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Hot Filter Temperature Influence on Low-Density Polyethylene Pyrolysis Fuel Yield: Integrating Experimentation and Simulation

Faadey-ismail Noipom,[1] Nattadon Pannucharoenwong,[1,*] Keyoon Duanguppama[2,*] and Snunkhaem Echaroj[1]

Abstract

This study investigates the influence of varying hot filter temperatures (100 °C, 200 °C, and 300 °C) on fuel yield and composition from low-density polyethylene (LDPE) pyrolysis in a fixed-bed reactor. The pyrolysis process was conducted at 300 °C with condensing unit temperatures set at 30 °C and -40 °C for the first and second condensers, respectively. Results indicate that increasing the hot filter temperature enhances secondary cracking, leading to a reduction in the primary fuel yield while increasing gas and second-condensate fuel fractions. At 300 °C, the second condenser fuel yield increased to 13 wt%, with a notable shift in chemical composition favoring larger hydrocarbon molecules. The first-condensate fuel exhibited a heating value increase from 42.4 MJ/kg at 100 °C to 44.8 MJ/kg at 300 °C, accompanied by increased viscosity and density. Simulated results using MATLAB extended the analysis beyond experimental conditions, predicting significant trends in fuel distribution, energy consumption, and product composition up to 800 °C. These findings provide critical insights into optimizing pyrolysis parameters for enhanced fuel quality and yield.

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1. Introduction

The global surge in plastic waste accumulation has led to significant environmental concerns, particularly due to the persistence of plastic materials in ecosystems and their contribution to pollution. The conversion of plastic waste into liquid fuel through pyrolysis has gained traction as an effective waste-to-energy approach, offering a sustainable means of mitigating plastic pollution while simultaneously generating valuable hydrocarbon fuels.[1-3] Among various thermochemical conversion methods, pyrolysis is particularly attractive due to its ability to process a wide range of plastic feedstocks and produce high-yield fuel fractions without requiring complex pretreatment steps.[4]

Pyrolysis is a thermochemical decomposition process where polymer chains break into smaller hydrocarbons. The type of plastic affects product composition; for instance, low-density polyethylene (LDPE) tends to yield a higher proportion of waxy and liquid hydrocarbons due to its long, linear chains and low aromatic content.

The efficiency and product composition of plastic pyrolysis are heavily influenced by operational parameters such as temperature, residence time, catalyst selection, and reactor configuration.[5-7] Fixed-bed reactors, commonly employed for laboratory-scale and industrial pyrolysis, provide controlled thermal degradation conditions for plastic waste. The condensation and filtration of pyrolysis vapors play a crucial role in determining the final product distribution, particularly the quality of liquid fuel obtained. Among these, hot filter temperature is a critical factor that affects secondary cracking reactions, molecular weight distribution, and phase separation of pyrolysis vapors.[8,9] Despite its significance, the

[1] *Research Unit of Energy Innovation for the Automotive Industry (EIAI), Department of Mechanical Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Pathum Thani, 12120, Thailand*
[2] *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering and Industrial Technology, Kalasin University, Kalasin, 46000, Thailand*
*E-mail: pnattado@engr.tu.ac.th (N. Pannucharoenwong); keyoon.du@ksu.ac.th (K. Duanguppama)

influence of hot filter temperature on product yields and fuel properties in fixed-bed pyrolysis systems remains underexplored.

Previous studies have demonstrated that varying condensation temperatures can selectively influence the separation of gasoline and diesel-like fuel fractions.[10-20] For instance, Pannucharoenwong reported that dual-stage condensation at 30 °C and -40 °C resulted in two distinct fuel fractions, although cross-contamination between fractions affected their calorific values. Adjusting hot filter temperatures may provide an additional means to refine fuel separation,[1] promoting selective condensation based on hydrocarbon chain length and molecular weight.[21] This approach could enhance fuel quality by preventing the inclusion of light volatiles in heavier fractions, reducing unwanted dilution effects. However, the trade-offs between improved separation efficiency and potential energy losses from increased gasification need further investigation.

The thermal decomposition of plastics, such as LDPE, follows a complex reaction pathway involving primary and secondary cracking reactions.[22] Primary cracking decomposes polymer chains into lower molecular weight hydrocarbons, whereas secondary cracking occurs at elevated temperatures, further breaking down intermediate products into smaller gaseous components[8]. The hot filter serves as a key intermediary stage where these secondary reactions can be regulated, dictating the balance between liquid and gaseous products. At higher hot filter temperatures, increased cracking activity can lead to a shift in product distribution, favoring gas formation over liquid fuel yield. This temperature-dependent transformation has critical implications for optimizing fuel production and ensuring energy-efficient operation of pyrolysis systems.

Beyond influencing fuel yield and composition, hot filter temperature affects the energy balance and system efficiency. Increasing the filter temperature may enhance the separation of specific hydrocarbon fractions, yet it also raises the risk of excessive energy consumption due to higher heat input requirements.[22] Furthermore, the secondary cracking reactions promoted at elevated temperatures can result in altered fuel properties, such as viscosity, heating value, and density, impacting the suitability of the fuel for practical applications.[23] To develop a comprehensive understanding of these interactions, a combination of experimental and computational methods is necessary.

This study employs both experimental analysis and MATLAB-based simulation techniques to systematically investigate the effects of varying hot filter temperatures on fuel yield and composition in LDPE pyrolysis. By extending the analysis beyond traditional experimental constraints, MATLAB modeling provides predictive insights into fuel distribution trends, secondary cracking intensities, and energy consumption patterns across a wider range of operating temperatures. The integration of experimental and computational approaches in this study aims to optimize pyrolysis conditions for improved fuel quality, economic feasibility, and environmental sustainability. The findings will contribute to the development of more efficient plastic pyrolysis systems with enhanced control over fuel separation and refinement, paving the way for industrial-scale applications.

Furthermore, the study examines how hot filter temperature influences the volatility and refining potential of pyrolysis-derived fuels. As temperatures increase, lighter hydrocarbons may bypass the primary condenser, altering the composition of the secondary fuel fraction. Understanding these shifts is crucial for tailoring pyrolysis fuels to specific energy applications. The results presented herein will not only advance knowledge on hot filter temperature optimization but also provide a framework for future research on scalable and sustainable waste-to-fuel technologies.

The role of secondary cracking at elevated temperatures in shaping fuel properties has been explored in various studies on plastic pyrolysis. Increasing pyrolysis temperatures resulted in a transition from liquid to gaseous products, with a corresponding increase in aromatic hydrocarbon content. This shift can enhance the calorific value of pyrolysis oil but may also lead to the formation of unwanted side products such as polycyclic aromatic hydrocarbons (PAHs), which require further refinement.[24] Similar findings were noted by Syamsiro *et al*.[21], who observed that high-temperature pyrolysis conditions favor the production of light gases such as methane, ethylene, and propylene, significantly impacting the fuel-to-gas ratio in pyrolysis reactors.

