EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(2), 431–443
https://doi.org/10.12912/27197050/217577
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.12.31
Accepted: 2026.01.31
Published: 2026.02.07

Performance evaluation of an integrated pyrolysis-distillation reactor for in-situ wax-like oil elimination from polypropylene waste

Chrisye France Longdong[1], Ibrahim Djamaluddin[2*], Irwan Ridwan Rahim[2]

[1] Department of Environmental Engineering, Faculty of Engineering, Hasanuddin University, Jl. Malino Km. 6, Makassar, Indonesia
[2] Graduate School of Engineering, Hasanuddin University, Jl. Malino Km. 6, Makassar, Indonesia
* Corresponding author's email: ibedije@gmail.com

ABSTRACT

The pyrolysis efficiency of plastic waste into fuel is generally constrained by the formation of wax-textured oil fractions. So it requires a catalyst or a separate advanced distillation process to obtain a liquid-phase oil fraction, which adds to production costs. In this study, a design for an integrated pyrolysis-distillation reactor configuration with fractional condensation was developed to enable low-temperature operation by applying a dissected energy system. This study aims to identify empirical elimination patterns of wax-like oils via slow-heating-rate control in an integrated reactor at low temperatures. To achieve this goal, polypropylene (PP) plastic pyrolysis-distillation experiments were carried out with slow heating rate control (2 °C/min), low-temperature operational application (200 °C, 250 °C, and 300 °C), and the visual physical characteristics of the oil fraction produced without the formation of a waxy textured oil fraction. The fractional condensation of the oil phase produced in condenser 1 is clear golden yellow, and that from condenser 2 is light clear yellow, similar to the gasoline and kerosene fuel groups in the light-medium fraction with carbon bonds C5 to C16. Meanwhile, the oil phase in condenser 3 is clear reddish-brown, similar to the diesel fuel group in the medium fraction, with carbon bonds ranging from C15 to C20. The results of this study can contribute to the development of large-scale pyrolysis reactors that are more efficient, lower-cost, and capable of producing high-quality liquid fuel without wax-like oil.

Keywords: pyrolysis-distillation integration, in-situ fractionation, wax-like oil, plastic fuel, polypropylene.

INTRODUCTION

Polypropylene (PP) plastic is one of the polymers in high demand globally (Charlesworth, 2021). With the widespread use of single-use plastics and low recycling rates, PP plastic is becoming one of the dominant types of plastic ending up in landfills and polluting the environment. (Andalia et al., 2025). As a widely used polymer with a high calorific value, PP plastic is an ideal raw material for high-value fuels and chemicals via pyrolysis (Vellaiyan et al., 2024). However, in the implementation of PP plastic pyrolysis, the efficiency of forming wax-like oil fractions requires a catalyst or a separate advanced distillation process to obtain a liquid-phase oil fraction (Aprianti et al., 2025; Zeb et al., 2023)influenced by the wax formation. It is essential to identify the wax source and determine the fuel types produced from various plastic waste. This research aims to investigate the outcomes of pyrolysis conducted at 450 °C using bentonite catalyst. Wax formation and pyrolysis oil stability were analyzed across different storage temperatures (16–42 °C. The formation of this wax-like oil results from imperfect pyrolysis of the PP polymer chain (Gebre et al., 2021). The presence of this wax-like oil can cause blockages in piping and condenser systems, thereby increasing maintenance costs for industrial-scale pyrolysis machines (Sangpatch et al., 2025).

The conventional method for eliminating wax-like oil fractions in the catalytic pyrolysis process is typically via a separate advanced distillation process after pyrolysis. Previous studies have generally produced PP plastic pyrolysis oil that has not been properly fractionated (Kusenberg et al., 2022). A single condenser, the simplest system, can only cool pyrolysis plastic steam to liquid oil products without significant separation (Krzywda & Wrzesińska, 2021). While the use of a multi-level condenser in a fractional system can increase the yield of the liquid phase, the oil fraction has not been properly fractionated (Saramath and Chanathaworn, 2024). The use of catalysts allows for the breakdown of larger carbon chains into smaller molecules, thereby reducing the likelihood of wax-tethered oil formation that typically occurs in catalystless pyrolysis (Palmay, Medina, et al., 2022). However, even if the pyrolysis process is carried out with a multi-level condenser and catalysts, it does not guarantee the absence of wax-textured oils (Hung et al., 2023). The presence of a catalyst in the pyrolysis process can increase production costs and pose logistical constraints if the pyrolysis plastic processing facility is far from the supplier or source of catalyst raw materials (Miandad et al., 2016).

Recent research continues to optimize the pyrolysis process through diverse reactor designs, adjustments of operational variables, and modifications to improve pyrolysis yields (Paavani et al., 2024). The reactor configuration and temperature play essential roles in the efficiency and effectiveness of the pyrolysis process (Nolasco Cruz et al., 2025). Research conducted by Thahir et al. (2019) that integrates high-temperature pyrolysis at 500–650 °C and distillation with bubble caps in a single small-capacity reactor system with a common heat source has optimized the yield of liquid oil products. However, it still cannot eliminate the formation of wax-like oils in the type of diesel fuel produced. The high-temperature pyrolysis process requires greater energy consumption, depending on the goal of accelerating the formation of a gas-phase or gas-dominant fuel (Marchetti et al., 2024; Vellaiyan et al., 2024). Meanwhile, pyrolysis research on large-scale reactors implementing distributed energy systems was carried out by Hung et al. (2023) at low temperatures (250–280 °C), under low pressure, and with three-stage catalyst use, offering advantages in terms of emission reduction and lower energy consumption. Based on previously reported research. Therefore, the researcher aims to eliminate the formation of waxy-textured oils without catalysts by integrating pyrolysis and distillation in a single system at a low heating rate and 200–300 °C. There is a gap in scientific data regarding the minimum operating temperature limit for large-scale integrated pyrolysis-distillation production and the low heating rate that can eliminate the formation of waxy textured oils in-situ without a catalyst. The research conducted by Thahir et al. (2019) is still on a laboratory scale with small reactor dimensions by placing the distillation chamber on top of it. Meanwhile, this study used a larger reactor dimension than the previous report so that it can accommodate plastic waste and obtain a larger amount of pyrolysis oil (Miandad et al., 2016). With the change in the dimensions of larger reactors directed to industrial scale, it is a challenge in temperature operations to obtain optimal oil fractionation results. If the thermal energy distribution process is uneven, there will be overcracking due to excess thermal in certain parts which can reduce the yield of pyrolysis oil fractions and plastic vapors into more non-condensed gases (Papuga et al., 2024). So to prevent overcracking, in this low-temperature pyrolysis study, the distillation chamber reactor design is placed next to the pyrolysis chamber, not above the high temperature as in previous research. This is done so that thermal energy from the same source can be well distributed to both pyrolysis-distillation chambers to achieve the temperature requirements of the degradation of plastics into hydrocarbon vapors and the temperature for the distillation process. In a study conducted by Vafin & Vankov (2025), it was proven that there is a difference in temperature on the surface of the pyrolysis chamber that is directly exposed to a higher thermal energy source than the temperature of the pyrolysis chamber shown on the thermometer. That is why the study Hung et al. (2019) applied a distributed thermal energy system in a low-temperature pyrolysis process that takes advantage of the temperature difference in the pyrolysis chamber and surfaces directly exposed to thermal energy sources. Although it applies the same pyrolysis-distillation integration principle as the previous research, there are differences in the design dimensions of the reactor configuration for industrial scale that apply distributed thermal energy systems at low temperatures.

