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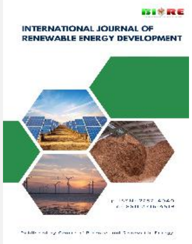

Research Article

Induction heating pyrolysis of landfilled plastic waste into valuable hydrocarbon fuels

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Abstract. This research investigated the pyrolysis process for plastic waste treatment using induction heating. The induction system involved a coil wrapped around insulated material to generate heat. The plastic waste was sourced from the Refuse-Derived Fuel (RDF) sorting process from a 15-year-old landfill in the province of Nonthaburi, Thailand. The pyrolysis was performed at temperatures ranging from 400 to 600°C with a batch reactor. The highest yield of pyrolysis oil was 27.6% wt. at 600°C. Energy consumption for converting plastic waste into oil ranged between 9.50 and 13.36 kWh, with the highest consumption at 600 °C. The produced pyrolysis oil at 600°C achieved the highest HHV of 41.33 MJ/kg. The GC/MS analysis of the pyrolysis oil revealed an increase in aromatic and hydrocarbons (C5-C11 and C12-C20) with rising temperature. These carbon fractions are suitable replacements for heavy oil or diesel fuel, as low-oxygenated compounds, and hydrocarbon content in pyrolysis oil are desirable. The amount of char produced at 400°C was the highest, with a yield that ranged from 45.2% wt. to 67.0% wt. Moreover, the pyrolysis process has a significant advantage in lowering greenhouse gas emissions (0.21–0.25% vol.), which releases less CO_2 than the combustion of plastic waste. The findings therefore suggest that pyrolysis oil, which is produced under optimum conditions, can be used as a substitute liquid fuel in the industrial sector, and is consistent with the circular economy's concepts, promoting sustainability and utilizing resource efficiency.

Keywords: Induction heating, Pyrolysis process, Plastic waste, RDF

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1. Introduction

In Thailand, the production of plastics utilized for consumption reached a total of over 34.3 million metric tons in the year 2022. (Kittithammavong *et al.*, 2023). The total domestic consumption of plastic in Thailand is 6.07 million tons. Of this, approximately 2.32 million tons (38.2 %) are used for packaging, particularly Single-Use Plastic (SUP), which generate the most waste. This category includes items such as hot bags, cool bags, handle bags, and plastic straws. Plastic waste after consumption amounts to around 1.91 million tons. The remaining 1.85 million tons (96.86%) causes environmental problems, with 0.06 million tons (3.14 %) escaping into the environment (Pollution Control Department, 2021). Of this, about 0.36 million tons (20.21 %) are reused. Post-consumer plastic waste (Single-Use Plastic) is shown in Fig. 1. In response, Thailand's Pollution Control Department has developed guidelines for managing plastic waste from 2018 to 2030, aiming to reduce waste generation and enhance recycling within the supply chain (Pollution Control Department, 2021).

Normally, plastic waste is often handled by landfilling, mechanical recycling, energy recovery (including co-processing and incineration), and chemical recycling techniques (Breyer *et al.*, 2017). Around 50% of all plastic debris produced is made up of polyethylene (PE), which has been recognized as the main component of all plastic waste (Rasaidi *et al.*, 2022). Thailand manages plastic waste through four main methods, each with challenges and implications. Landfilling is used for contaminated plastics like hot bags and handle bags that are costly to clean and recycle, but this method is expensive, and plastics degrade slowly. Recycling allows reuse but is limited by high costs and the need for material separation, leading to low recycling rates. Refuse-Derived Fuel (RDF) converts plastic waste into fuel for cement factories, utilizing its high calorific value. Incineration, whether for energy or not, poses environmental risks if poorly managed, releasing toxins into air, water, and soil, affecting the food chain.(Pollution Control Department, 2021). Furthermore, Thailand's energy usage has been rising annually by about 1%. One such policy is the Alternative Energy Development Plan 2015 (AEDP), which seeks to determine how to combine energy plans with alternative energy sources (Treedet *et al.*, 2020). Waste-to-

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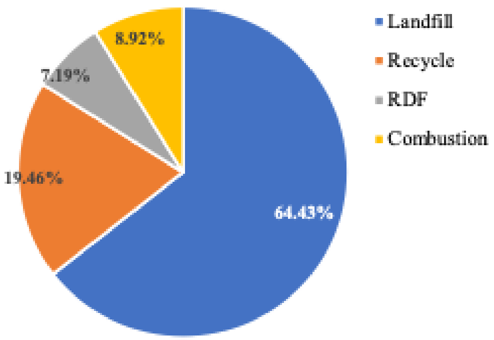


Fig.1 Plastic waste management in Thailand 2021

energy (WTE) is one of the most important techniques for obtaining energy from industrial and municipal solid waste (Duangjaiboon *et al.*, 2021).

Pyrolysis is a thermochemical reaction carried out in the absence of oxygen at a high temperature (often above 500°C) (Haryanto *et al.*, 2021; Thahir *et al.*, 2019; Treedet *et al.*, 2020). It transforms the waste plastic into a combination of solid-state hydrocarbons (referred to as char) and gaseous and liquid hydrocarbons (Haryanto *et al.*, 2021; Liu *et al.*, 2024; Özbay *et al.*, 2018). The distribution of products obtained by pyrolysis is highly dependent on the type of plastic, the kind of catalyst, and the reaction parameters, including temperature, flow rate, residence time, and heating rate. The waste plastic is heated to high temperatures (500–700 °C) during the pyrolysis process without the presence of oxygen, which yields several valuable products such as chemicals, petrol, and hydrocarbon fuels. (Anuar Sharuddin *et al.*, 2016; Dai *et al.*, 2024; Lopez *et al.*, 2017). Consequently, the pyrolysis process conversion of waste plastics into useful products such as liquid oil or pyrolysis oil not only reduces the negative environmental effects of plastic waste but also assists in preserving fossil fuels for use as a source of energy in the industrial sector or transportation in the future (Kumar *et al.*, 2024; Mirkarimi *et al.*, 2022; Zahra *et al.*, 2022). Additionally, any char residue formed at the bottom of the reactor can be repurposed as solid fuel (Marais *et al.*, 2024; Sunaryo *et al.*, 2023), further optimizing resource utilization, as depicted in Fig. 2

The principle of producing oil from plastic waste using this machine involves pyrolysis technology (Lopez-Urionabarrenechea *et al.*, 2015), which includes heating plastic waste until it becomes a gaseous product at a temperature of 500 °C in an oxygen-free atmosphere, utilizing nitrogen gas. In the presence of oxygen, the combustion of plastic waste results in the formation of ash rather than gaseous byproducts. At room temperature, water condenses the resulting gas, transforming it into a liquid or oil product. The use of catalysts helps improve oil quality, increasing the oil yield by 1-2 %. The plastic waste used in the production of oil comes from four types of plastic: i. Low-density polyethylene (LDPE) ii. High-density polyethylene (HDPE), iii. Polypropylene (PP) and iv. Polystyrene (PS) (Rasaidi *et al.*, 2022). It has been found that each type of plastic yields different types of oil according to its composition (Xayachak *et al.*, 2022).

