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Liquid Fuel Production by Co-pyrolysis of Plastic Waste Mixture: Influence of Temperature

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Abstract

The growing accumulation of the plastic waste poses serious challenges to environmental safety. Simultaneously, the rising global demand for fuel has intensified efforts to convert the plastic waste into various valuable products, such as fuel. Plastic is normally sulfur-free; therefore, it produces green fuel. Co-pyrolysis offers an environmentally friendly and effective disposal method for converting plastic waste mixture into valuable liquid fuels with a positive synergistic effect between various types of wastes. This study investigates the co-pyrolysis of polypropylene, polystyrene, and high-density polyethylene in an equal proportion of 1:1:1 by mass, with the temperature ranging from 350 to 470 °C. The results demonstrated a significant impact of temperature on the yield, fractional distribution and physiochemical properties of the liquid fuel product. Liquid fuel was characterized by using American Society for Testing and Materials (ASTM) standard test methods to evaluate its physicochemical properties, including calorific value, American Petroleum Institute (API) gravity, viscosity, and flash point. The characterization of fuel revealed that co-pyrolytic oils exhibited physiochemical properties either within or similar to the ASTM standard range of conventional kerosene fuel. Additionally, the highest liquid fuel yield of 95% was achieved at 470 °C. ASTM D86-23a distillation confirmed the maximum kerosene fraction of 49.5%, in the liquid fuel obtained at 470 °C.

Keywords

co-pyrolysis, plastic waste, liquid fuel, kerosene

1 Introduction

The rapid increase in plastic production on an industrial scale [1], consumption on a daily basis [2], and improper recycling of the plastic waste is triggering environmental issues in the form of land, air, and water pollution, adversely affecting human as well as animal life [3]. Over the past few years, there has been a growth in the consumption and production of plastic, which has led to a buildup of plastic in landfills, causing land contamination and increasing greenhouse gas emissions [4, 5]. A global environmental disaster involving disease transmission, garbage accumulation, unhygienic conditions, soil degradation, water contamination, and other issues are continuously increasing by the landfills [6]. According to research, only around 5% of all the manufactured plastic is recycled, and the remaining takes over 450 years to biodegrade [7]. Therefore, to preserve the environment and life, plastic waste disposal is a significant and developing issue that needs to be addressed right away [8].

There are various methods to recycle plastic waste mixture (PWM) including incineration [9], landfilling [10], gasification [11], and pyrolysis [12]. Considering the environmental problems, rising reliance on petroleum products and economically stable approaches, pyrolysis is one of the most effective processes to tackle all these issues simultaneously [8]. Pyrolysis is the thermal degradation of wastes in an oxygen-free environment, resulting in the production of pyrolytic oil, which can be directly used as a fuel [13]. Moreover, co-pyrolysis is the thermal decomposition of two or multiple wastes together in the absence of air or in an inert atmosphere [12, 14]. It has been reported that co-pyrolysis of different wastes has resulted in better product yield and physiochemical properties of

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the petroleum product when compared to the simple pyrolysis of wastes individually, because of the positive synergetic interactions among the waste materials [15, 16].

It has to be noted that the pyrolytic oil (PO) produced from single plastic feedstock or co-pyrolytic oil (CPO) produced from more than two or more types of plastic feedstocks does not contain sulfur compounds. Because there is negligible or no sulfur in the waste plastic feedstock, this characteristic advantage makes plastic waste mixture an advantageous source of alternative and green fuel as compared to fossil fuel, which results in the production of toxic SO_x gases [17].

Various studies of individual pyrolysis of plastic waste and co-pyrolysis of plastic waste with other materials or another type of plastic wastes have been reported. Only co-pyrolysis studies including plastic wastes will be discussed at this stage. The co-pyrolysis of low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), and polypropylene (PP) has been reported in a batch pyrolytic reactor, with the distillation process to obtain gasoline-like fuel. The mixture of 200 g of plastic mixture (20.5 wt.% LDPE, 14 wt.% HDPE, 20.5 wt.% PS and 45.5 wt.% PP) was fed to the reactor, with a heating rate of 20 °C/min, and a reactor temperature set to 700 °C. The yield of the liquid fuel mixture was 67%, consisting of a 50.3% gasoline fraction. The study concluded that the properties of the resulting gasoline did not meet the requirement criteria of European gasoline standards, whereas blending the product with ethanol showed enhanced fuel properties [18].

Moreover, waste PP, polyethylene (PE), and mixed plastic waste comprising of municipal and industrial plastics have been co-pyrolyzed in a reactor made up of stainless-steel. The temperature of the pyrolysis reactor was set to 480 °C at 101.3 kPa pressure, with a heating rate of 10 °C/min, and a reaction time of 80 min. The liquid product yield was 63%, with the properties resembling to commercial diesel fuel. However, the high amount of heavy fractions suggested the potential requirement of the optimization of process conditions [19].

