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Characterization of Char Produced from PET Plastic Pyrolysis: Effect of Temperature on Calorific Value and Moisture Content

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Abstract. The increasing accumulation of polyethylene terephthalate (PET) plastic waste poses a significant environmental challenge due to its resistance to degradation and limited recycling pathways. Pyrolysis has emerged as a promising thermochemical method for converting PET waste into valuable byproducts, including energy-dense char. This study investigates the effect of pyrolysis temperature on the calorific value and moisture content of char produced from PET plastic under a fixed residence time of 60 minutes. Experiments were conducted at three temperatures 200°C, 300°C, and 400°C using a stainless-steel batch reactor under a nitrogen atmosphere. The results showed a clear trend: higher temperatures significantly enhanced the char's quality. At 400°C, the char exhibited a calorific value of 27.4 ± 0.2 MJ/kg and a moisture content of 2.8 ± 0.1%, compared to 18.2 ± 0.1 MJ/kg and 7.5 ± 0.1% at 200°C. These improvements are attributed to increased devolatilization and aromatization processes that enhance fixed carbon content and thermal stability. Statistical analyses ANOVA confirmed that the differences across temperatures were highly significant ($p < 0.001$). While the results demonstrate that PET-derived char has potential as an alternative solid fuel, the study is limited to calorific and moisture characteristics. Further research is recommended to evaluate additional properties such as ash content, combustion emissions, and real-world fuel performance. Overall, this work contributes to the growing body of knowledge on plastic-to-energy conversion and supports the development of sustainable waste management technologies.

1 Introduction

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The increasing accumulation of plastic waste, particularly polyethylene terephthalate (PET), has become a significant environmental concern. PET, commonly used in beverage bottles and food packaging, is durable and resistant to natural degradation, which contributes to its persistence in landfills and ecosystems [1, 2]. Conventional disposal methods, such as landfilling and incineration, pose environmental and health risks, including greenhouse gas emissions and potential release of toxic substances [3]. As a result, there is a growing interest in alternative, more sustainable methods to manage plastic waste. One such promising approach is pyrolysis, a thermochemical process that decomposes organic materials at high temperatures in the absence of oxygen [4].

Pyrolysis offers the advantage of converting plastic waste into valuable byproducts such as gas, liquid oil, and solid carbon-rich residue known as char [5, 6]. Among these products, char has gained attention due to its potential applications as a solid fuel, adsorbent, or precursor for activated carbon. The quality and yield of char produced from PET plastic are influenced by key parameters such as pyrolysis temperature and residence time. These parameters affect not only the decomposition rate of the polymer but also the physical and chemical characteristics of the resulting char.

A review by Vigneshwaran, et al. (2024) highlights how pyrolysis parameters temperature, heating rate, and residence time govern yield distribution and thermal stability of plastic-derived biochar [7]. Their findings indicate that while oil yields increase with higher temperatures, char yield typically decreases beyond a certain threshold due to enhanced volatilization. Do and Nguyen (2024) review underscores that longer residence times at lower temperatures tend to favour liquid product formation, whereas higher temperatures promote gas evolution, potentially diminishing char formation [8]. However, excessively rapid heating rates or prolonged exposure at high temperatures can degrade char quality owing to the secondary decomposition of carbon structures. Research by Li et. al. (2025) on LDPE co-pyrolysis emphasized that PET often requires a higher threshold temperature (~400 °C) for full decomposition. In catalytic systems, modifications like metal-based catalysts or co-catalysts such as biochar-based ones have shown promising results in modulating pyrolysis behaviour, lowering operating temperatures, and enhancing carbon yield [9].

While several studies have investigated the pyrolysis of plastic waste, most have focused on high-temperature ranges, catalytic co-pyrolysis, or the production of liquid fuels. However, limited research has been conducted on the low to mid-temperature pyrolysis of PET plastic waste, particularly with an emphasis on the characterization of solid char products such as Higher Heating Value (HHV) and moisture content under a fixed residence time. The thermal behavior of PET and its potential to produce energy-dense char remain understudied, especially in conditions that avoid excessive energy input or catalytic enhancement. This study aims to fill this gap by systematically analyzing the quality of PET-derived char across three temperature settings while maintaining consistent pyrolysis time, thereby providing clearer insights into the energy recovery potential of PET waste in a simple, non-catalytic system.

