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Effect of Temperature on Co-Pyrolysis of Palm Kernel Shell and Plastic Waste under Natural Catalysts

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ABSTRACT

Pyrolysis is a potential process for converting solid waste, such as biomass and plastic waste, into useful fuels and chemicals in liquid, solid, and gas forms. The pyrolysis temperature is a critical factor that influences the amount and quality of the product. Furthermore, the use of natural catalysts such as calcium oxide and natural zeolite affects the pyrolysis products. Thus, the purpose of this study is to evaluate the influence of temperature on the amount and quality of pyrolysis products, especially pyrolysis oil, using calcium oxide and natural zeolite catalysts. Pyrolysis was carried out in a stainless steel fixed-bed reactor. The temperature was kept at 400, 450, and 500 °C. The pyrolysis vapor was cooled with a water-jacket condenser, and the oil and wax were collected in an oil chamber. This study found that the pyrolysis temperatures had a substantial impact on the pyrolysis product yields by reducing the char product from 31.25% to 13.9% when the temperature rose in tandem with the fluctuations of other products (wax, liquid, and non-condensable gas). At 450 °C, the liquid product acquired its maximum density, viscosity, heating value, and acidity, which were 906.7 kg/m^3, 2.2 cSt, 37.83 MJ/kg, and pH 6.2, respectively. Furthermore, increased temperature promoted the formation of aliphatic hydrocarbons..

1. INTRODUCTION

Rising energy demands and deteriorating climatic conditions have led to a greater emphasis on energy conservation and emission reduction. Simultaneously, major efforts are being made to develop and implement renewable and ecologically acceptable energy sources [1]. In contrast to traditional fossil fuels, biomass has emerged as a sustainable energy source capable of providing the rising need for clean energy via improved technological systems. This is due to the possibility for recycling biomass waste, which increases the value of goods across the whole industrial chain. As a result, biomass obtained from forestry waste or agricultural products is becoming more widely recognized as a viable bioenergy source, particularly in agro-based nations such as Indonesia, India, and China [2]. Because biomass is mostly composed of lignocellulosic material, biorefineries find it to be a desirable feedstock for producing biofuels and bio-based chemicals [3].

A wide range of biomass resources are widely available and easily accessible. These include sludge from wastewater treatment facilities and municipal solid wastes, bark, sawdust, and wood chips from forestry, and agricultural leftovers including wheat straw, rice husk, and palm kernel shell [4]. These substances often have a fair amount of energy in them. The palm kernel shell, in particular, sticks out as a particularly potential prospect for improving the bioenergy sector among agricultural leftovers. The palm kernel shell's high yield and low market value make it a valuable byproduct of processing facilities, which is one of its main advantages. Its waste composition also exceeds other accessible agricultural leftovers, especially in the areas of carbon and hydrogen [5]. Furthermore, the palm kernel shell is a copious biomass byproduct of palm oil extraction, providing a significant source of renewable energy in Indonesia. Indonesia is currently a major worldwide palm oil producer, accounting for around 60% of the world's palm oil supply [6]. The oil palm industry's substantial solid waste creates considerable environmental issues. Throughout the life cycle of oil palm production, only 10% of the overall process yield is edible oil, with the remaining 90% being biomass. During the milling process, 5.2–7% palm kernel shell (PKS) is extracted during nut breaking or shell/kernel separation [7]. In 2015, Indonesia has a solid residue of 8.4 million tons of palm kernel shell from palm oil production waste [8], [9].

Plastic, regarded as one of the most significant breakthroughs of the twentieth century, is widely used due to its low cost, lightweight nature, simple production, and a variety of attractive properties. By the end of 2021, the worldwide buildup of plastic garbage had reached nearly 6.3 billion tons, posing a severe risk to both human health and the natural ecology [10]. Currently, there are four methods for handling plastic waste: landfill disposal, incineration, physical recycling, and chemical recycling. Approximately 40% of plastic garbage is disposed of in landfills, 32% ends up in the environment, 14% is incinerated, and just 14% is recyclable [11], [12].

Because of theire high calorific value, biomass and plastic wastes are commonly used as fuel, particularly in developed countries. Both incineration and landfill processes have severe environmental consequences, such as groundwater pollution and the release of hazardous gasses [12]. In recent years, pyrolysis has developed as a forward-thinking alternative to incineration, liquefaction, and gasification technologies, providing an effective method of resource recovery. Pyrolysis may convert carbonaceous feedstocks like biomass and plastics into useful products, incliding pyroltic oil, char, and non-codensable gas. This technique is versatile, allowing for fine-tuning of product yields by changing parameters to satisfy individual requirements. The resultant gaseous product is recycled to meet the whole energy requirements, making pyrolysis a sustainable and ecologically benign technique [13].