The industrial relevance of optimizing hot filter temperature extends beyond fuel yield considerations. In large-scale waste-to-energy systems, balancing heat input, reaction kinetics, and product selectivity are crucial for achieving economic feasibility. Energy recovery strategies, such as utilizing non-condensable gases for reactor heating, have been suggested as a means to improve overall efficiency.[6] Additionally, studies have highlighted the need for integrated reactor designs that can modulate secondary cracking reactions through precise temperature control, thereby optimizing both product yield and energy consumption.[7]

From an environmental perspective, optimizing hot filter temperature can contribute to reducing the formation of

unwanted byproducts such as tar and char, which pose challenges for reactor operation and emissions control. Recent advances in pyrolysis reactor technology have demonstrated that controlled heating profiles can mitigate tar formation while maximizing liquid fuel recovery.[4] This aligns with broader efforts to develop sustainable and low-emission pyrolysis technologies for plastic waste management.

Overall, this study aims to fill the knowledge gap regarding the interplay between hot filter temperature and fuel yield optimization. By leveraging experimental data and simulation-based predictive modeling, this research provides a deeper understanding of the thermochemical pathways governing LDPE pyrolysis. The insights generated from this study will support the advancement of next-generation pyrolysis systems, ensuring that plastic waste valorization remains both economically and environmentally viable. The novelty of this research lies in the combination of the design of the dual-stage condensation system, hot filter mechanism and reactor configuration, which has not been previously explored for LDPE pyrolysis at this scale. This work contributes to the field by offering a comprehensive approach by combining both experimental investigation and simulation modeling to evaluate the influence of hot filtration on pyrolysis product distribution. Moreover, the simulation extends the findings beyond laboratory scale, allowing for a broader analysis of process behavior and scalability. thereby addressing critical gaps in current waste plastic pyrolysis systems.

2. Materials and methods

2.1 Feedstock

The primary raw material used in this study was LDPE plastic bags that had been discarded by various retail stores in Kalasin province. These plastic bag wastes were collected, manually sorted to remove any contaminants such as adhesives, labels, or residual organic matter, and subsequently subjected to a drying process. The drying process was conducted under direct sunlight for 24 hours to minimize moisture content before being stored in a tightly sealed container to prevent any potential reabsorption of moisture from the environment. This step was crucial to ensure that the pyrolysis process was not affected by excessive water content, which could lead to undesired secondary reactions such as hydrolysis.

Unlike some studies where feedstock undergoes mechanical preprocessing, such as shredding or granulation to improve heat transfer efficiency, the plastic bag waste used in this experiment was kept in its original form without size reduction. The approximate analysis of the raw material indicated a moisture content of less than 1 wt%, which is considered optimal for pyrolysis. Additionally, the proximate and ultimate analyses were conducted to determine the elemental composition and heating value of plastic bag waste. The high calorific value (HHV) was found to be 28.20 MJ/kg, suggesting a significant energy recovery potential.

2.2 Pyrolysis of plastic bag waste

The pyrolysis of plastic bag waste was conducted in a fixed-bed reactor system specifically designed for thermal degradation of polymeric materials. The experimental setup, as illustrated in Fig. 1, consisted of several key components, including a fixed-bed reactor, a hot vapor filtration unit, a first condenser equipped with an electrostatic precipitator (ESP), and a second condenser. Each component of the system was designed to facilitate efficient thermal decomposition of LDPE waste while maximizing the yield of valuable pyrolysis products. The entire system was controlled automatically, with

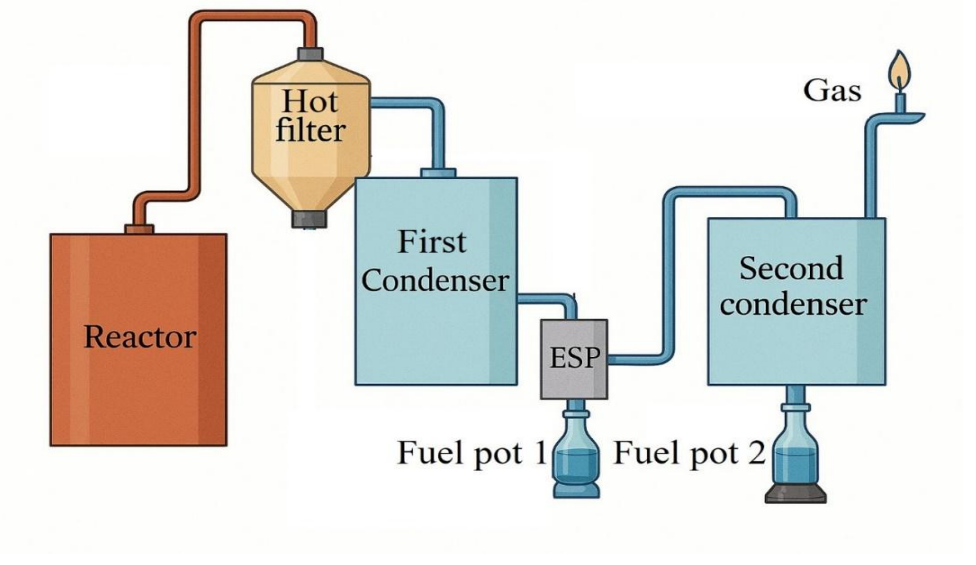

Fig. 1: The fixed bed reactor diagram for pyrolysis of plastic bag waste.[1]

real-time monitoring through sensors that measured parameters such as temperature, pressure, and gas composition.

The pyrolysis unit of plastic bag waste in supporting information (Fig. S1) shows the actual images of the various devices; the fixed-bed reactor, which served as the primary reaction chamber, was constructed from stainless steel grade 304 to ensure high thermal and chemical resistance. It had an internal diameter of 300 mm and a height of 500 mm. The hot vapor filter, responsible for capturing solid particulates and impurities from the gaseous pyrolysis products, had an inner diameter of 200 mm and a height of 600 mm. The first condenser, integrated with an ESP to enhance the collection of fine aerosols, had an inner diameter of 200 mm and a height of 300 mm. The ESP itself featured an inner diameter of 120 mm and a height of 500 mm. The second condenser, designed for additional cooling and condensation of pyrolysis vapors, featured a two-layer structure with an inner cylinder of 300 mm in diameter and 500 mm in height.

Unlike fluidized-bed pyrolysis systems that rely on inert carrier gas (such as nitrogen or argon) to transport pyrolysis vapors, this fixed-bed system operated under vacuum conditions, relying solely on the internal pressure differentials to direct vapor flow. To ensure a completely oxygen-free environment conducive to a closed-system pyrolysis reaction and to prevent any unwanted oxidation or combustion, the reactor system was purged with high-purity nitrogen gas (N_2) at a steady flow rate for a duration of 15 minutes prior to the initiation of heating, thereby displacing residual atmospheric oxygen and establishing an inert atmosphere maintained consistently throughout the thermal degradation process. This configuration effectively minimized the presence of oxygen, thereby preventing unwanted oxidation reactions that could degrade the quality of the pyrolysis products.