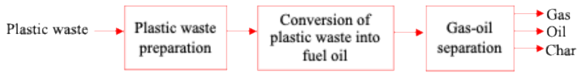


Fig. 2 Plastic waste pyrolysis process

Induction heating is a technique where an electrically conductive object, typically a metal, is heated through electromagnetic induction. This process involves generating eddy currents (also known as Foucault currents) within the metal, which encounter resistance and lead to Joule heating—a form of contactless heating for heating conductive materials. The process starts when an alternating current (AC) flows through an induction coil, and a rapidly shifting magnetic field is created around it, initiating the process. This method is particularly effective in plastic melting processes (Macrì *et al.*, 2022), where it avoids the energy losses typical of conventional heating coils that transfer heat through air convection and conduction from the coil to the plastic (Panda *et al.*, 2010; Vieweg *et al.*, 2016). The coil's position and operating frequency are crucial in induction heating, as they define the temperature profile for a workpiece (Sosa Sabogal *et al.*, 2021). In the metal industry, induction heating is versatile, enabling uniform heating, targeted surface heating, and smelting, which improves energy efficiency and minimizes waste (Cai *et al.*, 2020; Duong-Viet *et al.*, 2023).

Furthermore, compared to burning plastic waste, thermochemical recycling, or the pyrolysis process, allows one to significantly reduce greenhouse gas (GHG) emissions (Duong-Viet *et al.*, 2023). Regarding the heat source, renewable energy is considered to be a substitute for conventional burners, offering various advantages in terms of managing temperature profiles and maximizing pyrolysis stream yield. However, using ordinary electrical furnaces leads to low efficiency and high energy losses, as noted by certain authors (Duong-Viet *et al.*, 2023). Another energy-efficient, contactless, and pollution-free technique of heating ferromagnetic materials is electromagnetic induction heating, which creates an oscillating magnetic field inside induction coils using an AC power source. Induction heating represents a significant advancement in heating technology, offering more efficient energy use compared to traditional methods such as heating coils and gas(Giwa *et al.*, 2020; Lopez-Urionabarrenechea *et al.*, 2015). This process operates on the principle of induction, where a high-frequency alternating current is supplied to a coil, generating a magnetic field. This field interacts with ferromagnetic materials, inducing eddy currents that result in heat accumulation. Induction heating is employed in a variety of applications, including induction cookers, kettles, water heaters, and machines used for hardening, melting plastics, and melting glass. This technology allows for the quick and steady distribution of heat energy within the pyrolysis reactor. It satisfies the requirements for a quick pyrolysis process, including high energy efficiency, accurate temperature control, and quick heating rates. (Macrì *et al.*, 2022) However, limited research on landfilled plastic waste pyrolysis using electromagnetic induction heating reactor furnaces.

Numerous studies have examined the impact of temperature and plastic waste type on liquid yield. In order to produce liquid fuels, Budsaereechai et al. investigated the pyrolysis of plastic waste. They discovered that without a catalyst, a liquid yield of over 85% was achieved at 500 °C(Budsaereechai *et al.*, 2019). According to K. Jagodzińska et al.'s (2021) study on the amount of oil from landfilled plastic waste materials, the char yield drops approximately linearly with temperature, favoring the generation of pyrolysis vapors (both condensable and non-condensable). The yield of char reaches its lowest at 600°C, while the output of pyrolysis oil rises to 37.7% by weight (Jagodzińska *et al.*, 2021). In the methodology of induction pyrolysis, Duong-Viet et al. conducted an investigation into the process of magnetic induction-assisted pyrolysis of plastic waste, yielding liquid hydrocarbons through the utilization of a carbon catalyst. The study revealed a heightened yield of liquid products reaching 57%, thereby affirming the increased efficiency of the synergistic catalytic system and induction heating in the domain of waste plastic recycling (Duong-Viet *et al.*, 2023). Moreover, Sabogal (2021) studied an induction-heated reactor (IHR) for pyrolysis, achieving high heating rates and uniform temperature distribution, unlike traditional electrical furnaces. The IHR effectively processes solid recovered fuel, demonstrating reproducibility in product composition compared to larger fluidized bed reactors. They found that the tar fraction is herein defined as comprising all condensable organic compounds (7%wt.) possessing a molecular weight exceeding that of toluene. In the Induction Heated Reactor (IHR), 31% of the carbon was retained in the char after pyrolysis of Solid Recovered Fuel (SRF) pellets (1 cm high, 5 mm diameter) at 800°C. However, the results do not specify the energy consumption for heating the reactor.

This research focuses on the treatment and recovery of plastic waste in landfills, specifically polyethylene (PE) that cannot be recycled in the form of plastic bags from landfills. This investigates the pyrolysis process facilitated by electrical induction heating to convert this waste into fuel. There is limited research regarding the use of induction heating for this process, which provides rapid and stable heating while being more energy-efficient than conventional electric furnaces. This study also examines the electrical power used in the degradation of plastic waste. It is necessary to design the system to be suitable for the size of the pyrolysis reactor and the amount of waste to be transformed. This innovative approach utilizes an induction heating reactor that maintains a consistent temperature, enhancing the conversion efficiency by condensing the hot gases from the reactor into a liquid via a contact condenser. Unlike traditional pyrolysis that requires external fuel sources (such as LPG or solid fuel) for heating the reactor, this method employs electricity for induction heating, ensuring constant temperature control through automatic systems and minimizing environmental pollution by eliminating the need for burning fuel. Notably, there has been no prior research on the production of pyrolysis oil from landfill plastic waste while considering the electrical energy consumed in the system. The primary objective of this research is to develop a sustainable process that recycles PE plastic waste into fuel using an electrical induction heating reactor, thereby providing an environmentally friendly solution to plastic waste management.