Extensive study has been undertaken in recent years on co-pyrolysis of diverse feedstocks, which appears to be an interesting process involving both decomposition and polymerization. This co-pyrolysis is heavily impacted by mass and heat transmission between substances, the existence of hydrogen bonds, and free radical interactions. Throughout the procedure, strong physicochemical coupling reactions occur. Numerous researchers have worked to understand the pyrolysis mechanism of biomass. Their findings suggest that cellulose contributes radicals to the destruction of hemicellulose and lignin during pyrolysis. Specifically, the C-O cleavage on phenylpropane's side chain serves as a donor for the ring-opening of secondary cellulose pyrolysis products, favoring the formation of fatty chains [14]. In addition to free radical reactions between lignocellulose molecules, free radical interactions occur inside lignin molecules. Lu et al. [15] hypothesized a phenol-assisted hydrogen transfer mechanism during lignin pyrolysis that relies on the interaction of two free-radical processes, hydrogen extraction and hydrogen bond induction. Under moderate temperatures, hydrogen transfer on the β-O-4 atom of phenol during pyrolysis is more substantial than that caused by free radicals. During pyrolysis, the thermal degradation of biomass and polymers generates free radicals and intermediates at different temperatures. The interactions between these various free radicals determine the distribution and properties of the resultant products [16].

Catalytic pyrolysis is interesting because of the processes involved in pyrolysis oil upgrading. However, the use of synthetic catalysts greatly raises operational costs. Alternatively, natural catalysts can be used to upgrade pyrolysis oil because they are inexpensive and readily accessible. Currently, several natural catalysts have been used in pyrolysis experiments, yielding beneficial results. Hendrawati et al. [17] used natural zeolite in the pyrolysis of polypropylene and high-density polyethylene. Natural zeolite might increase the liquid yield of polypropylene and high-density polyethylene. Weng et al. [18] investigated the co-pyrolysis of polypropylene and hemicellulose using a CaO catalyst. They discovered that the CaO catalyst improved xylan breakdown and increased polypropylene production of tiny alkenes. Furthermore, the CaO catalyst has the potential to considerably increase the production of olefins and furan compounds. Vo et al. [19] carried out fast pyrolysis of cashew nut shells using a dolomite catalyst. They discovered that calcined dolomite increased dehydration, decarboxylation, cracking, and the formation of aromatic hydrocarbons and syngas (H_2 and CO). Dolomite also exhibited remarkable carbon capture activity at high temperatures. Fan et al. [20] used a MgO catalyst for microwave-assisted pyrolysis of low-density polyethylene. According to the findings of this study, increased catalyst-to-feedstock ratios, pyrolysis temperatures, and catalytic reaction temperatures enhanced alkene conversion to aromatics. Sonna et al. [21] investigated the effects of activated alumina on wasted grain pyrolysis. Their research found that the majority of the chemical components acquired with a catalyst at moderate temperatures were comparable to those obtained at high temperatures without a catalyst. Furthermore, the employment of a catalyst and high temperatures during the reactions reduced the amount of oxygenated molecules generated. Previous research has shown that some catalysts have a distinct catalytic activity. Thus, the use of a dual catalyst may affect the catalytic pyrolysis feature, which has to be investigated further. In this study, we consider to use calcium oxide and natural zeolite in catalytic pyrolysis due to their specific characteristics.

At higher temperatures, the release of volatile chemicals from the biomass and plastic matrix increases, influencing the composition and characteristics of the resultant bio-oil and gas fractions. The temperature-dependent evolution of gases during co-pyrolysis is an important factor that influences the calorific value and possible uses of the produced syngas [22]. However, the effect of temperature during co-pyrolysis of biomass, specifically palm kernel shell, and plastic waste is rare to be unveiled. Moreover, catalysts' involvement during co-pyrolysis can change the pyrolysis products, including their quality and quantity. Therefore, it is necessary to explore the impact of temperature on the catalytic co-pyrolysis of palm kernel shell and plastic waste.

This study seeks to unravel the intricate relationship between temperature and the outcomes of co-pyrolysis, to gain a thorough understanding of the evolution of liquid products. By clarifying how temperature affects product yields and physical and chemical properties, the research aims to optimize co-pyrolysis parameters. The research not only aligns with broader sustainable development goals but also offers practical solutions to address urgent challenges related to energy security and the proliferation of plastic waste.

