# Enhancing Pyrolysis Oil From Landfill Waste Plastic With Industrial Waste Catalyst

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This study investigates the production of catalytic pyrolysis oil from 10 -year-old landfilled plastic waste in Nonthaburi Province. The study performs pyrolysis of plastic waste using calcined fluid catalytic cracking (FCC) and bottom ash (BA) catalysts, focusing on their potential as alternative fuels. A fixed bed reactor operates at different temperatures 350 - 500 °C, with optimal results achieved at 450 °C. The maximum oil yield was achieved at 500 °C (47.00 %wt.) and at 450 °C with calcined FCC (42.64 %wt.). The maximum heating value reached 45.77 MJ/kg using the BA catalyst. Chemical composition analysis via FT-IR and GC-MS revealed hydrocarbons, primarily alkenes and alkanes. The presence of aromatics and hydrocarbons ($C_5 - C_{11}$ and $C_{12} - C_{20}$) increased with catalyst use, approaching petroleum fuel properties. The most prevalent composition consisted of hydrocarbons in the $C_5 - C_{20}$ range, with a peak area of 84.65 % obtained from pyrolysis at 450 °C using the calcined FCC catalyst. Furthermore, the gas products are analyzed using a gas analyzer. High levels of $H_2$ and low levels of $CO_2$ and $SO_2$ emissions indicate that the process can produce an alternative fuel while generating fewer greenhouse gases. This research is consistent with the circular economy's concepts, promoting sustainability and utilized resource efficiency.

**Keywords:** Pyrolysis, Plastic waste, Waste to energy, FCC catalyst, Landfill
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## 1. Introduction

Plastic waste management is a significant challenge in Thailand, driven by industrial and household waste contributions. Inefficient practices have made Thailand a major source of plastic waste leakage into oceans, threatening marine ecosystems [1]. Effective strategies focusing on reducing, reusing, and recycling (3Rs) are crucial, alongside energy recovery methods like pyrolysis [2, 3]. Catalytic pyrolysis enhances efficiency and yield, making it a promising approach for converting landfill plastics into usable fuels while addressing environmental concerns associated with plastic waste [4, 5]. Pyrolysis is advantageous for utilizing landfill plastics typically consisting of discarded materials such as polyethylene (PE), polypropylene (PP), and polystyrene (PS). These plastics are pyrolyzed to high temperatures without oxygen, leading to their breakdown into valuable byproducts like pyrolysis oil or fuel [6, 7]. The efficiency and yield of this process can be significantly enhanced through catalytic pyrolysis.

The cracking of long-chain polymer molecules into smaller hydrocarbons can be effectively facilitated by catalysts derived from industrial byproducts, such as those from coal-fired power plants and petroleum refineries [8]. The combination of these catalysts allows for more controlled and efficient pyrolysis, leading to the production of liquid hydrocarbon products like "pyrolysis oil" or "pyrofuel," which exhibit properties like traditional liquid fuels. These fuels can potentially be integrated into various commercial diesel fuels with some modifications to meet industry standards.

Fly ash and bottom ash are abundant waste byproducts from coal combustion in power plants. Fly ash, which contains oxides like silicon dioxide ($SiO_2$), aluminum oxide ($Al_2O_3$), and iron oxide ($Fe_2O_3$), is characterized by a high surface area and porosity, making it essential for improving the pyrolysis process [9]. These characteristics make it an effective catalyst for breaking down complex plastic polymers into valuable hydrocarbons. Similarly, bottom ash, though denser and less porous, also plays a role in promoting the degradation of polymers during pyrolysis. Both types of ash can be activated or calcined at high temperatures to further improve their catalytic performance. Fluid catalytic cracking (FCC) catalysts are essential in refining, and converting heavy hydrocarbons into lighter, valuable products like gasoline and olefins. These catalysts are mainly composed of zeolites, matrix materials, clay, and various additives. Zeolites, specifically Y-type zeolites, provide the acidity and thermal stability needed for efficient cracking. The matrix supports the catalyst and aids in pre-cracking larger molecules, while clay enhances the catalyst's strength, helping it withstand the abrasive conditions of the FCC unit [8, 10].

In previous research, a study on the catalytic pyrolysis of PE plastic bags using a burner powered by liquefied petroleum gas (LPG) found that temperatures between 300 and 450 °C produced a 52.6 % oil yield [11]. In contrast, a study on non-catalyst traditional slow pyrolysis using a distillation technique and an LPG burner under similar conditions yielded 46 % oil at temperatures between 350 and 450 °C [12]. In addition, the application of calcined fly ash as a catalyst in the pyrolysis of PE to generate aromatic hydrocarbons was investigated. Their findings revealed that the BTEX content in the resulting fuel oil rose to 22.12 wt% when pyrolysis was conducted at 700 °C, using fly ash calcined at 800 °C as the catalyst [9].

This study aims to explore the feasibility of producing oil fuels from plastic waste through catalytic pyrolysis, utilizing FCC and bottom ash as catalysts. Investigating this potential is, therefore, of paramount importance, as it could pave the way for more sustainable and circular economic models that prioritize both environmental protection and energy efficiency.

## 2. Materials and methods

### 2.1. Materials

A mass of 50 kg of plastic waste was sorted through a mechanical separation process at the Nonthaburi landfill. Subsequently, the plastic waste was collected and subjected to screening in order to eliminate smaller particulate matter. The waste was then reduced into smaller fragments with dimensions approximating 6.45 $cm^2$ $(2.54 \times 2.54$ cm$)$ to facilitate its introduction into the reactor and receive heat more uniformly [13]. The plastic waste sample was investigated the proximate analysis following the ASTM standard. Volatile organic compound (VOC) content was measured following the ASTM E872 standard, while moisture content was assessed using ASTM E871. The fixed carbon content was also determined with ASTM E872, and ash content was evaluated according to ASTM D1102.

Bottom ash (BA) was obtained from Nonthaburi's power plants, while the FCC was obtained from the petrochemical industry. The catalysts were pretreated by calcination at 600 °C for 2 h in a high-temperature furnace in an atmospheric environment. The catalyst's surface was examined using a field emission scanning electron microscope (FE-SEM).

### 2.2. Pyrolysis process of plastic waste

A total of 0.5 kg of prepared plastic waste was placed in the reactor. Pyrolysis was conducted at temperatures of 350, 400, 450, and 500 °C, using LPG as the heat source. The pyrolysis process utilizing LPG gas was subject to temperature regulation. Although no automatic control system was present, the researcher manually adjusted the gas volume to maintain consistency across all experimental trials. Each test exhibited a gradual increase in temperature at a uniform rate, with an average heating rate of 4-5 °C/min. Once the designated temperature was reached, an automated gas cut-off mechanism engaged to maintain the temperature within a threshold error of no more than $\pm$ 5 °C.

The pyrolysis temperature was monitored using a K-type thermocouple positioned at the mid-section of the reactor. The reaction was maintained for 2 hours to ensure complete pyrolysis. Through a comprehensive review of the literature, it was found that most studies utilized a slow pyrolysis process with reaction durations ranging from 1 to 2 hours in fixed-bed reactors [8, 14, 15]. These studies, particularly on polyethylene (PE) pyrolysis, reported that longer residence times tend to result in reduced hydrocarbon yields [16]. In this study, the primary feedstock was plastic bag waste, which predominantly consists of low-density polyethylene (LDPE). The FTIR analysis of the plastic waste confirmed characteristic spectra consistent with LDPE, validating the composition of the feedstock. To further justify the selected reaction time in this work, gas concentration profiles were continuously monitored during the pyrolysis process. The observed gradual decline in gas concentration over time indicates the depletion of volatile products, thereby confirming the completion of the pyrolysis reaction. Furthermore, consider the energy input required-specifically the consumption of LPG gas required to maintain the reactor temperature. Therefore, the chosen reaction duration in this study is deemed sufficient for the effective degradation of plastic waste into pyrolysis oil while maintaining energy efficiency.

