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Influence of Pyrolysis Time and Temperature on the Quality of Liquid Fuel Produced from Polymeric Waste.

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ABSTRACT: Increasing temperature in biomass pyrolysis reduces biochar yield while enhancing gas yield, with bio-oil yield peaking around 500-550°C. There is a notable trend indicating that biochar production increases when plastic waste generation surpasses a certain threshold. Depolymerization at varying temperatures and times is recognized as an effective method for disposing of polymeric waste. The paper investigates the effects of temperature and time on the quality of byproducts generated from the conversion of plastic waste, specifically focusing on liquid fuel characterization from samples obtained at the Ado-Ekiti central market dumpsite in southwest Nigeria, utilizing zeolite for depolymerization in a batch reactor. This process involves heating the waste in an inert atmosphere, which results in the formation of both condensable and non-condensable hydrocarbons, as well as biochar. The fuel analysis through proximate and ultimate methods indicates its viability as a fossil fuel substitute, with moisture content between 0.07% and 0.13% and high volatile matter of 96.02%, akin to diesel. The performance metrics reveal optimal gas generation at 470-490 ºC over 35-40 minutes, achieving efficiencies up to 90%. HDPE yields better gas rates than LDPE under similar conditions. In polypropylene pyrolysis, the best yield is 68-90% with specific heating parameters. Carbon content in diesel is 85.51%, while plastic-derived oils range from 80.02% to 83.72%. Plastic oils have a higher hydrogen content, and the pyrolysis oil exhibits varying densities, viscosities, and flash points, with cetane numbers averaging 40.00 to 47.0. The characterization results showed that the fuel samples closely match the properties of conventional diesel according to ASTM standards. The depolymerized polymeric waste is identified as sustainable and cost-effective to produce, making it a viable alternative fuel and a means for wealth generation from waste.

KEYWORDS: Temperature, Time, Characterization, Depolymerization, Plastic Waste.

1. INTRODUCTION

Nigeria is faced with a substantial and growing energy demand, increasing at 8% annually, driven by its population of 200 million, the highest in Africa. The significance of renewable energy production has been reinforced by the Nigerian government since the introduction of the National Renewable Energy and Energy Efficiency Policy in 2015 (Tulashie *et al.*, 2019) Plastic waste is escalating rapidly due to rising human populations, economic growth, urbanization, and lifestyle changes. This issue is compounded by the short life span of plastic, resulting in a daily increase in plastic waste. Current global plastic production is estimated at approximately 300 million tons annually and continues to rise. Plastics, composed of petrochemical hydrocarbons and mixed with additives such as flame-retardants, stabilizers, and oxidants, pose significant biodegradation challenges. Plastics are advantageous materials known for their cost-effectiveness, lightweight properties, and durability, allowing them to be molded for diverse applications (Thahir *et al.*, 2019).

Plastic trash threatens the global economy and endangers people, animals, and the environment, particularly in emerging and underdeveloped nations with inadequate recycling capabilities and weak regulations regarding plastics. Plastics contain various additives such as plasticizers, fire retardants, antioxidants, and others, depending on their type and usage. Plastic waste is the third largest component of municipal and industrial waste, trailing only food and paper. The advancement of technology that converts waste plastics into valuable energy not only aids in conserving land resources but also offers a substantial alternative energy source to fossil fuels. This conversion process emphasizes the increasing necessity for society to prioritize environmental sustainability to benefit future generations (Rafey and Siddiqui 2021).

1.1 Plastic Waste Garbage

Plastic waste poses serious threats to the global economy, human health, animal welfare, and the environment, especially in underdeveloped and developing countries where recycling systems are lacking and plastic regulations are weak. Common additives in plastics, such as plasticizers, fire retardants, and antioxidants, have been found to infiltrate human and animal systems as endocrine disrupting chemicals (EDCs). Many of these additives are classified as Persistent Organic Pollutants (POPs), known as "forever chemicals." The high production of plastic combined with low recycling rates leads to the accumulation of plastic waste in landfills and oceans, creating significant health and environmental hazards. Additionally, plastic waste management issues are compounded by the release of toxic substances during disposal and blocked drainage systems, which can result in flooding and damage to infrastructure; this situation is aggravated by rapid urbanization that reduces available landfill space in urban settings (Damodharan *et al.*, 2018).

Plastic waste is categorized into several types, each with specific uses. Polyethylene Terephthalate (PETE) is used in water bottles, ketchup bottles, mouthwash bottles, peanut butter containers, and salad dressing and vegetable oil containers. High-Density Polyethylene (HDPE) serves for milk and juice bottles, household cleaner bottles, shampoo bottles, butter and yogurt tubs, and plastic bags. Polyvinyl Chloride (PVC) is utilized in drain pipes, playground equipment, and various products and packaging. Low-Density Polyethylene (LDPE) includes plastic bags, shrink wraps, and squeeze bottles. Polypropylene (PP) is used for packaging materials, medical supplies, plastic furniture, automotive parts, and plastic films. vi. Polystyrene (PS) is found in food containers, egg cartons, disposable cups and bowls, and packaging materials. The Miscellaneous Plastics (MP) category encompasses various materials, including polycarbonate, polylactide, acrylic, acrylonitrile butadiene styrene (ABS), fiberglass, and nylon (Abbas and Shubar, 2018; Rajamohan and Kasimani, 2018).