2. Materials and methods

2.1 Materials

2.1.1 Induction heating system

The technique involves generating heat directly within ferrous objects placed within the induction field, causing their molecules to vibrate and produce heat rapidly. The design of the waste plastic pyrolysis furnace, which employs induction heating and is constructed from a stainless-steel tube with a diameter of 0.3 m and a height of 1.0 m, with the specific grade of stainless steel used for the reactor being 304L, which is capable of enduring temperatures of up to 1400°C. The coil used to heat the reactor is fabricated from a 6.35 (¼ inch) copper pipe with a diameter of 57 mm and a length of 5 meters, coiled to form 10 turns as shown in Fig. 3.

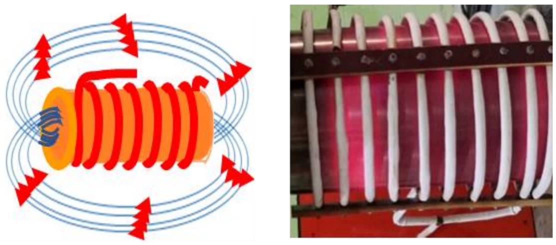


Fig. 3 The induction heating with pyrolysis reactor

2.1.2 Landfilled plastic waste

Plastic waste was obtained from a landfill in in Nonthaburi province. Opening landfills offers a chance to collect recyclables and produce RDF, which WTE power plants can use to generate electricity (Duangjaiboon *et al.*, 2021). To prevent metal and other potentially hazardous contaminants from preventing the subsequent mechanical separation equipment from working properly, plastic wastes from the landfill were first put through an on-site separation process. A multi-stage separation process was used to sort landfill waste for RDF production. A pre-shredder, with a 264-kW power rating, was used to process all landfill waste (LW). The conveyor belt, measuring 1.4 m by 1.2 m, transported the waste, which was reduced to less than 80 mm for use as raw material in the pyrolysis process (Rahothan *et al.*, 2023).

Excavated from the landfill, the plastic waste contained a wide range of contaminants, including wood, textiles, metals, and fines (Breyer *et al.*, 2017). Thermochemical processes can dispose of waste types that cannot be composted, such as plastic, foam, rubber, and clothes (Jagodzińska *et al.*, 2021; Sun *et al.*, 2020). Plastic waste recovered from the landfill separation process is shown in Fig. 3. The experiment utilized plastic waste sourced from landfills, specifically polyethylene (PE), that was several years old and had undergone heavy metal separation processes.

Substantial volumes of plastic waste that cannot pass through the separator are not shredded but are instead directed into an induction furnace for conversion into liquid fuel. Three characteristics of plastic waste samples taken from landfills were measured following ASTM standards: moisture content, amount of ash content and volatile organic compound evaporation.

2.2 Method for pyrolysis process

This research study outlined a methodology for designing and developing a system to convert plastic waste into liquid fuel using pyrolysis in an induction heating reactor. The primary goal was to transform unused plastic waste into alternative energy sources, thereby contributing to environmental conservation efforts in waste management.

Fig. 4 Landfilled plastic waste from the separation process

2.2.1 Pyrolysis process

The system was capable of processing 1 kg of plastic waste per cycle, depending on the waste's density, and operated with an environmental focus to ensure no detrimental impacts during the pyrolysis process. Product gas (non-condensable gases) exits the condensable retaining system and connects to the reactor via the drain line flows upward for gas species measurement. The gas produced was identified by continuous real-time quantification of Testo model 350 to analyse the gas composition of CO, CO_2, NO_x, SO_2, and H_2. A cyclone system captured dust particles generated during the reaction. The gases were then condensed into oil by a condenser unit, effectively converting plastic waste into liquid fuel through pyrolysis. The experiment set up for the conversion process is detailed in Fig. 4, demonstrating the operational mechanics of the induction heating reactor. The pyrolyzed plastic waste to oil fuel products by the pyrolysis induction reactor was weighed and recorded. In addition, after the reactor has cooled to room temperature, the residual solid products (char) were weighed and collected. Furthermore, systematic measurements of the resultant gas were recorded at five-minute intervals throughout the duration of these experiments.

2.2.2 Characteristics of Py- oil

GC/MS was used to analyze the py-oil obtained from the pyrolysis of landfilled plastic waste. According to the pyrolytic oil's inherent complexity, the compound distribution was identified by comparing the gas chromatogram peaks with those in a commercially available library. The Shimadzu QP2010 was used for the GC/MS analysis, and a DB-1701 column (length 60.00 m, ID 0.25 mm, film thickness 0.25 mm) was used as the GC column. The liquid fraction was dissolved in acetone and stored at 5 °C. It was filtered using a 0.45 mm microfilter before being injected into the GC/MS for analysis. In addition, the gross calorific value (HHV) of the Py-oil sample was determined as an important usability property. In compliance with ASTM D240, a bomb calorimeter (Leco model AC-350) was used to evaluate the feedstock's high heating value. This study focused was on producing pyrolysis oil using an electrical induction heating reactor and exploring its potential as a substitute for fuel oil and low-speed diesel. This approach not only offered a sustainable solution to managing plastic waste but also contributed to the development of renewable energy resources(Oufkir *et al.*, 2024).

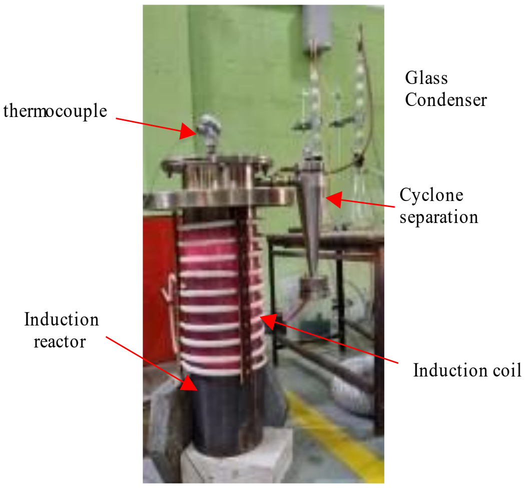


Fig. 5 Induction furnace used in plastic waste pyrolysis process.