During the pyrolysis trials, gases produced from the pyrolysis process passed through a cyclone and into a condenser, where they were condensed and separated into pyrolysis oil. Moreover, the gas product was analyzed using a flue gas analyzer, and the temperature was recorded every 5 minutes. Gaseous emissions were continuously monitored in real time using a Testo 350 gas analyzer to examine the gas composition, which included $CO, CO_2, NO_x, SO_2$, and $H_2$.

In catalytic trials, four types of catalysts of catalysts were used: non-calcined and calcined BA and FCC, with the latter calcined at 600 °C, to investigate their effect on the distribution of pyrolysis products. The catalyst was placed in a catalyst tube inside the pyrolysis reactor, with the weight ratio maintained at 5 wt%. The catalyst tube contained a small screen and fine quartz wool that supported the catalyst, preventing it from falling or mixing with the plastic during the reaction. Catalytic pyrolysis was performed at 450 °C. Pyrolysis gas vapor flowed through the catalyst tube, underwent catalysis, and then exited through the gas outlet pipe. The produced gas exited the reactor from the upper section, while solid products were collected in the bottom section.

The scheme of pyrolysis process using fixed-bed reactor as shown in Fig. 1. The chemical properties of the pyrolysis oil and commercial diesel were analyzed using FT-IR to identify the functional groups and chemical bonds within the range of 600 to $4,000$ cm$^{-1}$. Furthermore, the organic compounds present in the pyrolysis oil were identified and quantified through GC-MS analysis. The heating value of the produced pyrolysis oil and commercial diesel was determined using a bomb calorimeter.

The pyrolyzed plastic waste (char) and oil fuel produced by the pyrolysis reactor were weighed and recorded. The weight of the produced oil fuel and char can be calculated

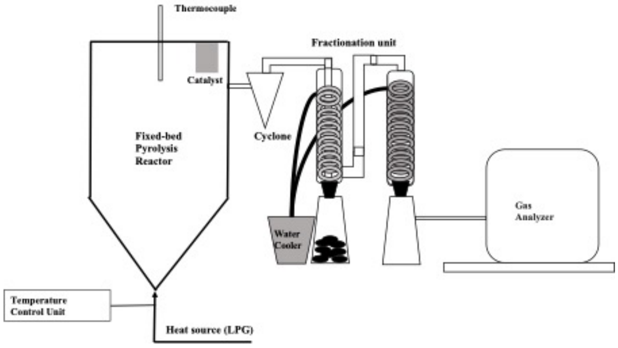


**Fig. 1.** Schematic diagram of pyrolysis process

using the equation below:

$$\text{Percentage of liquid product} = \frac{\text{mass of liquid product}}{\text{mass of fed plastic waste}} \times 100 \quad (1)$$

### 2.3. Statistical analysis

The calorific values and pyrolysis yield, which includes pyrolysis oil, gas, and char, were analyzed using SPSS 28.0 software (IBM, Chicago, IL, USA). The significant differences in the mean of the parameters were identified using one-way ANOVA and the least significant difference (LSD) test. Differences were statistically significant at $p < 0.05$.

## 3. Result and discussion

### 3.1. Characteristics of raw material

#### *3.1.1. Proximate analysis of plastic waste*

These properties are critical for determining the suitability of plastic waste as a feedstock for pyrolysis and ensuring consistent fuel production. The analysis of volatile organic compounds revealed that the plastic waste predominantly consisted of volatile matte, which accounted for between 96.31 % and 99.12 % by weight. Notably, plastic from landfills with a remarkable 99.12% volatility showed the largest release of volatile after being sieved into smaller pieces. These samples are particularly useful for energy recovery because of their high volatility, which is an indication of the significant amount of organic chemicals that may be rapidly transformed into fuel during the pyrolysis process. The study also observed significant variations in ash content, which ranged widely among the samples. The highest ash content, reaching 26.21 %, was found in non-sieved plastic waste extracted from 10-year-old landfills. The elevated ash content in these samples can be attributed to residual soil-like contaminants and other inorganic materials that have accumulated over time in the landfill. High ash content can pose challenges during pyrolysis, as it may lead to residue build-up in reactors, reducing efficiency and complicating the refining process. Therefore, understanding and managing ash content is crucial for optimizing the pyrolysis process and ensuring high-quality fuel output.

The separated plastic samples showed comparatively low moisture content values, ranging from 0.88 % to 3.69 % by weight. The screening and separation procedures that successfully eliminate biodegradable organic components and other moisture-retaining elements from plastic waste are probably the cause of the low moisture content. Consequently, pyrolysis benefits from low moisture. Additionally, removing moisture reduces the need for additional drying stages, which streamlines the pre-treatment step and increases energy yields [17]. Detailed results, including specific data for each property, are summarized in Table 2.

The composition of solid waste derived from the sieved ten-year-old landfills' refuse-derived fuel (RDF) reveals a substantial proportion of plastic waste amounting to 78.16 %. The chemical analysis by ultimate analysis plays a pivotal role in accurately estimating the material balance. Consequently, the carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) constituents of the samples were analyzed utilizing the Truspec Leco CHNS-932 analyzer, with results being presented on a dry weight basis. These findings from the previous research conducted by Rahothan et al. (2023), which investigated RDF production from landfilled waste as a renewable fuel source in Nonthaburi. The study disclosed that the carbon and hydrogen contents within the landfilled waste (LW) were measured at 66.24 wt% and 7.22 wt%, respectively. The elevated carbon percentage can be attributed to the substantial plastic content present. Furthermore, the nitrogen, sulfur, and oxygen contents within the LW were quantified at 0.47, 0.30, and 8.37 wt%, respectively [13].

The analyzed samples of plastic waste, including landfill plastic waste, newly produced plastic bags, and low-density polyethylene (LDPE) pellets, were evaluated using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy, with a particular focus on landfill plastic waste. The resulting plastic waste produced a distinct FTIR spectrum characterized by absorption bands at 2914, 2849, and 1462 $\mathrm{cm}^{-1}$, indicating C-H stretching and bending. Notably, a strong absorption band at 1015 $\mathrm{cm}^{-1}$, corresponding to $C-O$ stretching, was observed only in landfill plastic waste and was absent in newly produced plastic bags. Moreover, the LDPE pellet exhibited prominent absorption bands at the same wavelengths as the landfill plastic waste, confirming that these plastic wastes are of the LDPE type [18].

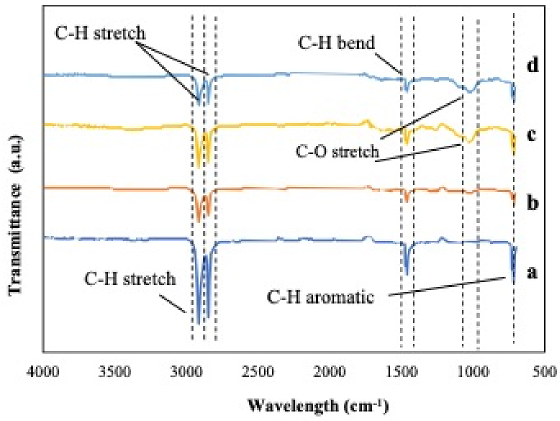


**Fig. 2.** FTIR spectra of a) plastic bag (new), b) LDPE (pellet) c) landfilled plastic waste (LF-1) and d) landfilled plastic waste (LF-2)

#### *3.1.2. Surface analysis by using scanning electron microscopy*

The microstructures of the four types of catalysts were performed at various magnifications. This analysis is used to investigate the scanning of the catalyst sample and surface characteristics with a scanning electron microscope with a FE-SEM, model SU 5000 as shown in Fig. 3. The FE-SEM analysis of the FCC catalysts showed that the raw FCC catalysts appeared as irregular lumps with a notably rough texture. The particles varied in size from 30 $\mu$m to 100 $\mu$m and were clustered into thick, sheet-like formations. When these catalysts were subjected to heating at 600 °C, their surface had a smoother outer surface.