Many types of plastic wastes have been co-pyrolyzed together, to the best of the authors' knowledge, there is no previous study which has specifically investigated the co-pyrolysis behavior of plastic waste mixture of PP, PS, and HDPE, while analyzing the influence of variable temperature on the product yields, fractions, and commercially important liquid fuel properties. Yields of co-pyrolytic products were obtained by using mass balance. Various volume fractions of the liquid fuel were evaluated by using the standard ASTM D86-23a [20] distillation. Physiochemical properties of the liquid fuel, including calorific value, American Petroleum Institute (API) gravity, viscosity, and flash point, were evaluated using American Society for Testing and Materials (ASTM) standard test methods for the fuels. Additionally, the comparison of the liquid fuel with ASTM standard specifications of the commercial kerosene has also been provided, because the fuel closely resembles to kerosene.

2 Experimentation

2.1 Raw materials and pre-treatment

The raw materials were a mixture of post-consumer or waste PP, PS and HDPE. The total PWM feed was 1.5 kg with a mass ratio of 1:1:1 (PP/PS/HDPE). The PWM was collected from various sources, cleaned and crushed to the average particle size of 3 mm. The raw material was purchased or collected in bulk quantity to prevent the variation of raw material properties during this research.

2.2 Pyrolysis equipment

2.2.1 Equipment specifications

Externally heated pyrolysis reactor volume: 16 L; material of construction: stainless steel 304; reactor inlet valve (V-101); reactor outlet valve (V-102); pressure relief valve (PRV-101); condenser inlet valve (V-103); liquid outlet collection vessel valve (V-104); gaseous collection vessel outlet valve (V-105); 250 L polyvinyl chloride (PVC) water cooling tank, pump with 735.5 W power (P-101).

2.2.2 Details of equipment

All the experiments were performed in a pyrolysis reactor setup consisting of a nitrogen cylinder, an externally heated resistant heater pyrolysis reactor, a jacketed cooling water condenser, a liquid collection vessel, a centrifugal pump and a cooling water PVC tank. The diagram of the experimental setup has been shown in Fig. 1.

A pyrolysis reactor with 16 L volume, made up of stainless steel 304 was used in this study. The reactor was externally heated with jacketed, with resistant heating elements. A thermocouple was also fitted to measure and control the feed temperature, connected to a proportional-integral-derivative (PID) controller. All the co-pyrolysis experiments were conducted in an inert atmosphere through an inlet valve (V-101), which was connected to the nitrogen cylinder, used to purge the nitrogen gas and create an inert atmosphere. The reactor was also connected

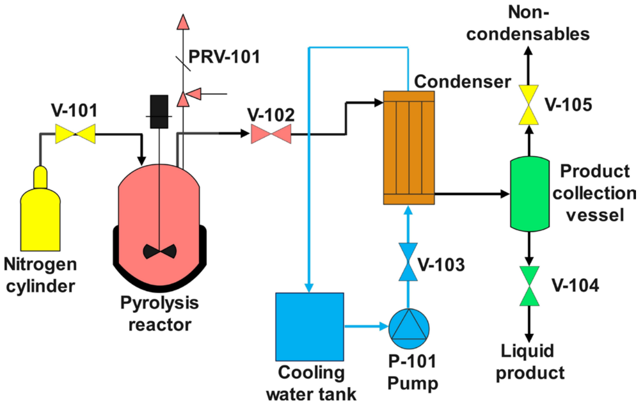

Fig. 1 Process flow diagram of externally heated pyrolysis reactor setup

to an outlet valve (V-102) used as an outlet for the co-pyrolytic products and nitrogen as well (during the purging process). A pressure relief valve (PRV-101) was fitted before the outlet regulating valve in the reactor to release the pressure to ensure that process is safe to handle.

Reactor was operated in semi-batch mode for all the co-pyrolysis experiments with 101.3 kPa inert pressure in the system created by using nitrogen gas before the start of each experiment. The co-pyrolytic products produced in the reactor were cooled down in the copper coil, water cooled jacketed condenser. Jacket was used for the cooling water, while copper coil for the co-pyrolytic product. The cooling water flow (50 L/min) was maintained by using a valve (V-103). stainless steel 304 product collection vessel (20 L volume) was used to collect the liquid product produced by co-pyrolysis. The outlet valve (V-104) was used to collect the liquid fuel product in the collection vessel for analysis and testing, and non-condensable gases were removed through another outlet valve (V-105).

A PVC tank of 250 L volume was used for the continuous flow of cooling water circulation in the condenser. 735.5 W centrifugal pump (P-101) was used for the continuous flow of cooling water towards condenser, which was returned to the PVC tank.

2.3 Experimental procedure

2.3.1 Procedure specifications

Total mixed plastic feed; 1.5 kg, composition; PP/PS/HDPE mass ratio of 1:1:1, operation mode; semi-batch, temperature; 350, 390, 430 and 470 °C, pressure; 101.3 kPa inert, reaction time; 40 min, power; 3 kW, nitrogen purging rate; 25 L/min, nitrogen purging duration; 30 min.

