}$
2.53	8-Heptadecene	$C_{17}H_{34}$
1.79	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.31	1-Decanol, 2-hexyl-	$C_{16}H_{34}O$
0.35	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
1.60	1-Hexadecanol	$C_{16}H_{34}O$
1.33	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.87	n-Nonadecanol-1	$C_{19}H_{40}O$
0.82	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.54	Behenic alcohol	$C_{22}H_{46}O$
0.58	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.58	13-Octadecenoic acid, methyl ester	$C_{19}H_{36}O_2$

Table 4. Mass Spectrometry of distillate plastic fuel distillate at 350 °C

Area (%)	Component Name	Formula
0.29	Cyclopentane, 1,2,3-trimethyl-, (1.alpha.,2.alpha.,3.beta.)-	C_8H_{16}
0.24	Styrene	C_8H_8
0.34	trans-2,4-Dimethylthiane, S,S-dioxide	$C_7H_{14}O_2S$
0.61	Cyclodecane	$C_{10}H_{20}$
0.89	1-Undecanol	$C_{11}H_{24}O$
1.33	Benzoic acid	$C_7H_6O_2$
1.24	1-Dodecanol	$C_{12}H_{26}O$
1.67	n-Pentadecanol	$C_{15}H_{32}O$
0.71	9-Eicosyne	$C_{20}H_{38}$
2.74	1-Tetradecanol	$C_{14}H_{30}O$
0.26	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
3.16	n-Pentadecanol	$C_{15}H_{32}O$
2.60	Carbonic acid, decyl undecyl ester	$C_{22}H_{44}O_3$
0.38	1-Decanol, 2-hexyl-	$C_{16}H_{34}O$
0.48	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
3.55	1-Hexadecanol	$C_{16}H_{34}O$
3.55	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.70	Benzene, 1,1'-(1,3-propanediyl)bis-	$C_{15}H_{16}$
0.26	1,19-Eicosadiene	$C_{20}H_{38}$
3.68	n-Nonadecanol-1	$C_{19}H_{40}O$
3.97	Heptadecane	$C_{17}H_{36}$
0.53	Chloroacetic acid, tetradecyl ester	$C_{16}H_{31}ClO_2$
0.59	1-Decanol, 2-hexyl-	$C_{16}H_{34}O$
0.57	9-Octadecen-1-ol, (Z)-	$C_{18}H_{36}O$
3.79	Behenic alcohol	$C_{22}H_{46}O$
3.99	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
3.31	n-Nonadecanol-1	$C_{19}H_{40}O$
4.32	Carbonic acid, eicosyl vinyl ester	$C_{23}H_{44}O_3$
0.98	Naphthalene, 2-phenyl-	$C_{16}H_{12}$
0.42	Eicosen-1-ol, cis-9-	$C_{20}H_{40}O$
3.00	Behenic alcohol	$C_{22}H_{46}O$
4.26	Eicosane	$C_{20}H_{42}$
2.06	1-Heneicosyl formate	$C_{22}H_{44}O_2$
1.48	Behenic alcohol	$C_{22}H_{46}O$
3.09	Docosane	$C_{22}H_{46}$
1.20	Behenic alcohol	$C_{22}H_{46}O$
2.70	Hentriacontane	$C_{31}H_{64}$
2.26	Hentriacontane	$C_{31}H_{64}$

Figure 5 displays a horizontal bar graph that shows the relationship between the amount of carbon (%) and the distillation temperature (°C) for light and heavy hydrocarbons in the sample. The graph shows that a distillation temperature of 250 °C resulted in liquid with a carbon content of C_6 - C_{12}, which is similar to gasoline fuel (light hydrocarbons) and decreases as the distillation temperature was increased. At a distillation temperature of 350 °C, the main production is liquid with carbon quantities C_{13}-C_{18} and a group of C_{19}-C_{23}, similar to diesel. While the heavy hydrocarbon component with a carbon content, C>24 will be generated at even higher temperatures. If the distillation temperature is increased further, all hydrocarbon fuel production

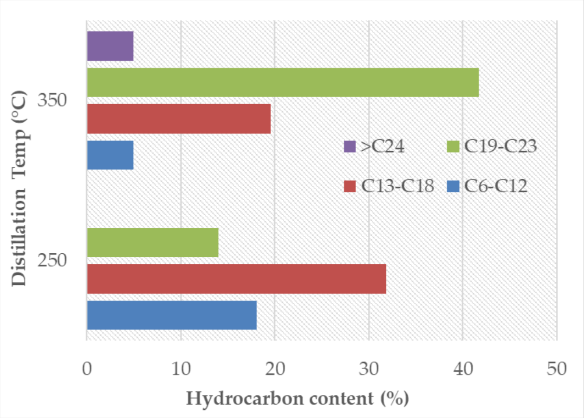

Figure 5. Effect of distillation temperature on hydrocarbon content

will decline. Thus, as temperatures rise, the number of hydrocarbons decreases. We can deduce that light hydrocarbons are exclusively created at low temperatures, whereas heavy hydrocarbons are produced at higher temperatures. This demonstrates the differences in volatility and boiling point properties between light and heavy hydrocarbons.

4. Conclusion

Pyrolysis without a catalyst continued by distillation of the plastic grocery bag which produced distillate plastic fuel for conventional fuel substitution was studied. The resulting fuel was evaluated using the CHN and MS method. Based on CHN analysis, it was found that the calorific value (CV) of plastic oil ranges from 43.362 to 44.364 MJ/kg, which is slightly below the calorific value of fossil-based fuels. The MS analytical data indicate that the distillate oil produced comprises a short and long-chain hydrocarbon components. The carbon number at the beginning of a short-chain hydrocarbon compound is C_7, whereas that of a long-chain hydrocarbon compound is C_{31}. Because the original raw material component was only straight-chain hydrocarbon compounds, LDPE waste plastic converted to heavy fuel contains alkane and alkene group compounds, which are aliphatic. The resulting distillate plastic fuel might be used in all heavy-duty engines, as feedstock for refineries, or to create electricity. Using this well-known technology could assist in addressing the environmental dilemma of plastic grocery bag waste, while also increasing renewable energy generation from LDPE waste.

Furthermore, the findings of this study can be used as a benchmark for the industry in developing pyrolysis technology to convert LDPE plastic waste into value-added goods. With growing awareness of the need for plastic waste management, it is hoped that this research will produce practical and adaptable solutions to reduce plastic's harmful influence on the environment. Using pyrolysis technology to treat LDPE plastic waste, such as grocery bags, is a significant step toward improved waste management and environmentally acceptable energy sources.

Some of the development and potential future implementations include process optimization to improve fuel quality such as removing unwanted compounds so that the oil can be used directly as liquid fuel in conventional engines. No less important is the integration in a sustainable plastic waste management system where the development of industrial-scale pyrolysis facilities to manage plastic waste directly in the city or at industrial sites. It can reduce the pile of plastic waste and produce fuel at once. In order to sustain the economy that industrial and economic scale development, investment in large-scale or modular pyrolysis facilities can be built near plastic waste sources, such as recycling centers or factories, to reduce transportation and waste processing costs.

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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.

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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.

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