However, there was a noticeable increase in the number and size of large pores on the surface. Additionally, with rising firing temperatures, the surface texture appeared somewhat smoother, suggesting a partial melting effect. The BA-raw catalysts have rough surfaces, lumpy textures, and thick, huge sheets. When the BA catalysts were calcined at 600 °C, their structure became increasingly porous. This contrasts with FCC catalysts, which are generally finer and less agglomerated. The larger and lumpier nature of the BA catalysts is due to their higher ash content compared to FCC catalysts. The elevated temperatures lead to a significant transformation in the catalyst's microstructure, enhancing the development of larger pores and altering the surface characteristics.

#### *3.1.3. Chemical composition of FCC and BA catalysts*

The experimental results from the EDS chemical composition analysis of the catalyst were obtained using a Field Emission Scanning Electron Microscope (FE-SEM) at a magnification of 5000x. The chemical composition of the cata-

**Table 1.** Proportions by weight of all elements in FCC and BA catalyst by XRF

| Component | Catalysts type | | Component | Catalysts type | |
|---|---|---|---|---|---|
| (%mass) | Bottom ash | Spent FCC | (%mass) | Bottom ash | Spent FCC |
| Si | 19.0181 | 19.4673 | Cr | 0.0388 | 0.0699 |
| Ca | 11.6018 | 0.5788 | Sr | 0.03 | 0.0077 |
| Al | 7.2193 | 20.0368 | Zr | 0.0294 | 0.0142 |
| Fe | 6.6241 | 0.8754 | Rb | 0.018 | |
| CI | 2.0806 | - | Sn | 0.0175 | 0.0175 |
| K | 1.8798 | 0.0699 | Ni | 0.0143 | 0.4036 |
| S | 1.2041 | 0.5839 | Br | 0.0044 | 0.0044 |
| P | 0.9687 | 0.3151 | As | | 0.0026 |
| Mg | 0.8352 | 2.4614 | Ce | | 0.33 |
| Ti | 0.7161 | 0.8989 | Co | | 0.011 |
| Na | 0.5881 | 0.2097 | Ga | | 0.0079 |
| Zn | 0.3121 | 0.0248 | La | | 4.1949 |
| Cu | 0.1793 | 0.0052 | Nb | | 0.0045 |
| Mn | 0.126 | 0.5788 | Sb | | 0.037 |
| Ba | 0.0727 | 0.0727 | V | | 0.7867 |
| Pb | 0.0671 | 0.0671 | Y | | 0.0133 |
| | | | LOI | 5.9 | 2.9 |

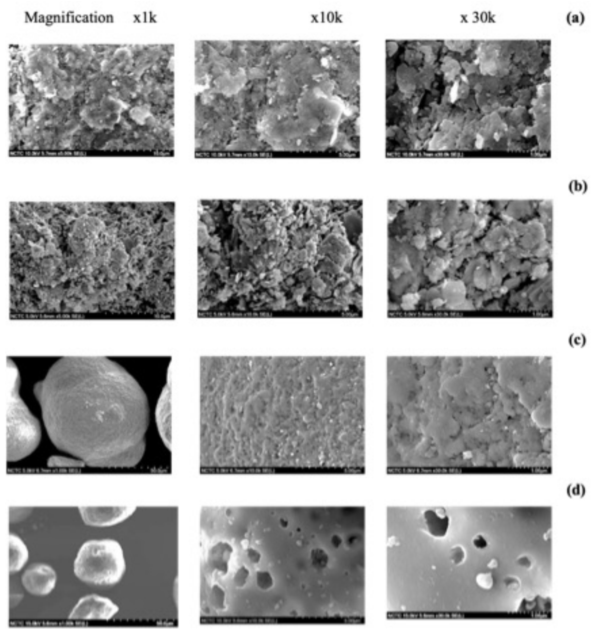


**Fig. 3.** Morphologies of catalysts by SEM analysis (a) BA (b) Calcined BA(c) FCC (d) Calcined FCC

lysts are summarized in Table 3. The elemental composition of the FCC catalysts is primarily characterized by high quantities of aluminum (20.7 %) and oxygen (49.0 %). The secondary elements present include silicon at 17.3 % and carbon at 7.3 %. Additionally, trace amounts of calcium, zinc, magnesium, titanium, sodium, and phosphorus are present, each contributing less than 1-2 % to the overall composition.

After the thermal treatment of the FCC catalyst to obtain calcined FCC, the carbon deposit on the FCC catalyst surface from coke formation slightly decreased to 6.1 %. the elemental composition remains largely consistent with the original FCC catalyst, although there are slight variations in the percentages of these elements. In comparison, the BA and calcined BA catalysts exhibit a different elemental profile. Notably, choline, potassium, and chromium are present in these BA samples but are absent in the FCC samples. Additionally, the BA catalysts show a higher carbon content, and a lower aluminum content compared to the FCC catalysts. This indicates that the BA catalysts have a different composition and possibly different properties or behaviors in their applications compared to the FCC catalysts. According to earlier studies, bottom ash has a surface area of less than 20 $m^2/g$, whereas FCC reaction numbers have a surface area in range of 80-147 $m^2/g$ [10, 19–22]. This could lead to varying catalyst performance to improve the pyrolysis oil quality.

The chemical compositions of the two catalysts, bottom ash (BA) and spent FCC catalyst, are presented in Table 1. The XRF spectrum analysis of BA and spent FCC catalysts revealed a high content of $SiO_2$ (19.01-19.46 wt.%) and $Al_2O_3$ (7.21-20.03 wt.%). These compositions were also observed in the XRF spectrum of zeolite, suggesting that it contains highly acidic active sites capable of enhancing dehydrogenation and hydrocracking reactions during the pyrolysis of plastic waste [23]. Additionally, various alkali metals (e.g., Ca, Mg, and K) and transition metals (e.g., Fe, Zn, Cu) were detected in the XRF spectrum of bottom ash and FCC, indicating that the bottom ash catalyst possesses diverse physicochemical properties. On the other hand, the spent FCC catalyst exhibited a high concentration of heavy metals such as Mn , Pb, Cr, and Ni, which is attributed to its prior use in the catalytic cracking of petrochemicals.

The XRD patterns of bottom ash and FCC are shown in Fig. 4. Three distinguished peaks were observed at $2\theta$ values between 10° and 80°, specifically at 20.98°, 26.86°, and 50.38°, corresponding to the $SiO_2$ phase, while peaks at 28.02° and 39.14° corresponded to $CaCO_3$. The characteristic peaks of FCC at $2\theta$ values of 20.98° and 26.58° corresponded to $SiO_2$. Additionally, the major crystalline phases of FCC were observed at $2\theta$ values of 6.4°, 10.36°, and 12.14°, which were identified as Faujasite ($Na_2Al_2Si_4O_{12} \cdot 8\,(H_2O)$). The minor peaks of FCC were observed at $2\theta$ values of 15.94° and 24.12°, which were identified as mullite ($Al_{4.52}Si_{1.48}O_{9.74}$). These characteristic peaks indicated the formation of the FCC zeolite phase, which was further supported by EDX analysis. Meanwhile, both the crystalline and amorphous structures of bottom ash were also observed, as shown in Table 3.