This study hypothesizes that the design of a large-scale bottom section of a pyrolysis

chamber, which is directly exposed to thermal energy sources, is widened to facilitate thermal energy distribution in the pyrolysis and distillation chambers. As previously reported (Zaid & Otaru, 2025), thermal distribution can be carried out at low temperatures. Therefore, the reactor design in this study employs slow-heating-rate control to provide sufficient residence time for degrading plastic polymers and for in-situ distillation, in contrast to the previous pyrolysis-distillation reactor configuration design, which uses high temperatures so that thermal energy can also be distributed to the distillation chamber with a bubble cap positioned above (Thahir et al., 2019). Although it can prevent the buildup of charcoal residues and reduce the waxy-textured oil entering the distillation chamber, it cannot be applied to industrial-scale pyrolysis, where the reactor dimensions are larger. That's why in this study, the pyrolysis and distillation chambers were placed in adjacent positions in series. The potential for the formation of waxy textured oils in the pyrolysis chamber exists. Still, it is hindered by the distillation chamber, which serves as the second thermal process, degrading the feedstock into light fractions before it enters the fractional condensation area (Heydariaraghi et al., 2016). It is hoped that this research can establish new operational parameters (temperatures) for the conversion of plastics into industrial-scale fuels that are more energy-efficient, do not require catalysts, and eliminate the formation of wax-textured oils. That way, it can prove the concept of Heat Integrated Distillation Columns (HIDiC), which, in general, can save energy very significantly compared to conventional distillation columns (Kiss & Olujic, 2014).

The purpose of this research is to develop an integrated pyrolysis-distillation reactor configuration that, in previous research, was carried out at high temperatures. However, in this study, the pyrolysis-distillation configuration was operated at low temperatures using a distributed energy system. Low-temperature pyrolysis at 200 °C, 250 °C, and 300 °C is tested for the phase stability of the liquid oil produced by an integrated fractional condensing system. To determine the success of this study by evaluating the performance of the configuration of an operational low-temperature integrated pyrolysis-distillation reactor without a catalyst, in producing liquid phase oil fuel without the formation of waxy textured oil. This study aims to empirically identify a pattern of elimination of wax-like oils by controlling slow heating rates in an integrated reactor at low temperatures. The result to be achieved is not just the production of oil from PP plastic, but also the proof of the principle that physical fractionation of plastic without a catalyst can be achieved using two thermal processes in situ at low temperatures, without the formation of waxy-textured oil. The investigation focused on controlling the slow heating rate, the operational use of low temperatures, and the visual and physical characteristics of the oil fractions generated by the three condensers across nine iterations to ensure data consistency. The results of this study are expected to contribute to the development of industrial-scale pyrolysis reactors that are more efficient, low-cost, and capable of producing quality liquid fuel.

MATERIALS AND METHODS

Preparation and characterization of raw materials

This study used 90 kg of used PP plastic waste for clothing packaging collected by scavengers from shopping centers and malls in the city of Manado, North Sulawesi, Indonesia. PP plastic waste is collected at the location because it can be found in dry conditions, is easy to sort, and has not been mixed with other waste, so it has not been contaminated. The selection of PP plastic types is based on their thermal characteristics, which tend to produce wax-like oil fractions when processed by conventional pyrolysis methods without catalysts at low temperatures (Zolghadr et al., 2022).

In contrast to the standard procedure that carried out the enumeration into small sizes, in this study, the PP plastic waste was put into the reactor in its original form without going through enumeration (Figure 1a). This approach was chosen to evaluate the efficiency of pyrolysis-distillation reactors in the decomposition of PP plastics, while minimizing costs and energy consumption at the pre-treatment stage (Harussani et al., 2022). Before the process starts, the PP plastic raw material is cleaned of physical contaminants and dried. Then it was measured with a digital scale, per 10 kg of PP plastic waste, to conduct nine experiments, as shown in Figure 1b. It is then inserted into the inside of the reactor through a plastic inlet hole at the top. The reactor is also equipped with a

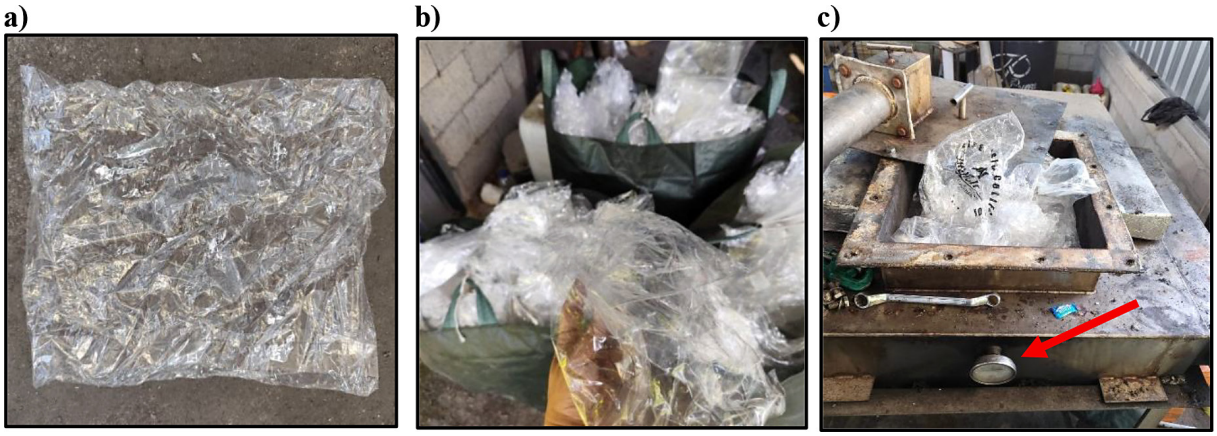

Figure 1. Condition of PP plastic waste (a) PP plastic whole form, (b) 10 kg PP plastic, (c) PP plastic in reactor and bimetal thermometer

bimetal thermometer to measure the temperature in the pyrolysis chamber, as shown in Figure 1c.