3. Result and Discussion

3.1 Material characteristics

The samples of landfilled plastic waste (LPW) were used for thermogravimetric analysis (TGA; Mettler Toledo: SDTA 851e) to identify the thermal degradation curve. The weight loss of plastic waste in an N_2 atmosphere (Flow rate 20ml/min) with a range of 30-1000 °C (heating rate: 20 °C/min), and the TG curve is shown in Fig. 6.

The relatively wide degradation range showed a slight drop at 100 °C due to moisture content and a rapid drop around 450 °C due to volatile content, with maximum weight loss occurring at 480 °C. The degradation pattern of plastic waste , observed from the shape of the weight loss curves, corresponded well with the study by Das et al. which showed sa similar curve for PE (Das *et al.*, 2018). Furthermore, the remaining weight was 22.04 wt.%, indicating that the landfilled plastic waste contained a high proportion of non-pyrolyzed components. The proximate analysis of plastic waste is shown in Table 1

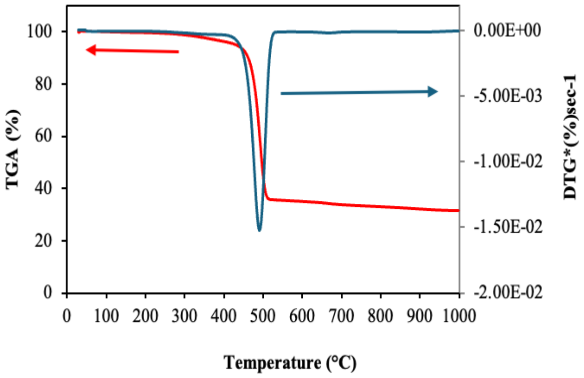


Fig. 6 TGA curves of landfilled plastic waste.

Table 1
Properties of landfilled plastic waste

Plastic waste	Volatile matter (%wt.)	Moisture content (%wt.)	Ash (%wt.)	Calorific value (MJ/kg)
Non-sieved 15-year-old landfills	94.25	3.75	22.04	33.27
Sieved 15-year-old landfills	97.31	2.69	10.21	36.23

A large portion of the volatile matter in plastic waste consists of various organic compounds, ranging from 94.25 to 97.31 %wt. The findings showed that 97.31% wt. of the most volatile compounds were released from plastic waste samples excavated from 15-year-old landfills that had been finely sieved. Unsieved 15-year-old landfill samples had the highest ash concentration (22.04%wt.), , which could be attributed to the presence of soil-like contaminants in the landfilled plastic waste (Canopoli *et al.*, 2020; Kaewpengkrow *et al.*, 2012). The low moisture content of the separated plastic wastes (only 2.69–3.75 wt.%.) may be attributed to the screening machine's removal of biodegradable organic compounds from the waste. A solid fuel's thermal characteristics are determined by its composition, and the pyrolysis process will influence the fuel's heating behavior. The TGA results indicate the temperature range pertinent to the decomposition of plastic waste in the induction pyrolysis reactor.

3.2 The analysis of products distribution from the pyrolysis process

The process of plastic degradation is initiated at thermal thresholds ranging from 400°C to 600°C. The outcomes of plastic pyrolysis yield two distinct types of products: condensable gases, which represents the liquid byproduct comprising crude oil (naphtha), heavy oil (diesel), light oil (gasoline), and wax. Non-condensable gas, primarily short-chain hydrocarbons, possess a high calorific value (Hegedüs *et al.*, 2024; Kartik *et al.*, 2022; Xayachak *et al.*, 2022).

The amount of oil obtained, and the char produced from pyrolyzing 1 kg of plastic waste at high temperatures for 90 min further supports these results, as shown in Fig. 7. The product distribution, including the proportions of oil, gas, and residue (char), was calculated using the formula provided by Thahir et al.(Thahir *et al.*, 2019).

Liquid Yield:

$$\text{Py}-\text{oil (wt.\%)} = \frac{\text{Quantity of oil}}{\text{Quantity of plastic waste}} \times 100\% \qquad (1)$$

Residue Yield (Char):

$$\text{Char (wt.\%)} = \frac{\text{Quantity of char residue}}{\text{Quantity of plastic waste}} \times 100\% \qquad (2)$$

Gas Yield:

$$\text{Gas (wt.\%)} \quad = \quad 100\text{- (Py-oil + char)} \qquad (3)$$

Fig. 7 presents the amount of oil obtained to the amount of char produced by pyrolyzing 1 kg of plastic waste for 90 min. The oil yield ranged between 18.2 and 27.6 % wt., the highest yield achieved at 600 °C. Nevertheless, at 600 °C, the char yield was the lowest, indicating optimal plastic decomposition at this temperature. This result is consistent with the study carried out by Khan et al. (2016), which examined the properties of fuel produced by pyrolyzing plastic waste using high-density polyethylene (HDPE) in a laboratory reactor made of stainless steel that was self-designed. In their study, HDPE waste was completely pyrolyzed at temperatures between 330 and 490 °C over 2 to 3 h (Khan *et al.*, 2016). However, this study found that using an electric induction technique for the pyrolysis process to manage plastic waste was most effective at 600 °C for 1.5 h.

The findings indicated that lower thermal conditions resulted in a reduced yield of liquid and gaseous products, accompanied by an elevated char yield ranging from 45.2 to 67.0 wt.%, with the maximum char production occurring at 400 °C, attributable to incomplete pyrolysis reactions. This study produced a relatively high amount of char due to the contamination of the plastic waste with soil particles from long-term landfill exposure (Kaewpengkrow *et al.*, 2012). As a consequence, the investigators assessed the heating value of char as a metric for its prospective utilization as a solid fuel alternative to coal within the industrial domain. The char properties varied from lumps to powders, depending on the pyrolysis temperature. Table 2 delineates the analytical findings regarding the heat value and characteristics of the solid yield (designated as char).