For each experimental run, 1 kg of dried plastic bag waste was loaded into the reactor chamber. The reactor was then sealed to create an airtight environment, and the heating process was initiated using an external electric heating coil. The temperature gradually increased to 300 °C at a controlled heating rate. The hot vapor filter unit was maintained at three different temperature setpoints: 100 °C, 200 °C, and 300 °C, to investigate its influence on vapor filtration efficiency and final product composition. The first condenser was cooled using a refrigeration system employing R404 as the working fluid, maintaining a temperature of 30 °C. It was also equipped with a 15 kV ESP to enhance the removal of fine particulates and tar-like substances from the pyrolysis vapors. The second condenser, designed to facilitate deeper cooling and further condensation, was operated at a temperature of -40 °C using the same refrigeration system.

To ensure process stability and consistency, the temperature profiles of all system components were continuously monitored and adjusted as necessary. The total duration of the pyrolysis reaction was maintained at 2 hours, during which the plastic bag waste underwent thermal decomposition, breaking down into smaller hydrocarbon molecules. At the end of the reaction period, the heating system was switched off, and the reactor was allowed to cool to room temperature before product collection.

The solid, liquid, and gaseous products obtained from the pyrolysis process were then analyzed for their composition and energy content. The kinetics of the pyrolysis reaction, including the reaction order and activation energy, were determined using the Arrhenius equation. The kinetic behavior of LDPE decomposition was further characterized through thermogravimetric analysis (TGA) to assess the weight loss patterns under controlled heating conditions. The kinetic data obtained from this study provide valuable insights into the optimal conditions required for maximizing product yield and improving process efficiency.

The reaction kinetics and thermal decomposition pathway of LDPE are depicted in supporting information (Fig. S2), illustrating the temperature-dependent breakdown of polymer chains and the subsequent formation of pyrolysis oil, syngas, and char. These findings contribute to a better understanding of the fundamental mechanisms underlying plastic waste pyrolysis and offer potential pathways for the valorization of waste plastics into useful energy carriers.

2.3 Mass balance

The pyrolysis of plastic bag waste produced three primary outputs: liquid fuel, ash, and non-condensable gas. The fuel yield was calculated in two stages: the first portion from the added weight of fuel pot 1, and the second from fuel pot 2. The ash yield included residues retained in the reactor, hot filter, and gas line, while the gas yield was derived by subtracting the fuel and ash yields from the total input (*i.e.*, 100%). The calculations are expressed Eqs.(1)-(3) as follows:

$$Y_{Fuel} = \frac{W_{ESP}+W_{Fuel\ pot\ 1}+W_{Fuel\ pot\ 2}\ (g)}{W_{Plastic\ waste\ bag}\ (g)} \times 100 \quad (1)$$

$$Y_{Ash} = \frac{W_{Reactor}+W_{Hot\ filter}+W_{Gas\ line}\ (g)}{W_{Plastic\ waste\ bag}\ (g)} \times 100 \quad (2)$$

$$Y_{Gas} = 100 - Y_{Fuel} + Y_{Ash} \quad (3)$$

where Y_{Fuel}= Yields of fuel (wt%), Y_{Ash}= Yields of ash (wt%), Y_{Gas}= Yields of gas (wt%), W_{ESP}= Weight of the component ESP (g), $W_{Fuel\ pot\ 1}$= Weight of the component fuel pot 1 (g), $W_{Fuel\ pot\ 2}$ = Weight of the component fuel pot 2 (g),

$W_{Plastic\ waste\ bag}$ = Weight of the component plastic bag waste (g), $W_{Reactor}$ = Weight of the component reactor (g), $W_{Hot\ filter}$= Weight of the component hot filter (g), $W_{Gas\ line}$= Weight of the component gas line (g).[20]

2.4 Energy balance and process efficiency

The energy efficiency (η) of the pyrolysis system is defined as the ratio of the useful energy recovered in the form of liquid fuel products to the total energy input, which includes both the chemical energy content of the plastic feedstock, and the thermal energy required to heat the reactor system Eqs. (4) and (5).

$$\eta = \frac{E_{output\ from\ liquid\ fuels}}{E_{total\ energy\ input}} \times 100 \quad (4)$$

$$\eta = \frac{m_{fuel} \times HHV_{fuel}}{(m_{LDPE} \times HHV_{LDPE}) + Q_{Thermal}} \times 100 \quad (5)$$

where m_{fuel} = Combined mass of the liquid fuels (kg), HHV_{fuel} = Weighted or average higher heating value (MJ/kg) of the liquid fuel, m_{LDPE} = Mass of LDPE feedstock (kg), HHV_{LDPE} = Higher heating value of LDPE (~43 MJ/kg), $Q_{Thermal}$ = Thermal energy input to raise LDPE from ambient to reactor temperature (MJ).

2.5 Simulation

Pyrolysis of LDPE is a thermal decomposition process that occurs in the absence of oxygen, producing valuable fuel products. This research aims to simulate the pyrolysis process using MATLAB, analyzing mass balance, product yields, and energy requirements under varying hot filter temperatures (100–800 °C). The study compares experimental data with simulation predictions, integrating kinetics, heat transfer, and energy balance models.

The algorithm in Fig. 2 enables predictive modeling of pyrolysis yields and energy consumption across a broader temperature range, supporting process optimization and comparison with experimental results.

2.5.1. Reaction kinetics in LDPE pyrolysis

The decomposition of LDPE follows Arrhenius kinetics, represented by Eq. (6):

$$k = Aexp\left(\frac{-Ea}{RT}\right) \quad (6)$$

where k is the reaction rate constant (s^{-1}), A is the pre-exponential factor (s^{-1}), Ea is the activation energy, R is the universal gas constant (8.314 J/mol · K), T is the temperature (K).

2.5.2 Heat transfer and energy balance

Heat transfer occurs via conduction, convection, and radiation: Conduction: Governed by Fourier's law Eq. (7),

$$q_{cond} = \frac{k_{steel}(T - T_{ambient})}{d} \quad (7)$$

where k_{steel} is the thermal conductivity (W/m · K), and d is the wall thickness.

Convection: Modeled by Newton's Law of Cooling Eq. (8),

$$q_{conv} = hA(T - T_{ambient}) \quad (8)$$

When h is the convective heat transfer coefficient ($W/m^2 \cdot K$), A is the reactor surface area.

Radiation: Modeled by Stefan-Boltzmann Law Eq. (9),

$$q_{rad} = \epsilon\sigma A(T^4 - {T_{ambient}}^4) \quad (9)$$

where σ is the Stefan-Boltzmann constant ($W/m^2 \cdot K^4$), ϵ is the emissivity.

Total heat input is calculated as Eq. (10):

$$Q_{input} = m_{LDPE}Cp(T - T_{initial}) + m_{LDPE}\Delta H \quad (10)$$

where ΔH is the heat of pyrolysis.