Integrated pyrolysis-distillation reactor and experimental procedure

The methodology applied uses a quantitative descriptive experimental approach with a tightly controlled heating protocol. The pyrolysis experiment was conducted using a prototype owned by the startup Waus Energy/PT. Supermoon Lestari International in the city of Manado, North Sulawesi, Indonesia. The batch-type pyrolysis reactor is integrated with an in-situ pyrolysis chamber, a distillation chamber, and a fractional condensation system. The reactor is constructed of stainless steel and equipped with a bimetal thermometer on the upper wall for internal temperature monitoring. Although it has the same concept as the research by Thahir et al. (2019) on a small-scale high-temperature system, the significant difference in this study is the configuration design for a larger reactor and a distributed energy system for low-temperature operation, to prepare for its development to an industrial scale. As shown in Figure 2, the distillation chamber is in series with the pyrolysis chamber, which is close to the thermal energy source. This is done so that the distribution of thermal energy in the lower cross-section of the pyrolysis chamber is high enough to degrade the plastic polymer, and the lateral cross-section of the pyrolysis-distillation chamber boundary is low enough for the distillation process. The technical advantages of the pyrolysis-distillation reactor configuration with a series-parallel multi-condenser are that it is directly connected to the output bottle or container. This configuration allows the plastic vapor generated by pyrolysis in the pyrolysis chamber to enter the distillation chamber, where it gradually undergoes fractional condensation into oil based on the boiling point of the hydrocarbon chain type. Oil fraction bottles and containers are tightly attached to each condenser outlet to prevent oil mass loss due to gas volatility and ensure that all pyrolysis liquid products are optimally captured for quantitative analysis (Anene & Fredriksen, 2018).

Figure 2 shows a configuration diagram for pyrolysis-distillation integrated with fractional condensation. The experiment was carried out using 10 kg of prepared PP plastic waste. The sample is then heated and melted in the reactor's pyrolysis chamber, producing plastic vapor containing hydrocarbons. The plastic vapor flows through the distillation chamber adjacent to the pyrolysis chamber due to heat from the reactor and the vacuum. Heavy fractions, such as wax-textured oils, carried by plastic vapors, will stick to the walls and barrier plates in the distillation chamber due to the pre-condensed design of the stainless steel pipes between the distillation and pyrolysis chambers. While the non-condensed light fraction plastic vapor continues to flow through the stainless steel pipes, it flows continuously into condenser chambers 1 and 2, where it eventually forms liquid bubbles on the barrier plates in each chamber. The steam condensed in condenser 1 and condenser 2 is stored in their condensing chamber plates and then falls into the oil fraction holding bottles 1 and 2. The heavy fraction plastic vapor retained in the distillation chamber undergoes a second

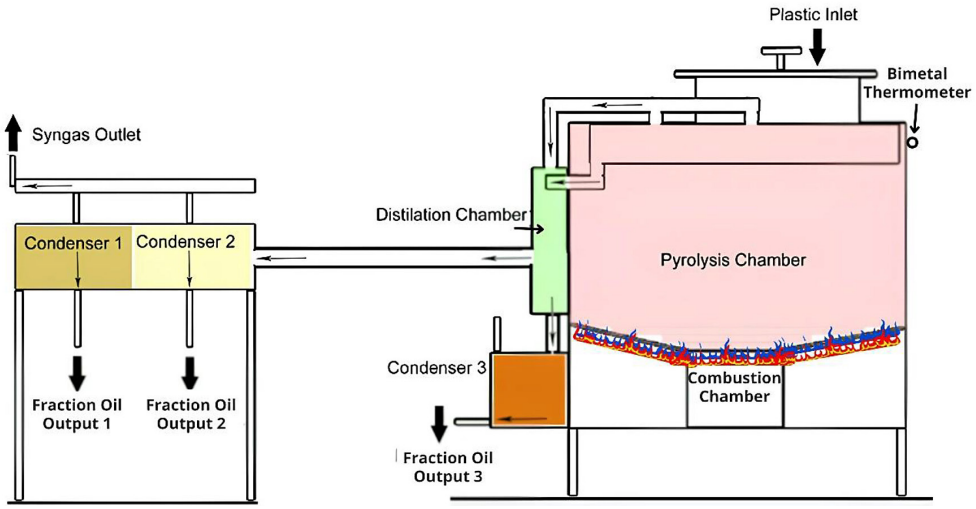

Figure 2. Integrated pyrolysis-distillation configuration diagram with fractional condensation

thermal process back into a light fraction, which is passed to condensers 1 and 2.

Meanwhile, the medium fraction plastic vapor that has undergone the second thermal process will fall into the condenser chamber 3 through a barrier plate and a small hole between the distillation chamber and the condensing chamber. Plastic vapor that becomes a non-condensed gas will flow out through the pipe at the end of the condenser. To accurately control the parameters, the reactor is equipped with a bimetal thermometer with a maximum measurement range of 400 °C for the pyrolysis room-temperature monitor.

The configuration arrangement and pyrolysis-distillation process are carried out in a workshop room rather than a laboratory to simulate real-life applications in the development of industrial-scale stainless steel prototypes. As shown in Figure 3, a visual display of the experimental setup is provided. The plastic inlet hole at the top of the pyrolysis chamber is enlarged to make it easier to insert large plastic without shredding, thereby saving pre-treatment costs. Bimetal thermometers with a maximum measurement scale of 400 °C are used because the maximum operating temperature in the pyrolysis chamber is only about 300 °C. The ignition chamber contains four stoves that are gradually ignited to control the rate of heating in the reactor. The pyrolysis chamber is designed to be widened, inspired by a frying pan

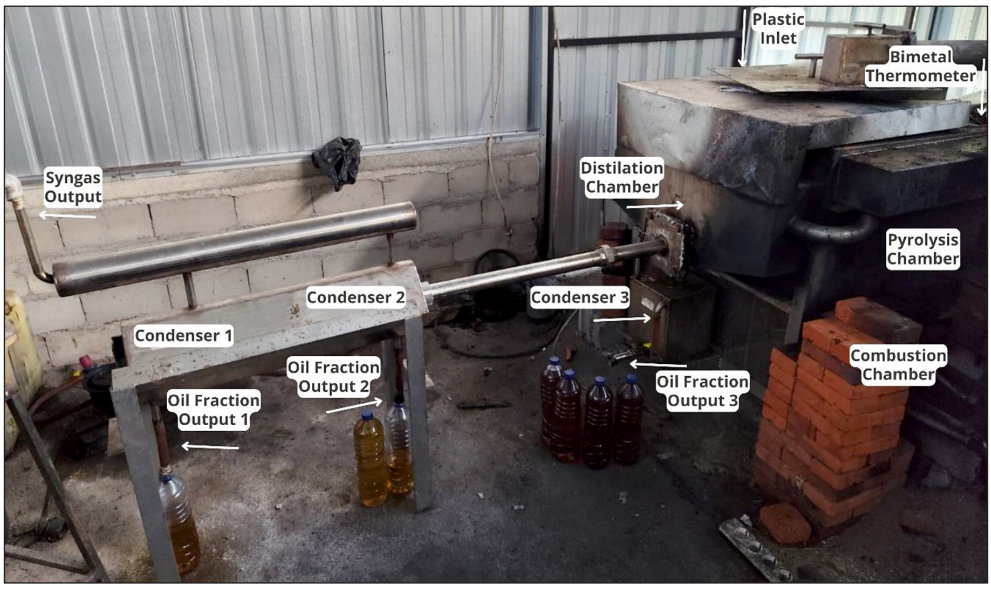

Figure 3. Integrated pyrolysis-distillation reactor configuration with three condensers mounted in series and parallel from the distillation chamber