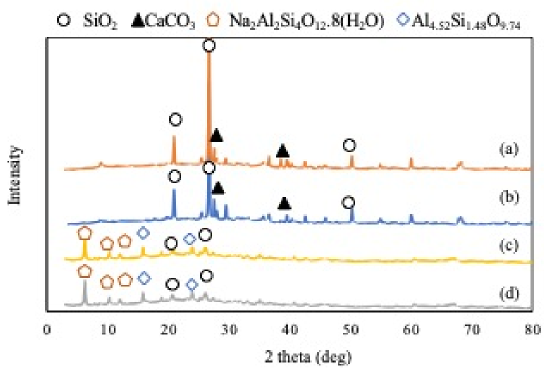


**Fig. 4.** X-ray diffractograms of catalysts (a) BA 600 (b) BA raw (c) FCC 600 and (d) spent FCC

### 3.2. Pyrolysis products from pyrolysis process

The pyrolysis process applied to sieve small-size plastic waste produced three main products: solid (char), liquid (pyrolysis oil), and gas. To regulate the heating rate, the gas source (LPG) was manually adjusted. The heating rate of the pyrolysis process ranged from 4.33 to 5.21 °C/min. The heating rate was measured every 5 minutes over a total duration of 120 minutes and is shown in Fig. 10. The results indicate that the rising temperature was consistent, allowing effective control of plastic waste degradation. The highest heating rate was observed at a pyrolysis temperature of 350 °C, while the slowest heating rate was observed at 500 °C due to restrictions imposed by the LPG valve for safety reasons.

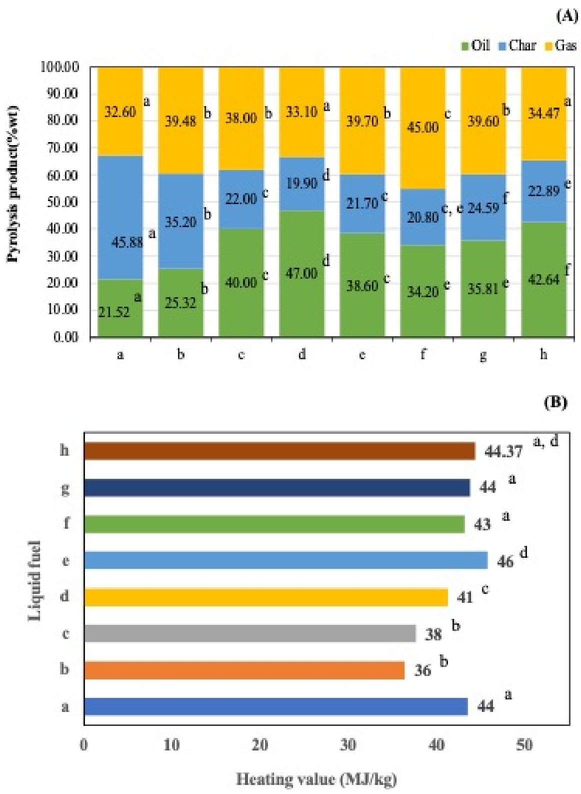


**Fig. 5.** (A) Pyrolysis yield products and (B) heating value of (a) Py-oil 350 °C, (b) Py-oil 400 °C, (c) Py-oil 450 °C, (d) Py-oil 500 °C, (e) Py-oil 450 °C with BA , (f) Py-oil 450 °C with calcined BA , (g) Py-oil 450 °C with FCC, and (h) Py-oil 450 °C with calcined FCC

This study focused on the vapor products (volatiles), which were subsequently condensed into pyrolysis oil. The yield of pyrolysis oil varied significantly ($p < 0.05$), ranging from 21.52 % to 47.00 % by weight, with the highest oil yield achieved at a pyrolysis temperature of 500 °C, as shown in Fig. 6. Pyrolysis temperatures lower than 450 °C (e.g., 350 and 400 °C) may not provide enough thermal energy for complete depolymerization, leading to lower oil yields and higher solid residue. The result indicated that at 450 °C under non-catalytic conditions shows a noticeably higher oil yield compared to other temperatures. This trend can be attributed to the fact that 450 °C is an optimal temperature range for thermal degradation of long-chain polymer molecules. At this temperature, sufficient energy is provided to break down the polymer chains into smaller hydrocarbon molecules, which are more likely to remain in the liquid phase. Although pyrolysis at 500 °C resulted in a higher oil yield compared to 450 °C, the increase was only approximately 7 wt%. This higher temperature also led to a significant rise in gas formation and required considerably more energy input. Notably, the amount of LPG gas used as the external energy source increased by over 50 % when the pyrolysis temperature was raised from 450 °C to 500 °C. Therefore, despite the marginal improvement in oil yield, operating at 500 °C may not be economically or energetically favorable for commercial-scale applications. Consequently, the elevated oil yield at 450 °C indicates a favorable balance between depolymerization and secondary cracking, making it a critical temperature point for maximizing liquid fuel production and liquid fuel quality in non-catalytic pyrolysis. Notably, the high proportion of pyrolysis oil was achieved at 500 °C (47.00 %wt) and 450 °C (42.64 %wt) using calcined FCC as a catalyst. In addition, 450 °C with FCC and with bottom ash did not show a significant difference ($p < 0.05$). The substantial yield of pyrolysis oil under these conditions is attributed to the catalytic effects of calcined FCC, which efficiently facilitates the breakdown of long-chain polymer molecules into valuable liquid hydrocarbons.

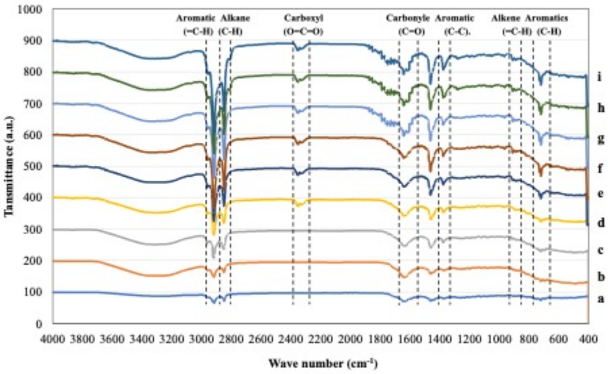


**Fig. 6.** FTIR spectra of different pyrolysis oil (a) Py-oil 350 °C (b) Py-oil 400 °C (c) Py-oil 450 °C (d) Py-oil 500 °C (e) Py-oil 450 °C with BA (f) Py-oil 450 °C with calcined BA (g) Py-oil 450 °C with FCC (h) Py-oil 450 °C with calcined FCC (i) Commercial Diesel

On the other hand, the procedure produced the largest amount of pyrolysis gas, reaching 40.00 % by weight at 450 °C with bottom ash. This finding suggests that bottom ash tends to encourage gas formation over liquid oil more significantly than FCC. The composition and surface properties of bottom ash likely enhance the cracking reactions that lead to the production of smaller gaseous molecules. Additionally, at a higher temperature of 400 °C without any catalyst, the pyrolysis process produced the highest proportion of gas, amounting to 33.10-39.48 %wt. This finding highlights that higher temperatures, coupled with BA catalysts at 450 °C, primarily result in the release of volatiles in gaseous form rather than condensation into liquid oil. These findings are consistent with and build upon previous research. For instance, Gaurh and Pramanik [9] demonstrated that catalytic pyrolysis of polyethylene using FCC as a low-cost catalyst resulted in significant yields of benzene, toluene, ethyl benzene, and xylene (BTEX) compounds, with optimal results observed at temperatures around 450 °C. Their results suggest that higher temperatures favor the formation of liquid hydrocarbons, aligning with the optimal temperature of 450 °C for pyrolysis oil production found in this study. Miandad et al. [24] also investigated the effect of different plastic waste types on pyrolysis liquid oil yields and reported that increasing temperatures generally enhance liquid yields, although specific yields varied based on the type of plastic and experimental conditions. Their findings support the notion that temperatures around 450 °C are effective for maximizing liquid production, consistent with the results of this research.