1.2 Plastic waste management

In the analysis of plastic waste management, both conventional and innovative technologies are emphasized. Conventional methods include landfilling, which faces challenges due to land shortages from urbanization, raising environmental concerns about toxic chemicals leaching into groundwater, leading to a decline in its use. Incineration or open burning is another common practice, especially in developing regions, contributing significantly to air pollution with harmful emissions, including dioxins, furans, and mercury, which threaten public health and the environment. Mechanical recycling recycles plastics without significantly altering their chemical structure and is categorized into downcycling, resulting in lower quality materials, and upcycling, which improves the quality or value of materials. These methods highlight the ongoing challenges and processes necessary for effective plastic waste management (Sharma *et al.*, 2020).

1.3 Pyrolysis Technologies

Pyrolysis is a process that thermally decomposes plastic waste at temperatures between 300–900°C in an oxygen-free environment, producing liquid and gaseous fuels. During this procedure, plastics are heated, breaking down into simpler hydrocarbons rather than being burned. This method, known as thermal depolymerization, converts plastics back into their original monomers, fuels, and other valuable materials. Compared to traditional recycling methods, pyrolysis has significant advantages, as typical recycling often results in downgraded products with lower quality and functionality due to the loss of crucial properties like clarity, strength, and flexibility over repeated recycling cycles (Anuar *et al.*, 2016). Pyrolysis is classified into three types based on heating rates: slow pyrolysis, characterized as non-isothermal; fast pyrolysis, which is isothermal; and ultra-fast or flash pyrolysis. Slow pyrolysis, also known as carbonization, involves incrementally heating organic materials in an oxygen-free environment to produce char with around 80% carbon retention. This method is distinct from fast pyrolysis, which heats materials quickly (400–600°C) under isothermal conditions to generate a significant amount of liquid fuel within seconds, and is commonly applied to plastics, utilizing heating rates of 100°C/s. Ultra-fast or flash pyrolysis further accelerates this process with heating rates ranging from 100 to 10,000°C/s, primarily yielding gases and bio-oil while maintaining very short residence times (Tumuluru 2016).

1.4 Pyrolysis Technology processing

Thermal pyrolysis, also known as thermal cracking, is a process that decomposes plastic materials through depolymerization or cracking at elevated temperatures, ranging from 350 to 900°C, in an environment devoid of oxygen. This method results in the production of gaseous, liquid, and carbonized char components. The liquid fuel, which is primarily obtained from the condensed volatile products, consists of a variety of hydrocarbons including paraffins, isoparaffins, olefins, naphthenes, and aromatics. The physical properties of the liquid fuel obtained by this process largely vary with the plastic type (Sharaddin *et al.*, 2018). Microwave-assisted pyrolysis is an innovative technology utilizing microwave dielectric heating to generate heat in materials through their dielectric properties. In this technique, microwaves interact with an absorbent, which in turn conducts thermal heat to plastic. The efficiency of this heating process is impacted by the absorbent's physical properties, its volume ratio, and variations in microwave power, leading to different product distributions. Research demonstrates that microwave-induced pyrolysis offers notable advantages over conventional thermal and catalytic methods, highlighting its potential in the production of valuable chemicals and fuels (Sharma *et al.*, 2020).

Catalytic pyrolysis is a technique that heats polymeric materials in a zero-oxygen environment utilizing catalysts to enhance degradation. The use of different catalysts, such as ZSM-5, Y-zeolite, fluid catalytic cracking (FCC), and MCM-41, improves process efficiency by specifically targeting reactions while lowering the temperature and time required.

These catalysts serve to decrease energy demands, alter the product composition by facilitating cracking, and accelerate the overall process duration. Additionally, silica alumina and various zeolites are commonly employed to further refine the pyrolysis of plastic waste (Rajendran *et al.*, 2020). Factors influencing the pyrolysis process include the composition of the chemical feedstock, which determines the yield and type of products produced. The cracking temperature and heating rate are crucial as they affect the speed of thermal decomposition. The type of reactor utilized can have varying impacts on efficiency and output. Additionally, the duration of the reaction is important for achieving optimal results. The application of catalysts can enhance the reaction rates and product quality. Lastly, the condensation process plays a significant role in the collection and separation of pyrolytic products (Stefanidis *et al.*, 2014).