that requires only a small amount of fire, but the thermal energy is distributed evenly and quickly. The distillation chamber is designed to be directly attached to the pyrolysis chamber so that it can use the same thermal energy as the pyrolysis chamber. Condenser 1 and condenser 2 appear to be one piece, but inside there are two condensing chambers designed to condense a fraction of light oil that successfully passes through the pipeline between the distillation chamber and the light oil condenser. The results can be directly accommodated in bottles because the condensed pyrolysis oil remains stable at room temperature. Condenser 3 is designed to condense a fraction of medium oil. It is positioned below the distillation chamber to condense the second heavy-oil fraction into a medium fraction. The pipe at the end serves as an outlet for plastic vapor that becomes gas but does not condense.

Thermal control procedures

In all pyrolysis processes, the process begins with a gradual heating stage from room temperature to 100 °C for 60 minutes. The pyrolysis process has not yet occurred at this temperature, but it is carried out to remove oxygen and stabilize the reactor's thermal conditions. Furthermore, the temperature is increased linearly at a heating rate of 2 °C/min until it reaches 200 °C, 250 °C, and 300 °C, respectively. Three experimental iterations were performed at each maximum temperature, for a total of nine experiments for data validation. To obtain numerical results for thermal control and heating rate, measurements are done manually. Using a digital stopwatch that rings every 5 minutes to observe visually, the bimetal thermometer shows a 10 °C increase in temperature, corresponding to a heating rate of 2 °C/minute, without the need for special clocks or speedometers, which can increase the cost of tools in pyrolysis operations. The most crucial thermal control process is from the room temperature (30 °C) at the initial minute to the maximum temperature of the triplo experiment 1, which shows 200 °C at the 110th minute, the triplo 2 experiment 2 shows 250 °C at the 135th minute, and the triplo 3 shows 300 °C at the 160th minute. Once the temperature has reached the maximum target for each triple experiment, the process is to maintain the temperature until the pyrolysis-distillation process is completed.

Data collection and analysis of wax-like oil elimination

The main parameters in this experiment were the process of controlling the slow heating rate (2 °C/min), the operational application of low temperatures (200 °C, 250 °C, and 300 °C), and the visual physical characteristics of the oil fractions (without waxy textured oil) collected in each of the holding bottles of the three condensers. The process of controlling the low heating rate is presented in a table of temperature rise over time from pyrolysis-distillation experiments. The operational application of low temperatures is evidenced by the bimetal thermometer images showing the figures for 200 °C, 250 °C, and 300°C, which are measured during the pyrolysis-distillation process. Analysis and visual physical characteristics of oil fractions were carried out by assessing the clarity and phase of the oil products at room temperature, which are indicators of the success of fractionating plastic hydrocarbon vapor into liquid oil fractions. The absence of wax-like oil fractions in the condenser and container bottle output lines was confirmed in the cumulative observations table from nine experiments. All data from visual and quantitative observations taken during the pyrolysis-distillation process are being temporarily recorded. It was then analyzed to map the effect of low-temperature operations on the in-situ elimination of waxy-textured oils without the use of catalysts and on oil-phase stability after 3x24 hours post-pyrolysis-distillation.

RESULT AND DISCUSSION

Pyrolysis experiment thermal control process

Table 1 shows the process of controlling the temperature rise over time during the pyrolysis-distillation experiment, with a stopwatch set to sound every 5 minutes and observations on the bimetal thermometer on the reactor. Thermal control and observation processes were carried out on this experiment. The process starts from the reactor heating phase and reaches maximum temperatures of 200 °C, 250 °C, and 300 °C at a heating rate of 2 °C/min, with a ±2 °C deviation, as the process parameters.

The thermal energy source for this experiment comes from four stoves, each adjustable in size and lit gradually. The reactor heating phase

Table 1. The process of controlling temperature rise over time in pyrolysis-distillation experiments

Time (minutes)	Target temperature (°C)	Rated actual temperature (°C)	Deviation (°C)	Phase
0	30	30	0,0	Room temperature (initial)
30	90	90	0.0	Pre-heating stage of the reactor
35–60	100	101	+1,0	Reactor heating stage
75	130	131	+1.0	Beginning of PP melting point
90	160	161	+1.0	PP melting point
110	200	201	+1,0	Thermal degradation of the triple experiment 1
135	250	251	+1.0	Thermal degradation of the triplo experiment 2
160	300	301	+1,0	Thermal degradation of triplo 3 experiment

Note: Manual thermal control process with a stopwatch sounding every 5 minutes.

is carried out from room temperature to 100 °C over up to 60 minutes, including the reactor pre-heating stage. In fact, the stopwatch sounds at the 30th minute during the pre-heating stage of the reactor, and the bimetal thermometer shows 90 °C, the 90 °C target, and 10 1°C, the 100 °C target, for the experiment carried out. In the initial phase of the PP melting point, the bimetal thermometer shows a reading of 131 °C, which is 1 °C above the target of 130 °C. Then, during the PP melting point phase, the bimetal thermometer shows a reading of 161 °C, which is 1 °C above the target of 160 °C. At the maximum temperature target of 200 °C at the 110th minute in the thermal degradation stage of the triplo 1 experiment, the bimetal thermometer showed 201 °C. Furthermore, at the 135th minute of the thermal degradation stage of the triplo 2 experiment, the bimetal thermometer recorded 251 °C, the target maximum temperature of 250 °C. At the target maximum temperature of 300 °C at the 160th minute in the thermal degradation stage of the triplo 3 experiment, the bimetal thermometer showed 301 °C.

Figure 3 shows the actual measurement of the maximum operating temperature during the experiment. There are three maximum temperature variables indicated by the bimetal thermometer in the experiment, corresponding to temperature variations of 200 °C, 250 °C, and 300 °C. The application of thermal control and temperature measurement over time, as in this experiment, is a standard operating procedure in industrial-scale reactors. Without having to use a special clock and speedometer in pyrolysis operations that add to the cost of the equipment, it is sufficient to use a stopwatch that sounds every 5 minutes and a bimetal thermometer installed in the reactor for visual observation.