2.3.2 Procedure details

Raw materials were first cleaned and crushed, then preheated to 120 °C to remove any moisture content. Three raw material samples with a total of 1.5 kg of feed of PP/PS/HDPE were used with a mass ratio of 1:1:1 (500 g of each plastic type). Samples were measured in the required quantity, mixed, and fed to the pyrolysis reactor. Nitrogen cylinder was then connected to the inlet reactor valve (V-101) and co-pyrolysis setup was then pressurized using nitrogen at 300 kPa while closing the collection vessel outlet valves (V-104 and V-105), and leakage checking was conducted by using the detergent mixed foaming water.

To create the inert (nitrogen) atmosphere in the co-pyrolysis system, the nitrogen was purged at a volumetric flow rate of 25 L/min for 30 min to create the inert atmosphere in the whole system. While nitrogen was purged, reactor inlet and outlet valves (V-101 and V-102), as well as two collection vessel outlet valves (V-104 and V-105) remained open.

When the nitrogen purging was completed, the reactor inlet valve (V-101) and product collection vessel liquid product outlet valve (V-105) were closed. Outlet reactor valve (V-102), which was used for the flow of the products produced by co-pyrolysis and product collection vessel valve (V-105) used to remove and dispose of the non-condensable gases, remained open. The set point temperature within the range of 350–470 °C was set on the PID controller, and each sample was heated with 3 kW power using an externally heated resistant heater element. When the set point temperature was reached, a reaction time of 40 min for each sample was provided.

The yield of liquid fuel below 350 °C was insufficient to perform the ASTM D86-23a [20] distillation and evaluation of the properties. Therefore, the temperature below 350 °C was not included in the study. Similarly, the optimum liquid fuel yield of 95% was obtained at 470 °C, with a negligible residue of 0.3%. Whereas, temperature higher than 470 °C was not possible to check, because there was insufficient amount of residue to be converted into the liquid product. Moreover, high residence time of the co-pyrolysis process is because of the large reactor volume.

The co-pyrolytic products produced in the reactor (which include condensable and non-condensable products) were then cooled down in the condenser in its copper-made coil, which was surrounded by the cooling water jacket, in which continuous flow of water at room temperature condensed major part of the product. Whereas residue and non-condensable gases were also produced in small quantities. The constant flow of cooling water (50 L/min) was maintained by using a flow regulating valve (V-103). The liquid fuel condensed in the condenser was then collected in the product collection vessel for further analysis and testing. Whereas, residue produced in the reactor and gases (which were non-condensable in nature) were disposed of. The co-pyrolysis process was semi-batch, because liquid fuel collection was continuous, whereas raw materials were charged batch-wise.

3 Product characterization

3.1 Standard specifications of kerosene

Each co-pyrolytic product obtained was compared to the standard ASTM specifications, used for the commercial kerosene fuel, because most of the samples showed a major fraction of kerosene when tested using ASTM D86-23a [20] distillation. The ASTM standard specifications of the kerosene fuel are provided in Table 1 [21–24].

3.2 Testing standards for fuel

The liquid fuel testing was performed by using the ASTM standards [20, 25–28]. Testing included ASTM D86-23a [20] distillation, calorific value using ASTM D240-19 [25], API gravity using ASTM D1298-12b(2017)e1 [26], viscosity using ASTM D445-24 [27], and flash point using ASTM D92-24 [28]. Three phase mass balance was also performed, and the yields of CPO, semi-solid residue, and non-condensables were measured. Only liquid fuel products were tested, as the aim of this study was restricted to the liquid fuel products. Non-condensable gases and the residue were disposed, because their characterization was out of the scope for this research.

3.3 Error and repeatability

All the experiments and tests were performed twice, and average values were reported. If an error of greater than 5% was observed, then the relevant test method or experiment was repeated until the error between two values was not reduced to 5%.

4 Results and discussion

4.1 Co-pyrolysis products

Total PWM feed of 1.5 kg consisting of PP/PS/HDPE with fixed mass ratio of 1:1:1 was processed at four different co-pyrolysis temperatures of 350, 390, 430, and 470 °C (more details about the other process conditions have already been provided in Section 2.3.1). The product obtained in each of these four experiments was observed to be in the form of liquid fuel, semi-solid residue, and non-condensable gases, with various proportions as an impact of variable temperature. These proportions have been discussed with graphical representation in Section 4.1.1 in detail. Liquid fuel was the major product of the experiments.