2.6 Fuel properties analysis

2.6.1 Heating value analysis

The heating value of the fuel was determined in accordance with DIN 51900 using an S.M.D Torino bomb calorimeter. The analysis was performed by placing a precisely measured 1 g sample of fuel into a bomb cup, which was then oxygenated to a pressure of 25 bar. The bomb cup was subsequently submerged in a calorimeter bucket containing 2 L of water to ensure consistent heat transfer. Once the setup was complete, the calorimeter was activated, and an ignition switch was used to initiate combustion via a conductive wire. The fuel sample underwent complete combustion over a period of approximately 20 minutes, during which the system recorded temperature changes. The higher heating value (HHV) of the fuel was computed automatically by the calorimeter's integrated software, ensuring precise and repeatable results.

2.6.2 Kinetic viscosity analysis

The viscosity of the fuel was analyzed in compliance with ASTM D445, which is the standard test method for kinematic viscosity measurement of petroleum-based fuels. The viscosity analysis was conducted at 40 °C using a Cannon-Fenske Viscometer (size 350), a precision glass capillary tube designed for accurate viscosity determination. The test procedure involved filling the viscometer with the fuel sample,

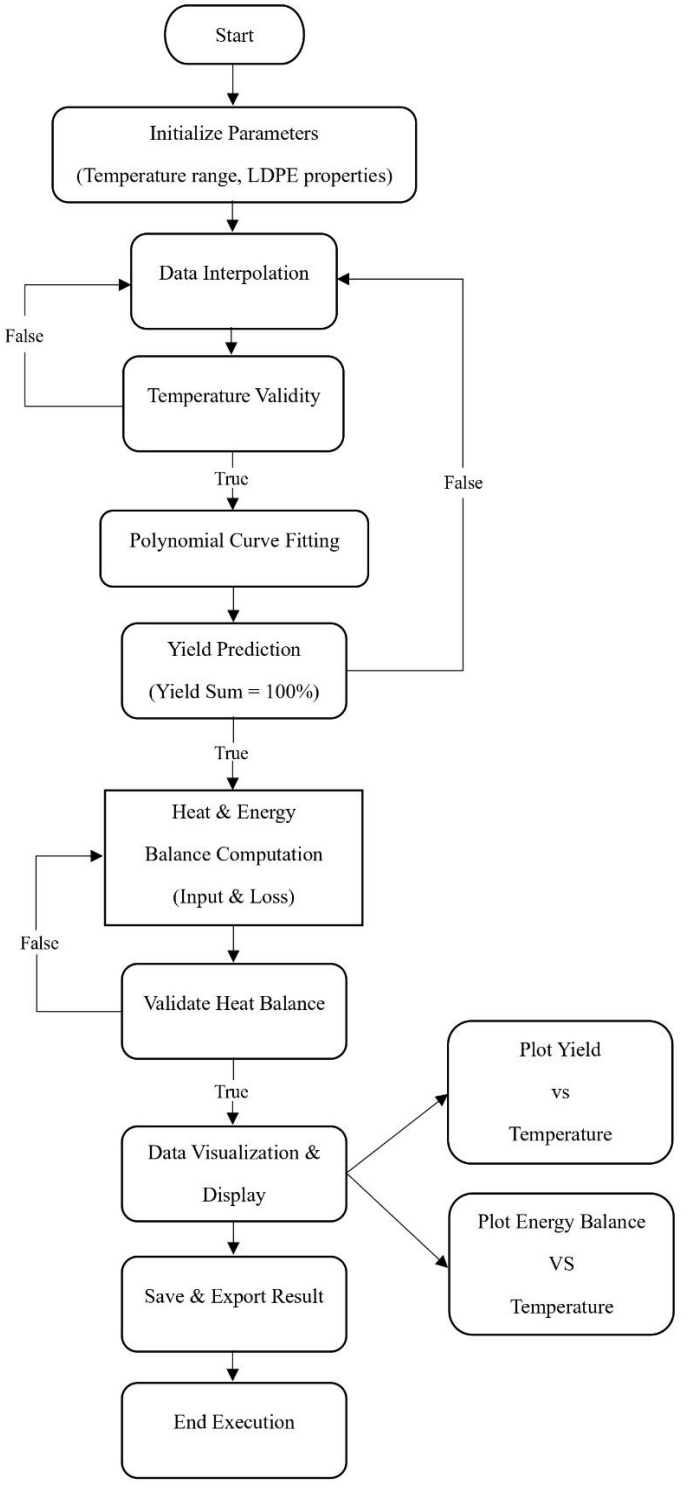

Fig. 2: Predictive algorithm modeling of Pyrolysis.

placing it in a temperature-controlled bath, and measuring the time required for the fuel to flow under gravity through the capillary tube. The kinematic viscosity was calculated based on the measured flow time and the viscometer's calibration constant.

2.6.3 Density analysis

The density of the fuel was measured according to ASTM D4052, a standard test method using a digital density meter. A 5 mL sample of fuel was carefully placed in a pre-calibrated measuring cup and weighed at a controlled room temperature of 15 °C. The density was determined by dividing the sample's mass by its volume, with the results expressed in g/cm³. This method ensured high accuracy and repeatability, providing essential information about the fuel's mass-to-volume ratio, which is a critical parameter for fuel combustion efficiency.

2.6.4 Flash and fire point analysis

The flash and fire points of the fuel were determined based on ASTM D93, the standard method for measuring the flash point of fuels using a pensky-martens closed-cup tester. The flash point is the lowest temperature at which the fuel vapors momentarily ignite when exposed to an ignition source, whereas the fire point is the lowest temperature at which the fuel can sustain continuous combustion. During the test, the fuel sample was heated gradually while being stirred. At specific temperature intervals, a flame source was introduced to determine the precise moment when ignition occurred. The flash and fire point values are critical for evaluating the fuel's safety characteristics and handling requirements.

2.6.5 Gas chromatography-mass spectrometry (GC/MS) of fuel analysis

The chemical composition of the fuel was analyzed using a Shimadzu GCMS-QP2010 GC/MS system. The analytical procedure began with a 1:1 dilution of the fuel in ethanol, followed by filtration using a 2 µm Filtrex nylon filter to achieve a 10% concentration. The prepared fuel sample was then introduced into the GC/MS system equipped with a Restex Rtx-5MS column (Restex, USA), featuring a 0.25 µm thick film, a 0.25 mm diameter, and a 30 m length.

Helium was used as the carrier gas, flowing through the system at a velocity of 40 m/s. The gas chromatography (GC) system was programmed to maintain an initial temperature of 60°C for 2 minutes, after which the temperature was ramped up to 270 °C at a rate of 5 °C/min and held at this temperature for 5 minutes. The mass spectrometry (MS) system operated using electron impact ionization (EI) at 70 eV, with an interface temperature of 250 °C and an ion source temperature of 230 °C. The MS system performed scans in the 20-260 m/z range at an interval of 0.5 s per scan.

The resulting spectral data were processed using Shimadzu LabSolutions GCMS software, which cross-referenced the obtained spectra with the NIST database for compound identification. This analytical method followed the procedure suggested by Duanguppama *et al*.,[8] ensuring reliable identification of hydrocarbons and other organic compounds present

3. Results and discussion

Pyrolysis of plastic bag waste under reaction temperature of 300 °C, three levels of hot filter temperature of 100 °C, 200 °C and 300 °C, first condensing unit temperature of 30 °C and second condensing unit temperature of -40 °C, the products were fuel, ash and gas. The fuel obtained from pyrolysis was divided into two parts: fuel from the first condensing unit and fuel from the second condensing unit. With details of the product yields and properties of the fuel were as follows.