2. METHODS

2.1 Material

The palm kernel shell was purchased from Pandeglang, Indonesia, and sieved to 3-6 mm. The palm kernel shell was sun-dried for two days to eliminate the unbound water content. The LDPE grocery bag was employed in this investigation. It was sliced into pieces no larger than 2 cm. A palm kernel-to-plastic combination was made in a 1:1 ratio. Pyrolysis of pure palm kernel shell and plastic with calcium oxide (CaO) and natural zeolite (NZ) mixes was also carried out. CaO and NZ, which served as catalysts in pyrolysis tests, were acquired from PT. Brataco Indonesia with no physical or chemical alterations. The catalysts were mixed with the PKS in a ratio of 0.75:1. The proximal and final analyses of palm kernel shell and LDPE are reported in Table 1.

Table 1. Physical and chemical properties of the pyrolysis feedstocks [9]

Proximate analysis (% db)	Palm kernel shell	LDPE
Volatiles	74.0–76.0	99.08–99.7
Fixed carbon	22.1–23.0	0.0
Ash	1.9–3.0	0.3–0.92
Ultimate analysis (% db)		
Carbon	45.1–50.73	84.98–86.35
Hydrogen	5.1–5.97	13.58–14.94
Oxygen	40.83–49.2	0.0-0.08
Nitrogen	0.36–0.56	0.0
Sulfur	0.04–0.95	0.0–0.2
Lignocellulosic component (% db)		
Cellulose	20.8–27.7	
Hemicellulose	21.6–22.3	
Lignin	44.0–50.7	
Heating value (MJ/kg)	19.19	46.15

2.2 Experiment

The pyrolysis procedure was carried out in a batch reactor made of stainless steel and heated electrically. The reactor measures 200 mm in height and diameter. A water-cooled condenser measuring 2.1 meters was attached to the reactor's exit to keep the vapor temperature below 40 degrees Celsius. A proportional integral derivative (PID) controller was used to control the 3.0 kW electric heater, which produced the required heat. For non-catalytic pyrolysis, a total of 300 g of palm kernel shell and LDPE was placed inside the reactor, whereas for catalytic pyrolysis, 525 g of palm kernel shell, LDPE, and a catalyst were combined. The feedstock was heated from ambient to 400, 450, and 500 degrees Celsius, and this temperature was maintained until no more pyrolytic fumes exited the condenser. The bio-oil was then weighed, and any remaining char in the reactor was separated from the catalyst and weighed as well. Figure 1 shows a schematic of the experimental setup. The amount of non-condensable gas (NCG) was estimated by noting the disparity. The pyrolysis product yields were calculated using Equations 1–3.

$$Y_{liquid} = \frac{m_{liquid}}{m_{feedstock}} \times 100\% \tag{1}$$

$$Y_{wax} = \frac{m_{wax}}{m_{feedstock}} \times 100\% \tag{2}$$

$$Y_{char} = \frac{m_{char}}{m_{feedstock}} \times 100\% \tag{3}$$

$$Y_{NCG} = 100\% - (Y_{liquid} + Y_{wax} + Y_{char}) \tag{4}$$

Where Y_{liquid}, Y_{wax}, Y_{char}, and Y_{NCG} represent the yields of liquid, wax, char, and non-condesable gas, respectively; and m_{liquid}, m_{wax}, m_{char}, and $m_{feedstock}$ represent the mass of liquid, wax, char, and feedstock (palm kernel shell and plastic waste), respectively. To reduce experimental error, each experiment was replicated, and the mean data were evaluated and discussed.

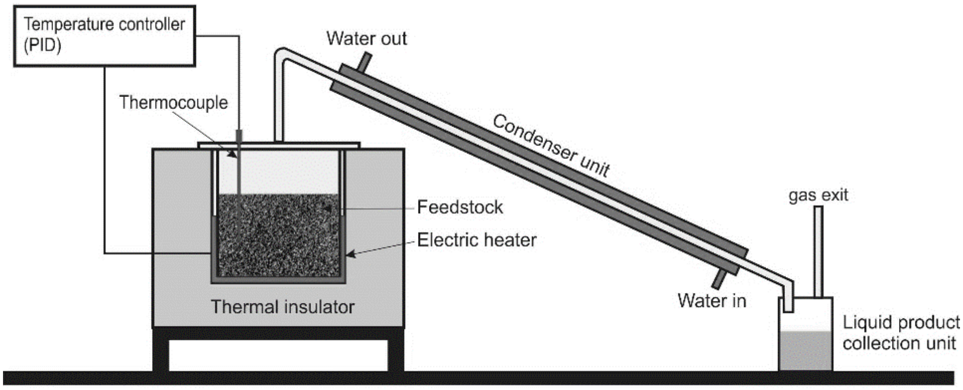

Figure 1. Schematic diagram of pyrolysis system

2.3 Product Analysis

The quantity and weight of the collected fluid outputs were examined to determine their density. The viscosity of the fluid products was measured using an NDJ 8 S viscometer from WANT Balance Instrument Co., Ltd., China. The medium for the viscosity measurements was a glass beaker filled with 75 ml of pyrolytic oil heated to 40 degrees Celsius. The rotational velocity and rotor variant were adjusted to meet the viscosity specifications. Meanwhile, a pre-adjusted digital pH meter measured their acid levels. The caloric value of the pyrolysis oil was measured using a Parr 6050 Bomb Calorimeter supplied by Parr