1.5 Plastic Pyrolysis Process

Pyrolysis is a process where materials are broken down at high temperatures in an inert atmosphere. In waste management, it converts waste into three products: liquid (oil), solid (char), and gas (syngas). These products can serve as energy sources or chemical feedstocks. The yield of each product can be controlled by varying the pyrolytic conditions. Pyrolysis is a thermochemical process used for treating different waste types, functioning optimally within a temperature range of 300 to 1200 °C, in environments devoid of oxygen or filled with inert gases. This method requires lower temperatures compared to conventional combustion and is associated with reduced emissions of air pollutants and greenhouse gases (John *et al.*, 2023). Pyrolysis is an effective technique for converting plastic waste into fuel through a process that involves heating plastics to high temperatures without oxygen, resulting in the thermal and chemical depolymerization of the organic material. During this process, plastic materials are subjected to high temperatures, often in the presence of a catalyst, to facilitate the gentle cracking of long polymer chains. This leads to the production of gases that can be condensed into low-sulfur-content distilled waste plastic oil. The incorporation of catalysts is essential as they help to minimize the formation of toxic byproducts like dioxins and furans (Tumuluru, 2015).

The thermal degradation of plastics during pyrolysis generates three key fractions: gas, crude oil, and solid residue. The crude oil, which contains higher boiling point hydrocarbons, results from non-catalytic pyrolysis. To effectively produce gasoline and diesel from plastic waste, it is crucial to optimize several parameters, including catalyst type, pyrolysis temperature, and the plastic-to-catalyst ratio. The quality of crude oil can be improved through co-pyrolysis with coal or shale oil, which reduces viscosity. Several conversion methods for plastics to fuels are available, such as gasification, pyrolysis, plasma processing, and incineration. Pyrolysis is particularly noteworthy as it transforms plastic waste into solid, liquid, or gaseous fuels by thermally decomposing long-chain polymers into simpler molecules in the absence of oxygen. The primary outputs of pyrolysis include high-calorific-value combustible gas, combustible oils, and carbonized char (Shanker *et al.*, 2012).

1.5 Cracking temperature and heating rate

Temperature significantly affects the cracking reaction of polymer materials, primarily through Van der Waals forces that maintain molecular integrity. An increase in temperature can precipitate cracking; however, not all polymers respond similarly due to these forces. When molecular vibrations exceed a certain threshold, evaporation occurs, yet if the energy in the polymer chains exceeds the enthalpy of carbon-carbon (C-C) bonds, chain breakage may ensue. This behavior elucidates why high molecular weight polymers generally decompose instead of boiling upon heating. The ideal temperature for C-C bond disruption should remain stable across various plastics, yet different studies indicate significant variability. For example, the initiation temperature for cracking polypropylene (PP) has displayed inconsistencies, often due to the positioning of temperature sensors in heating equipment, impacting temperature readings. Research by Karaduman et al. revealed considerable temperature discrepancies in externally heated tubes, demonstrating substantial heat loss at their ends (Achilias *et al.*, 2017).

In plastic pyrolysis, "Heating rate" refers to the temperature increase per unit time, playing a crucial role in both the process and product distribution. Fast pyrolysis is marked by rapid temperature fluctuations, reaching heating rates up to 10,000 K/s, which complicates accurate measurement; therefore, surface temperature is commonly utilized as a proxy. Conversely, slow pyrolysis involves a gradual temperature increase over minutes. A significant study by Saha and Ghoshal examined the pyrolysis of Coca-Cola PET bottles, focusing on the impact of heating rates through thermogravimetric analysis (TGA). Their findings, presented in Figure 2.3, illustrate a plot of dAlpha/dT against absolute temperature for heating rates ranging from 10 to 25 K/min. The results indicate that higher heating rates enhance the speed of pyrolysis reactions (Beena, 2012)

1.6 Reactor types

The selection of the reactor type in plastic pyrolysis significantly influences various operational factors such as heat transfer rates, the mixing of plastics with pyrolysis products, residence time, and the reflux level of primary products. Pyrolysis reactors are classified based on two primary criteria: firstly, the feeding and product removal processes, which categorize them into batch, semi-batch, and continuous reactors; secondly, the heat transfer methods and flow patterns of the feedstock and products, leading to classifications as fixed bed, fluidized bed, and screw kiln reactors. Various types of reactors are employed in the pyrolysis process, including batch, semi-batch, continuous, fixed bed, fluidized bed, and screw kiln reactors (Urishev, 2019). A batch reactor operates by processing materials in discrete batches, while a semi-batch reactor allows for ongoing extraction of pyrolysis products, often enhanced by

using an inert carrier gas for greater efficiency. Continuous reactors feed materials and extract products simultaneously, predominantly utilized in industrial applications by companies such as Mitsui R21 and Fuji, particularly for secondary pyrolysis where semi-batch systems prove advantageous. The fixed bed reactor maintains a stationary bed, simplifying design and operations, yet it encounters difficulties with irregular plastic feedstocks and thermal conductivity, potentially leading to temperature inconsistencies during batch processing. In contrast, the fluidized bed reactor is favored in commercial scenarios due to its improved uniformity in temperature and composition, alongside efficient heat and mass transfer; however, it must address challenges related to bed material loss and gas separation. The screw kiln reactor utilizes an extruder to transport feedstock into a controlled oxygen-free environment, applying external heat for effective temperature regulation, which permits efficient separation of solids from pyrolysis products. This reactor design assists in handling the high viscosity of plastics and ensures precise control of the feeding rate via the extruder's rotational speed. Each reactor type presents unique operational advantages and challenges pertinent to the pyrolysis process (Zohuri, 2021).