Low-temperature operational application

In the pyrolysis experiment with a maximum temperature of 200 °C (Figure 4a), the reactor

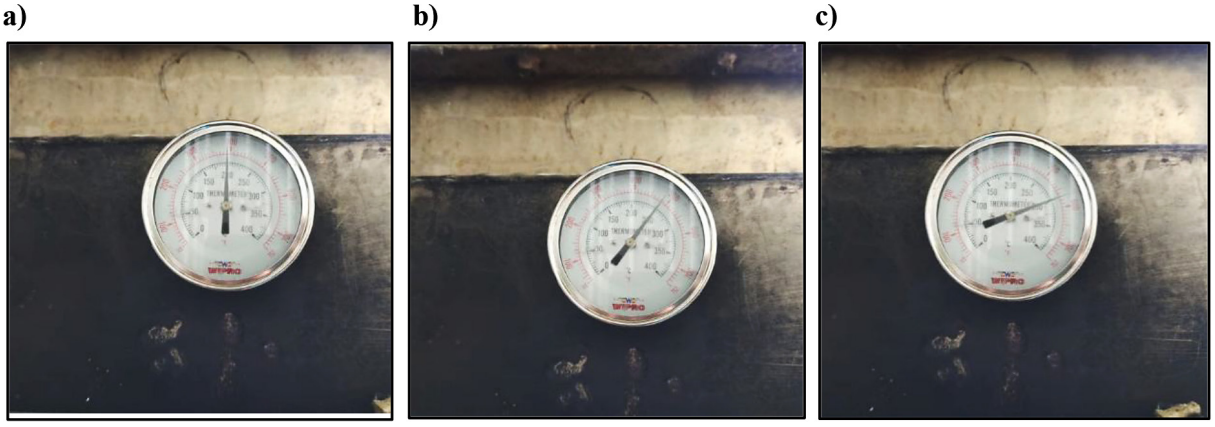

Figure 4. Actual measurement of the maximum operating temperature per triple experiment on a bimetal thermometer while the fractional condensation-distillation experiment is in progress (a) temperature 200 °C at 110 minutes, (b) temperature 250 °C at 135 minutes, (c) temperature 300 °C at 160 minutes

heating process is started at about 100 °C for up to 1 hour. At a heating rate of 2 °C/min, it takes 50 minutes to reach a maximum temperature of 200 °C. The pyrolysis-distillation process with fractional condensation at a maximum temperature of 200 °C lasts for 4 hours and 10 minutes. Thus, the total time from the machine's heating process to the completion of the pyrolysis-distillation process was 6 hours, as shown in Table 2. The pyrolysis process indicator is complete when the bimetal thermometer on the machine shows a gradual decrease from 200 °C.

Furthermore, the pyrolysis experiment with a maximum temperature of 250 °C (Figure 4b) begins with the reactor heating process of about 100 °C for up to 1 hour. At a heating rate of 2 °C/min, it takes 75 minutes to reach a maximum temperature of 250 °C. The pyrolysis-distillation process with fractional condensation at a maximum temperature of 250 °C lasts for 3 hours and 15 minutes. Thus, the total time from the machine's heating process to the completion of the pyrolysis-distillation process was 5 hours and 30 minutes, as shown in Table 3. The pyrolysis process indicator is complete when the bimetal thermometer on the machine shows a gradual decrease from 250 °C.

Meanwhile, the pyrolysis experiment with a maximum temperature of 300 °C (Figure 4c) begins with the reactor heating process of around 100 °C for up to 1 hour. At an average heating rate of 2 °C/min, it takes 100 minutes to reach a maximum temp erature of 300 °C. The pyrolysis-distillation process with fractional condensation at a maximum temperature of 300 °C lasts for 2 hours and 20 minutes. Thus, the total time from the machine's heating process to the completion of the pyrolysis-distillation process was 5 hours, as shown in Table 4. The pyrolysis process indicator is complete when the bimetal thermometer on the machine shows a gradual decrease from 300 °C.

Visual analysis of results and physical characteristics of oil fractions

Based on the results of nine repetitions of the experiment conducted with three repetitions at each maximum temperature of 200 °C, 250°C, and 300 °C (Table 5). The integrated pyrolysis-distillation configuration system demonstrates stable performance in converting 10 kg of PP plastic waste into a fully liquid oil fraction, without producing wax-textured oil fractions. In theory, the melting point of PP plastic ranges from 130 °C to 170 °C, which affects its thermal degradation behavior during pyrolysis (Khair et al., 2023). However, in this study, heating the reactor gradually from room temperature to 100 °C for up to 60 minutes results in more evenly distributed thermal conditions in the reactor. Pyrolysis chambers under such thermal conditions change the size of PP

Table 2. Pyrolysis-distillation process with fractional condensation at a maximum temperature of 200 °C

Temperature maximum (°C)	Reactor heating (100 °C)	Heating rate 2 °C/min		Total pyrolysis-distillation time
		Duration of time 100 °C to 200 °C	Duration of time at 200 °C	
200	1 hour	50 minute	4 hour 10 minute	6 hour

Note: Experiments at 200 °C were performed three times.

Table 3. Pyrolysis-distillation process with fractional condensation at a maximum temperature of 250 °C

Temperature maximum (°C)	Reactor heating (100 °C)	Heating rate 2 °C/minute		Total pyrolysis-distillation time
		Duration of time 100 °C to 250 °C	Duration of time at 250 °C	
250	1 hour	75 minute	3 hour 15 minute	5 hour 30 minute

Note: Experiments at 250 °C were performed three times.

Table 4. Pyrolysis-distillation process with fractional condensation at a maximum temperature of 300 °C

Temperature maximum (°C)	Reactor heating (100 °C)	Heating rate 2 °C/minute		Total pyrolysis-distillation time
		Duration of time 100 °C to 300 °C	Duration of time at 300 °C	
300	1 hour	100 minute	2 hour 20 minute	5 hour

Note: Experiments at 300 °C were performed three times.

Table 5. Pyrolysis-distillation results with fractional condensation at temperatures of 200 °C, 250 °C, and 300 °C

Temperature maximum (°C)	Experiment number	Total PP plastic	Wax-like formation	Phase stability	Appearance
200	1	10 kg	None	Stable liquid	Golden yellow
200	2	10 kg	None	Stable liquid	Bright yellow
200	3	10 kg	None	Stable liquid	Reddish brown
250	1	10 kg	None	Stable liquid	Golden yellow
250	2	10 kg	None	Stable liquid	Bright yellow
250	3	10 kg	None	Stable liquid	Reddish brown
300	1	10 kg	None	Stable liquid	Golden yellow
300	2	10 kg	None	Stable liquid	Bright yellow
300	3	10 kg	None	Stable liquid	Reddish brown

Note: The oil liquid is stable without the formation of wax-like oil.

plastic without chopping it down to a more uniform size (Nugroho et al., 2023).