Instrument Company, Moline, Illinois, USA. A 0.70-0.72 ml sample of pyrolytic oil extracted from the top layer was burned in an oxygen-saturated calorimeter to determine its energy content.

A gas chromatography–mass spectrometry (GC–MS) QP2010 SHIMADZU apparatus was used to determine the chemical structure of pyrolysis oil, which varies with the catalyst used. The gas chromatography capillary column was an Agilent HP-5MS (30 m x 0.25 mm x 0.25 m), using ultra-pure helium gas as the carrier gas at a split ratio of 32.3:1. The substances were identified by comparing chromatographic peak regions and retention time data to those in the NIST library.

3. RESULTS AND DISCUSSION

Figure 2 depicts the relationship between pyrolysis temperature and product yields, which include liquid, wax, noncondensable gas, and char. The temperature rise reduced the char output from 31.25% to 13.90% while increasing the wax yield from 31.25% to 13.9%; nevertheless, the non-condensable gas tended to reach its maximal value (64.3%) at 450 ^{o}C. At that pyrolysis temperature, however, the liquid output was at its lowest point (7.55%). Higher temperatures hastened the degradation of both palm kernel shell and plastic waste, resulting in a decrease in char product as temperatures climbed. Pyrolysis temperature had a substantial impact on the pyrolysis process, influencing the quantity of product yields; at temperatures ranging from 400 ^{o}C to 450 ^{o}C, the liquid and wax products dropped as the non-condensable gas product increased. It means that at 400 ^{o}C, the pyrolysis reaction to generate liquid and wax is quicker than at 450 ^{o}C. At 500 ^{o}C, however, the pyrolysis reaction to make liquid and wax is faster, whereas the pyrolysis reaction to generate non-condensable gas takes longer. As a result, the yield of liquid and wax products increased as non-condensable gas decreased.

The liquid product produced in our investigation was lower than that of Hassan et al. [23]. This was induced by the action of catalysts, which speed up the conversion of liquid and wax into non-condensable gas. This catalyst activity was also highlighted by Nguyen et al. [24], You et al. [25], and Ahmed et al. [26]. This might be considered a disadvantage. Nonetheless, the primary purpose of catalytic pyrolysis should be to yield a high-quality organic fraction. The catalyst promoted deoxygenation processes such as dehydration, decarboxylation, and decarbonylation, as well as volatile cracking, which resulted in the generation of non-condensable gases and a drop in oil yield. Furthermore, Diels-Alder reactions happened when the catalyst used to reduce furfural was transformed into hydrocarbons [26].

During pyrolysis, biomass is converted into activated biomass, which then decomposes into tar (bio-oil), char, and non-condensable gas. Further increases in temperature accelerate the devolatilization process, reducing the char product and boosting the secondary reaction of tar to create non-condensable gases [8]. Plastic pyrolysis, on the other hand, follows a distinct pathway in which it decomposes directly into more complicated products such as non-condensable gas, liquid, wax, aromatic, and char, with temperature-controlled reaction rates. A certain temperature produces a specific dominating product. Furthermore, by raising the temperature, the wax product can change from liquid to fragrant to char [27]. Based on the pyrolysis process of biomass and plastic, the wax product is exclusively produced during plastic pyrolysis. Correlating with our findings at 450 ^{o}C, which produced the least liquid product, we may hypothesize that plastic decomposed into non-condensable gas, reducing the liquid product until it was near to the wax at that temperature.