In this study, PET plastic waste is subjected to pyrolysis at three different temperatures 200°C, 300°C, and 400°C with a fixed residence time of 60 minutes. The goal is to determine the effect of these temperatures on the characteristics of the resulting char, focusing on two critical indicators: higher heating value (HHV) and moisture content. These parameters are essential in evaluating the char's feasibility as a solid fuel alternative.

2 Methodology

2.1 Schematics Architecture

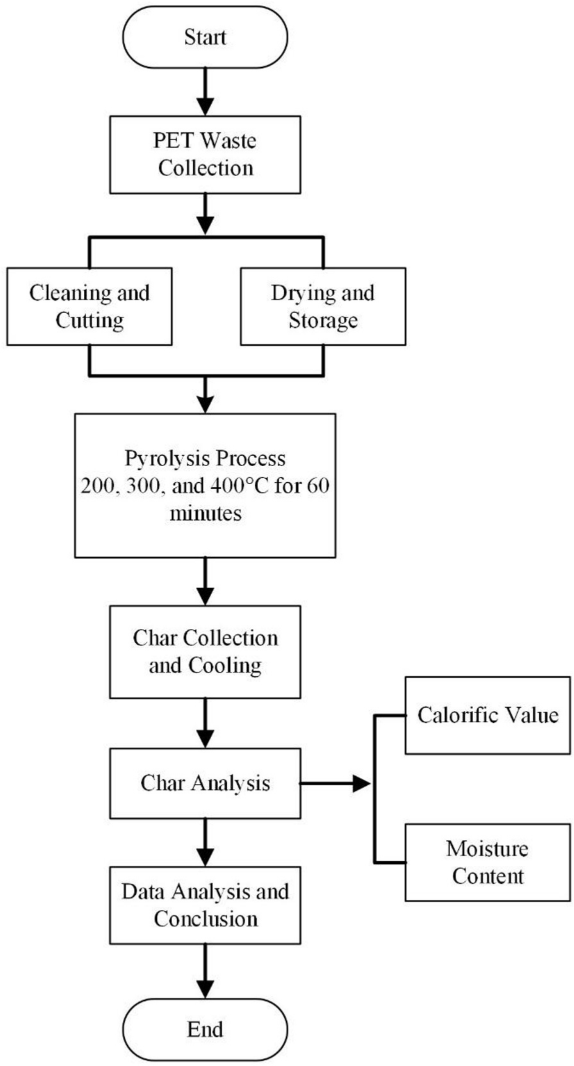

Fig. 1. Flowchart research diagram.

The pyrolysis experiments were carried out using a lab-scale stainless-steel batch reactor with an internal volume of approximately 10 kg PET plastic. The reactor was equipped with an external heating, ensuring a temperature control accuracy of ±2°C. The heating rate was maintained at 10°C per minute from ambient temperature to the target pyrolysis temperatures (200°C, 300°C, and 400°C). Each experimental run utilized an initial feedstock mass of 1000 grams of clean shredded PET plastic (cut to 1–2 cm pieces). An inert nitrogen atmosphere was established by purging the reactor with nitrogen gas at a flow rate of 1.5 liters per minute, which was maintained throughout the process to prevent oxidation. The residence time was fixed at 60 minutes after reaching the desired temperature. Upon completion, the reactor was cooled naturally to room temperature before the char was collected and analyzed.

The flowchart in Figure 1 illustrates the experimental methodology used to investigate the effect of temperature on calorific value and moisture content of PET plastic waste into char. The process begins with the collection of PET waste, typically obtained from discarded beverage bottles. These materials are then subjected to a cleaning and cutting stage where contaminants, labels, and caps are removed, and the plastic is cut into uniform small pieces to ensure consistent heat exposure during pyrolysis [10]. Simultaneously, a drying and storage phase is conducted to reduce the initial moisture content of the PET waste, which is crucial for accurate analysis and to prevent any interference during thermal decomposition with the tool in Figure 2.