3.1 Effect of the hot filter temperature on products yield

Fig. 3 shows that with the increased hot filter temperature from 100 to 300 °C, the first fuel yield decreased continuously from 71 to 55 wt%. This is comparable to the findings of Suttibak,[25] who reported a maximum bio-oil yield of 64.6 wt% from sugarcane bagasse at 499 °C. Similarly, H. V. Ly *et al*.[26] obtained a yield of 50.68 wt% from furniture processing residue at 450 °C. Meanwhile, the yields of second fuel and gas had clearly continued to increase. The maximum yield of second fuels and gas was 13 wt%. This was because the increased temperature in the hot filter results in higher pressure inside the system, causing the pyrolysis vapor to not be fully condensed by the first condenser.[1] However, the increased temperature in hot filter did not affect the change in ash yield because the ash content was approximately 18 wt%.

3.2 Effect of the hot filter temperature on properties and chemical composition of first fuel

The analysis results of the first fuel in Table 1 show that an increase of the hot air filter temperature from 100 to 300 °C increased the heating value from 42.4 to 44.8 MJ/kg. In addition, the fuel obtained from the hot filter temperature of 300 °C also significantly increased the viscosity and density of the fuel. The bio-oil produced in our study exhibited a viscosity range of 1.4–4.51 cSt, comparable to cassava peel-derived bio-oil (2.10–3.87 cSt) reported by Oni *et al*.[27] However, its high oxygen content reduces stability and heating value, as highlighted by Vasudevan *et al*.[28] Therefore, upgrading methods such as hydrodeoxygenation or catalytic cracking are essential to meet fuel-grade requirements. It was shown that the increase in temperature and pressure inside the system significantly helped to separate the light pyrolysis vapor from the first condenser.[2] When considering the flash and fire point, it was found that the fuels from the three experiments were able to ignite at a temperature of approximately 25 °C.

The chemical composition analysis results in Fig. 4 show that increasing the hot filter temperature from 100 °C to 300 °C reduced the proportion of small molecules in the fuel while increasing the proportion of larger molecules. At a hot air filtration temperature of 300 °C, the composition of Cyclononane (C_9H_{18}) and 1-Dodecene ($C_{12}H_{24}$) increased to a maximum of 23.5 wt% and 25 wt%, respectively. However, the fuel obtained from the hot filter at temperatures of 200 °C and 300 °C still contained chemical components in the gasoline group, and thus this fuel was flammable at room

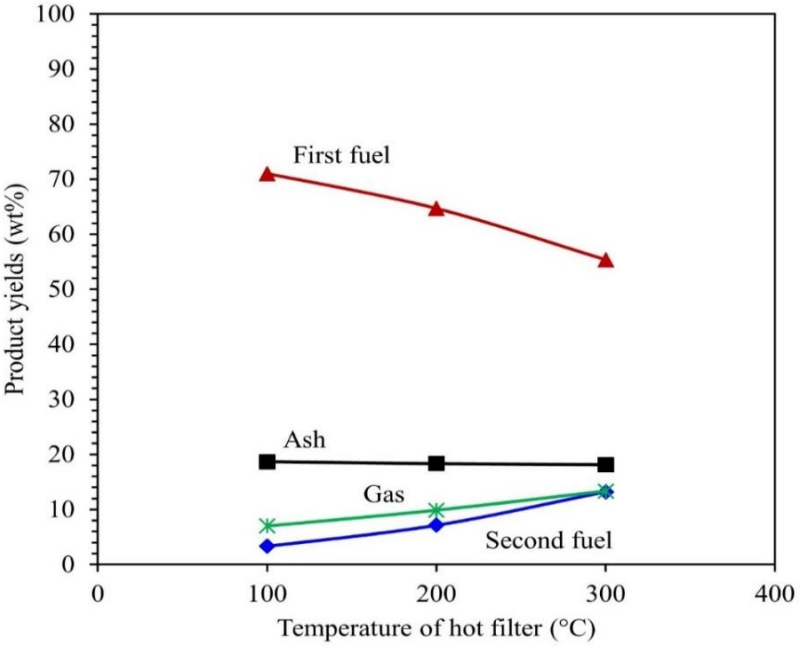

Fig. 3: Effect of the hot filter temperature on products yield.

Table 1: Properties of the first fuel.

Fuel properties	Temperature of hot filter (°C)		
	100	200	300
High heating value (MJ/kg)	42.4±0.8	43.1±0.3	44.8±0.2
Kinetic viscosity (cSt)	1.4±0.3	2.1±0.5	4.5±0.1
Density (kg/m^3)	732.1±2.8	793.4±3.1	825.6±2.4
Flash point (°C)	Fuels flash and ignite at room temperature ~25°C.		
Fire point (°C)			

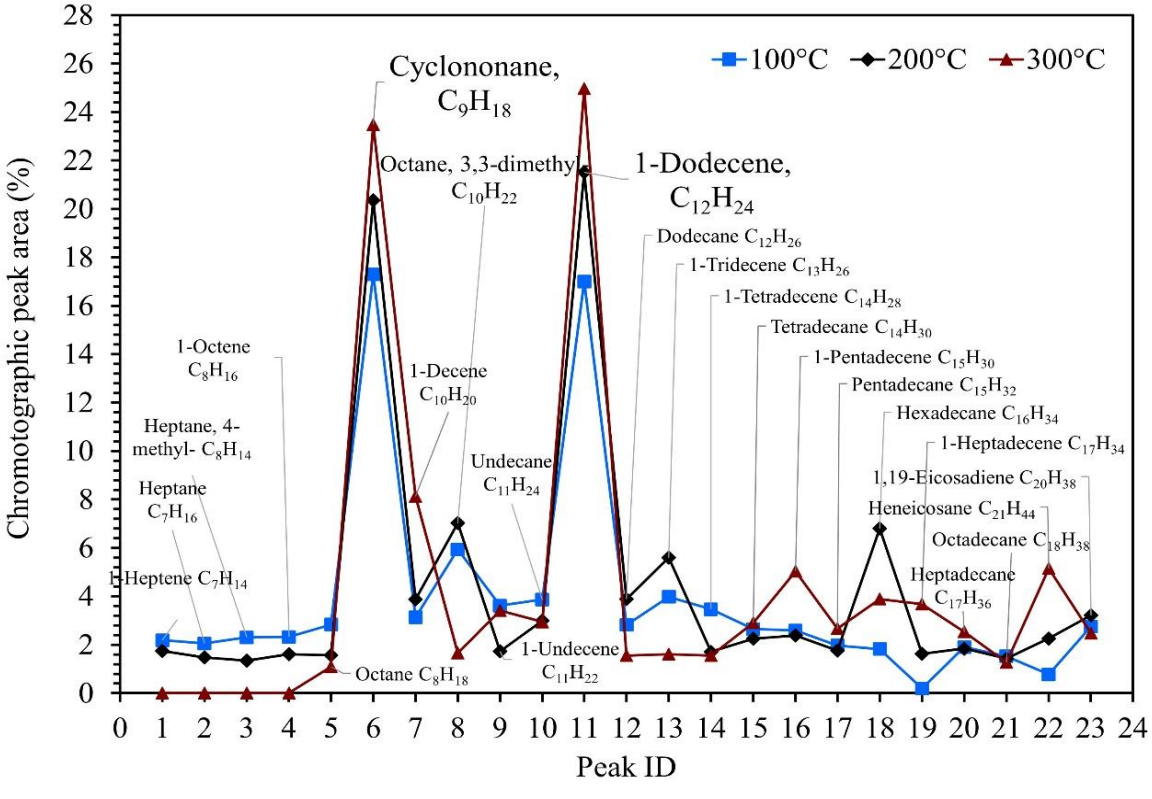

Fig. 4: Effect of hot filter temperature on chemical composition change of the first fuel.