Table 1 ASTM D1655-21c [21] and ASTM D3699-13be1 [22] standards for kerosene fuel

Properties of fuel	ASTM standards range for kerosene
Calorific value (MJ/kg)	42.8 (minimum) [21]
API Gravity at 15.6 °C (°)	37–51 [21]
Viscosity at 40 °C (mPa s)	0.78–1.6 [22]
Flash point (°C)	38 (minimum) [21]

Details of the ASTM D86-23a [20] distillation and resulting fractions have been discussed in Section 4.1.2. ASTM D86-23a [20] of the liquid fuel showed that it was a mixture of fractions having boiling range of heavy fuel oil, diesel, kerosene and naphtha with various proportions depending on the co-pyrolysis temperatures. Physiochemical properties of the liquid fuel were closer or within the range of kerosene fuel; therefore, its physiochemical properties were compared to the standard property ranges of the commercial kerosene fuel, as discussed in Sections 4.1.3 to 4.1.6. These properties included calorific value, API gravity, viscosity and flash point, respectively.

4.1.1 Product distribution of co-pyrolysis

The co-pyrolysis of PWM yields CPO as a major liquid fuel product, along with the semi-solid residue and a non-condensable gas. Fig. 2 represents the product distribution in the form of yields at different co-pyrolysis temperatures (350 °C to 470 °C) in terms of liquid product (wt.%), residue (wt.%), and non-condensable gases (wt.%). Yield can be defined as the ratio of the quantity of a specific product to the quantity of feedstock used [29]. The yield of the co-pyrolysis products mainly depends upon the reaction temperature, reaction time and heating rate [30]. Parameters other than temperature were kept as constant (refer to Section 2.3.1 for the other parameters).

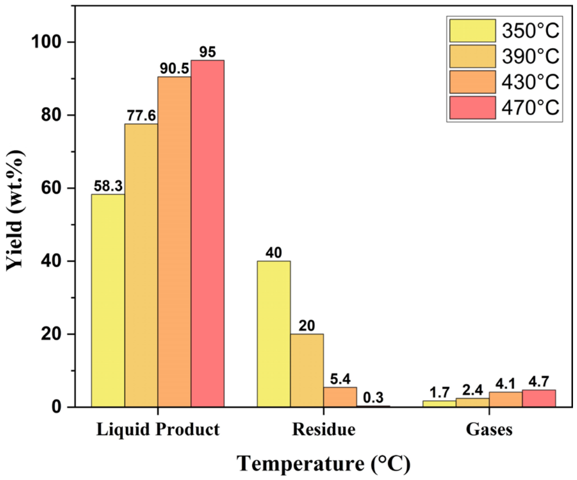

Fig. 2 Product distribution at various temperatures

At 350 °C, the liquid fraction, residue, and gas fraction were observed to be 58.3%, 40%, and 1.7%, respectively. The significant amount of residue at this temperature indicates an incomplete thermal degradation of the PWM. Although the liquid fraction is dominant, gas production remains minimal. At 390 °C, the product distribution shifted to 77.6% liquid, 20% residue, and 2.4% gas. The reduction in residue and the substantial increase in liquid yield suggest improved conversion efficiency, while gas production increased slightly but remained relatively low.

At 430 °C, the liquid yield reached 90.5%, whereas residue yield decreased up to 5.4% and the gaseous yield increased further to 4.1%. At this stage, liquid yield was observed to be high, indicating higher conversion of the PWM to the liquid fuel. While the production of residue was significantly reduced. The increase in gaseous yield suggested an enhanced decomposition of the heavier hydrocarbons into the more volatile components. At 470 °C, it was observed that the liquid yield further increased to an optimum value of 95%, while the yield of residue dropped to a minimum value of 0.3%, and non-condensable gas production increased to 4.7%. The liquid product yield was observed to be the highest at this stage. This temperature showed almost complete thermal decomposition of the PWM into the liquid and gaseous products, with minimal solid residue remaining. The slight increase in gas fraction compared to the lower temperatures indicates further breakdown of heavier hydrocarbons into lighter and gaseous components.

Results showed that the yield of the liquid fuel increased consistently with the co-pyrolysis temperature, reaching a maximum value of 95% at 470 °C. This showed that the higher temperature enhanced the conversion of PWM into the liquid hydrocarbons. Residue decreased sharply as the temperature increased, dropping from 40% at 350 °C to nearly negligible (0.3%) at 470 °C. This indicated the higher thermal degradation of the PWM at elevated temperatures. Non-condensable gaseous production increased gradually with the increasing temperature, from 1.7% at 350 °C to 4.7% at 470 °C. This showed that heavy hydrocarbons were decomposed to lighter hydrocarbons as the co-pyrolysis temperature increased.

Previous studies reported that the liquid yield from the pyrolysis of waste plastic bags increased from 8% to 45% as the temperature was increased from 250 °C to 450 °C. This increase was attributed to enhanced secondary cracking at higher temperatures [31].