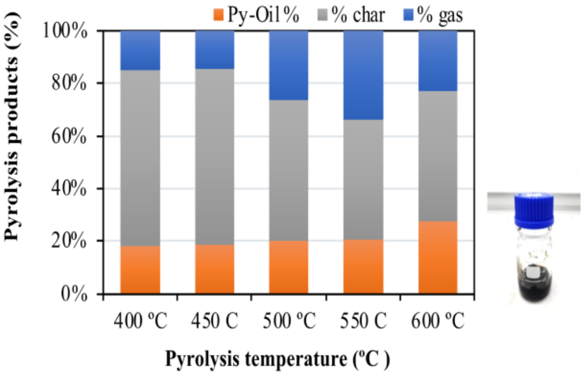


Fig. 7 The product distribution produced from the pyrolysis process at various temperatures

Table 2 demonstrates that higher temperatures result in finer char powder. The analysis of the heat value revealed a decrease in heat value due to the overall heat distribution during the reaction, in line with the findings of Kaewpengkrow et al. (2012) who found that the heat properties of char from the pyrolysis process decrease as the pyrolysis temperature increases (Kaewpengkrow *et al.*, 2012). Nonetheless, the residual char retains sufficient calorific value for use as a solid fuel in industrial furnaces(Sunaryo *et al.*, 2023). These findings

Table 2
The analysis of the heating value of char from pyrolysis of plastic waste.

Temperature (°C)	Py-oil and Char products	Heating value (MJ/Kg)
400		14.28 ± 1.37
450		12.28 ± 1.31
500		10.46 ± 2.15
550		10.28 ± 1.12
600		9.85 ± 1.26

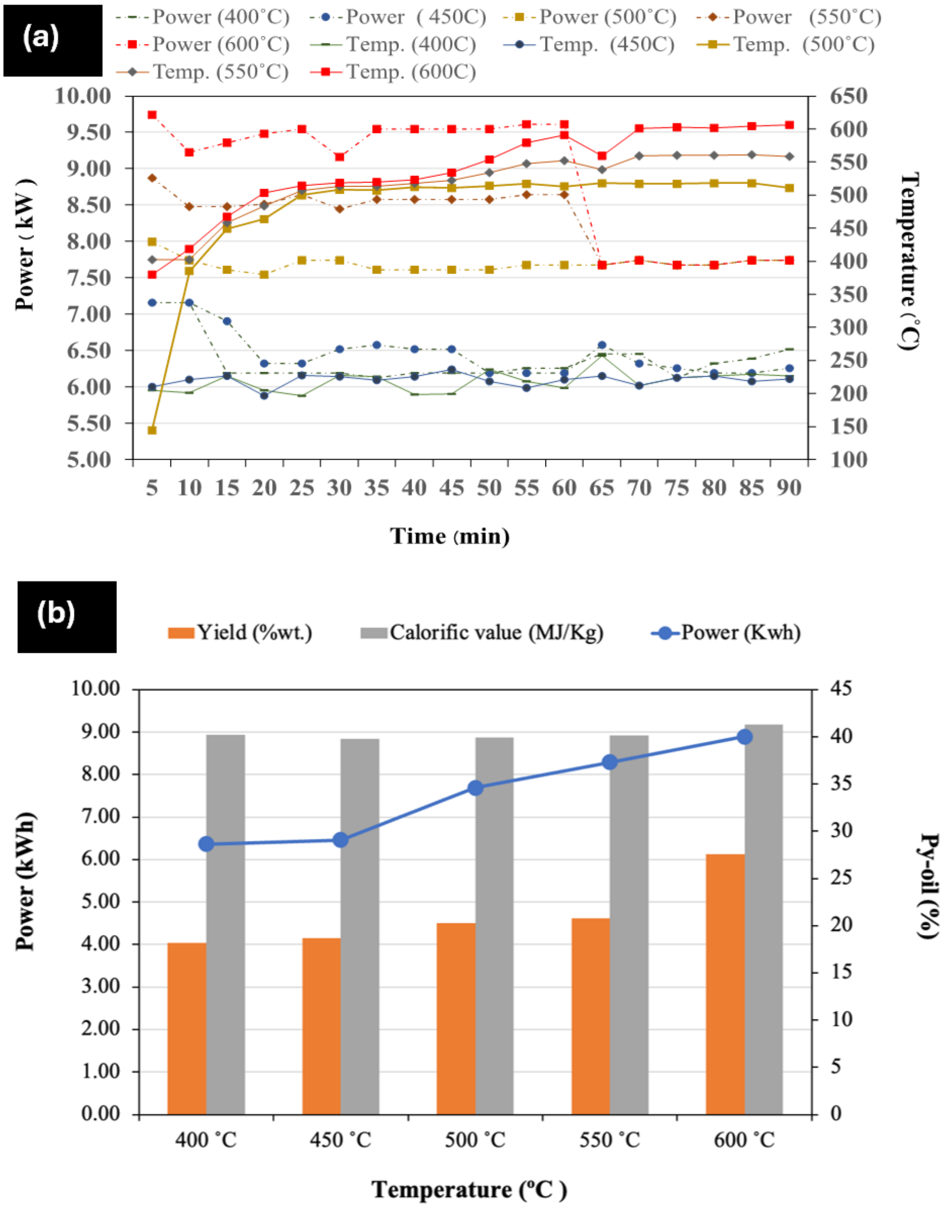


Fig. 8 (a) The relative of energy consumption and temperature in an induction furnace **(b)** The amount of oil, heating value, and energy used measured during the plastic waste pyrolysis process at different temperatures (°C).

align with those of Sabogal *et al.* (2021), who investigated the rapid pyrolysis of solid recovered fuel using a small-scale induction heated reactor (IHR) in comparison to FBR reactors. Their study reported reported high repeatability in IHR data (Sosa Sabogal *et al.*, 2021).

The information detailed in this table reveals that the heating value of char fluctuated between 9.85 and 14.28 MJ/kg, indicating that the volatile fractions contained within the plastic waste were largely transformed into gaseous products during the pyrolysis process. The heating value of the char exhibited a decrement in relation to the increasing temperature. This finding is consistent with the research conducted by Sunaryo et al., which revealed that the heating value of char derived from plastic waste demonstrates considerable variability with pyrolysis temperatures, particularly at 450 °C, yielding a higher heating value (HHV) of 3575 Cal/g (14.95 MJ/Kg). The results indicate that the dominant chemical element within the char is carbon (solid carbon), thereby suggesting its potential for conversion into solid fuel (Sunaryo *et al.*, 2023).