These results corresponded well with Prurapark et al. [25] who explored the impact of temperature on pyrolysis oil produced from HDPE and PET in a mobile pyrolysis plant. Their study confirmed that temperatures near 450 °C are optimal for achieving the highest yields of pyrolysis oil, aligning with the findings of this study and reinforcing the importance of maintaining precise temperature control during pyrolysis. The distribution of pyrolysis products at different pyrolysis conditions is shown in Fig. 5A. The values with different superscript letters in a column are significantly different ($p < 0.05$).

The alignment with previous research highlights the 450 °C temperature threshold for effective liquid fuel production and emphasizes the need for further investigation into catalyst properties and reaction conditions to maximize the efficiency and economic viability of pyrolysis processes.

### 3.3. Pyrolysis oil characterization

#### *3.3.1. The calorific value of pyrolysis oil*

The heating value of the pyrolysis oil varied significantly across different experimental conditions, reflecting the impact of both temperature and catalyst type on the energy content of the oil (Fig. 6B). Conversely, pyrolysis conducted at a lower temperature range of 350 to 500 °C without a catalyst yielded pyrolysis oil with a heating value ranging from 36.38 to 43.16 MJ/kg. The lowest heating value was observed in the pyrolysis process conducted at 400 °C, highlighting the critical role of temperature and catalyst choice in influencing the energy content of the oil. This finding suggests that both lower temperatures and the absence of catalysts result in a less efficient conversion process, yielding pyrolysis oil with lower energy density. The reduced heating value at lower temperatures can be attributed to the incomplete thermal degradation of the plastic waste and the water content in the pyrolysis oil component.

The pyrolysis oil obtained at 450 °C using BA as a catalyst exhibited the highest heating value of 45.77 MJ/kg. This high heating value is indicative of the effective conversion of plastic waste into energy-dense hydrocarbons under optimal catalytic conditions. In comparison, pyrolysis conducted at the same temperature of 450 °C but using calcined FCC resulted in a slightly lower heating value of 44.37 MJ/kg, affecting its catalytic efficiency and thus the quality of the produced pyrolysis oil. However, BA and FCC600 were not significantly different ($p < 0.05$). It shows the same result as previous study about impact of calcination on the FCC catalyst's performance in pyrolysis [26]. The presence of FCC likely facilitated the breakdown of long-chain polymers into more stable and energy-rich liquid products [10]. The experiment shows that while the calorific value of the pyrolysis oil is influenced by the temperature at which it occurs, the calorific value of the pyrolysis oil is not significantly impacted by the type of catalyst used. Nevertheless, it is also necessary to investigate the chemical composition using alternative methods because the employment of catalysts may have an unclear impact on the oil's calorific value to producing valuable liquid fuels.

These results are consistent with the study by Lange [27], which reported a heating value of 45.20 MJ/kg for pyrolysis oil produced from thermoplastics. The close alignment between their findings and the values observed in this study supports the robustness of the pyrolysis conditions used here. The similarity in heating values suggests that the pyrolysis process used in this study is both effective and comparable to advanced pyrolysis technologies reported in the literature, reinforcing its potential for energy recovery and sustainable waste management applications.

#### 3.3.2. *FTIR analysis*

The functional groups and chemical bonds in the produced pyrolysis oil were characterized using FT-IR, which identifies molecular vibrations associated with various chemical bonds.

The chemical components identified in the pyrolysis oil are significant as they resemble functional groups found in conventional diesel fuel, suggesting the oil's potential as a fuel alternative. Notably, only the pyrolysis oil produced at 450 °C with specific catalysts-such as bottom ash (BA), calcined BA, FCC, and calcined FCC-contained these diesel-like functional groups. In contrast, oils produced without catalysts lacked certain groups, like carboxyl, which may impact fuel quality and performance. Among the samples, pyrolysis at 450 °C with calcined FCC yielded oil most similar to commercial diesel, featuring key components such as alkanes, aromatics, and carbonyls. These findings align with Prurapark et al. [25]'s study, reinforcing the effectiveness of calcined FCC catalysts in enhancing pyrolysis oil quality for potential use as a diesel substitute.

In the catalytic pyrolysis process, especially with calcined FCC catalysts, promotes the production of fuel-quality pyrolysis oil by enhancing the formation of functional groups that resemble those in diesel fuel. The absence of catalysts, on the other hand, reduces the oil's similarity to commercial diesel, particularly by missing key groups such as carboxyl.

#### 3.3.3. *Pyrolysis oil composition by GC-MS analysis*

GC-MS analysis could be used to determine the distribution of carbon and to compute the selectivity of derived pyro-oil at different temperatures (Fig. 8). This liquid portion was thoroughly characterized using GC/MS techniques, and approximately 100 compounds were identified. The total peak area was 100% for each pyrolysis condition. The range of hydrocarbons determined the pyro-oil product's selectivity [28]. The GC-MS was employed to analyze the liquid fraction, revealing the presence of over 50 distinct compounds. This advanced technique facilitates comprehensive qualitative and quantitative analyses, bypassing traditional extraction and dilution processes. The pyrolysis oil was categorized into acids, alcohols, aromatics, esters, ethers, furans, hydrocarbons (HC) in the $C_5$ to $C_{11}$, $C_{12}$ to $C_{20}$ and $C > 20$ ranges, ketones, nitrogen-containing hydrocarbons ( N -compounds), and phenol. The study found that pyrolysis conducted at 500 °C without a catalyst resulted in the highest concentration of C12-C20 hydrocarbons (70.11 % peak area), while pyrolysis at 350 °C yielded a higher proportion of C5-C11 hydrocarbons and a greater presence of aromatics (32.96 % peak area).

The main material utilized in this work, LDPE, is a thermoplastic polymer with a good strength-to-density ratio, according to a study on its thermal breakdown. When the homolytic bonds in the polymer chain are broken during PE's thermal breakdown, two radicals are produced:

$$R' - (CH_2)_4 - CH_2 - R', \rightarrow R' - (CH_2)_4 - CH_2 + R' \quad (2)$$

In the diffusion process, $\beta$-scission is essential:

$$R' - (CH_2)_4 - CH_2 \rightarrow R' - (CH_2)_2 - CH_2 + CH_2 = CH_2 \quad (3)$$

Alkanes and dienes are then produced. An intermolecular hydrogen transfer process is what produces alkanes [29, 30]. The quality of the pyrolysis oil, particularly from

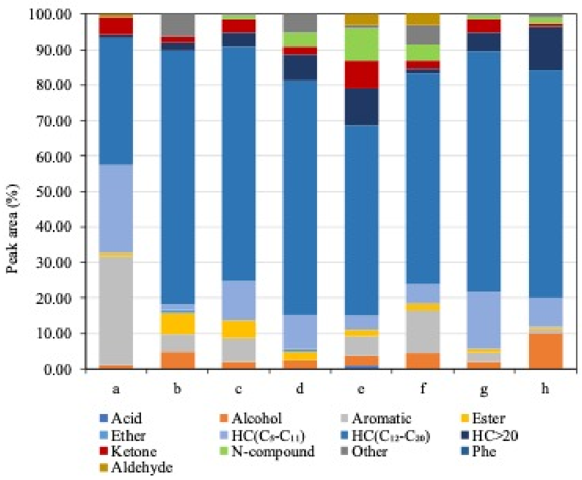


**Fig. 7.** Pyrolysis oil composition by GC-MS (a) Py-oil 350 °C (b) Py-oil 400 °C (c) Py-oil 450 °C (d) Py-oil 500 °C (e) Py-oil 450 °C with FCC (f) Py-oil 450 °C with calcined FCC (g) Py-oil 450 °C with BA (h) Py-oil 450 °C with calcined BA