When the temperature is increased at a rate of 2 °C/min., the bimetal thermometer in the reactor shows maximum experimental temperatures of 200 °C, 250 °C, and 300 °C. At this stage, the degradation of PP plastic into plastic vapor containing hydrocarbons begins. Theoretically, the degradation temperature of PP plastic to hydrocarbon vapor ranges from 374.9 °C to 495.15 °C (Zhang et al., 2022). However, in this study, the temperature displayed on a bimetal thermometer with a maximum scale of 400 °C on the side of the reactor only reflected the temperature in the pyrolysis chamber. Meanwhile, the temperature on the cross-sectional surface of the bottom of the pyrolysis chamber, which is directly exposed to fire from the ignition chamber, can be adjusted based on the number of fire sources on the production stove (Vafin & Vankov, 2025). With this reactor made of heat-resistant materials such as stainless steel, the bottom surface directly exposed to the fire can be set to a temperature range where PP degrades into plastic vapor. This experiment is supported by previous research by Hung et al. (2023) using the microwave pyrolysis method at a pyrolysis temperature of 250–280 °C, which measures the temperature of plastic degradation on surfaces directly exposed to heat sources on an industrial scale. This is relevant in the field, where thermometers in industrial-scale pyrolysis reactors only show the temperature in the pyrolysis chamber instead of the temperature on the surface of the pyrolysis chamber that is directly exposed to heat sources (Djurdjevic et al., 2023). In contrast to thermometers in small-scale pyrolysis reactors in laboratories, whose cross-sectional surface temperature differs slightly from the temperature in the pyrolysis chamber (Akinsade et al., 2024).

The pyrolysis plastic vapor formed in the pyrolysis chamber then moves towards the distillation chamber. In theory, the temperature required for the distillation of pyrolysis results is in the light fraction (<175 °C), the middle fraction (175–360 °C), and the heavy fraction (>360 °C) (Zeb et al., 2023). With the pyrolysis-distillation integration configuration, the distillation process uses the same heat source as the pyrolysis process. The temperatures of the pyrolysis chamber and distillation chamber can be set to the distillation process temperature. That is why a heating rate of 2 °C/min was used, as the experiment performed two different pyrolysis-distillation processes simultaneously with different temperature requirements. Thermal breakdown, in the form of plastic vapor, transforms long PP polymer chains into shorter chains, such as gasoline (C5-C12), kerosene (C12-C16), diesel (C15-C18), and waxy textured oils (C23+) (Eldahshory et al., 2023; Parku et al., 2020). The light- to medium-fraction mixtures will continue to be directed to condensers 1 and 2 for condensation, while the medium- and heavy-fraction mixtures will be retained in the distillation chamber for the thermal process to return the light- and medium-fraction hydrocarbon vapors (Park & Lee, 2021). The intermediate fraction, separated from the heavy fraction after the second thermal process in the distillation chamber, will fall and condense in condenser 3.

Various previous studies have reported that pyrolysis at low temperatures can produce waxy-textured oils (Irawan et al., 2022). A scientific description of the physical characteristics of the wax-like oil obtained from low-temperature plastic pyrolysis can also be elaborated. As reported in

previous studies, wax-textured oil fractions tend to be thicker, amber-brown, cloudy, and form a waxy precipitate when cooled to room temperature (Aprianti et al., 2025; Palmay, Haro, et al., 2022). Thus, the physical characteristics of the wax-formed and non-wax-formed oil fractions that are visually observed can serve as a scientific outcome parameter, as the fuel fraction of plastic pyrolysis oil containing wax and ash can be classified as low quality (Thahir et al., 2019).

In this study, the effectiveness of the pyrolysis-distillation configuration with fractional condensation, applied to a distributed energy system, is clearly evident in the visual characteristics of the resulting pyrolysis oil fraction. Visually, the results of the experiment show the color gradation and clarity of the oil from PP plastic pyrolysis, produced by the three condensers, without a wax-like oil fraction, as described in the previous study. The result of this oil fraction is shown in Figure 5, which shows that the pyrolysis-distillation oil product stored for 3x24 hours at room temperature remains stable in the liquid phase without forming waxy-textured oil. The oil fractions from condensers 1, 2, and 3 in the tightly sealed bottle remain stable in the fluid oil phase, with no visually apparent wax deposits.

As reported in a study by Eldahshory et al. (2023), the oil fraction obtained from the pyrolysis of PP plastics, with or without a catalyst, is a mixture of hydrocarbons with carbon atoms ranging from C5 to C25. Based on the GC-MS analysis, the results of PP plastic pyrolysis oil can be classified into gasoline (C5-C12), kerosene (C12-C16), and diesel (C15-C20) fuel groups. The results of the PP plastic distillation study conducted by Zeb et al. (2023) into light, medium, and heavy fractions are used as comparative parameters to classify the types of pyrolysis-distillation fuels in this study.

In this study, the maximum operating temperatures of 200 °C, 250 °C, and 300 °C correspond to the distillation of the light fraction <175 °C and the middle fraction 175–360 °C. In all experiments, the fractional condensation of the oil phase in Figure 5a (condenser 1) is clear golden yellow, and in Figure 5b (condenser 2), it is bright clear yellow. Identify the results of the research oils on these two condensers, similar to the gasoline and kerosene fuel groups in the light-medium fraction with C5 to C16 carbon bonds. Meanwhile, the oil phase in Figure 5c, in condenser 3, is a clear reddish-brown. Identifies the oil yield in condenser 3, similar to the diesel fuel group in the intermediate fraction with carbon bonds of C15 to C20. The reddish-brown color in the oil fraction from condenser 3 can be caused by aromatic compounds and residual charcoal ash carried by PP plastic vapor (Mufrodi et al., 2024). This liquid oil fraction can then be filtered to remove charcoal residue, ash, and aromatic compounds that are also condensed (Navarro et al., 2022).

CONCLUSIONS

This research has successfully developed an integrated pyrolysis-distillation configuration for low-temperature operations that avoids the formation of wax-like oils. Slow heating rate control

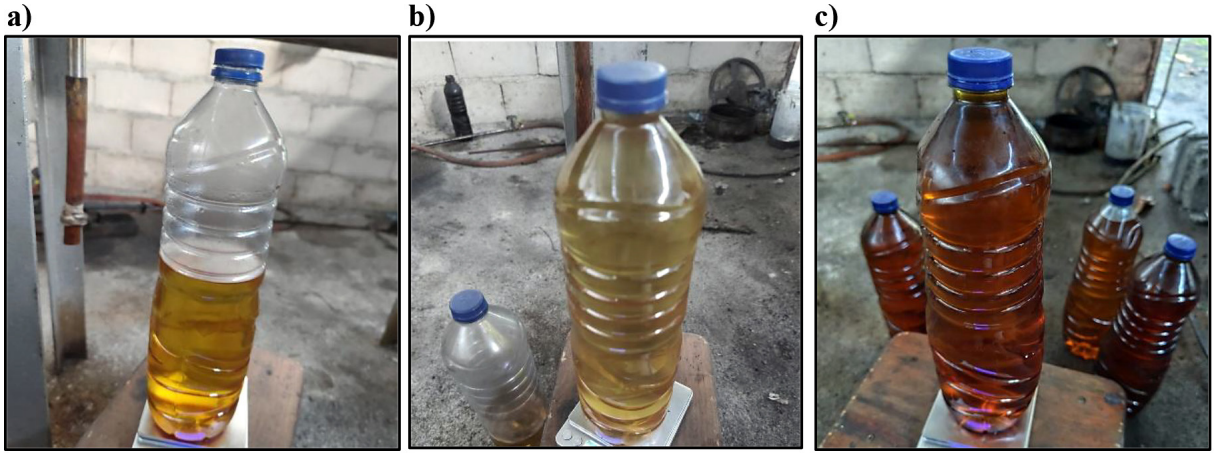

Figure 5. Pyrolysis-distillation oil products stored for 3 x 24 hours remain stable in the liquid phase without the formation of wax-like oil (a) oil fraction in condenser 1, (b) oil fraction in condenser 2, (c) oil fraction in condenser 3

