Transformation of Plastic Waste into Pyrolytic Carbon Via Pyrolysis: Structural Examination by X-Ray Diffraction Analysis for Sustainable Environmental Applications

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ABSTRACT

The ongoing rise in plastic trash production has emerged as a significant environmental issue owing to the non-biodegradable characteristics and prolonged persistence of synthetic polymers. Traditional disposal methods, including landfilling and incineration, lead to soil pollution and greenhouse gas emissions. Pyrolysis has emerged as an efficient thermochemical conversion method that transforms waste plastics into useful products, including liquid fuels, combustible gases and carbon-rich solid wastes. This study involved the conversion of waste plastic packaging sheets into activated carbon via an oxygen-limited pyrolysis process. The acquired carbon sample was analysed by X-ray diffraction (XRD) to examine its structural characteristics. The XRD pattern exhibited a large diffraction band within the range of $2\theta = 20°–30°$, corresponding to the (002) plane of disordered carbon structures. The lack of distinct diffraction peaks validated the dominance of amorphous carbon with minimal graphitic organization. The acquired material demonstrated a significantly deficient turbostratic carbon structure, which is advantageous for adsorption and environmental remediation purposes. This research illustrates an economical and sustainable approach for transforming plastic trash into useable carbon materials, advancing the circular economy and waste valorisation. The pyrolysis experiment was performed via a laboratory-scale cylindrical reactor constructed from a sealed metallic chamber. Plastic packaging trash was fed into the reactor and externally heated under conditions of limited oxygen. Following thermal degradation, a carbonaceous solid residue was acquired, which was then converted into activated carbon through crushing, purification, and drying before XRD characterisation.

Keywords: Plastic waste, Pyrolysis, Pyrolysis char, Carbonaceous material, Plastic-derived carbon carbon, XRD, Amorphous carbon, Sustainable materials, Circular economy

INTRODUCTION

The manufacture of plastic has surged dramatically in recent decades due to its affordability, lightweight characteristics, mechanical durability, and resistance to chemical deterioration. Annually, approximately millions of tonnes of plastic trash are produced, resulting in significant ecological and environmental issues [1][2].

Prevalent polymers in plastic packaging trash comprise polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). Owing to their persistent molecular configurations, these materials necessitate several centuries for natural decomposition [3].

Conventional waste management methods encompass:

- Landfilling
- Incineration
- Mechanical recycling

Nonetheless, these technologies have numerous constraints, such as land utilisation, release of hazardous gases, and deterioration of polymer quality following multiple recycling processes [4]. Pyrolysis has garnered considerable interest as a viable alternative technique for the remediation of

plastic waste. The process entails the thermal breakdown of polymers at temperatures typically between 300 and 800 °C in an anoxic environment, yielding:

- Pyrolysis oil
- Syngas
- Carbonaceous char

The solid carbonaceous residue can be transformed into plastic-derived carbon, which has applications in water purification, gas storage, supercapacitors, catalytic support, and energy storage systems [5]. The characteristics of plastic-derived carbon are significantly influenced by factors like pyrolysis temperature, residence period, heating rate, and activation techniques. Structural characterisation is crucial for assessing the quality and prospective applications of the synthesised material.

X-ray diffraction (XRD) is a crucial characterisation technique employed to ascertain crystallinity, phase composition, and interlayer organization of carbon materials [6].

The aim of this study is to synthesise activated carbon from waste plastic via pyrolysis and examine its structural properties using XRD analysis.

MATERIALS AND EXPERIMENTAL METHODOLOGY

1.1 Materials Used Figure 1: Plastic packaging trash contained within the cylindrical pyrolysis reactor chamber.

The basic material comprised discarded plastic packaging films sourced from residential garbage. The gathered plastics were rinsed with distilled water to eliminate dust and contaminants and subsequently dried under ambient conditions.

Table 1: Materials Utilised in the Experiment

Material	**Purpose**
Plastic packaging films	Carbon source
Pyrolysis reactor	Thermal decomposition
Heating source	Providing required temperature
Condenser	Cooling hydrocarbon vapours
Collection vessel	Collecting liquid products
Carbon residue	Pyrolytic carbon precursor

Figure 2: Configuration of the laboratory-scale pyrolysis reactor, heated by an external gas burner.