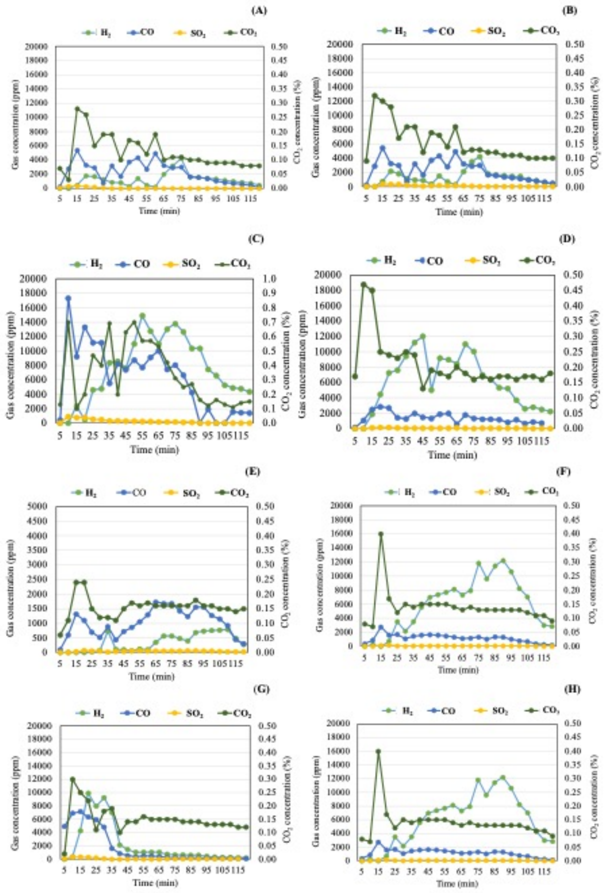


**Fig. 8.** Gas composition emitted from the pyrolysis process (A) 350 °C, (B) 400 °C, (C) 450 °C, (D) 500 °C, (E) 450 °C with BA (F) 450 °C with calcined BA, (G) 450 °C with FCC (H) 450 °C with calcined FCC

processes at 350 °C and 450 °C without a catalyst, was comparable to conventional diesel fuel, characterized by a high proportion of alkanes ranging from $C_9$ to $C_{32}$. This indicates that the pyrolysis oil possesses a high heating value and shows promise as a potential alternative fuel. The observed trends in hydrocarbon content align with Rajendran et al. [31], who noted similar improvements in hydrocarbon yields with optimized conditions.

The main hydrocarbon products in the pyrolysis oil were in the range of $C_{12} - C_{20}$, accounting for 66.06 % to 84.65 % of the peak area. The highest proportions were observed at 450 °C, with the order of abundance being calcined FCC > 500°C > 450°C with FCC , respectively. A high amount of hydrocarbon in the range of $C_5 - C_{11}$ (peak area 4.01-24.81%), or gasoline-like hydrocarbon, was revealed by pyrolysis oil at 350 °C > 450°C > 450°C with calcined FCC, respectively. Alkanes, including pentadecene, heptadecane, and cyclotetracosane, were identified as minor hydrocarbon components, accounting for 2-4 % of the peak area. Moreover, the pyrolysis of hydrocarbons with carbon numbers greater than 20 (HC > 20) resulted in lower proportions, ranging from 0.9 % to 12.18 % of the peak area. Despite having a high concentration of $C_5 - C_{11}$, it is the condition that produces the least amount of pyrolysis oil. This could be because just a small amount of polymer bonds with low vaporization are broken down by the temperature at 350 °C, which was not sufficient to break down the entire mass of plastic waste. This study demonstrates that optimizing temperature and catalyst conditions greatly improves the quality of pyrolysis oil, positioning it as a viable alternative fuel with properties comparable to those of conventional liquid fuels.

However, pyrolysis at 350 °C resulted in the highest concentration of aromatic hydrocarbons, attributed to the presence of PAHs in the pyrolysis oil. This may be due to the low temperature, which is insufficient to degrade plastic waste into smaller molecules such as benzene or aliphatic hydrocarbons. Generally, naphthalene, phenanthrene, and pyrene were the predominant polycyclic aromatic hydrocarbon (PAH) species found in both the liquid and gaseous products [32]. A high amount of aromatic (peak area 1.16-30.63 %) was revealed by pyrolysis oil at 350 °C > 450°C with calcined BA, respectively and pyrolysis oil at 500 °C wasn't found. It. may be due to high temperature can breaking double bond of aromatic compound [19, 33]. The results were consistent with those of Lai et al. [34]'s study utilizing bottom ash, which found that the catalytic process using bottom ash increased the hydrocarbon compound of alkane more than pyrolysis oil from non-catalysts.

These findings align with existing literature, demonstrating the effectiveness of specific catalysts in improving hydrocarbon yields and reducing undesirable components. Especially, the addition of FCC catalyst shifted the product composition towards increased hydrocarbons of $C_5 - C_{11}$ and $C_{12} - C_{20}$, a trend also observed by Kongngoen et al. [10] in their studies on catalytic pyrolysis.

Moreover, other components that affect the quality of pyrolysis oil include oxygenated compounds such as aldehydes, ketones, esters, and alcohols, as well as nitrogen-containing compounds. In terms of acid content, all pyrolysis conditions showed lower acidity, which is a significant advantage of pyrolysis oil derived from plastic waste. Aldehyde levels slightly increased to 3.35 % with the BA catalysts, while they were nearly zero with the FCC catalyst. This reflects the effectiveness of these catalysts in reducing aldehyde formation, which is a significant factor in the instability of pyrolysis oil [35]. A small number of esters, ranging from 0.53 % to 5.89 % of the peak area, was observed in pyrolysis oil at the following temperatures: 400 °C $>$ 450°C $>$ 500°C. The highest concentration of alcohol, at 10.10% of the peak area, was obtained from pyrolysis oil at 450 °C with calcined FCC. The presence of ketone compounds ranged from 1.77 % to 7.98 %, while nitrogen-containing compounds were notably high, between 1.12 % and 9.19 %. This reflects the higher nitrogen content in biomass compared to plastic waste [36]. The findings align with Kongngoen et al. [10], who explored the cracking of heavy wax from mixed plastics using spent FCC catalysts which the spent FCC catalyst enhanced diesel-range hydrocarbon production while limiting aromatic compound formation to 20-40 % peak area during the wax cracking process. These findings suggest that the FCC catalyst enhances hydrocarbon content. The detail of chemical composition of catalytic pyrolysis utilizing calcined FCC is presented in Table A.1.

The study found that increasing the calcination temperature of bottom ash did not enhance the surface area, and consequently, it did not affect catalysis or increase oil yield and hydrocarbon composition. In contrast, the FCC catalyst demonstrated greater efficiency in promote oil yield and hydrocarbon composition due to its larger reaction surface area, which encourages more effective thermal cracking reactions. The calcined FCC at 600 °C resulting in increased oil yield and carbon composition that break down into smaller molecules. This observation aligns with Wong et al., which indicates that the carbon formation or coke deposited on the surface of the FCC catalyst used in the petrochemical industry decomposes when exposed to high temperatures [19, 20]. From the process of calcination the catalyst at 600 °C, a weight loss of 3-6 % was observed, which is relatively small. This may be due to the minimal amount of carbon attached to the surface, making the catalyst suitable for reuse. Consequently, this configuration supports the reusability of the catalysts. Nevertheless, the used catalysts will undergo further investigation for reconditioning and cleaning to enable their reuse in future research. Therefore, the study confirms that optimizing temperature and catalyst conditions significantly enhances the quality of pyrolysis oil, making it a viable alternative fuel with characteristics similar to conventional liquid fuels.