3.3 Effect of temperature on liquid fuel yield and energy consumption

The yield of liquid fuel derived from pyrolysis facilitated by induction heating, aimed at the remediation of plastic waste, specifically targets polyethylene (PE) materials, and was experimentally assessed using plastic waste sourced from landfills. Fig. 8 (a) and (b) illustrates the electrical power consumption and thermal regulation of the induction apparatus. Thermal profiles of internally of the reactor were systematically monitored during various experimental runs conducted at atmospheric pressure, as depicted in Fig. 8 (a). The energy consumption, oil products, and heating value during the pyrolysis of plastic waste at various temperatures are displayed in Fig. 8(b).

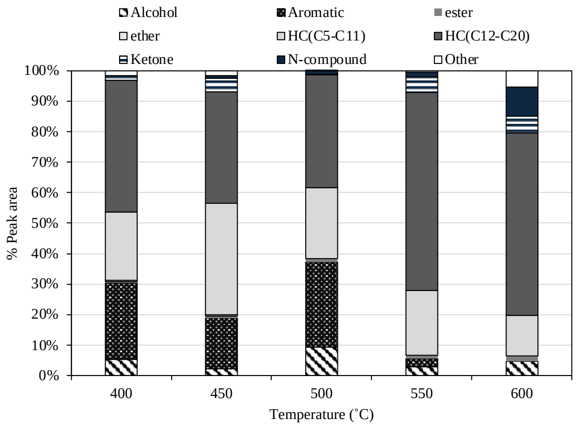


Fig. 9 Product group distribution of Py-oil in various pyrolysis conditions (a),400 °C (b), 450 °C,(c) 500 °C (d) 550 °C and (e) 600 °C

Fig.8(a) illustrates the correlation between the electrical power consumption and temperature employed during the pyrolysis of 1 kg of plastic using an induction furnace to produce liquid fuel. The average electrical power consumption was ranged from 5.90 to 8.9 kW (Fig. 8(a), equivalent to 7.5- to 13.35 kWh (Fig.8b) throughout the process for 1.5 hours. Throughout all pyrolysis temperatures, the heating rate remained relatively uniform, with the target temperature reached after 30 minutes. It was determined that under an average thermal setting of 600 °C, the process exhibited the highest mean electrical power consumption, quantified at 13.35 kWh. The findings elucidate that an increase in pyrolysis temperature corresponds to an escalation in average electrical power consumption. Notably, within the 400-550 °C range, the temperature the temperature increased rapidly, while at 600 °C, it rose more gradually, taking approximately 60 minutes. The energy consumption to the amounts of oil produced are shown in Fig. 8(b).

The landfilled plastic waste was subjected to thermal treatment at temperatures ranging from 400 to 600 °C to facilitate the production of pyrolysis oil. At 600 °C, the yield of oil was recorded at 26.13%, while a production range of 17.23-19.69 %wt. was observed at temperatures of 400-550 °C. The analysis indicated that the optimal temperature for oil

Table 3
Product selectivity (%peaks area) of the pyrolysis oil at 600°C by GCMS

Peak no.	Retention time	Peak area (%)	Compounds	Compound group
1	4.29	0.93	2,4-Dimethyl-1-heptene	HC(C5-11)
2	7.03	0.25	3-Pyridinamine	N-compound
3	7.20	0.65	1-Decene	HC(C5-11)
4	7.36	0.24	Decane	HC(C5-11)
5	8.96	0.94	1-Undecene	HC(C5-11)
6	9.10	0.49	Undecane	HC(C5-11)
7	10.68	0.83	Dodecane	HC(C12-20)
8	11.92	0.68	1,13-Tetradecadiene	HC(C12-20)
9	12.02	1.91	1-Tridecene	HC(C12-20)
10	12.13	1.70	Tridecane	HC(C12-20)
11	13.29	0.69	7-Tetradecene	HC(C12-20)
12	13.37	2.40	1-Tetradecene	HC(C12-20)
13	13.48	1.52	Tetradecane	HC(C12-20)
14	13.55	0.25	2-Tetradecene, (E)-	HC(C12-20)
15	14.16	0.42	Undecane	HC(C5-11)
16	14.31	0.24	Undecane	HC(C5-11)
17	14.59	0.65	1,13-Tetradecadiene	HC(C12-20)
18	14.71	2.96	1-Pentadecene	HC(C12-20)
19	14.82	1.47	Pentadecane	HC(C12-20)
20	15.21	0.92	Cyclohexane, 1,2,4-trimethyl-	HC(C5-11)
21	16.28	0.60	1,16-Hexadecanediol	Alcohol
22	16.41	2.60	1-Hexadecene	HC(C12-20)
23	16.55	2.28	Hexadecane	HC(C12-20)
24	18.66	0.44	11-Hexadecen-1-ol, (Z)	Alcohol
25	18.86	2.25	1-Heptadecene	HC(C12-C20)
26	19.07	1.69	Heptadecane	HC(C12-C20)
27	19.61	0.24	(trans)-2-nonadecene	HC(C12-C20)
28	21.79	0.43	9H-Fluorene,9-methylene-	Other
29	22.23	0.56	Ethanol,2-(9-octadecenyloxy)-	Alcohol
30	22.51	2.25	1-Octadecene	HC(C12-C20)
31	22.83	1.88	Octadecane	HC(C12-C20)
32	25.76	0.56	1,19-Eicosadiene	HC(C12-20)
33	25.88	2.29	Z-5-Nonadecene	HC(C12-20)
34	25.99	1.75	Nonadecane	HC(C12-20)
35	26.08	0.26	1-Nonadecene	HC(C12-20)
36	27.19	2.71	5-Eicosene, (E)-	HC(C12-20)
37	27.27	2.06	Eicosane	HC(C12-20)
38	27.55	0.58	iso-pinocamphone	Ketone
39	28.12	4.42	10-Heneicosene (c,t)	HC(C12-20)
40	28.42	0.27	2-acetyl-1-pyrroline	N-compound
41	28.65	0.71	6-Tridecene, 7-methyl-	HC(C12-20)
42	28.72	0.23	Hexadecanamide	N-compound
43	28.84	3.96	Heptafluorobutyric acid, n-octadecyl ester	Other
44	29.21	0.92	E-11,13-Dimethyl-12-tetradecen-1-ol acetate	Ester
45	29.57	3.47	1-Tricosene	HC(C12-20)
46	30.14	2.63	9-Octadecenamide, (Z)-	N-compound
47	30.39	4.55	Cyclotetracosane	HC(C12-20)
48	31.39	2.84	Z-12-Pentacosene	HC(C12-20)
49	32.63	3.24	Octadecane	HC(C12-20)
50	34.09	0.88	1-Eicosanol	HC(C12-20)