A cylindrical metallic reactor was engineered and constructed to execute the pyrolysis process. The reactor was positioned above a gas hob, supplying the requisite heat energy for the breakdown of plastic materials. The lack of oxygen in the chamber during heating inhibited complete combustion and facilitated the thermal cracking of long polymer chains.

1.2 Pyrolysis Procedure

The purified plastic trash was placed into a sealed pyrolysis chamber. The pyrolysis process was conducted in a sealed cylindrical metallic reactor under oxygen-limited conditions. The reactor was externally heated using an LPG gas burner. During operation, the reactor temperature was maintained within the range of approximately 450–670 °C for a total residence time of about 21 hours. These conditions enabled the thermal decomposition of plastic polymers into liquid hydrocarbons, non-condensable gases, and a carbon-rich solid residue (pyrolysis bio-char).

The chamber was heated in an oxygen-deficient environment to avert total combustion. Upon heating, elongated polymer chains experienced thermal degradation:

Plastic Polymer → Hydrocarbon Vapours + Gases + Carbon Char

The gaseous byproducts exited the reactor and traversed a cooling system, where condensable vapours converted into liquid hydrocarbon products, while non-condensable gases either fled or were collected separately.

The residual solid was gathered and processed into activated carbon. The reactor temperature rose due to external heating, resulting in the breakup of polymer chains into smaller hydrocarbon molecules. The produced outputs were liquid hydrocarbons, non-condensable gases, and a carbon-rich char accumulated within the reactor.

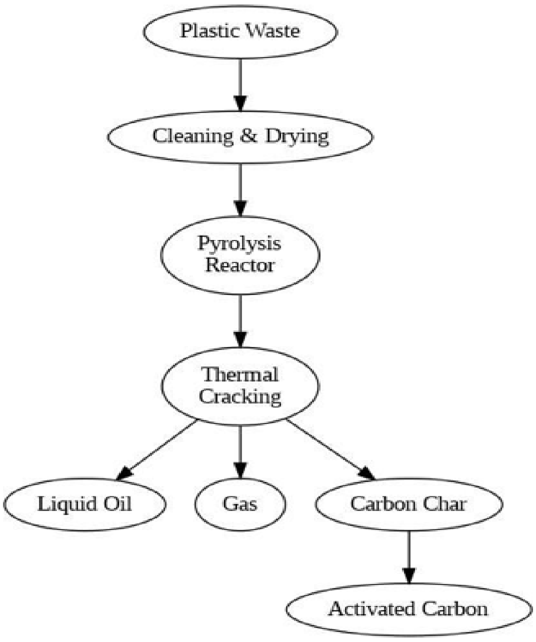

Figure 3: Flow Diagram of the Plastic Pyrolysis Process

1.3 X-Ray Diffraction Characterization

X-ray diffraction research was conducted over a 2θ range of roughly 10°–120° to examine the crystal structure of the synthesized Pyrolysis carbon.

X-rays interacting with periodic atomic planes adhere to Bragg's law:

$n\lambda = 2d\sin\theta$

where:

- n= order of diffraction
- λ= X-ray wavelength
- d= interplanar spacing
- θ= diffraction angle

The diffraction pattern conveys information about crystallinity, lattice arrangement, and structural imperfections.

Figure 4: Carbonaceous residue produced from the pyrolysis of plastic trash.

Upon concluding the pyrolysis cycle and cooling the reactor, a dark, carbon-dense residue was extracted from the chamber. The residue comprised partially carbonised plastic particles, ash, and carbon aggregates.

1.4 Preparation of Plastic-Derived Pyrolysis Char

The acquired carbonaceous residue was manually pulverised with a mortar and pestle to diminish the particle size. The pulverised substance was subsequently rinsed with distilled water to eliminate loose impurities and soluble pollutants. The cleaned material was subjected to drying in an oven at around 80–100 °C for many hours to eliminate moisture. The desiccated black powder served as the activated carbon specimen for structural characterisation.