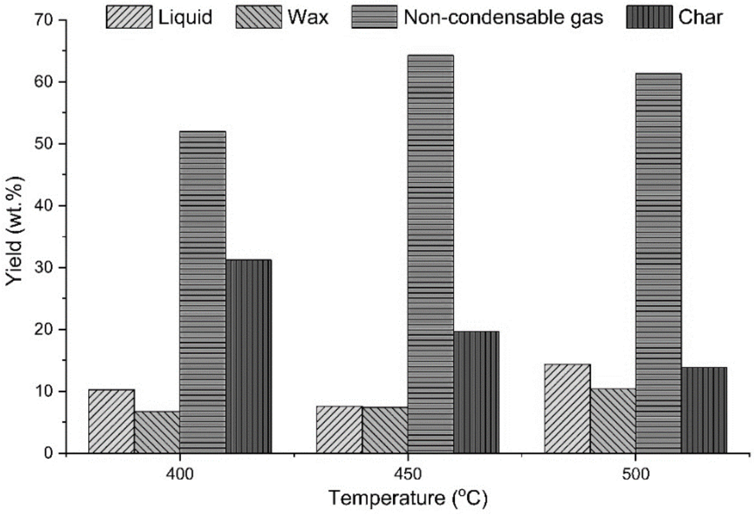

Figure 2. Pyrolysis Yields

The density and viscosity of the pyrolytic oil were affected by the pyrolysis temperature as shown in Figure 3. The maximum density of pyrolytic oil was observed at a pyrolysis temperature of 450 °C (906.7 kg/m^3); meanwhile, at below and above temperatures, the density was lower (796.7 kg/m^3 and 836.7 kg/m^3, respectively). The pyrolytic oil is a mixture of liquid and wax products from the co-pyrolysis of palm kernel shell and LDPE; thus, the higher fraction of wax in the liquid product results in a higher density. At a pyrolysis temperature of 450 °C, the ratio of liquid to wax was 1.02 (Figure 2), indicating that the mass fraction of liquid and wax products is almost equal. On the contrary, at pyrolysis temperatures of 400 and 500 °C, the liquid fraction was higher, resulting in a lower density of pyrolytic oil. A similar finding obtained by Muniyappan et al. [28] showed that the density of co-pyrolysis of biomass and plastic wastes at the ratio 1:1 ranged from 885.7 kg/m^3 to 912.8 kg/m^3, depending on the temperature and catalytic environment.

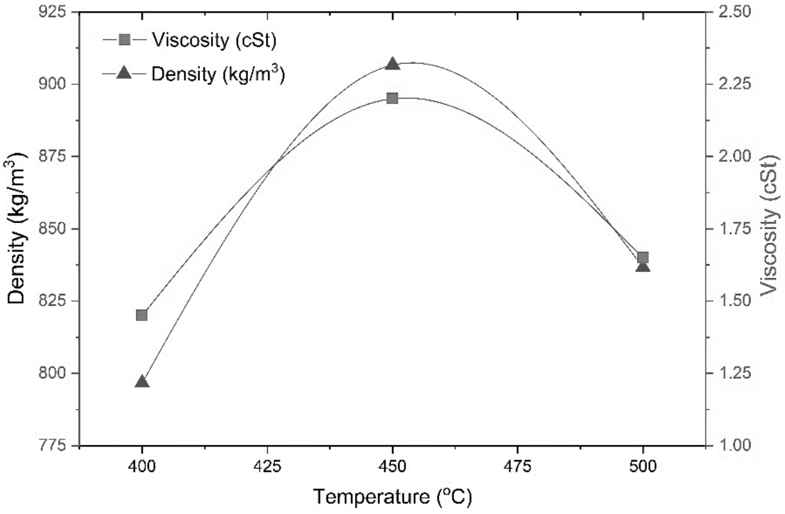

Figure 3. Density and viscosity of pyrolytic oil (liquid and wax)

The viscosity-to-temperature relationship (Figure 3) showed a similar pattern, with the pyrolytic oil's viscosity peaking at 450 °C (2.2 cSt). Aside from determining the ratio of liquid and wax fractions, pyrolysis oil viscosity has a considerable impact on the chemical makeup of the liquid product. At 450 °C, the liquid-to-wax ratio was about equal, increasing the viscosity of the pyrolytic oil product due to the huge quantity of wax. The product was mostly made up of a low-carbon chain-length species with a considerable proportion of wax, resulting in a high viscosity of pyrolysis oil. Our analysis found a lower viscosity than the literature [28], ranging from 2.45 to 3.4 cSt. Our work employed palm kernel shell, which has a lower viscosity of pyrolytic oil (1.21–1.5 cSt) than usual biomass (11 cSt) [29], [30]. This explains the observed behavior.

The heating value of the pyrolytic oil ranged from 34.5 to 37.8 MJ/kg, peaking at 450 °C (Figure 4). Our findings were consistent with the earlier study published by Hassan et al. [23] (32.20–37.78 MJ/kg). In general, the heating value of pyrolytic oil produced by the co-pyrolysis of biomass and plastic waste is higher than that of biomass pyrolysis and lower than that of plastic waste pyrolysis. The high heating value of pyrolytic oil derived from plastic trash is due to the source's chemical component, which contains relatively little oxygen [31]. The heating values of pyrolytic oil from biomass and plastic waste are around 20–25 MJ/kg and 41–45 MJ/kg, respectively [31], [32]. The heating value of pyrolytic oil is determined by its chemical makeup, especially the presence of hydrocarbons. Figure 7 depicts the pyrolysis oil heating value pattern, which revealed a similar hydrocarbon pattern. Furthermore, the increasing temperature increased the percentage of aliphatic hydrocarbons (Figure 6), which has a high H/C ratio and corresponds to a greater heating value [33].