(2 °C/min) can provide sufficient residence time for degrading plastic polymers and for in-situ distillation. The distributed energy system can be carried out at low-temperature operations (200 °C, 250 °C, and 300 °C) with the design of the bottom section of the pyrolysis chamber, where direct exposure to the thermal energy source is increased. The process of thermal energy distribution by placing the distillation chamber next to the pyrolysis chamber in series, allows for two thermal processes to occur using the same thermal energy source. So that the potential for heavy oil fractions from the pyrolysis chamber can be thermally degraded in the distillation chamber into light and medium fractions before entering the fractional condensation area. Thus, a pattern has been empirically established to eliminate waxy-textured oils by controlling the heating rate with an integrated pyrolytic distillation reactor at low temperatures.

Based on the analysis of results and physical characteristics, and on comparative parameters from the previous study, the pyrolysis-distillation oil fraction produced in this study remained stable, without wax-like oil, at room temperature. The fractional condensation of the oil phase produced in condenser 1 is clear golden yellow, and that from condenser 2 is light clear yellow, similar to the gasoline and kerosene fuel groups in the light-medium fraction, with carbon bonds C5 to C16. Meanwhile, the oil phase in condenser 3 is clear reddish-brown, similar to the diesel fuel group in the medium fraction, with carbon bonds ranging from C15 to C20.

This research resulted in a new conceptual model for converting PP plastics into fuel via an integrated pyrolysis-distillation configuration with fractional condensation at low temperatures, without a catalyst. It is directly beneficial to the plastics processing industry, providing a basis for the development of industrial-scale pyrolysis reactors. Large dimensions that are more efficient, low-cost, and able to produce high-quality liquid fuel without wax-like oil.

REFERENCES

1. Akinsade, A., Akinola, A. O., Yaru, S. S., Eiche, J. F. (2024). Thermal and structural modelling of laboratory-scale pyrolysis reactor. *Saudi Journal of Engineering and Technology*, *9*(2): 51-57. https://doi.org/10.36348/sjet.2024.v09i02.004
2. Andalia, W., Pratiwi, I., Afrah, B. D., Akbar, I., & Ammarullah, M. I. (2025). Optimized pyrolysis of household plastic waste in Indonesia for oil production: Hydrocarbon profiling, fuel alternative, and potential biomedical application. *Results in Chemistry*, *15*, 102247–102247. https://doi.org/10.1016/j.rechem.2025.102247
3. Anene, A. F., & Fredriksen, S. B. (2018). Experimental study of thermal and catalytic pyrolysis of plastic waste components. *Sustainability*, *10*(11), 3979; https://doi.org/10.3390/su10113979
4. Aprianti, N., Rahmawati, R., Satria, Ermada, F. J., Fariza, O., Alamsyah, R., & Kismanto, A. (2025). Catalytic pyrolysis of different plastics using low-cost catalysts: Wax characteristics and oil stability. *Energy, Ecology and Environment*, *10*(1), 110–124. https://doi.org/10.1007/s40974-024-00346-4
5. Charlesworth, D. R. (2021). Moving Mountains: Will chemical recycling help solve the plastic waste crisis? *The 15th Annual GPCA Forum, 2021, Dubai, UAE. IHS Markit Oil, Midstream, Downstream and Chemicals*.
6. Djurdjevic, M., Papuga, S., & Kolundzija, A. (2023). Analysis of the thermal behavior of a fixed bed reactor during the pyrolysis process. *Chemical Industry*, 78(1): 29-40. https://doi.org/10.2298/hemind221217024d
7. Eldahshory, A. I., Emara, K., Abd-Elhady, M. S., & Ismail, M. A. (2023). Catalytic pyrolysis of waste polypropylene using low-cost natural catalysts. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-37769-8
8. Gebre, S. H., Sendeku, M. G., & Bahri, M. (2021). Recent Trends in the Pyrolysis of Non-Degradable Waste Plastics. *ChemistryOpen*, *10*(12), 1202–1226. https://doi.org/10.1002/open.202100184
9. Harussani, M. M., Sapuan, S. M., Rashid, U., Khalina, A., & Ilyas, R. A. (2022). Pyrolysis of polypropylene plastic waste into carbonaceous char: Priority of plastic waste management amidst COVID-19 pandemic. *Science of The Total Environment*, *803*, 149911. https://doi.org/10.1016/j.scitotenv.2021.149911
10. Heydariaraghi, M., Ghorbanian, S., Hallajisani, A., & Salehpour, A. (2016). Fuel properties of the oils produced from the pyrolysis of commonly-used polymers: Effect of fractionating column. *Journal of Analytical and Applied Pyrolysis*, *121*, 307–317. https://doi.org/10.1016/j.jaap.2016.08.010
11. Hung, Y.-C., Ho, C.-H., Chen, L.-Y., Ma, S.-C., Liu, T.-I., & Shen, Y.-C. (2023). Using a low-temperature pyrolysis device for polymeric waste to implement a distributed energy system. *Sustainability*, *15*(2), 1580. https://doi.org/10.3390/su15021580
12. Irawan, A., Kurniawan, T., Nurkholifah, N., Melina, M., Nandiyanto, A., Firdaus, M., Alwan, H., & Bindar, Y. (2022). Pyrolysis of polyolefins into

chemicals using low-cost natural zeolites. *Waste and Biomass Valorization*, *14*, 1705–1719. https://doi.org/10.1007/s12649-022-01942-3