Table 2: Preparation steps of pyrolysis char sample

Step	Procedure	Purpose
1	Collection of pyrolysis char	Obtain carbon precursor
2	Crushing and grinding	Reduce particle size
3	Washing with distilled water	Remove impurities
4	Drying at 80–100°C	Remove moisture
5	Powder collection	XRD sample preparation

Figure 5: X-ray diffraction instrument used for structural analysis of the synthesized carbon material.

The carbon powder was affixed to the sample holder of an X-ray diffractometer. The diffraction pattern was documented within a 2θ range of roughly 10° to 120° utilising Cu-Kα radiation. The acquired data was examined to ascertain the crystallinity and structural configuration of the carbon substance.

RESULTS AND DISCUSSION

1.5 XRD Analysis

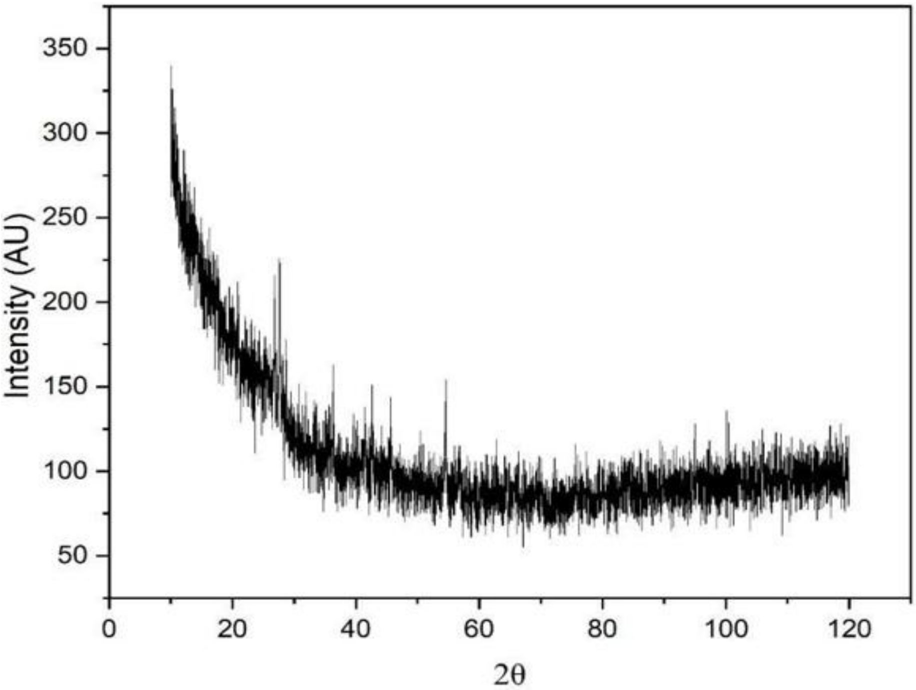

Figure 6: displays the XRD pattern of the activated carbon synthesised from plastic pyrolysis.

The diffraction spectrum has a wide diffraction peak between about 20° and 30° (2θ), corresponding to the (002) reflection of carbon materials [7].

Table 3: Analysis of XRD Characteristics

XRD Observation	Interpretation
Broad peak around 20°–30°	Disordered carbon (002) plane
Absence of sharp peaks	Amorphous structure
Low peak intensity	Poor graphitic ordering
Broad diffraction width	Small crystallite size and defects
High background noise	Porous, defect-rich carbon

1.6 Carbon Structural Configuration

Highly crystalline graphite displays a distinct diffraction peak at roughly 2θ = 26°, indicative of uniformly arranged graphene layers. The observed diffraction profile is consistent with XRD patterns reported for activated carbon and other amorphous carbonaceous materials in the literature. The broad diffraction feature around 2θ = 20°–30° indicates disordered carbon layers with low graphitic ordering. Although the structural characteristics resemble those of activated carbon, no physical or chemical activation treatment was applied in the present work; therefore, the synthesized material is more accurately described as plastic-derived pyrolysis bio-char.