Similar trends were observed in previous studies, where the co-pyrolysis of PWM containing 45% PP, 35% LDPE, and 25% HDPE was performed at various temperatures. The yield of the liquid fuel increased from 26.7% to 32.8% within the range of 450 °C to 500 °C [32]. However, it was noted that with a further increase in temperature, the liquid yield decreased while the gaseous yield increased [32–34]. Moreover, when municipal plastic waste mixture containing 5.6% PET, 8.7% PS, 26.9% PP and 58.8% PE was pyrolyzed, the liquid yield increased from 80.5% to 84% within the range of 500 °C to 600 °C [35]. This confirmed a direct relation of temperature with the liquid fuel yield. However, beyond an optimal temperature of 470 °C, further increase may lead to a decline in the liquid yield due to the secondary cracking, favoring higher gas formation [34].

Based on the observations and previous studies, higher co-pyrolysis temperatures, such as 430 °C and 470 °C proved to be optimum for maximizing liquid yield, with minimal residue. Thus, our results indicated that increasing the temperature enhanced the liquid yield, which ranged from 58.3% to 95%.

4.1.2 ASTM D86-23a distillation

The ASTM D86-23a [20] method was used to perform the distillation of CPO to obtain different fractions. The initial boiling points (IBPs) and end boiling points (EBPs) of the kerosene fraction were selected according to the ASTM D3699-18 standard [36]. The fractions included the lighter fraction (comprising both light and heavy naphtha, IBP to 145 °C), the kerosene fraction (145–300 °C), and the heavier fraction (comprising diesel and heavy fuel oil, above 300 °C) as shown in Fig. 3. In this study, kerosene fractions were observed to be the major fractions, especially at high temperatures. It should be noted that diesel fraction (DF) combined with heavy fraction or heavy fuel

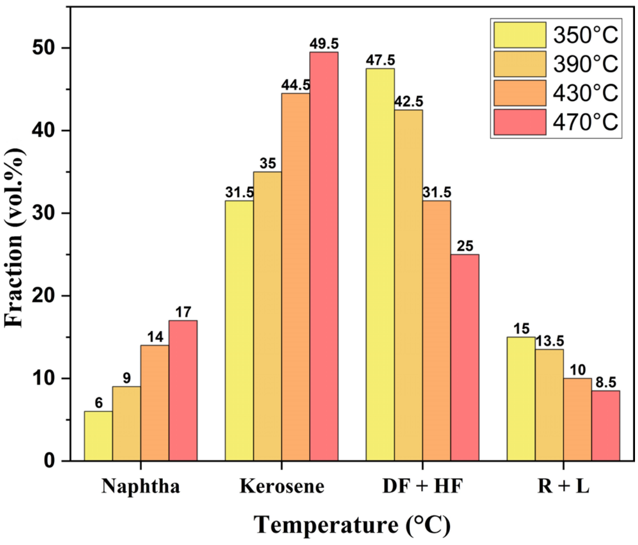

Fig. 3 ASTM D86-23a [20] fractions of CPO obtained at different temperatures

oil (HF) has been represented by (DF + HF), while residue (R) combined with evaporation losses (L) have been represented by (R + L).

When the ASTM distillation of CPO obtained at 350 °C was performed, 6 vol.% of naphtha, 31.5 vol.% of kerosene, 47.5 vol.% of (DF + HF), and 15 vol.% of (R + L) were obtained. The high amount of (DF + HF) indicates that the CPO produced at this temperature contains a greater proportion of heavy fractions as compared to lighter ones. At 390 °C, the kerosene yield increased to 35 vol.%, while 9 vol.% of naphtha, 42.5 vol.% of (DF + HF), and 13.5 vol.% of (R + L) were obtained. This increase in kerosene fraction suggests that increasing co-pyrolysis temperature enhanced the formation of lighter fractions.

A significant rise in the yield of kerosene was observed at 430 °C, reaching a value of 44.5 vol.%, while naphtha, (DF + HF) and (R + L) were recorded to be 14 vol.%, 31.5 vol.%, and 10 vol.%, respectively. The substantial increase in kerosene fraction at this stage confirms the shift toward the formation of lighter fractions with increasing temperature. At 470 °C, the yield of kerosene further enhanced to an optimum value of 49.5 vol.%, while naphtha, (DF + HF), and (R + L) were observed to be 17 vol.%, 25 vol.%, and 8.5 vol.%, respectively. The lowest fraction of (DF + HF) and the highest fraction of kerosene at this temperature further confirmed the strong correlation between temperature and the production of lighter fractions.

The kerosene fractions obtained in this study ranged from 31.5 to 49.5 vol.%, while the optimum yield was observed at 470 °C. The trend indicates that increasing the co-pyrolysis temperature leads to a higher kerosene fraction, demonstrating a direct relationship between temperature and the proportion of lighter fractions in the CPO.