Figure 4 also shows the acidity of the pyrolysis oil from the co-pyrolysis of palm kernel shell and LDPE plastic using calcium oxide and natural zeolite catalysts. This pH fluctuated from 5.6 to 6.2, peaking at 450 °C during pyrolysis. In general, pyrolysis oil from biomass is very acidic, with a pH of roughly 2.55 [29]. By mixing with plastic material and including the catalyst, especially calcium oxide, the acidity of the pyrolytic oil might be decreased.

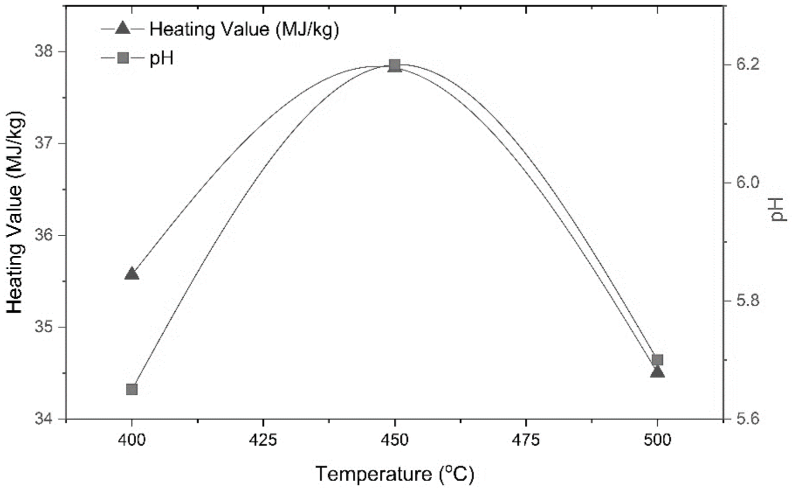

Figure 4. Caloric value and pH value of pyrolytic oil

The liquid product of the co-pyrolysis process was analyzed using the GC–MS technique, yielding a diverse spectrum of chemical compositions (Figure 5). In all, 89 to 90 chemical compounds were identified. The chemical compounds were classified according to their chemical groups (Figures 6 and 7) and carbon chain lengths (Figure 8).

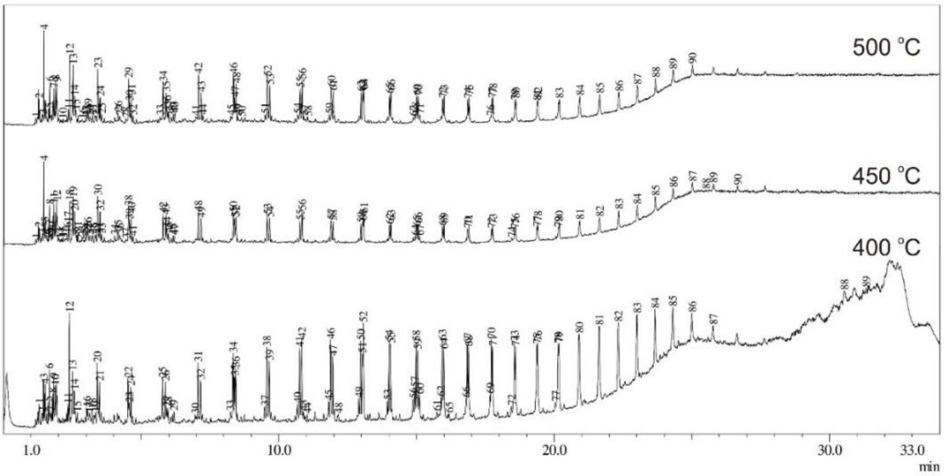

Figure 5. GCMS results

Figure 6 depicts the relationship between pyrolysis temperature and the chemical makeup of the liquid product, which includes aliphatics, cyclists, aromatics, polycyclic aromatic hydrocarbons (PAH), alcohols, ketones, phenols, and others. The increase in temperature raised the proportion of aliphatic hydrocarbons (from 61.35% to 70.28%), PAH (from 0.86% to 4.63%), and phenols (from 2.29 to 3.10%) while decreasing the fractions of cyclic hydrocarbons (from 5.61% to 0.92%), alcohols (21.94% to 12.29%), and ketones (from 4.83% to 3.40%). Meanwhile, aromatic hydrocarbons reached their peak at 450 °C (8.96%) during pyrolysis. It implies that alcohol and ketone molecules are converted into aliphatic hydrocarbons by releasing oxygen, whereas cyclic hydrocarbons develop into PAHs by structural rearrangements.