production was 600 °C. It is particularly noteworthy that at the elevated temperature of 600 °C, the maximum energy consumption for the transformation of plastic waste into oil was ascertained. Pyrolysis oil produced were analysed to find the heating value by using a bomb calorimeter to compare the properties of pyrolysis oil and commercial diesel. The calorific value of Py-oil was displayed in Fig. 8(b). The highest heating value at 41.33 MJ/kg was produced at 600 °C. The heating value ranged from 39.82 MJ/kg and 41.33 MJ/kg. This finding is consistent with research by Subhashini (2023), who compared the thermal pyrolysis of modal plastic compounds in a fixed-bed reactor with that of waste plastic (Subhashini *et al.*, 2023). The induction heating technique demonstrates to be suitable for the pyrolysis process in managing plastic waste and produce alternatives fuel.

3.4 The analysis of pyrolysis oil composition by GC-MS

Typically, pyrolysis of polymer from plastic waste was thought to produce complex fractions, particularly py-oil products. GC/MS techniques have provided a detailed characterization of this liquid portion from the peak area percentages, and more than 50 compounds have been identified. The chromatogram peak areas may be presented as a percentage of peak area (pa%) and considered to be reasonably linear with the quantity of each chemical for discussion purposes.

As shown in Fig. 8, hydrocarbon and aromatic compound proportions varied with temperature, with the lowest temperature of 400 for 65%, as a likely result of their conversion to primarily hydrocarbon compounds (Al-Salem, 2019). Product distributions of Py-oil from pyrolysis of plastic waste were identified into 9 groups: alcohol, aromatic, ester, ether, hydrocarbons (C5-C11 and C12-C20), ketones N-compound (amine and amide), and others. However, it should be mentioned that this estimation does not allow for cross-species comparisons of amount as displayed in Fig. 9.

Alkanes, such as Undecane, Cyclohexane, and 1,2,4-trimethyl-, were the minor hydrocarbons (13.04 – 36.39% peak area). The primary hydrocarbon products in the py-oil with high temperature were C12–C20 (36.23–64.90 % peak area), with the largest proportions obtained at 600 > 550 > 500 °C. Pyrolysis at 450–500°C produced a high amount of hydrocarbon in the range of C5-C11 which is the range of gasoline-like hydrocarbon and the result agreed well with Hegedüs *et al.,* 2024 (Hegedüs *et al.*, 2024). This suggests that these temperatures effectively break down large hydrocarbon molecules into lighter ones that might be used as fuel. A comparatively high yield of C12–C20 hydrocarbons (59.52%) was obtained; the temperature of 600°C produced the maximum yield. These carbon fractions are viable in place of diesel fuel (Das *et al.*, 2018; Khan *et al.*, 2016; Rahman *et al.*, 2023; Singh *et al.*, 2019). From the GCMS chromatograms, as indicated in Table 3, the pyrolysis oil's 50 primary product selectivity at 600°C (peak area similarity of more than 50%) was determined.

3.5 Effect of temperature on the amount of product gas composition

Plastic waste was pyrolyzed at different temperatures, including 400°C, 450°C, 500°C, 550°C, and 600°C, and various gases were detected. Produced gas yield and its volumetric composition are compared in Fig. 10. The gases measured included H_2, CO, CO_2, and SO_2. However, NO_X and NO_2, which are pollutants that require treatment before being released into the atmosphere, were not detected in the test. The pyrolysis process generates fewer gas emissions compared to plastic waste combustion, making it a more environmentally friendly process.

According to the test results, the best specific energy consumption index observed was 13.35 kWh (0.048 kW/g) when comparing the electricity consumption with the amount of oil obtained at 600 °C. The measurements of CO_2 gas production per amount of oil obtained showed varying results: at 400 °C, 0.21 % of CO_2 gas by volume was recorded; at 500 °C, the CO_2 gas increased to 0.25%; and at 600 °C, it decreased to 0.20%. These results indicated that the pyrolysis process at 600 °C was the most suitable temperature for optimizing oil yield versus gas emissions.