### 3.4. The composition of gaseous products

The composition of gas emissions from the pyrolysis process is also an important aspect to investigate. Normally, a flue gas analyzer is a critical tool employed to measure and analyze the composition of gases emitted from combustion sources such as boilers, furnaces, and engines. The gas products were measured including carbon dioxide ($CO_2$), carbon monoxide (CO), hydrogen ($H_2$), and sulfur dioxide ($SO_2$). For $CO_2$ emissions, the gas produced at 450 °C without a catalyst consistently demonstrated the highest concentrations at all time points, reflecting a substantial $CO_2$ release. The catalytic pyrolysis process at 450 °C with calcined FCC in our investigation had the lowest $SO_2$ emissions at pyrolysis period, suggesting was more effective with less sulphur dioxide release (Fig. 9). This contrasts with pyrolysis produced at 400 °C without a catalyst, which showed the highest $SO_2$ emissions, particularly notable between 15 and 30 minutes.

The pyrolysis gas produced at 450 °C without a catalyst exhibited the highest CO emissions at the 30 -minute mark, while pyrolysis oil with bottom ash peaked in CO levels between 65 and 110 minutes. $H_2$ emissions were generally lower, but the gas produced with bottom ash calcined at 600 °C showed the highest $H_2$ concentrations, starting at 730 ppm at 20 minutes and peaking at 12,234 ppm at 90 minutes. These findings align with Zheng et al. [37], who noted that catalytic conditions significantly influence CO and $SO_2$ emissions during pyrolysis. Their research indicated that catalyst type can reduce these emissions, supporting our observation of how calcined FCC and bottom ash catalysts affect emission levels. In summary, our research indicates that the pyrolysis conditions and catalysts employed result in decreased emissions of $CO_2$ and $SO_2$, indicating a more effective and sustainable procedure.

These findings indicated that the $H_2$ generation was observed within the range of 1,186-5,937 ppm with the highest concentration recorded at 500 °C and 450 °C with BA catalyst. These findings demonstrated that a clear increase in $H_2$ occurred with an increase in the pyrolysis temperature[38]. Hydrogen gas constitutes the predominant component of the generated gaseous mixture. This phenomenon arises from a degradation mechanism, primarily characterized by the random scission of polymeric chains. The pyrolysis process primarily generates hydrogen gas through random scission, which decomposes long polymer chains into smaller molecules by depolymerizing plastic waste at high temperatures. This results in a gaseous mixture of $CO, CO_2, H_2$, and various hydrocarbons gas. The significant hydrocarbon production stems from the high carbon and hydrogen content of the plastic feedstock and efficient heat transfer during pyrolysis, with rapid heating enhancing polymer breakdown and gas formation. The generated gaseous products (syngas; $H_2 + CO$) can be employed in synthesis processes to manufacture chemicals or biofuels post-cleaning, or they may be combusted directly to supply energy and heat [38]. Several key chemical reactions occur during the process: thermal cracking breaks down hydrocarbons into smaller molecules and hydrogen, represented as:

$$pC_nH_x \rightarrow qC_mH_y + rH \tag{4}$$

In carbon formation, hydrocarbons decompose into solid carbon (coke) and hydrogen gas:

$$C_nH_x \rightarrow nC + x/2H_2 \tag{5}$$

In the methanation reaction, carbon monoxide reacts with hydrogen to produce methane $(CH_4)$ and water:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{6}$$

The water-gas shift reaction occurs when carbon monoxide reacts with water vapor to produce carbon dioxide and hydrogen:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{7}$$

The use of the metal oxide catalyst enhances $H_2$ production, reduces undesirable by-products such as tar and solid carbon, and promotes the conversion of larger hydrocarbons into lighter gas fractions with higher value [17, 39, 40]. This result indicated that the average $H_2$ generation was improved by the BA calcined catalyst to 5937 ppm, which is near the pyrolysis temperature at 500 °C with an average of 6005 ppm. The pyrolysis process and the observed catalytic effects are both explained by fundamental concepts [9, 41, 42]. Catalysts like calcined FCC and metal oxides enhance the breakdown of complex feedstock into simpler compounds by providing alternative pathways with lower activation energy, reducing harmful emissions such as $SO_2$ and CO , while promoting valuable hydrocarbons (Fig. 8). The effects of temperature are substantial; higher temperatures result in lighter hydrocarbons and larger emissions of $CO_2$, whereas lower temperatures favour heavier molecules and higher CO levels. Zeolites and other catalysts help feedstock deoxygenate into simpler hydrocarbons, which enhances fuel quality [10, 19].

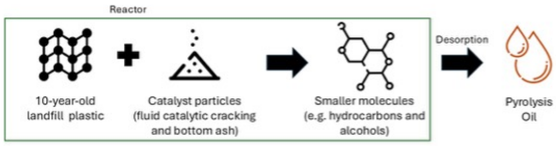


**Fig. 9.** Mechanisms of the pyrolysis process

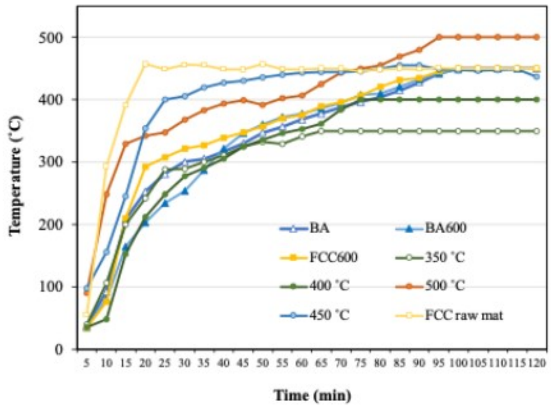


**Fig. 10.** Heating rate performed of various pyrolysis conditions

In order to reduce harmful emissions and maximize desired product yields, the emission profile optimisation system modifies the pyrolysis conditions and catalyst types. According to our findings, employing calcined FCC successfully lowers CO and $SO_2$ emissions. These results suggest the possibility of producing cleaner fuel by improving knowledge of how temperature and catalytic processes affect pyrolysis efficiency and environmental impacts.

## 4. Conclusions

This study investigates the content and quality of fuel oil made from plastic trash that is taken from landfills and pyrolysed at temperatures ranging 350 °C and 500 °C, both with and without catalysts. The pyrolysis oil production varied from 21.52 % to 47.00 % by weight, with a calcined FCC catalyst yielding the maximum yield of 42.64 % at 450

**Table 2.** Proximate analysis of plastics waste

| Plastic waste type | Volatile content (%wt.) | Moisture content (%wt.) | Ash content (%wt.) |
|---|---|---|---|
| Non sieved 10-year-old landfills | $96.31 \pm 0.01$ | $3.69 \pm 0.01$ | $26.21 \pm 0.01$ |
| Sieved 10-year-old landfills | $97.25 \pm 0.01$ | $2.75 \pm 0.01$ | $12.04 \pm 0.01$ |
| Sieved 10-year-old landfills of 2x2 inches | $99.12 \pm 0.01$ | $0.88 \pm 0.01$ | $8.78 \pm 0.01$ |