A similar trend has been reported in previous studies. When PS, LDPE, HDPE, and PP were co-pyrolyzed, the lighter fractions increased with increasing temperatures [37]. Similarly, when LDPE bags were pyrolyzed, higher amounts of lighter fractions were obtained at higher temperatures, suggesting that higher temperatures enhanced the formation of lighter fractions [38]. The findings of this study align with previous research, where an increase in temperature resulted a higher yield of lighter fractions. The fraction of the liquid fuel within the boiling range of 145–300 °C was considered as kerosene, the fraction above this boiling range was considered as a mixture of diesel and heavy fuel oil, whereas, the fraction below this boiling range was considered as naphtha fraction [36, 39, 40].

Therefore, this research concludes that higher temperatures are favorable for the higher amount of lighter fractions and kerosene as compared to the diesel and heavy fuel oil in the co-pyrolysis of PWM. The optimum fraction of kerosene was observed to be 49.5 vol.% at 470 °C.

4.1.3 Calorific value

The calorific or heating value is defined as the amount of energy released when a fuel is burned in the presence of air [41]. A high calorific value of CPO indicates its potential as a viable energy source [42]. The calorific values of the obtained CPO ranged from 35.8 MJ/kg to 40.5 MJ/kg, as shown in Fig. 4. Among the various temperatures, the highest calorific value was recorded at 470 °C, which closely resembles the commercial kerosene fuel. However, all values remained closer but below the ASTM standard range. With increase in temperature, a gradual increase in calorific value was observed.

In our previous study on the co-pyrolysis of waste cooking oil (WCO) and waste lubricating oil (WLO), a similar trend of increasing calorific value with rising temperature was observed, which was attributed to the formation of deoxygenated compounds [12].

A similar trend has been observed in the pyrolysis of LDPE waste, where the calorific value increased with increasing temperature from 250 to 300 °C [43]. Likewise, when waste LDPE bags were pyrolyzed, the calorific value also increased with increasing temperature [31]. These previous studies validate the trend observed in this research.

Based on previous research and ASTM standard ranges, it can be inferred that co-pyrolysis temperatures above 400 °C produce CPO with relatively higher calorific values. The CPO obtained at 470 °C demonstrated the closest resemblance to the calorific value of kerosene.

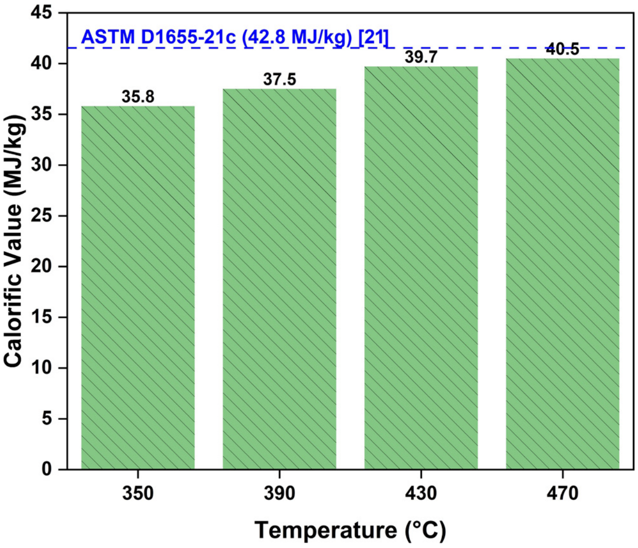

Fig. 4 Calorific values of CPO at various temperatures

However, below this temperature, a lower calorific value as compared to the standard value of calorific value of kerosene was observed, likely due to the incomplete thermal cracking and the improper breakdown of heavier hydrocarbons into higher energy volatile fractions.

4.1.4 API gravity

API gravity is a very important parameter that indicates whether fuel is heavier or lighter than water. API gravity is related inversely to the density of the fuel, indicating that denser fuels exhibit lower API gravity. Fuels with an API gravity greater than 10 are typically lighter than water, whereas those with an API gravity below 10 are comparatively heavier [44]. API gravity is evaluated based on the specific gravity (SG), which is also referred as relative density, or the ratio of a fluid's density at 15.6 °C to the density of water at the same temperature. The calculation of API gravity was performed using the following formula [14, 45]:

$$\text{API} = \frac{141.5}{\text{SG}} - 131.5.$$

The API gravities of the CPO samples ranged within 37.1° to 60.2°, as shown in Fig. 5. The API gravities in the range of 350 °C to 430 °C fall within the ASTM defined range, whereas at 470 °C, it exceeded the ASTM limits, confirming the presence of lighter hydrocarbon fractions at higher temperatures. This trend indicates that API gravity increases with rising temperature.

In our previous study, it was observed that higher co-pyrolysis temperatures during the co-pyrolysis of WLO and WCO enhanced the thermal decomposition of heavy components, leading to the formation of lighter hydrocarbons with higher API gravities or lower densities [12].