Similar chemical group compositions of LDPE pyrolysis have also been reported in the literature. Chaudhary et al. [34] discovered that the pyrolytic oil of LDPE contains aliphatic, aromatic, and phenolic groups with hydrocarbon chain lengths ranging from C_5 to C_{35}. Meanwhile, Koç and Bilgesü [35] found that the chemical groups in LDPE pyrolysis oil included aliphatics, cyclics, alcohols, and carbonyls. By including a catalyst (MoO_3 and silica mixture), the chemical compositions altered, increasing the proportion of aliphatics while decreasing cyclics, alcohols, and carbonyls. The total quantity of aliphatics, cyclics, alcohols, and carbonyls derived from catalytic LDPE pyrolysis were 61.54%, 8.74%, and 26.53%, respectively, which agrees with our findings.

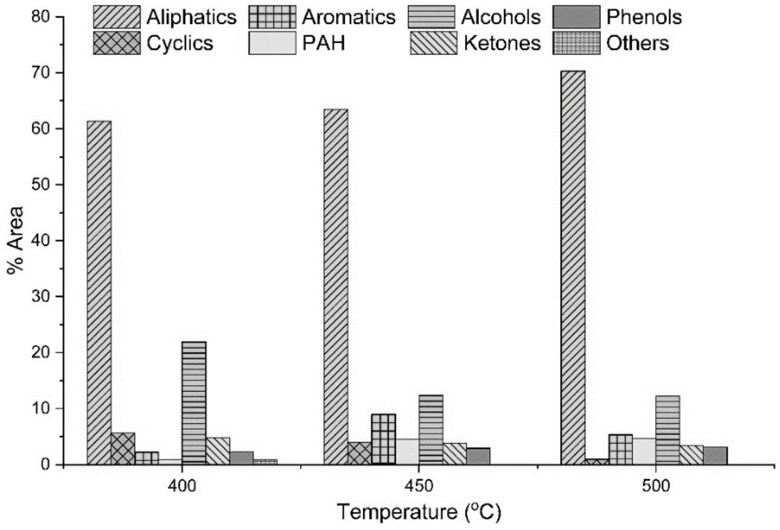

Figure 6. Chemical compound species of pyrolytic oil

The liquid byproduct of pyrolysis from plastic material contains a substantial quantity of hydrocarbons, whereas biomass pyrolysis produces a large number of oxygenated chemicals. In theory, mixing plastic and biomass in the same ratio yields the same percentage of hydrocarbons and oxygenated chemicals. However, mixing palm kernel shell with LDPE during pyrolysis increased the amount of hydrocarbons from 70.10% to 80.06% (Figure 7). Because waste plastic has a greater H/C ratio, it creates more hydrogen free radicals during pyrolysis. Concurrently, free radicals of hydrogen created from waste plastic during co-pyrolysis participate in the hydrogenation process [36]. In this example, hydrogen free radicals interacted with oxygenated molecules, resulting in lower alcohol and ketone compounds and increased hydrocarbon synthesis. In other words, free radicals of hydrogen were formed during the pyrolysis of LDPE, which interacted with free radicals and oxygenates in the palm kernel shell, resulting in hydrogenation, which increased their conversion into hydrocarbons while decreasing the oxygenates. The proportion of hydrocarbons increased with temperature, showing that at higher temperatures, LDPE released more free radicals of hydrogen to produce hydrocarbons.

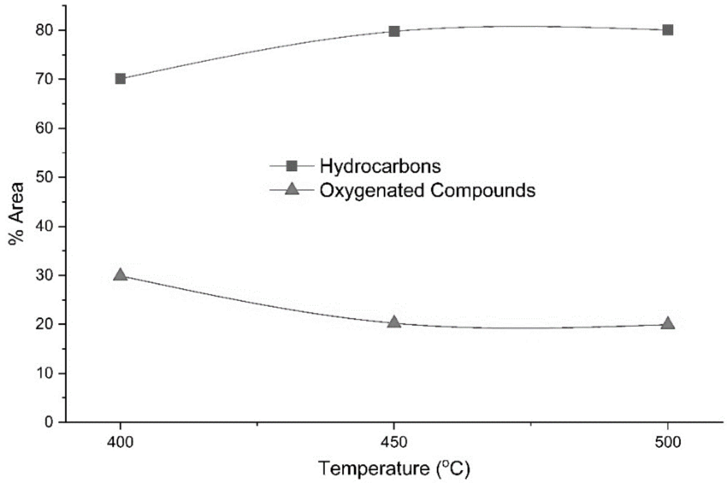

Figure 7. Total hydrocarbons and oxygenated compounds in liquid product

Furthermore, calcium oxide accelerates the deoxygenation process by decarboxylation and decarbonylation processes, whereas natural zeolite neutralizes the oxygen content of pyrolytic oil [37], [38]. As a result, introducing catalysts in the pyrolysis process hastened the removal of oxygenated molecules while increasing the hydrocarbon percentage. Furthermore, the elimination of oxygenated compounds reduced the amount of liquid and wax products by increasing the non-condensable gas (Figure 2).