**Table 3.** Proportions by weight of all elements in FCC and BA catalyst by FE-SEM

| Element (%wt.) | FCC | Calcined FCC | BA | Calcined BA |
|---|---|---|---|---|
| C | 7.3 | 6.1 | 9.7 | 7.9 |
| O | 49.0 | 48.9 | 49.7 | 43.1 |
| Si | 17.3 | 16.3 | 14.3 | 9.6 |
| Ca | 0.2 | 0.2 | 8.5 | 3.9 |
| Cl | - | - | 6.3 | 18.9 |
| Al | 20.7 | 21.2 | 4.8 | 3.3 |
| Fe | 0.9 | 1.2 | 1.9 | 0.5 |
| K | - | - | 0.9 | 1.9 |
| Mg | 1.1 | 1.8 | 0.9 | 0.3 |
| Ti | 0.4 | - | 1.0 | 0.2 |
| S | - | 0.2 | 0.8 | 0.5 |
| Na | 0.3 | - | 0.5 | 6.2 |
| P | 1.4 | - | 0.5 | 1.0 |
| Cr | - | - | 0.3 | 2.7 |
| Total | 100% | 100% | 100% | 100% |

°C. Due to incomplete pyrolysis, a considerable amount of char was generated at 350 °C. The oil generated at 450 °C using a bottom ash catalyst had a maximum heating value of 45.77 MJ/kg. The pyrolysis at 450°C with an FCC calcined catalyst showed the highest composition of hydrocarbons ($C_5 - C_{11}$ and $C_{12} - C_{20}$). The oil's chemical properties were examined and found to be comparable to those of commercial diesel. Alternative fuels can be produced by catalytic pyrolysis, as indicated by the observation that emissions, especially $CO_2$, were lower than those from other thermochemical processes. These results encourage resource efficiency and sustainability, which are key components of the circular economy. In order to further improve oil characteristics for energy sustainability and environmental benefits, future research should concentrate on using reaction times, different plastic waste kinds and catalysts.

## 5. Acknowledgements

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## A. Appendix

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**Table A.1.** Product selectivity (area%) of the pyrolysis oil from calcined FCC (obtained from the 50 highest % peaks area out of a total of 100 peaks)

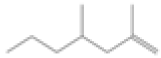
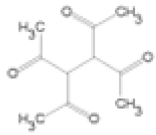
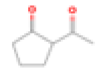
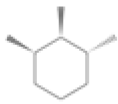
| No. | RT (min) | Peak area (%) | Compound name | formula | Chemical structure |
|---|---|---|---|---|---|
| 1. | 4.29 | 0.50 | 2,4-Dimethyl-1heptene | $C_5 - C_{11}$ |  |
| 2. | 7.20 | 0.82 | 1-Decene | $C_5 - C_{11}$ |  |
| 3. | 7.35 | 0.37 | Decane | $C_5 - C_{11}$ |  |
| 4 | 8.96 | 1.39 | 1-Undecene | $C_{12} - C_{20}$ |  |
| 5. | 7.61 | 0.22 | Decanedioic acid, didecyl ester | Ester |  |
| 6 | 8.76 | 1.04 | Cyclopentane, propyl- | $C_5 - C_{11}$ |  |
| 7. | 8.96 | 1.39 | 1-Undecene | $C_5 - C_{11}$ |  |
| 8. | 9.10 | 0.78 | Undecane | $C_5 - C_{11}$ |  |
| 9. | 10.68 | 1.18 | Dodecane | $C_{12} - C_{20}$ |  |
| 10. | 11.83 | 0.51 | 3,4-diisopropyl-2,5-dimethyl-3-hexene | $C_{12} - C_{20}$ |  |
| 11. | 12.13 | 1.87 | Tridecane | $C_{12} - C_{20}$ |  |
| 13. | 12.23 | 1.51 | 2Acetylcyclopentanone | Ketone |  |
| 14. | 12.36 | 0.83 | Naphthalene, 2-methyl- | Aromatic |  |
| 16. | 12.46 | 1.18 | Cyclohexane, 1,2,3-trimethyl-, (1.alpha.,2.alpha.,3. beta) | $C_5 - C_{11}$ |  |
| 17 | 13.27 | 0.96 | 1,13Tetradecadiene | $C_{12} - C_{20}$ |  |
| 18. | 13.47 | 1.41 | Tetradecane | $C_{12} - C_{20}$ |  |
| 19. | 14.71 | 3.60 | 1-Pentadecene | $C_{12} - C_{20}$ |  |
| 20. | 14.82 | 1.82 | pentadecane | $C_{12} - C_{20}$ |  |
| 21. | 16.42 | 2.88 | 1-Hexadecene | $C_{12} - C_{20}$ |  |
| 22 | 16.56 | 2.22 | Hexadecane | $C_{12} - C_{20}$ |  |
| 23 | 16.67 | 0.32 | 7-Hexadecene, (Z)- | $C_{12} - C_{20}$ |  |

**Table A.1** Cont.

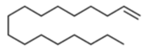
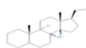
| No. | RT (min) | Peak area (%) | Compound name | formula | Chemical structure |
|---|---|---|---|---|---|
| 24 | 18.86 | 2.56 | 1-Heptadecene | $C_{12}-C_{20}$ |  |
| 25 | 19.07 | 2.04 | Heptadecane | $C_{12}-C_{20}$ |  |
| 26. | 19.22 | 0.30 | 1-Heptadecene | $C_{12}-C_{20}$ |  |
| 27. | 19.36 | 0.45 | Benzene | Aromatic |  |
| 28. | 19.61 | 0.29 | 1-Heptadecene | $C_{12}-C_{20}$ |  |
| 29 | 22.51 | 2.29 | 1-Octadecane | $C_{12}-C_{20}$ |  |
| 30 | 22.82 | 1.91 | Octadecane | $C_{12}-C_{20}$ |  |
| 31. | 23.05 | 0.23 | 3-Octadecene | $C_{12}-C_{20}$ |  |
| 32. | 23.63 | 0.21 | 5-Octadecene | $C_{12}-C_{20}$ |  |
| 33. | 25.75 | 0.55 | 1,19Eicosadiene | $C_{12}-C_{20}$ |  |
| 34. | 25.87 | 2.18 | 1-Heptadecene | $C_{12}-C_{20}$ |  |
| 35 | 25.98 | 1.86 | Nonadecane | $C_{12}-C_{20}$ |  |
| 36 | 26.07 | 0.31 | 1-Nonadecene | $C_{12}-C_{20}$ |  |
| 37. | 27.18 | 2.75 | 3-Eicosene, (E)- | $C_{12}-C_{20}$ |  |
| 38. | 27.27 | 2.09 | Eicosane | $C_{12}-C_{20}$ |  |
| 39. | 28.12 | 4.33 | 1-Docosanol | Alcohol |  |
| 40. | 28.29 | 0.30 | Dodecane | $C_{12}-C_{20}$ |  |
| 41. | 28.42 | 0.35 | 2,4,6-Trimethyl-3heptene | $C_{5}-C_{11}$ |  |
| 42. | 28.64 | 0.36 | 1-Docosanol | Alcohol |  |
| 43. | 28.84 | 4.07 | 14-.BETA.-HPREGNA | HC ($>C_{20}$) |  |
| 44 | 28.97 | 0.50 | Cyclododecane | $C_{12}-C_{20}$ |  |

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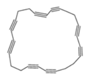
**Table A.1.** Cont.

| No. | RT (min) | Peak area (%) | Compound name | formula | Chemical structure |
|---|---|---|---|---|---|
| 45 | 29.58 | 3.85 | 10-Heneicosene (c,t) | ($> C_{20}$) |  |
| 46. | 30.14 | 1.62 | 9- | N− compound |  |
| 47. | 30.40 | 4.01 | Cyclotetracosane | ($> C_{20}$) |  |
| 48. | 31.40 | 2.82 | Pentacosane | ($> C_{20}$) |  |
| 49 | 32.63 | 3.02 | Hexacosane | ($> C_{20}$) |  |
| 50. | 34.15 | 2.08 | Eicosane | $C_{12} - C_{20}$ |  |

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