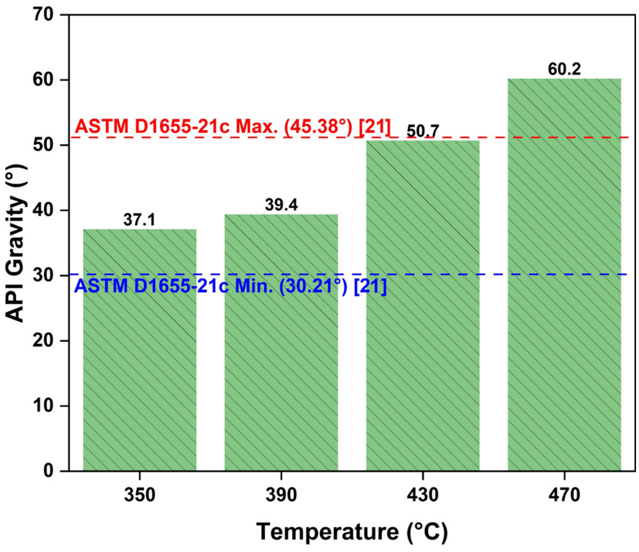

Fig. 5 API gravities of CPO at various temperatures

Previous studies showed that during the pyrolysis of waste LDPE bags in a batch reactor, the specific gravity decreased with rising temperature, implying a corresponding rise in the API gravity [31]. Similarly, when *Parthenium hysterophorus* (a type of lignocellulosic biomass) was pyrolyzed, the results showed that higher temperatures promote the formation of lighter, more volatile compounds with lower densities, lower specific gravities, and higher API gravities [46]. The results indicated that API gravities of the co-pyrolytic samples within 350 °C to 430 °C fall within the ASTM defined range, whereas at 470 °C, it exceeded the ASTM limits. Beyond this range, the fuel exhibits significantly higher API gravity, suggesting an increased presence of lighter fractions, which may affect fuel performance or blending requirements.

4.1.5 Viscosity

Dynamic viscosity is also a crucial parameter of the fuel, defined as internal resistance to the flow of a liquid. The viscosities of the CPO obtained from the co-pyrolysis of PWM was observed to range within 0.78 mPa s to 1.03 mPa s, as shown in Fig. 6. The CPO obtained at each co-pyrolysis temperature falls within the ASTM defined range. A decreasing viscosity trend with increasing temperature was observed, which is because of the higher proportion of lighter fractions formed at higher temperatures.

According to our recent study on the co-pyrolysis of WLO and WCO, the kinematic viscosity of the fuel samples decreased with increasing temperature, indicating the presence of shorter hydrocarbon chains, reduced intermolecular entanglement, lower resistance to flow, and a higher proportion of unsaturated chains [12].

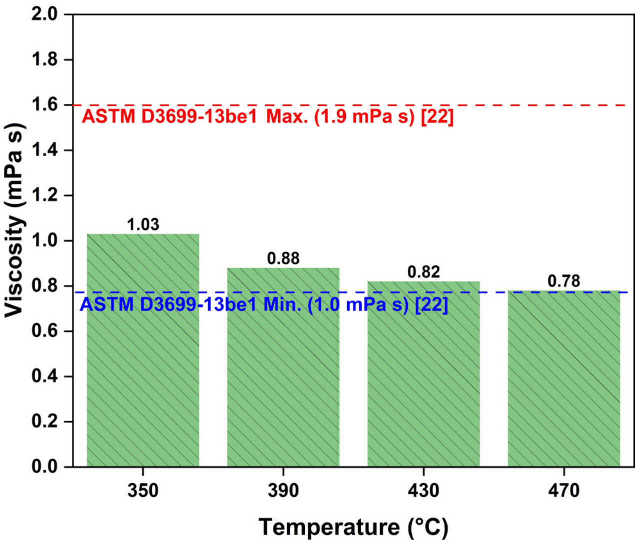

Fig. 6 Dynamic viscosities of CPO at various temperatures

Another previous study confirmed the similar decreasing viscosity trend, where a mixture of solvent and each individual plastic (HDPE, LDPE, and PP) was pyrolyzed separately at varying temperatures. The viscosity of PO samples obtained from each plastic waste type consistently decreased as the temperature was increased from 120 °C to 260 °C [47]. Similarly, during the pyrolysis of waste tires, the kinematic viscosities decreased as the temperature was increased [48], further validating the trend observed in this research. Based on these findings, it can be concluded that the co-pyrolysis of PWM should be conducted at any temperature range between 350–470 °C to achieve a dynamic viscosity within the ASTM standard range. Above this temperature, the viscosity may fall below the ASTM defined range, which is undesirable. Higher temperatures are favorable for the production of lighter fractions, thereby reducing the viscosity beyond the acceptable limit.

4.1.6 Flash point

Flash point is the lowest temperature at which a fuel ignites momentarily in the presence of oxygen. It is a critical parameter for ensuring the safe handling of the fuel, as a lower flash point indicates higher volatility [2, 14]. The flash points of the CPO obtained at different temperatures were observed to be within the range of 33 °C to 47 °C, as shown in Fig. 7. A decreasing trend in the flash point was observed with the rising temperature, which can be attributed to the presence of higher volatile fractions at the elevated temperatures. The CPO obtained at 350 °C resulted flash points above ASTM defined range, while the sample at 390 °C meets the minimum required limit of the ASTM standard exactly. However, at temperatures beyond 390 °C, the flash points decreased below the ASTM defined range.