Benefits of pyrolysis technology in plastic waste management include its high heating value and feed selectivity. The liquid fuel produced from plastic waste typically has a density that allows for a heating value of around 10,000 kcal/L, making it suitable for use in industries such as boilers, cement factories, steel mills, and glass factories. Additionally, pyrolysis technology is adaptable, able to process various types of waste plastics without the need for prior shredding. The entire conversion process from plastic to fuel occurs within the pyrolysis reactor, enhancing convenience and reducing labor requirements. Notably, there are also applications of co-pyrolysis where plastics are processed alongside waste paper, biomass, and medical waste plastics (Ugwu v 2022).

Biomass resources in Nigeria, encompassing agricultural residues, forest resources, aquatic biomass, and waste, are extensive but underutilized. Concurrently, plastic pollution presents a considerable environmental challenge, necessitating effective solutions. These biomass resources hold the potential to significantly enhance energy generation and mass production each year, thereby bolstering Nigeria's energy security and environmental sustainability. This paper aims to experimentally explore how variations in pyrolysis temperature and duration affect the yields of products from the conversion of plastic waste, ultimately seeking to improve energy output. The paper explores enhanced biomass conversion methods for bioenergy production, emphasizing its role in sustainable energy and reduced fossil fuel dependency. It highlights the potential to convert waste plastics into energy sources, positively impacting economic growth, environmental sustainability, and renewable energy in Nigeria. By examining various conversion pathways, the research identifies strategies to optimize energy production, improve waste management, and promote environmental sustainability. The study's results aim to guide policymakers, researchers, and industry stakeholders in developing effective bioenergy strategies to address energy challenges and foster economic growth through renewable energy initiatives in Nigeria.

2. MATERIALS AND METHOD

Materials used in a specific context: Polyethylene Terephthalate (PETE), High-Density Polyethylene (HDPE), and Low-Density Polyethylene (LDPE). These materials are significant in various industrial applications due to their unique properties and versatility. The plastic waste material is collected from the Ado-Ekiti State central market. The collected plastic waste is cleaned and dried to eliminate impurities. After sorting, the plastic is shredded into smaller pieces, preparing it for further processing. A zeolites catalyst is employed as a reagent in this process. For the pyrolysis of the shredded plastic, a laboratory-scale semi-batch reactor is utilized, complemented by an electric heater, condenser, pump, and a collecting bottle to gather the resulting products. Materials utilized for characterization consist of a variety of samples: Raw HDPE LDPE, PETE and PP liquid fuel samples mixture in a 1:1 ratio. Conventional diesel, and gasoline are assessed using various laboratory equipment including a silica crucible, muffle furnace, beaker, and two-mouthed conical flask. Temperature measurements may be conducted with a thermometer, and samples can be stored in a desiccator. The experiments investigated the pyrolysis of 100% Polyethylene Terephthalate (PET), High Density Polyethylene (HDPE) chips, Low- Density Polyethylene (LDPE) chips Polypropylene (PP) sourced from post-consumer plastic chips. A controlled sample of 1.00 kilogram of these chips was introduced into a reactor catalyzed with zeolite, focusing on maintaining uniform placement. The heating zone of the furnace generated the highest temperatures, leading to the sealing of the reactor for the pyrolysis process, which commenced after one minute of heating. The subsequent thermal decomposition of the plastics produced gases that were cooled via a water condenser to around 30 ºC, allowing for the separation of liquid and non-condensable gases. The experiment concluded when the output ceased and the internal temperature surpassed 500 ºC. Temperature measurements indicated a notable gradient, with the reactor's inner space reaching 1030 ºC and the outer wall stabilizing at 550 ºC by the end of the experiment. During the experiment, measurements of space temperature (T_1) and wall temperature (T_2) were simultaneously recorded. Results indicated a notable temperature gradient, with final stabilized values of 1050 ºC for T_1 and 600 ºC for T_2 by the end of the experiment.

For calorific value determination, a bomb calorimeter is utilized, while a CHNS/O elemental analyzer provides compositional analysis. A pycnometer is employed for density measurements, and a programmable rheometer is used to analyze the flow properties of the substances. The proximate analysis aimed to determine the fuel sample's

moisture content, volatile matter, ash content, and calorific value. Initially, the mass of a silica crucible was measured using a digital weighing balance, labeled as W_1 (g). A 1.00 g sample was placed into the crucible, and its mass after addition was recorded as W_2 (g). The sample underwent thermal treatment in an oven at 105°C for one hour. After this process, the crucible was carefully cooled in a desiccator to room temperature before its mass was recalibrated. This heating, cooling, and weighing cycle was repeated until a consistent mass, referred to as W_3 (g), for the anhydrous sample was reached. The percentage moisture content of the specimen was computed using equation 1.

$$M_C = \frac{W_2 - W_3}{W_2 - W_1} x100 \quad (1)$$

Where M_C is percentage moisture content.