13. Khair, H., Listiany, B., & Utami, R. (2023). Pyrolysis of polypropylene plastic waste: An analysis of oil quantity, density, viscosity, and calorific value. *IOP Conference Series Earth and Environmental Science*, *1268*(1), 12056–12056. https://doi.org/10.1088/1755-1315/1268/1/012056
14. Kiss, A., & Olujic, Z. (2014). A review on process intensification in internally heat-integrated distillation columns. *Chemical Engineering and Processing*, *86*, 125–144. https://doi.org/10.1016/j.cep.2014.10.017
15. Krzywda, R., & Wrzesińska, B. (2021). Simulation of the Condensation and Fractionation Unit in Waste Plastics Pyrolysis Plant. *Waste and Biomass Valorization*, *12*(1), 91–104. https://doi.org/10.1007/s12649-020-00994-7
16. Kusenberg, M., Zayoud, A., Roosen, M., Thi, H. D., Abbas-Abadi, M. S., Eschenbacher, A., Kresovic, U., De Meester, S., & Van Geem, K. (2022). A comprehensive experimental investigation of plastic waste pyrolysis oil quality and its dependence on the plastic waste composition. *Fuel Processing Technology*. https://doi.org/10.1016/j.fuproc.2021.107090
17. Marchetti, L., Guastaferro, M., Annunzi, F., Tognotti, L., Nicolella, C., & Vaccari, M. (2024). Two-stage thermal pyrolysis of plastic solid waste: Set-up and operative conditions investigation for gaseous fuel production. *Waste Management*, *179*, 77–86. https://doi.org/10.1016/j.wasman.2024.03.011
18. Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M., & Nizami, A. S. (2016). Catalytic pyrolysis of plastic waste: A review. *Process Safety and Environmental Protection*, *102*, 822–838. https://doi.org/10.1016/j.psep.2016.06.022
19. Mufrodi, Z., Syamsiro, M., Biddinika, M. K., Hakika, D. C., Prawisudha, P., Budiasih, K. S., & Purnomo, C. W. (2024). Investigation and characterization of polypropylene plastic waste pyrolysis oil: Effect of temperature and fractional condensation. *Journal of Ecological Engineering*, *26*(1), 163–172. https://doi.org/10.12911/22998993/195533
20. Navarro, P., Hernández, E., Rodríguez-Llorente, D., Maldonado-López, I., Santiago, R., Moya, C., Belinchón, A., Larriba, M., & Palomar, J. (2022). Fine-tune simultaneous dearomatization, desulfurization and denitrogenation of liquid fuels with CO_2-derived cyclic carbonates. *Fuel*, *321*, 124005. https://doi.org/10.1016/j.fuel.2022.124005
21. Nolasco Cruz, J., Pérez Hernández, I., Echegaray Franyutti, J., Vaca Espino, R. M., & Cárdenas, E. A. Z. (2025). Plastic recycling for liquid fuel production and its use in thermal engines. *Ecological Engineering & Environmental Technology*, *26*(5), 61–81. https://doi.org/10.12912/27197050/202778
22. Nugroho, R., Alhikami, A., & Wang, W.-C. (2023). Thermal decomposition of polypropylene plastics through vacuum pyrolysis. *Energy*. https://doi.org/10.1016/j.energy.2023.127707
23. Paavani, K., Agarwal, K., Alam, S. S., Dinda, S., & Abrar, I. (2024). Advances in plastic to fuel conversion: Reactor design, operational optimization, and machine learning integration. *Sustainable Energy & Fuels*, *9*(1), 54–71. https://doi.org/10.1039/d4se01045k
24. Palmay, P., Haro, C., Huacho, I., Barzallo, D., & Bruno, J. (2022). Production and analysis of the physicochemical properties of the pyrolytic oil obtained from pyrolysis of different thermoplastics and plastic mixtures. *Molecules*, *27*. https://doi.org/10.3390/molecules27103287
25. Palmay, P., Medina, C., Donoso, C., Barzallo, D., & Bruno, J. C. (2022). Catalytic pyrolysis of recycled polypropylene using a regenerated FCC catalyst. *Clean Technologies and Environmental Policy*, *25*(5), 1539–1549. https://doi.org/10.1007/s10098-022-02453-4
26. Papuga, S., Savkovic, J., Djurdjevic, M., & Ciprioti, S. (2024). Effect of feed mass, reactor temperature, and time on the yield of waste polypropylene pyrolysis oil produced via a fixed-bed reactor. *Polymers*, *16*. https://doi.org/10.3390/polym16101302
27. Park, C., & Lee, J. (2021). Pyrolysis of polypropylene for production of fuel-range products: Effect of molecular weight of polypropylene. *International Journal of Energy Research*, *45*(9), 13088–13097. https://doi.org/10.1002/er.6635
28. Parku, G. K., Collard, F.-X., & Görgens, J. F. (2020). Pyrolysis of waste polypropylene plastics for energy recovery: Influence of heating rate and vacuum conditions on composition of fuel product. *Fuel Processing Technology*, *209*, 106522. https://doi.org/10.1016/j.fuproc.2020.106522
29. Sangpatch, T., Kanokkantapong, V., Puasuwon, P., Prasertsak, T., & Tuntiwiwattanapun, N. (2025). Development of a catalyst co-pyrolysis process for producing pyrolysis oil and wax from cooking oil contaminated polypropylene plastic. *Scientific Reports*, *15*(1), 27440. https://doi.org/10.1038/s41598-025-13255-1
30. Saramath and Chanathaworn. (2024). Influence of waste plastic types on product yields through pyrolysis process using a novel batch reactor with a fractional condensation system. *Chiang Mai Journal of Science*, *51*(6), 1–16. https://doi.org/10.12982/CMJS.2024.091
31. Thahir, R., Altway, A., Juliastuti, S. R., & Susianto. (2019). Production of liquid fuel from plastic waste using integrated pyrolysis method with refinery distillation bubble cap plate column. *Energy Reports*, *5*, 70–77. https://doi.org/10.1016/j.egyr.2018.11.004

32. Vafin, D., & Vankov, Y. (2025). Modeling of the thermal state of the radiation chambers of hydrocarbon pyrolysis furnaces with a large number of burner tiers. *Современные Наукоемкие Технологии (Modern High Technologies)*. https://doi.org/10.17513/snt.40300
33. Vellaiyan, S., Chandran, D., Venkatachalam, R., Ramalingam, K., Rao, R., & Raviadaran, R. (2024). Maximizing waste plastic oil yield and enhancing energy and environmental metrics through pyrolysis process optimization and fuel modification. *Results in Engineering*, *22*, 102066–102066. https://doi.org/10.1016/j.rineng.2024.102066
34. Zaid, Z. A. A. A., & Otaru, A. (2025). Low-heating-rate thermal degradation of date seed powder and HDPE plastic: Machine learning CDNN, MLRM, and thermokinetic analysis. *Polymers*, *17*. https://doi.org/10.3390/polym17060740
35. Zeb, W., Roosen, M., Knockaert, P., Janssens, S., Withoeck, D., Kusenberg, M., Hogie, J., Billen, P., Tavernier, S., Van Geem, K. M., & De Meester, S. (2023). Purification and characterisation of post-consumer plastic pyrolysis oil fractionated by vacuum distillation. *Journal of Cleaner Production*, *416*, 137881. https://doi.org/10.1016/j.jclepro.2023.137881
36. Zhang, Y., Fu, Z., Wang, W., Ji, G., Zhao, M., & Li, A. (2022). Kinetics, product evolution, and mechanism for the pyrolysis of typical plastic waste. *ACS Sustainable Chemistry & Engineering*, *10*(1), 91–103. https://doi.org/10.1021/acssuschemeng.1c04915
37. Zolghadr, A., Kulas, D., & Shonnard, D. (2022). Evaluation of pyrolysis wax as a solvent in polyolefin pyrolysis processing. *Industrial & Engineering Chemistry Research*, *61*(30), 11080–11088. https://doi.org/10.1021/acs.iecr.2c01493