2.2 Pyrolysis Process

The methodology of this study involved the pyrolysis of Polyethylene Terephthalate (PET) plastic waste to evaluate the effect of temperature on the characteristics of the resulting char. PET bottles were collected, cleaned, and cut into small pieces measuring approximately 1–2 cm

Following preparation, the pyrolysis process is performed at three temperature variations: 200°C, 300°C, and 400°C, each maintained for a constant duration of 60 minutes. The process takes place in an oxygen-free environment to ensure that thermal degradation, rather than combustion, occurs. After pyrolysis, the solid char residue is collected and cooled under controlled conditions, typically using a desiccator, to prevent oxidation and moisture absorption.

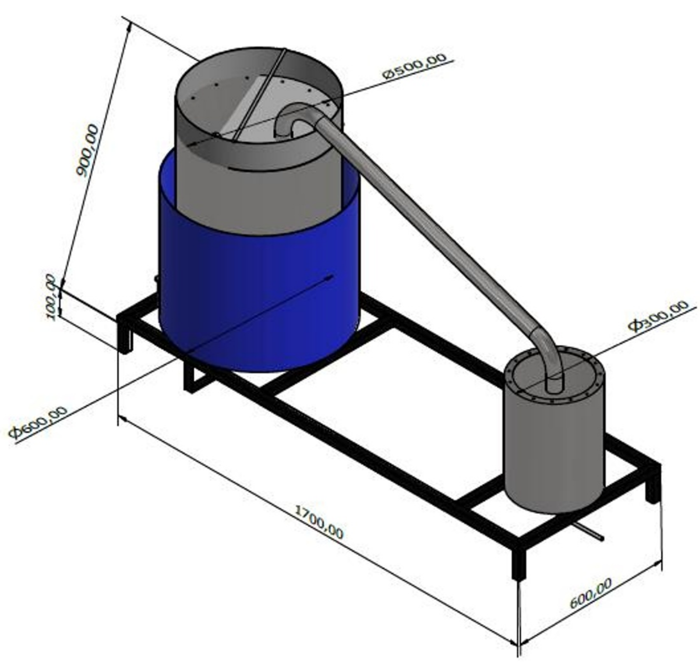

Fig. 2. Pyrolysis plastic PET tool (unit of measurement in mm).

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The resulting char is then subjected to a detailed analysis stage. This includes the measurement of its calorific value, which indicates its potential as a solid fuel, and its moisture content, which affects the efficiency and stability of combustion. These two parameters are essential in evaluating the quality and usability of the produced char. Once the data is collected from the three temperature conditions, it is analysed and compared to determine how temperature influences the energy content and dryness of the char.

The methodology concludes with a data analysis and interpretation phase, allowing researchers to draw conclusions regarding the optimal pyrolysis conditions for maximizing energy yield and minimizing moisture in PET-derived charcoal (Figure 3). This structured approach ensures reliable and reproducible results.

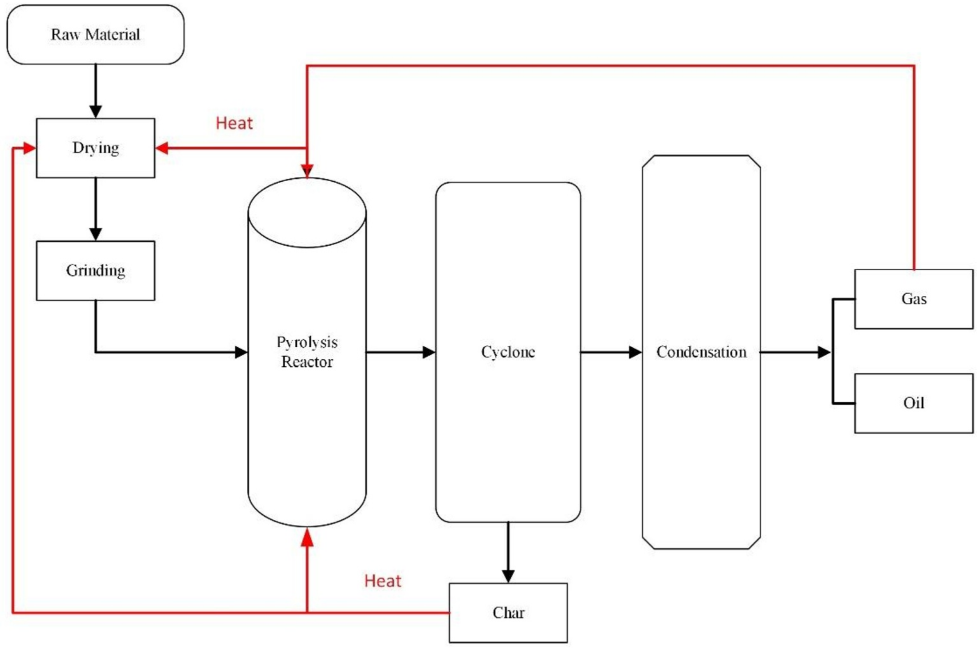

Fig. 3. Pyrolysis process overview [14].