temperature. Increasing the hot air filter temperature raises the system pressure, preventing small molecules such as benzene from condensing in the first condenser.

3.3 Effect of the hot filter temperature on properties and chemical composition of second fuel

The analysis of the properties of the second fuels in Table 2 showed that the three tested fuels had slightly different values in the range of 42.1-42.7 MJ/kg. The viscosity was similar in the range of 1.3-1.6 cSt. The density was in the range of 731-739 kg/m^3. In addition, all three tested fuels were also flammable at a temperature of approximately 25 °C. The analyzed fuel properties are like those obtained from previous experiments in the same type of reactor.[1,2] Therefore, it can be explained that the change in hot filter temperature from 100 to 300 °C does not significantly change the properties of the fuel.

When considering the chemical composition in Fig. 5, increasing the hot filter temperature significantly increased the yield of Benzene (C_6H_6) and Toluene (C_7H_8). As the hot filter temperature increases, the chemical composition of the fuel of the two condensers changes significantly. The chemical composition of small molecules increases while the chemical composition of large molecules decreases.

Moreover, the observed reduction in fuel yield between the first and second condensers is primarily attributed to the effect of increasing hot filter temperatures, which promote intensified secondary cracking reactions of pyrolysis vapors. At elevated temperatures (200–300 °C), the hot filter facilitates thermal degradation of heavier hydrocarbon compounds into smaller, more volatile molecules. As a result, a significant portion of the pyrolysis vapor bypasses the first condenser, which operates at 30 °C, and instead condenses in the second condenser maintained at −40 °C, or exits as non-condensable gas. This behavior is evident in the decline of the first fuel yield from 71 wt% at 100 °C to 55 wt% at 300 °C, accompanied by a corresponding increase in second fuel and gas yields. Additionally, the increased pressure and vapor velocity at higher hot filter temperatures reduce residence time in the first condenser, further limiting the condensation of heavier molecules. This shift in vapor phase behavior underscores the critical role of hot filter temperature in governing product selectivity, vapor residence time, and the overall phase distribution of pyrolysis products across the condensation system.

3.4 Experimental energy efficiency

The effect of process temperature on the fuel yield and energy recovery efficiency from LDPE pyrolysis was investigated across three different temperature conditions: 100 °C, 200 °C, and 300 °C. A constant feedstock mass of 1 kg LDPE with a

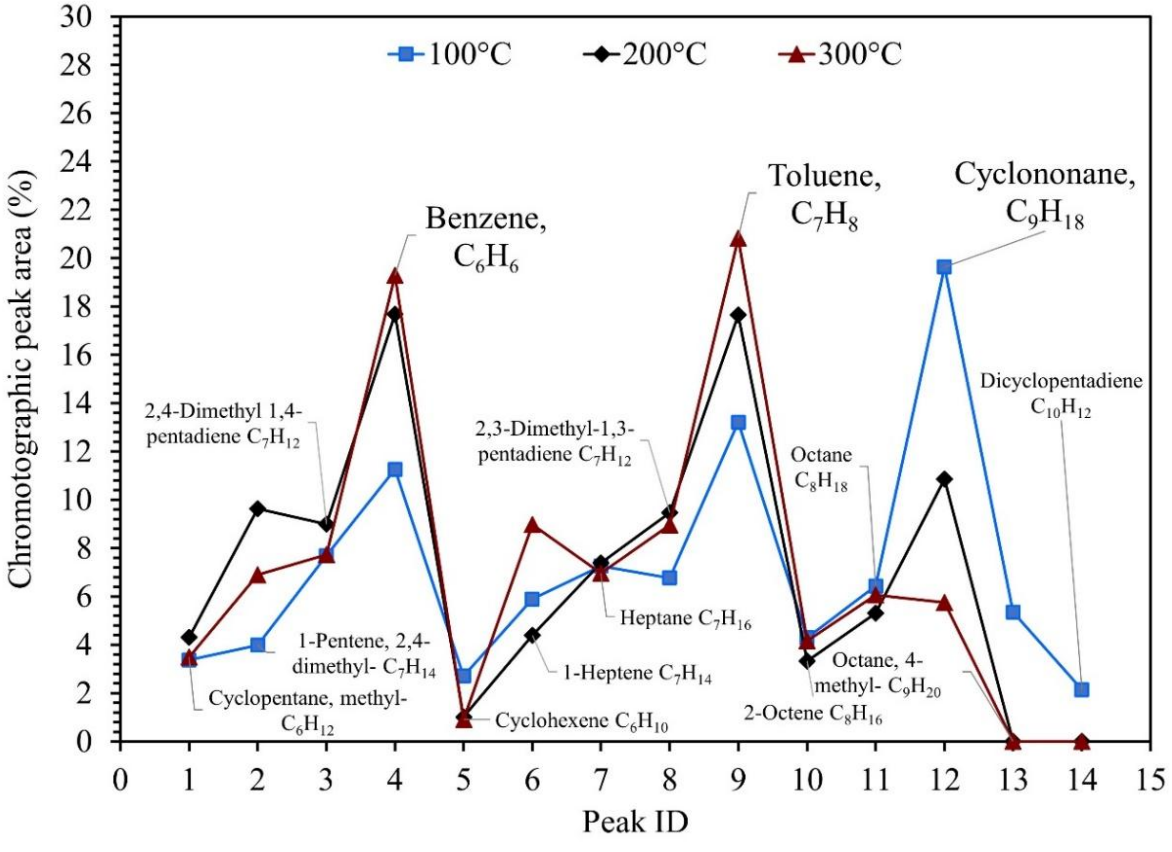

Fig. 5: Effect of hot filter temperature on chemical composition change of the second fuel.

Table 2: Properties of the second fuel.

Fuel properties	Temperature of hot filter (°C)		
	100	200	300
High heating value (MJ/kg)	42.7±0.2	42.1±0.5	42.5±0.1
Kinetic viscosity (cSt)	1.5±0.1	1.3±0.7	1.6±0.4
Density (kg/m^3)	734.5±3.4	739.1±3.2	731.8±3.5
Flash point (°C)	Fuels flash and ignite at room temperature ~25°C.		
Fire point (°C)			

Table 3: Fuel yield, HHV, and efficiency at varying pyrolysis temperatures.