The volatile matter content determination involved igniting the sample at 950°C, where the moisture-free sample weight was recorded as W_3(g) using a digital weighing balance. The sample underwent additional heating in a covered crucible within a muffle furnace for 7 minutes, following ISO 1974/562 guidelines. After cooling in a desiccator, it was weighed again yielding a weight of W_4(g). The volatile matter percentage was calculated using a specific equation 2.

$$V_M = \frac{W_3 - W_4}{W_3 - W_1} x100 \quad (2)$$

Where: V_M is percentage volatile matter, $W_3 - W_4$ is the loss in weight of the moisture sample and $W_3 - W_1$ is the initial weight of the moisture-free sample

The experiment involved measuring the weight of a silica crucible using a computerized balance, recorded as W_1(g). A mass of 1.00 g of the sample was transferred into the crucible with a spatula, and the weight was recorded as W_6(g). The sample was then incinerated at 750 °C in a muffle furnace in the presence of oxygen until a consistent mass was reached. The weight of the residual ash was noted as W_7(g). The procedure was performed in triplicate on all combustible components of the fuel samples. To determine the ash content and specific gravity proportion in the samples, equations 3 and 4 were utilized.

$$A_C = \frac{W_7 - W_1}{W_6 - W_1} x100 \quad (3)$$

Where: A_C is percentage ash content, $W_7 - W_1$ is the weight of residual ash formed and $W_6 - W_1$is the weight of liquid fuel initially taken.

$$S_G = \frac{W_3 - W_1}{W_2 - W_1} x100 \quad (4)$$

Proximate and ultimate analyses of various fuel samples, including conventional diesel were carryout for analysis.

3. RESULTS AND DISCUSSION

The study assessed the properties of liquid fuel derived from the pyrolysis of various single plastic wastes, utilizing zeolite as a catalyst. The fuel was evaluated through proximate and ultimate analysis to compare its characteristics against standard conventional oil, positioning it as a potential substitute for fossil fuels. Table 1 provides data on the yield of solid, liquid, and gaseous products, as well as the absorbent to polymer ratio, run time, and microwave power utilized in the process. The Table 1 details yields from microwave pyrolysis of various plastics: HDPE (3 kW, 76 min) yields 0.40% solid, 83.92% liquid, and 15.68% gas; LDPE (3 kW, 72 min) yields 0.80% solid, 80.62% liquid, and 14.45% gas; PP (3 kW, 68 min) yields 15.89% solid, 70.82% liquid, and 13.29% gas; and PETE (1.8–3 kW, 38 min) yields 36.60% solid, 34.28% liquid, and 24.32% gas.

Table 2 outlines the physical properties of pyrolysis oil derived from various types of plastic waste in comparison to conventional diesel. Key parameters include moisture content (0.07% to 0.13%), high volatile matter (96.02% similar to diesel), low ash and fixed carbon content, and a slightly lower gross heating value than diesel, indicating comparable performance across plastic types.

Proximate, ultimate, and physical properties of liquid fuel samples, alongside conventional diesel analysis, are detailed in Tables 3, 4, and 5. Table 3 compares the ultimate analysis (wt%) of pyrolysis oil from various plastic wastes (HDPE, LDPE, PP, PETE) with standard diesel. It highlights that carbon content in diesel is 85.51%, while plastic-derived oils range from 80.02% to 83.72%. Hydrogen levels are notably higher in plastic oils, reaching 17.42% for HDPE/HZSM-5, compared to 12.34% in diesel. Oxygen remains minimal, and nitrogen and sulfur percentages are low in all samples. Table 4 outlines the physical properties of pyrolysis oil from different plastic waste types in comparison to standard diesel. The density ranges from 0.70 to 0.79 g/cm³, and API gravity spans from 37.84 to 48.19. Kinematic viscosity is mainly between 2.55 and 2.78 cm²/s. Flash points are approximately 51.88 to 68.00 °C; cloud points range from -20.00 to 14.00 °C; pour points are around -20.50 to -7.00 °C; fire points vary from 45.78 to 77.98 °C, and cetane numbers average between 40.00 and 47.00.