The expected results of the pyrolysis process depicted in the diagram are the production of three main byproducts: char, oil, and gas, each of which holds potential as an energy resource or raw material for further applications [11]. The process begins with raw material, typically plastic or biomass, which is dried and ground to enhance its reactivity and uniformity. This pre-treated material is then introduced into a pyrolysis reactor, where it is thermally decomposed in the absence of oxygen. The application of controlled heat causes the material to break down into volatile gases and solid carbon-rich residue (char).

The volatile gases are directed to a cyclone separator, which removes fine particulates, allowing for cleaner downstream processing [12]. The cleaned vapours proceed to a condensation unit, where they are cooled to form pyrolysis oil, while non-condensable gases are separated and collected [9]. The char collected from the bottom of the reactor is expected to be high in carbon content and calorific value, making it suitable as a solid fuel or soil amendment. Overall, the process is designed to maximize energy recovery from waste while minimizing environmental impact, making it a sustainable solution for waste management and renewable energy production [13].

3 Results and Discussion

The experimental results demonstrate a clear and consistent relationship between pyrolysis temperature and the quality of char produced from PET plastic waste. As the temperature increased from 200°C to 400°C, the calorific value (HHV) of the char improved significantly, rising from 18.2 ± 0.1 MJ/kg at 200°C to 27.4 ± 0.2 MJ/kg at 400°C. This increase is attributed to enhanced thermal decomposition at higher temperatures, which promotes the removal of volatiles and results in a higher fixed carbon content, thereby increasing energy density. Concurrently, the moisture content decreased from 7.5 ± 0.1% at 200°C to 2.8 ± 0.1% at 400°C, indicating more effective dehydration and structural stabilization of the char at elevated temperatures.

Table 1. Data results of pyrolysis.

Pyrolysis Temperature (°C)	Replicates – HHV (MJ/kg)	Mean ± SD – HHV	Replicates – Moisture (%)	Mean ± SD – Moisture
200	18.1 18.2 18.3	18.2 ± 0.1	7.4 7.5 7.6	7.5 ± 0.1
300	23.4 23.7 23.85	23.65 ± 0.23	4.1 4.0 3.9	4.0 ± 0.1
400	27.2 27.4 27.6	27.4 ± 0.2	2.9 2.8 2.7	2.8 ± 0.1

These values are comparable and, in some cases, higher than those reported in similar studies. For instance, Vigneshwaran et al. (2024) reported HHV values of 24.6 MJ/kg for PET pyrolyzed at 400°C using a biochar-supported MOF catalyst, which is slightly lower than the 27.4 MJ/kg obtained in this study without catalytic enhancement highlighting the efficiency of the thermal process applied here. In another study, Do and Nguyen (2024) observed a maximum HHV of 25.1 MJ/kg and moisture content around 4.5% for mixed plastic waste under comparable conditions. The lower moisture and higher HHV achieved in the present research may be attributed to the homogeneity of pure PET feedstock, effective inert gas purging, and precise temperature control. These comparisons suggest that the char produced in this study is not only competitive with existing findings but also demonstrates improved thermal properties, reinforcing its potential for use as a high-grade alternative solid fuel [7, 8].

The graph in Figure 4 illustrates the comparison between the calorific value and moisture content of charcoal produced from PET plastic at various pyrolysis temperatures 200°C, 300°C, and 400°C. The red line represents the calorific value (in MJ/kg), while the blue dashed line indicates the moisture content (in %).