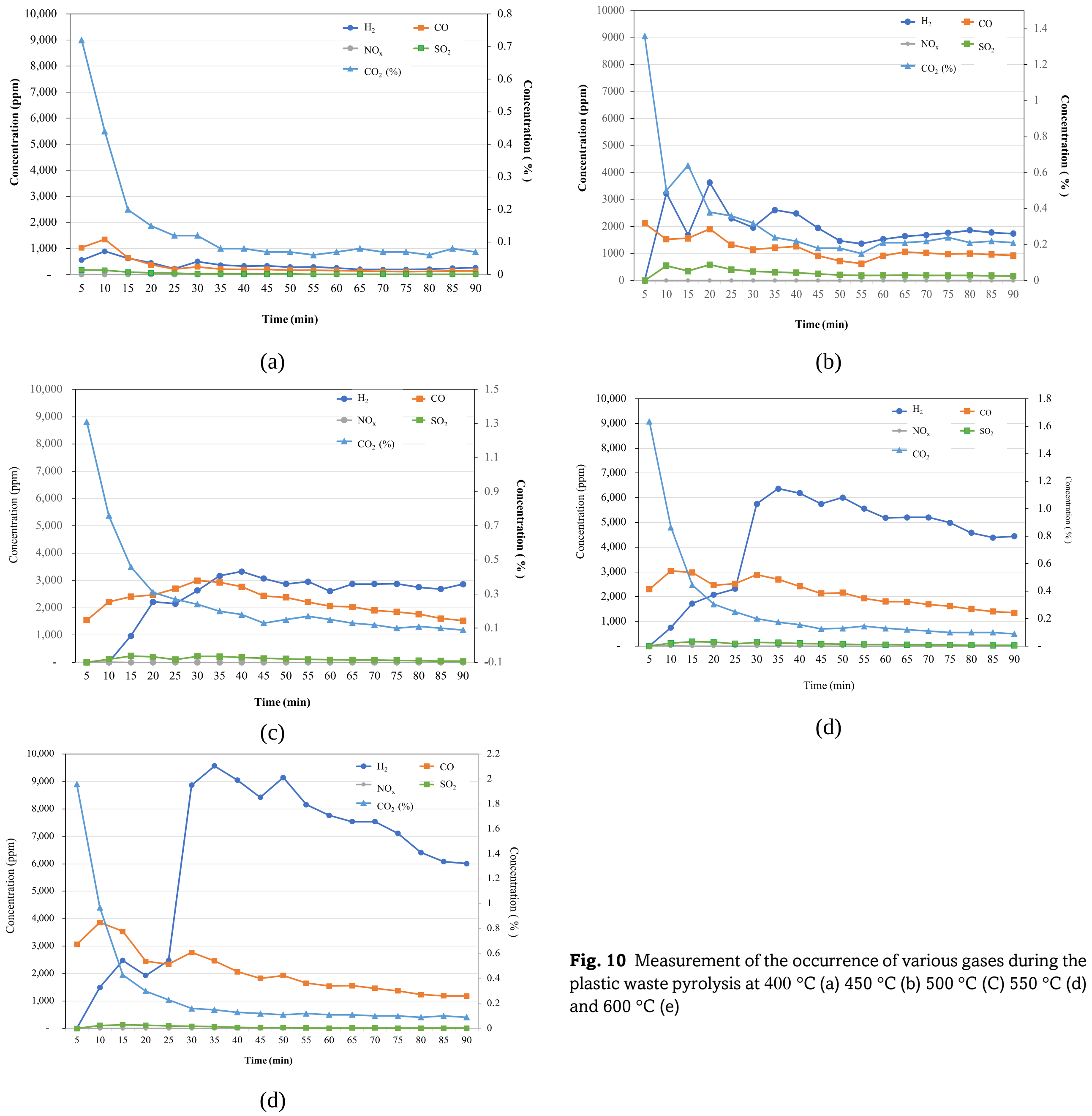
The findings resulting from the assessment of the emission of various gases throughout the 400 -600 °C pyrolysis procedure of plastic waste is illustrated in Fig. 9. This specific temperature facilitates the production of a considerable volume of CO during the preliminary stage of the combustion process. The average CO concentration ranged from 324.83– 2209.67 ppm, which is highest the pyrolysis temperature at 500 °C. Thereafter, following a duration of 20 minutes, the concentration of CO diminishes, accompanying reductions in CO_2, SO_2, and H_2. Particularly interesting is the absence of NO_X and NO_2 during the 400 °C trial. The highest gas emissions were observed is 500 °C. CO levels were highest during the initial pyrolysis stage, which is consistent with findings by Noppadol *et al,* (2023). Afterward, the CO and H_2 levels dropped after 45 minutes. In addition, the pyrolysis's initial CO_2 content was also discovered. There is also the benefit of NO_X and NO_2 gases being detected at a concentration of 0.5 ppm inside, which progressively drops to 0 ppm after 10 minutes.

This result indicated that the average H_2 generation was in range of 359.17– 6114 ppm, which is the highest concentration at 600 °C with an average of 6114 ppm. Hydrogen gas constituted the majority of the produced gas. This is caused by a degrading mechanism, primarily via random scission of polymer chains. Depolymerization at higher temperatures initiates this breakdown process, producing a gaseous fraction that contains hydrocarbons, CO, H_2 and CO_2 (Kaewpengkrow *et al.*, 2012). This is attributed to the high hydrogen concentration and the rapid heat transfer of LPF. The decomposition reactions can be described by the following equations:

Thermal cracking: $aC_nH_x \longrightarrow bC_mH_y + cH$ (1)
Carbon formation: $C_nH_x \longrightarrow nC + x/2H_2$ (2)

However, H_2 gas was more prominent during the first 30 min and decreased by 55 min. These findings demonstrated that a clear increase in H_2 occurred with an increase in the pyrolysis temperature. The thermal cracking of heavier hydrocarbons is the main reason for the increase in hydrocarbon gas (Kaewpengkrow *et al.*, 2012), This is advantageous since H_2 has a high calorific value and may be recovered and used to heat reactor processes. The results suggest that the pyrolysis process generated less greenhouse gas (CO_2) emission compared to combustion of plastic waste.

The generated gas can be utilized in a synthesis process to create chemicals or biofuels after being cleaned up, or it can be burned directly to provide energy and heat. The reactor design, process variables, and feedstock properties have a



(a)

(b)

(c)

(d)

(d)

Fig. 10 Measurement of the occurrence of various gases during the plastic waste pyrolysis at 400 °C (a) 450 °C (b) 500 °C (C) 550 °C (d) and 600 °C (e)

significant impact on the yields of products and their composition (Latha *et al.*, 2023). Consequently, the process of pyrolysis for the management of plastic waste via induction heating is identified as being highly energy-efficient and possesses the capability to generate alternative fuel.

4. Conclusions

The pyrolysis of plastic waste via induction heating achieved the highest oil yield (27.6 wt.%) at 600°C, which was also the most effective for oil production. Higher energy consumption at 600°C facilitated optimal plastic degradation into pyrolytic oil. The oil products were classified into nine groups, including alcohols, aromatics, esters, ethers, hydrocarbons (C5-C11 and C12-C20), ketones, and nitrogenous compounds. Minor hydrocarbons (13.04–36.39%) included undecane and cyclohexane, while C12–C20 hydrocarbons (36.23–64.90%) were predominant at 600°C, followed by 550°C and 500°C. Hydrocarbons in the gasoline-like C5-C11 range were abundant at 450–500°C. These fractions can serve as diesel or heavy oil substitutes. Pyrolytic oil with high aromatic and low oxygenated content is desirable, making it a viable alternative fuel for industrial applications. The findings demonstrated that at 600°C, CO and H_2 concentrations peaked early at 2086.06 and 6114.61 ppm, respectively. CO levels were highest at 500°C (2209.67 ppm), whereas at 600°C, CO emissions were comparatively lower. Interestingly, the findings indicated that pyrolysis generates fewer greenhouse gases than direct combustion, making it an effective plastic waste management strategy that mitigates emissions. Additionally, the high heating value and significant char yield underscore its potential as a solid fuel alternative. This research highlights a sustainable approach to converting landfilled plastic waste into alternative fuels, aligning with circular economy principles. Future studies should focus on optimizing plastic particle size to enhance thermal efficiency. Furthermore, pre-cleaning landfill plastic is recommended to improve oil yield and overall process efficiency.

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