Table 1: Solid, liquid and gaseous yields

Plastic	Microwave power (kW)	Time (min)	Absorbent plastic ratio	Solid (wt. %)	Liquid (wt. %)	Gas (wt. %)
HDPE	3	76	1:2	0.40	83.92	15.68
LDPE	3	72	1:2	0.80	80.62	14.45
PP	3	68	1:2	15.89	70.82	13.29
PETE	1.8–3	38	2.4	36.60	34.28	24.32

Table 2: Proximate analysis of Pyrolysis oil from different plastic waste

Proximate Analysis (wt%)									
Parameter	Standard Diesel	HDPE/ RAW	LDPE/ RAW	PP/ RAW	PETE/ RAW	HDPE/ HZSM-5	LDPE/ HZSM-5	PP/ HZSM-5	PETE/ HZSM-5
Moisture Content (MC) (%)	0.00	0.07	0.13	0.12	0.09	0.11	0.12	0.11	0.08
Volatile matter (VM) (%)	96.02	99.00	99.04	99.12	99.00	99.40	99.50	99.40	99.10
Ash Content (AS) (%)	3.02	0.01	0.16	0.25	0.14	0.14	0.15	0.14	0.12
Fixed carbon (FC) (%)	0.30	0.01	0.04	0.03	0.05	0.03	0.03	0.03	0.04
Gross Heating Value GHV MJ kg−1	45.34	44.25	45.60	44.29	42.00	45.84	46.10	46.2	42.4

Table 3: Ultimate Analysis of Pyrolysis oil from different plastic waste

Ultimate Analysis (wt%)									
Parameter	Standard Diesel	HDPE/ RAW	LDPE/ RAW	PP/ RAW	PETE/ RAW	HDPE/ HZSM-5	LDPE/ HZSM-5	PP/ HZSM-5	PETE/ HZSM-5
Carbon (%)	85.51	80.64	80.20	80.20	80.02	82.35	83.37	83.43	83.72
Hydrogen (%)	12.34	16.05	14.16	15.24	14.10	17.42	14.12	15.22	15.66
Oxygen (%)	0.00	0.00	0.02	0.01	0.01	0.00	0.01	0.00	0.01
Nitrogen (%)	0.08	0.04	0.05	0.04	0.06	0.01	0.02	0.02	0.03
Sulfur (%)	0.40	0.05	0.10	0.04	0.06	0.05	0.12	0.03	0.05

Table 4: Physical Properties of Pyrolysis oil from different plastic waste

Physical properties									
Parameter	Standard Diesel	HDPE/ RAW	LDPE/ RAW	PP/ RAW	PETE/ RAW	HDPE/ HZSM-5	LDPE/ HZSM-5	PP/ HZSM-5	PETE/ HZSM-5
Density (g/cm3)	0.72	0.77	0.72	0.75	0.70	0.78	0.79	0.80	0.78
API Gravity	37.84	47.20	44.00	45.30	42.60	48.19	47.84	45.80	12.90
Kinematic Viscosity (cm2/s)	2.55	2.66	2.78	2.62	270	2.67	2.78	2.68	2.63
Flash Point (°C)	68.00	51.88	65.00	51.90	64.50	54.98	67.00	52.00	64.30
Cloud Point (°C)	-20.00	6.00	14.00	6.00	13.00	8.00	13.00	6.00	8.00
Pour Point (°C)	-20.50	-7.00	-7.00	-8.00	-7.00	-8.00	-9.00	-7.00	-8.00
Fire Point (°C)	77.98	62.00	64.60	63.00	45.78	64.00	77.00	63.98	62.89
Cetane Number	47.00	41.00	44.00	42.00	43.00	40.00	41.00	42.00	44.00

3.1 Polyethylene Terephthalate (PETE)

Figure 1 presents the correlation between temperature and heating duration during the pyrolysis process of Polyethylene Terephthalate (PETE), showing the percentage yield obtained at varying conditions. Figure 2 illustrates the relationship between space temperature and wall temperature over the duration of heating, highlighting the variations observed during the heating period. After undergoing a cooling process in a water-cooling condenser, the gases were collected, achieving a temperature of about 30 ºC. The collection procedure also involved separating liquid gases from non-condensable gases. The optimal production rate for gas generation is achieved with a heating time of 35 to 40 minutes and a temperature setting between 470 and 490 ºC. Under these conditions, the gas production efficiency is between 70% and 90%. Figure 3 illustrates the yield rate of liquid fuel in relation to heating time, emphasizing the fluctuations noted throughout the heating duration. The optimal yield is achieved at 40 minutes, where the yield rate reaches 90. However, yields decline when the heating time is below this optimal threshold.

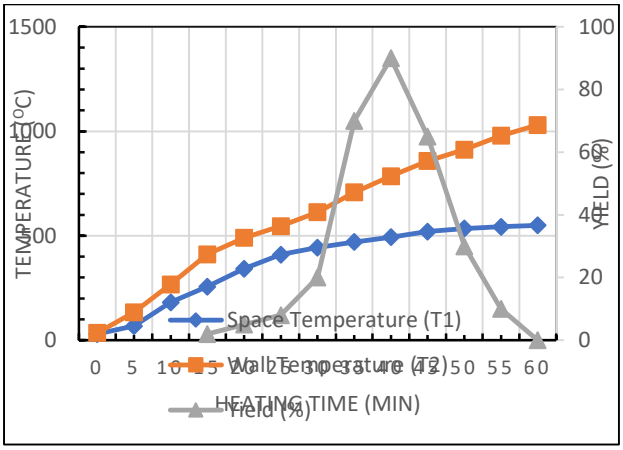

Figure 1: Effects of temperature and heating time on Polyethylene Terephthalate (PETE) yields