Temperature (°C)	Fuel Yield (wt%)	HHV (MJ/kg)	Energy Output (MJ)	Efficiency (%)
100	71	42.55	30.21	69.25
200	64	42.60	27.26	62.49
300	55	43.65	24.01	55.01

HHV of 43 MJ/kg was used in each experiment. Additionally, a thermal input of 0.6325 MJ was applied, resulting in a total energy input of 43.6325 MJ per experiment.

As shown in Table 3, fuel yield decreased with increasing temperature. At 100 °C, the fuel yield was highest at 0.71 kg, followed by 0.64 kg at 200 °C, and 0.55 kg at 300 °C. Despite the declining fuel yield, the HHV of the produced fuel generally increased with temperature. The HHV rose from ~42.55 MJ/kg at 100 °C to ~43.65 MJ/kg at 300 °C, suggesting a higher energy density in the fuel produced at elevated temperatures, potentially due to increased aromatic content or more complete breakdown of polymer chains.

Energy efficiency was calculated as the ratio of energy output to the total energy input. The highest efficiency was observed at 100 °C, with a value of 69.25%. This efficiency gradually declined with an increase in temperature, dropping to 62.49% at 200 °C and 55.01% at 300 °C.

The reduction in efficiency at higher temperatures may be attributed to increased formation of non-condensable gases and ashes, which were not quantified in the liquid yield analysis. These by-products do not contribute to the measured fuel output but still consume input energy, thus reducing overall process efficiency.

3.5 Simulation analysis of hot filter temperature effect

To extend the experimental findings, MATLAB-based simulations were performed to analyze the effect of hot filter temperature on pyrolysis product distribution and energy consumption. The model integrates experimental data, kinetic parameters, and heat transfer calculations to predict yield variations and thermal efficiency across a wide temperature range (100–800 °C). These simulations offer deeper insights into how varying hot filter temperatures influence secondary cracking reactions, energy efficiency, and overall product composition, which is crucial for optimizing LDPE plastic pyrolysis systems.

3.5.1 Predicted Yield Distribution

Hot filter temperature plays a crucial role in determining the final distribution of pyrolysis products by influencing secondary cracking reactions. At lower temperatures (100 °C), primary pyrolysis dominates, leading to a higher proportion of heavier hydrocarbons in the first condenser stage. These heavy fractions result from the thermal depolymerization of LDPE into long-chain hydrocarbons, which condense before undergoing further breakdown. As the hot filter temperature increases to 200–300 °C, enhanced cracking reactions promote the breakdown of these long-chain hydrocarbons, leading to a gradual reduction in first-stage fuel yield while increasing the production of gas and lighter liquid fractions in the second condenser.[9]

Beyond 400 °C, simulations predict that gasification becomes the dominant reaction as shown in Fig. 6, significantly reducing the liquid fuel yield. This shift is attributed to radical-driven decomposition mechanisms, where increasing temperature favors the formation of smaller hydrocarbon molecules such as methane (CH_4), ethylene (C_2H_4), and propylene (C_3H_6).[29] The decomposition pathways at high temperatures align with previous experimental findings, which indicate that elevated thermal cracking conditions promote hydrogen abstraction and β-scission reactions, leading to increased gas formation.[10]

Simulated GC-MS predictions further confirm that higher hot filter temperatures selectively favor the production of aromatic hydrocarbons such as benzene, toluene, and xylene (BTX compounds). This shift alters the chemical composition of the condensed fuel fractions, which is critical for refining pyrolysis oil into higher-value petrochemicals.[24] The findings align with previous studies on the fast pyrolysis of contaminated sawdust in a circulating fluidized bed reactor,

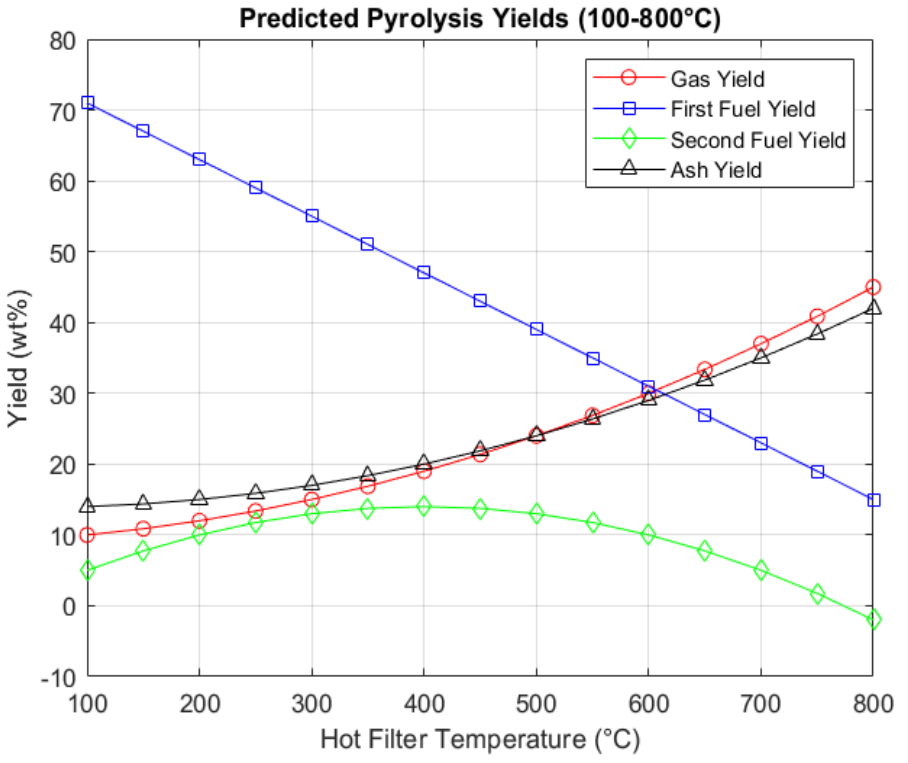

Fig. 6: Predicted Pyrolysis Yields (100-800°C).

which demonstrated that higher temperatures influence the selective formation of aromatic hydrocarbons.[8] Additionally, excessive temperature increases beyond 600°C contribute to unwanted coke formation and excessive gasification, negatively impacting the overall liquid fuel yield.[21]. Many researches also confirmed the presence of coke and its negative contributions to the reaction.[22,24]

Energy balance analysis suggests that although higher temperatures improve the selective separation of fuel fractions, they also increase energy losses due to uncondensed vapors. This finding highlights the need to optimize the hot filter temperature range to maximize liquid fuel yield while maintaining energy efficiency.[22]

3.5.2 Energy balance analysis

The MATLAB simulation incorporates fundamental heat transfer and energy balance equations to evaluate the energy demands across varying hot filter temperatures. The total heat input required for pyrolysis was computed using the mass of LDPE, specific heat capacity, and enthalpy of pyrolysis. The results indicate that at higher hot filter temperatures, increased energy input is required to sustain cracking reactions, leading to significant energy losses due to uncondensed vapors and heat dissipation through reactor walls.