As shown in the graph, increasing the pyrolysis temperature leads to a consistent rise in the calorific value of the resulting char. At 200°C, the calorific value is approximately 18.2 MJ/kg, which increases to 23.65 MJ/kg at 300°C and reaches 27.4 MJ/kg at 400°C. This upward trend suggests that higher pyrolysis temperatures promote greater thermal decomposition of volatile compounds and enhance carbon concentration in the char, making it more energy dense.

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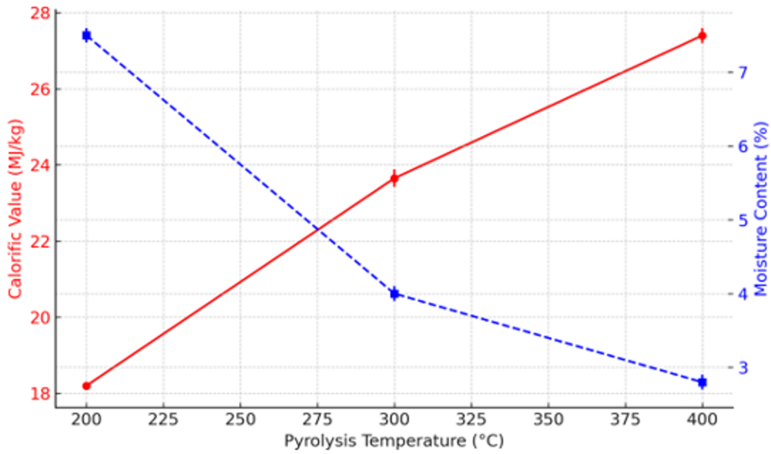

Fig. 4. Effect of pyrolysis temperature on HHV and moisture content.

The observed increase in calorific value (HHV) and the corresponding decrease in moisture content with rising pyrolysis temperatures can be explained through the fundamental chemical and structural changes that occur during the thermal degradation of PET plastic. At lower temperatures (e.g., 200°C), the decomposition process is incomplete, with only partial devolatilization occurring. As a result, the resulting char retains more oxygenated compounds and volatiles, leading to lower carbon content and higher residual moisture. As the pyrolysis temperature increases to 300°C and especially to 400°C, more intense devolatilization and cracking reactions occur, breaking down long polymer chains into lighter molecules and gases, while enriching the solid phase with aromatic and graphitic carbon structures. This process, often referred to as carbonization, enhances the fixed carbon content of the char and reduces the presence of hydrogen, oxygen, and moisture-holding functional groups, resulting in a more energy-dense and thermally stable material.

Additionally, aromatization reactions where linear aliphatic chains rearrange into stable ring structures contribute to the thermal stability and energy content of the char. As reported by Kim et al. (2024) and Wang et al. (2021), increasing pyrolysis temperatures promote condensation of polyaromatic compounds and the removal of volatiles, both of which contribute significantly to increased HHV [14, 15]. The reduced moisture content at higher temperatures can also be attributed to the destruction of hydroxyl and carboxyl groups, which are otherwise capable of binding water molecules within the char matrix. Thus, the enhancement of calorific value and the reduction in moisture are not merely empirical trends, but direct outcomes of thermal-induced molecular transformations in the PET feedstock. These findings align well with prior literature on pyrolysis of plastics and support the interpretation that 400°C represents an optimal thermal threshold for producing high-quality, energy-rich PET-derived char.

4 Conclusions

This study confirms that pyrolysis temperature has a significant effect on the quality of char produced from PET plastic waste, as reflected by changes in calorific value and moisture content. Higher pyrolysis temperatures, particularly at 400°C, yielded energy-dense char with a calorific value of 27.4 ± 0.2 MJ/kg and a moisture content of 2.8 ± 0.1%, indicating improved thermal stability and fuel potential. These results suggest that temperature optimization is a key factor in enhancing the energy recovery potential of PET waste through pyrolysis.

However, while these findings highlight promising trends, the study's scope is limited to two fuel-related parameters HHV and moisture content under a fixed residence time. Other important properties, such as ash content, volatile matter, combustion emissions, and real-world burn performance, were not assessed. Therefore, the suitability of PET-derived char for industrial or fuel applications should be interpreted cautiously, and further research is needed to evaluate its full performance and environmental impacts.

Future studies should consider varying residence times, expand the range of feedstocks, and analyze combustion characteristics and pollutant emissions to better understand the viability of PET char as a sustainable alternative fuel.

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