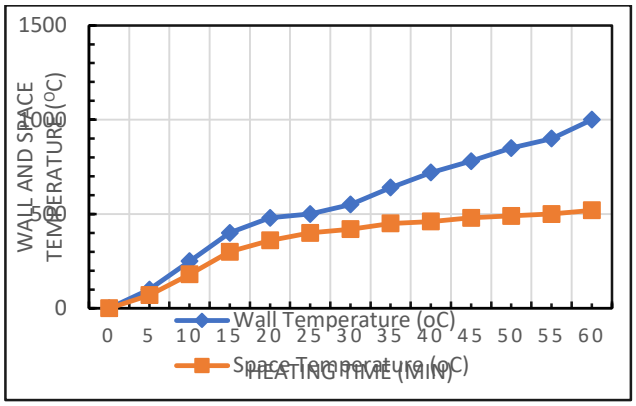

Figure 2: Space temperature and wall temperature per heating time.

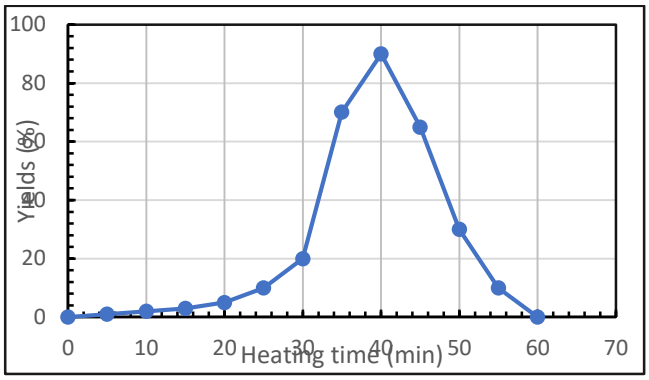

Figure 3: Yield rate per heating time

Table 5 presents the flame test outcomes for Polyethylene terephthalate (PETE) across different temperature ranges. Initially, at temperatures between 250 to 348 °C, PET exhibits a blue flame. As the temperature increases to the range of 410 to 445 °C, this is accompanied by a yellow flame. In the subsequent range of 450 to 489 °C, the intensity of the blue flame decreases while the yellow flame becomes more pronounced. At 495 °C, a bright yellow flame is noted, which subsequently diminishes as temperatures rise further, reaching 500 to 550 °C.

Table 5: Polyethylene terephthalate flame test

Temperature (ºC)	Types of Flame
250 – 348	Burns with a blue flame
410 – 445	Yellow flame appears on the blue flame
450 – 489	Blue flame reduces with more yellow flame
495	Bright yellow flame
500 – 550	Yellow flame reduces gradually

3.2 High-Density Polyethylene (HDPE)

Figure 4 shows the correlation between temperature and heating time, focusing on the yielding rate of High-Density Polyethylene (HDPE) during pyrolysis, expressed as a percentage. The findings indicate that an optimal production rate occurs with heating for 35-45 minutes at 470-500 ºC, yielding gas rates of 50-90%. The gases are then cooled to about 30 ºC in a water-cooling condenser, followed by the separate collection of liquid and non-condensable gases. Table 6 summarizes the flame test results for high density polyethylene across different temperatures. It shows a blue flame from 250-348°C, with a concurrent yellow flame appearing at 410-445°C. As temperatures rise from 450-489°C, the blue flame decreases, giving way to a bright yellow flame at 495°C, before the yellow flame gradually diminishes between 500-550°C

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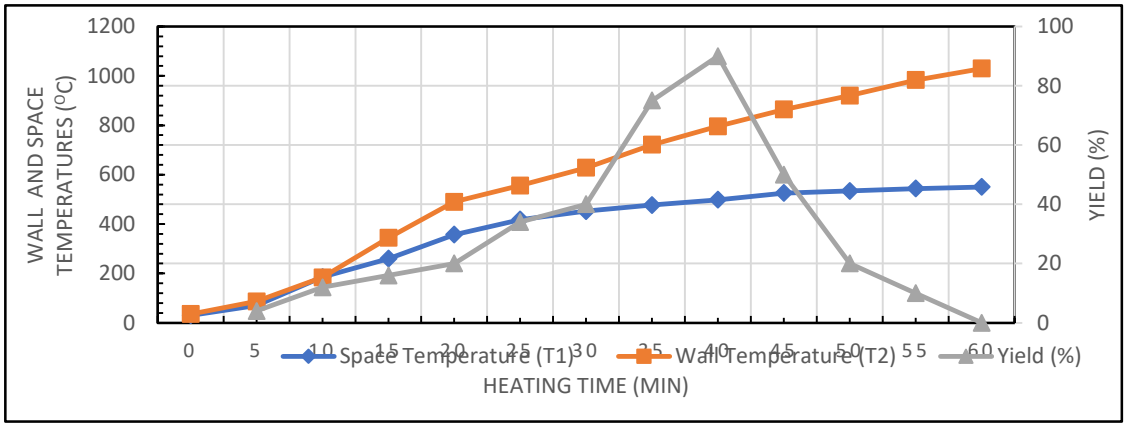