The heat loss calculations include conduction through the reactor wall, convection to the surrounding environment, and radiative losses. From Fig. 7, the simulations reveal that at temperatures exceeding 500 °C, heat losses surpass the additional energy required for pyrolysis, making further temperature increases inefficient from an energy conservation standpoint. Industrial-scale pyrolysis systems must account for this balance to optimize reactor insulation and thermal efficiency. This corresponded well with heat transfer data from other researches.[18,19] A similar investigation of co-pyrolysis blends of camel manure, date pits, and plastic waste highlighted the importance of balancing thermal energy input to optimize product yield while minimizing inefficiencies.

3.5.3 Effect on fuel composition

Simulated GC-MS predictions for extended temperature ranges confirm that increasing the hot filter temperature beyond 300 °C enhances the separation of lighter hydrocarbons, leading to an enrichment of small-molecule compounds in the second condenser. This behavior is advantageous for improving fuel volatility and refining potential. Conversely, beyond 400 °C, heavier hydrocarbon retention in the first condenser decreases significantly, marking a transition toward gasification-dominated reactions. This trend aligns with previous studies indicating that excessive temperature increases favor the formation of non-condensable gases at the expense of liquid hydrocarbons.[20,21] At temperatures beyond 600 °C, the formation of polycyclic aromatic hydrocarbons (PAHs) and coke deposits becomes more prominent, negatively impacting fuel quality and reactor

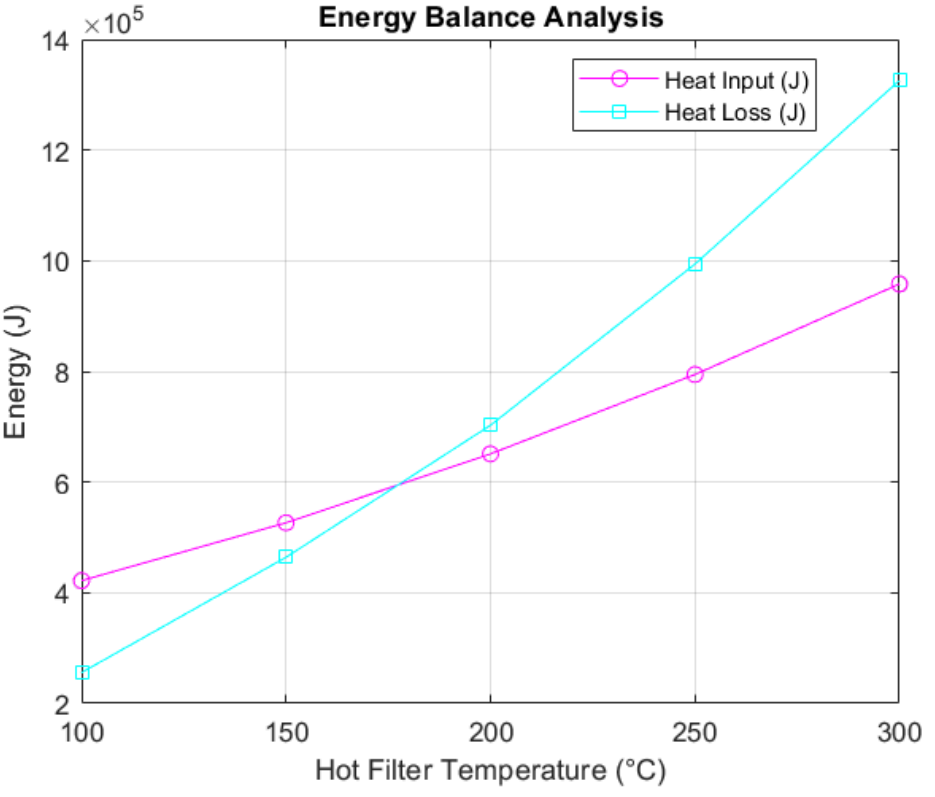

Fig. 7: Energy balance analysis.

performance. To mitigate these effects, process optimization strategies should focus on maintaining the hot filter temperature within an optimal range (typically 350–500 °C) to maximize fuel yield while minimizing coke formation and energy losses.

4. Conclusion

This study highlights the significant role of hot filter temperature in shaping the fuel yield distribution, chemical composition, and energy balance during the pyrolysis of LDPE. Experimental results demonstrate that increasing the hot filter temperature from 100 °C to 300 °C enhances secondary cracking reactions, leading to a reduction in primary condensate yield while increasing gas and second-condensate fractions. A notable shift in hydrocarbon composition was observed, with higher hot filter temperatures promoting the formation of heavier hydrocarbon chains in the first condenser while increasing the proportion of light hydrocarbons in the secondary fuel.

The MATLAB-based simulation extended the experimental findings, allowing for predictive analysis beyond the tested temperature range. Simulated results indicate that at temperatures exceeding 400 °C, further secondary cracking leads to an increased formation of non-condensable gases, reducing overall liquid fuel yield. Additionally, the energy balance analysis revealed that higher hot filter temperatures require additional heat input to sustain cracking reactions, with diminishing returns observed beyond 500 °C due to excessive heat loss and reduced liquid yield. Compared to similar pyrolysis systems, our process achieved a competitive yield and energy balance. Suttibak[25] and Ly *et al.*[26] reported yields of 64.6% and 50.68%, respectively, for biomass waste feedstocks. These findings reinforce the importance of optimizing hot filter temperature to balance energy efficiency, product selectivity, and fuel quality.

The impact of hot filter temperature on fuel properties was also evident in viscosity, density, and heating value variations. At 300 °C, the first-condensate fuel exhibited a heating value increase from 42.4 MJ/kg to 44.8 MJ/kg, suggesting a higher energy content due to enhanced separation of heavier hydrocarbons. Simultaneously, viscosity and density increased, reflecting a shift toward a more diesel-like fuel composition. The second-condensate fuel, primarily composed of lighter hydrocarbons such as benzene and toluene, remained relatively stable in its physical properties, reinforcing the role of hot filtration in refining fuel fractions.

The integration of experimental data with simulation not only validated the observed trends but also provided a predictive framework for process optimization. By fine-tuning hot filter temperatures, industrial-scale pyrolysis systems can enhance fuel separation, improve yield efficiency, and optimize the economic viability of the process. Future research

should focus on refining kinetic models to improve simulation accuracy, exploring the use of catalysts to further enhance product selectivity, and conducting a comprehensive techno-economic analysis to assess the commercial feasibility of optimized LDPE pyrolysis systems. Additionally, further studies on the environmental impact of varying hot filter temperatures could contribute to sustainable advancements in waste-to-fuel conversion technologies. Future Work or Scale-up Potential. The current reactor design can be upscaled by adding multiple reactor units in parallel or increasing reactor volume with corresponding thermal control. Upscaling is feasible with appropriate insulation and automation control. The main application of this system is in decentralized waste-to-energy conversion facilities, especially in rural areas or developing regions.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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