The synthesised carbon had a broad peak, signifying that the carbon layers are randomly orientated, resulting in a turbostratic carbon structure [8].

The large peak broadening indicates:

- Short-range atomic ordering
- Increased defects
- Expanded interlayer spacing
- Low graphitization degree

These structural imperfections augment the quantity of active adsorption sites, rendering the material effective for pollutant elimination.

1.7 Comparison with Graphitic Carbon

Table 4: Comparative Analysis of Graphite and Synthesised pyrolytic Carbon

Property	**Graphite**	**Synthesized Carbon**
Crystal structure	Highly crystalline	Predominantly amorphous
2θ peak	~26° sharp peak	Broad 20–30° hump
Graphitic ordering	High	Low
Defect concentration	Low	High
Surface activity	Moderate	Potentially increased due to structural defects
Adsorption capability	Lower	Requires BET and adsorption studies for confirmation

Table 5: Summary of Experimental Observations

Parameter	**Observation**
Plastic type	Mixed packaging plastic
Reactor type	Cylindrical closed metallic reactor
Heating source	External gas burner
Pyrolysis atmosphere	Oxygen-limited
Solid product	Black carbonaceous residue
Final sample	Fine carbon powder
XRD nature	Predominantly amorphous
Carbon structure	Turbostratic carbon

POTENTIAL APPLICATIONS

The produced plastic-derived activated carbon can be utilised in various domains:

1.8 Environmental Applications

- Removal of dyes from industrial wastewater [9]
- Adsorption of heavy metals

- Removal of organic contaminants

1.9 Energy Storage

The defect-rich carbon structure can be used as:

- Supercapacitor electrodes
- Battery electrode additives
- Catalyst support materials [10]

1.10 Gas Purification

Due to its porous nature, the material may be utilized for:

- CO_2 capture
- Volatile organic compound adsorption
- Air purification

LIMITATIONS

The current work is limited by the lack of BET surface area measurements, pore size distribution studies, and adsorption performance evaluations. Thus, the adsorption capacity of the synthesised pyrolysis bio-char has been deduced from its structural properties seen using XRD and existing literature, rather than through direct experimental confirmation.

FUTURE SCOPE

Scope

Additional enhancement of the synthesised pyrolytic carbon can be accomplished through:

Chemical activation with KOH, $ZnCl_2$, or H_3PO_4

Determination of BET surface area

SEM analysis for morphological assessment

FTIR analysis of functional groupings

Raman spectroscopy for the investigation of graphitisation

Adsorption investigations utilising methylene blue or heavy metal ions.

CONCLUSION

This study successfully demonstrated a sustainable approach for converting plastic packaging waste into a carbon-rich material through an oxygen-limited pyrolysis process. The pyrolysis experiment was carried out in a laboratory-scale cylindrical metallic reactor operated at temperatures ranging from approximately 450–670 °C with a residence time of about 21 hours. Thermal degradation of the plastic waste resulted in the formation of liquid hydrocarbons, non-condensable gases, and a carbonaceous solid residue.

X-ray diffraction (XRD) analysis revealed a broad diffraction band within the 2θ range of approximately 20°–30°, corresponding to the (002) plane of disordered carbon structures. The absence of sharp crystalline peaks confirmed that the synthesized material predominantly consists of amorphous turbostratic carbon with low graphitic ordering, short-range atomic arrangement, and a high degree of structural defects. These structural characteristics are comparable to those reported for activated carbon and other carbonaceous adsorbent materials in the literature.

The observed defect-rich and amorphous carbon structure suggests potential applicability in environmental remediation, adsorption processes, gas purification, and energy-storage-related applications. However, since no physical or chemical activation treatment was performed during material preparation, the obtained product is more accurately classified as plastic-derived pyrolysis bio-char rather than activated carbon.

Overall, the findings demonstrate that waste plastics can be effectively transformed into valuable carbonaceous materials through a simple and low-cost pyrolysis route, thereby contributing to waste valorization and circular economy initiatives. Future studies should focus on chemical or physical activation, BET surface area analysis, pore structure characterization, and adsorption performance evaluation to further establish the practical utility of the synthesized pyrolysis bio-char.

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