Figure 4: Effects of temperature and heating time on High-Density Polyethylene (HDPE) yields

Table 6: High density polyethylene flame test

Temperature (°C)	Types of Flame
250 – 348	Burns with a blue flame
410 – 445	Yellow flame appears on the blue flame
450 – 489	Blue flame reduces with more yellow flame
495	Bright yellow flame
500 – 550	Yellow flame reduces gradually

3.3 Polypropylene (PP)

Figure 5 demonstrates the relationship between temperature and heating time in Polypropylene (PP) pyrolysis, indicating that a yield rate of 68-90% of gases is optimal with a heating time of 40-45 minutes at 490-520 ºC. Afterward, gases are cooled to approximately 30 ºC using a water-cooling condenser for the separate collection of liquid and non-condensable gases. Table 7 details the flame test results for polypropylene across different temperatures: burning with a blue flame at 250-292°C, introducing a yellow flame at 370-440°C, a decrease in blue and increase in yellow at 440-499°C, a bright yellow flame at 500-530°C, and a gradual reduction in flame intensity between 530-600°C.

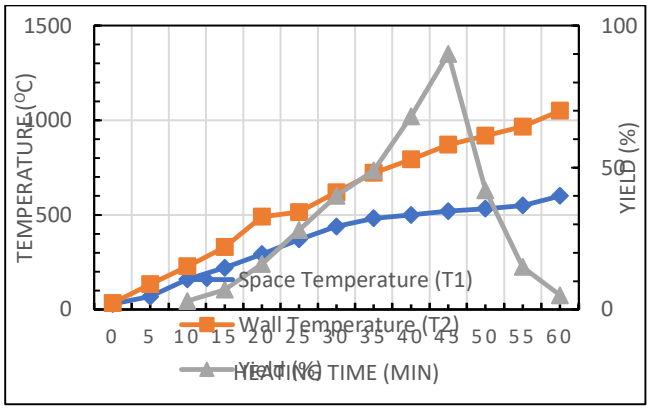

Figure 5: Effects of temperature and heating time on polypropylene (PP) yield

Table 7: Polypropylene flame test

Temperature (°C)	Type of frame
250 – 292	Burns with a blue flame
370 – 440	Yellow flame appears on the blue flame
440 – 499	Blue flame reduces with more yellow flame
500-530	Bright yellow flame
530 – 600	Yellow flame reduces gradually

Liquid fuels, including high-density options like gasoline and diesel, can be directly combusted or refined, especially useful in regions with limited fuel access. Produced solid residues, or carbonized char, serve as fuels or soil amendments and find application in producing carbon black. Environmentally, pyrolysis aids waste management by converting plastics into valuable products and significantly reduces greenhouse gas emissions. The Pyrolyzed oil is a renewable alternative to fossil fuels that promotes energy independence, reduces waste, and lowers greenhouse gas emissions. It also provides economic benefits by creating jobs and contributing to a circular economy. The pyrolyzed liquid fuel shows distinct advantages over diesel, such as an average calorific value that allows for efficient combustion. Sourced from waste, it promotes sustainability and offers potential for lower greenhouse gas emissions, as well as varied applications beyond transportation. However, optimal use requires engine modifications, contributing to waste management and enhanced efficiency compared to commercially available fuels.

4. CONCLUSION

Implementing recycling waste plastic offers substantial opportunities for local diesel fuel production and innovative techniques. While plastic liquid fuel can serve as a substitute for diesel in engines. Effective processing of plastic waste is crucial for addressing environmental concerns. Modifications to engines are possible to accommodate the combustion needs of plastic pyrolysis oil. The zeolite catalytic depolymerization of polymeric plastic waste yields around 100-150 ml of plastic liquid fuel per kilogram of plastic waste, significantly outperforming earlier units due to advancements, reduced unit height, and improved thermal pyrolysis processes. Yield comparisons indicate that this modern unit achieves superior oil production compared to its predecessors. The analysis of liquid fuel produced from the depolymerization of polymeric waste indicates its potential as a viable alternative to conventional diesel. The fuel samples demonstrated negligible moisture content, sulfur, nitrogen, and ash, along with high fixed carbon, cetane number, volatile matter, and hydrogen content, which support their classification as quality energy resources. Increasing temperature in biomass pyrolysis diminishes biochar yield and boosts gas yield, with bio-oil yield reaching its maximum at 500-550°C. A significant correlation exists where biochar production rises when plastic waste generation exceeds a specific limit. Depolymerization at different temperatures and durations is acknowledged as an efficient approach for polymeric waste disposal. Refining processes such as distillation can further enhance fuel purity, while blending can improve overall quality for direct engine use.

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