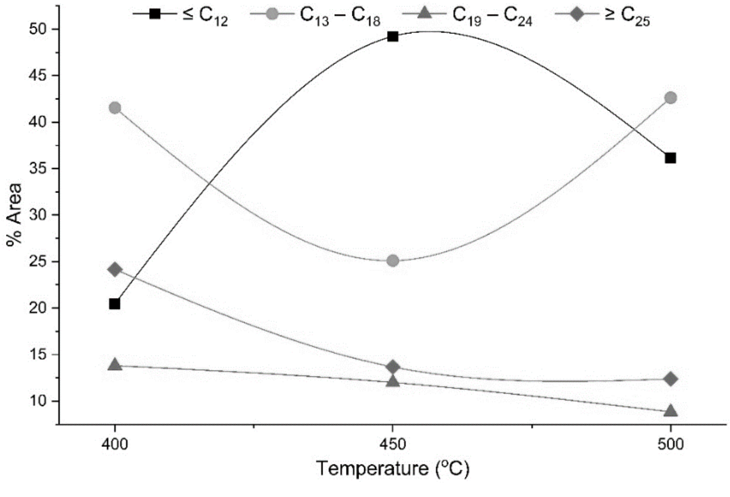

Figure 8. Carbon chain length in liquid product

Figure 8 displays the relationship between pyrolysis temperature and the carbon chain length of the liquid product. As temperature increased, long chain-length hydrocarbons, C_{19}–C_{24} and ≥C_{25}, decreased from 13.81% to 8.85%, and from 24.17% to 12.37%, respectively. Short chain-length hydrocarbons (≤C_{12})

peaked at 450 ^{o}C (49.23%), whereas medium chain length reached a minimum of 25.09% at the same temperature. In general, higher temperatures enhanced the degree of feedstock devolatilization and pyrolytic vapor cracking in lighter compounds. Increasing the temperature from 400 ^{o}C to 450 ^{o}C reduced the quantity of C_{13}–C_{18}, C_{19}–C_{24}, and $\geq C_{25}$. The longer chain-length hydrocarbons were decreased as the temperature increased owing to pyrolysis vapor cracking. Conversely, when C_{13}–C_{18} increased, the fraction of $\leq C_{12}$ decreased. It was most likely produced by the natural zeolite's activity in the oligomerization reaction. This reaction lengthens the hydrocarbon chain length through polymerization [39]. As a result, the number of short-chain hydrocarbons dropped as the number of medium-chain hydrocarbons increased.

4. CONCLUSION

The catalytic co-pyrolysis of palm kernel shell was carried out in a fixed bed reactor at varying temperatures. At a pyrolysis temperature of 500 ^{o}C, the liquid and wax products produced the highest yields (14.35% and 10.40%, respectively). The density and viscosity of the pyrolytic oil followed a similar trend, with the maximum values at 450 ^{o}C (906 kg/m^3 and 2.20 cSt, respectively). Similarly, the heating value and acidity obtained their greatest values at a pyrolysis temperature of 450 ^{o}C (37.82 MJ/kg and pH 6.20, respectively). The co-pyrolysis of palm kernel shell and plastic waste produced a diverse spectrum of chemical compounds in the liquid product. As the temperature rose, the percentage of aliphatic hydrocarbons, polycyclic aromatic hydrocarbons, and phenols increased while cyclic hydrocarbons, alcohols, and ketones decreased. Furthermore, increasing the temperature increased the overall number of hydrocabons while decreasing the amount of oxygenated compounds. The increasing temperature reduced the long chain length hydrocarbons while fluctuating the short and medium chain length hydrocarbons. The catalyst enhanced the non-condensable gas product by reducing the liquid and wax. Moreover, the catalyst also improved the formation of aliphatics by reducing cyclics, alcohols, and oxygenated compounds. This laboratory-scale work might serve as a valuable starting point for future research, particularly into the catalytic pyrolysis mechanism at wide range temperatures and natural catalyst deactivation during pyrolysis.

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