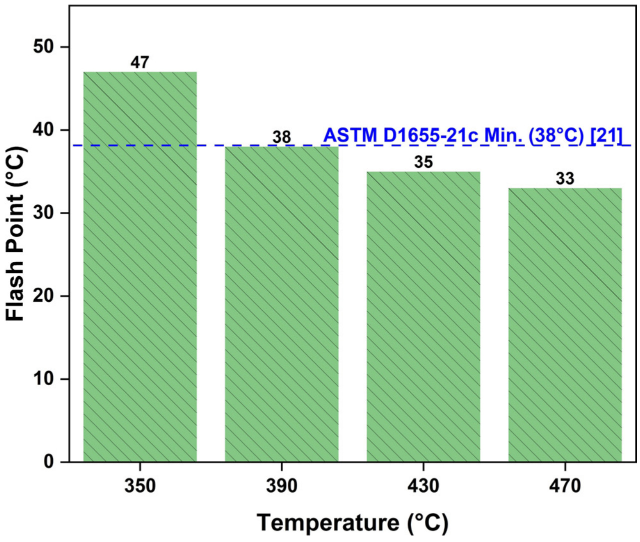

Fig. 7 Flash points of CPO at various temperatures

In our previous research on the co-pyrolysis of WLO and WCO showed that increasing the temperature led to the lower flash points, likely because of the enhanced formation of lighter fractions from the decomposition of heavier components [12].

Other previous studies have also reported a similar trend, where the pyrolysis of waste PP resulted a decreasing trend of flash points as the temperature was increased from 250 °C to 350 °C [49]. Similarly, when waste LDPE bags were pyrolyzed, the flash points decreased from 96 °C to 27 °C with increasing temperature [29]. According to the results, it can be concluded that CPO obtained at 350 °C and 390 °C meet the minimum ASTM defined flash point limit, making it safer for handling. However, at higher temperatures, the flash points decreased below the ASTM standard range, increasing the volatility of the fuel, which poses potential hazards.

5 Conclusion and future recommendation

This study discussed the co-pyrolysis of mixture of post-consumer or waste PP, PS, and HDPE with an equal mass ratio at 3 kW power, 40 min residence time, 101.3 kPa inert atmospheric pressure, a 25 L/min nitrogen purge rate, and a 30 min nitrogen purging time under varying temperatures ranging from 350 °C to 470 °C. Product distribution and ASTM D86-23a [20] distillations of CPO were studied to identify the various yields and fractions, respectively.

The physiochemical properties including calorific values, API gravities, dynamic viscosities, and flash points of CPO were evaluated according to the ASTM standard test methods. Additionally, the effect of different co-pyrolysis temperatures on the kerosene fractions obtained *via* ASTM distillation in the boiling range of 145 to 300 °C were also examined. Physiochemical properties were also compared to the standard ASTM specifications of the commercial kerosene fuel.

The results showed that the highest liquid fuel yield of 95% was obtained at 470 °C, with a negligible amount of residue, indicating the presence of lighter compounds. The maximum kerosene fraction of 49.5% was obtained through the ASTM distillation of CPO produced at 470 °C. Additionally, the physiochemical properties of the liquid fuels were observed to be either within or similar to the ASTM standard ranges or limits of the commercial kerosene fuel.

Future studies can focus on enhancing fuel efficiency and quality by co-pyrolyzing plastic waste mixture (PWM) with other substances, such as waste oils, biomass or additional polymeric wastes. Additionally, the use of different catalysts can optimize the yield and improve key fuel physiochemical properties. Residue and gases can also be analyzed and used for the suitable purposes.

Furthermore, studies on large scale applications and process optimization could help in the commercialization of this method for sustainable fuel production. Scalability and industrial application of this laboratory scale co-pyrolysis research requires technoeconomic assessment, changes in the design of heating system, such as design of the burner for large scale heating, instead of electric heating. Moreover, semi-batch mode of operation needs to be converted into the continuous mode. Fuel produced in this research can also be directly used in the industries or blended with the commercial fuels.

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Abbreviations

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
CPO	Co-Pyrolytic Oil
DF	Diesel Fraction
EBP	End Boiling Points
HF	Heavy Fraction or Heavy Fuel Oil
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
IBP	Initial Boiling Point
L	Evaporation Losses
PID	Proportional Integral Derivative
PO	Pyrolytic Oil
PP	Polypropylene
R	Residue
PRV	Pressure Relief Valve
PS	Polystyrene
PVC	Polyvinyl Chloride
SG	Specific Gravity
PWM	Plastic Waste Mixture
WCO	Waste Cooking Oil
WLO	Waste Lubricating Oil

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