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Kinetic Study of Thermal Pyrolysis of Polypropylene Waste from North Refineries Company

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Abstract

The process of pyrolysis is the thermal degradation of plastic waste in the absence of oxygen at high temperatures, which leads to the decomposition of the material to form a mixture of gases, liquids, and some solid residues. To investigate the pattern of degradation that occurs in the plastic materials when subjected to the reaction conditions that would be employed for pyrolysis, thermal gravitational analysis studies were conducted. Consequently, the TGA analysis was conducted at a moderate reaction temperature of 900 °C for a duration of 30 minutes while being agitated with nitrogen flow. The objective of the experiment was to predict the plastic's weight reduction over time and temperature. The process included heating about 10 mg of the polypropylene (in nitrogen) at a rate of 5 °C min-1 to a final temperature of 900 °C. The sample spent thirty minutes at that temperature. The goal of this investigation was to construct a polypropylene thermal model for the production of green fuel. In the present work, a kinetic model was developed for the thermal degradation of North Refineries Company polypropylene plastic waste via TGA data obtained at no-isothermal conditions. The TGA data was coupled with the Arrhenius equation to find the thermal degradation kinetics. Different models were examined to figure out the most suitable model that fits the thermal degradation kinetics and it was found that the Coats-Redfern model is the one that fits the mechanism of thermal degradation of the waste. The predicted activation energy and pre-exponential factor obtained from analysis of the kinetics data based on the Coats-Redfern model were 128.74 kJ/mol and 2.603. The value of the activation energy for polypropylene indicates within average values of the activation energy in other literature, in agreement with other similar literature reports.

Keywords: Thermal pyrolysis, Waste Plastics, Kinetics, Green fuel.

دراسة حركية التحلل الحراري لمخلفات البولي بروبيلين من شركة مصافي الشمال

الخلاصة:

عملية الانحلال الحراري هي تحلل حراري للنفايات البلاستيكية في غياب الأكسجين عند درجات حرارة عالية، مما يؤدي إلى تحلل المادة لتكوين خليط من الغازات والسوائل وبعض المخلفات الصلبة. من أجل دراسة نمط التحلل الذي يحدث في المواد البلاستيكية عند تعرضها لظروف التفاعل التي يمكن استخدامها للانحلال الحراري أجريت دراسات تحليل الجاذبية الحرارية. ونتيجة لذلك، تم إجراء تحليل TGA عند درجة حرارة تفاعل تبلغ 900 درجة مئوية لمدة 30 دقيقة بتدفق النيتروجين. كان الهدف من التجربة هو التنبؤ بانخفاض وزن البلاستيك بالنسبة للوقت ودرجة الحرارة. تضمنت العملية تسخين حوالي 10 ملجم من البولي بروبيلين (في جو من النيتروجين) بمعدل 5 درجات مئوية على الأقل إلى درجة حرارة نهائية قدرها 900 درجة مئوية. تم ابقاء العينة لمدة ثلاثين دقيقة عند درجة الحرارة المذكورة. الهدف من هذا البحث هو بناء نموذج حراري من مادة البولي بروبيلين لإنتاج البنزين الأخضر. في العمل الحالي، تم تطوير نموذج حركي للتحلل الحراري للنفايات البلاستيكية المصنوعة من مادة البولي بروبيلين التابعة لشركة مصافي الشمال من خلال بيانات TGA التي تم الحصول عليها في ظروف غير منتظمة الحرارة. تم ربط بيانات TGA مع معادلة أرينيوس لإيجاد حركية التحلل الحراري. تم فحص نماذج مختلفة لمعرفة النموذج الأنسب الذي يناسب حركية التحلل الحراري وتبين أن نموذج كوتس-ردفيرن هو الذي يناسب آلية التحلل الحراري للنفايات. كانت طاقة التنشيط المتوقعة والعامل الأسي الذي تم الحصول عليه من تحليل البيانات الحركية بناءً على نموذج كوتس-ريدرسن مساوي لـ 128.74 كيلو جول / مول و 2.603. تشير قيمة طاقة التنشيط للبولي بروبيلين الى انها ضمن القيم المتوسطة لطاقة التنشيط في الأدبيات الأخرى وذلك بالاتفاق مع تقارير الأدبيات المماثلة الأخرى.

1. Introduction

Pyrolysis, which converts plastic waste into biodiesel, is a novel and ecologically conscious strategy for addressing the issue of plastic waste while simultaneously yielding a commodity of considerable value. Pyrolysis involves heating plastic waste to an extremely high temperature without oxygen, breaking down the long polymer chains into smaller hydrocarbon molecules [1, 2]. Instead of burning, the plastic breaks down into a mixture of simpler molecules. The smaller monomer units are then put together through the process of polymerization [4, 5].

Polymers are widely used in industry for different applications, including but not limited to food processing, agriculture, aerospace, automation, and construction. All these diverse applications result in a large quantity of plastic waste and a smart waste management system. Waste management primarily concentrates on converting waste into energy at a lower cost and with realistic fuel specifications [3]. Recycling waste can significantly reduce the amount of waste destined for landfills. Landfill is a concern because it affects soil's biological properties and may release toxic materials into the air after decades [7, 8]. This contamination threatens biological diversity and climate.

The growing needs of modern civilization are driving more plastic usage, despite these environmental risks. Initiatives for recycling and the creation of novel materials have been launched as ways to address these issues and lessen the environmental impact of plastic [8]. Many different types of plastic may be recycled into new forms of energy, oil, and chemicals. These include polystyrene (PS), polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) [9].

Pyrolysis is a controlled temperature-induced thermal decomposition of waste plastic that generates liquid oil in an atmosphere devoid of oxygen [10]. The two primary pyrolysis processes are defined by the gas retention period in the pyrolyzer. With a heating rate of 10-200 °C per second, pyrolysis is a quick process that takes half a minute to ten seconds. Rapid pyrolysis produces more liquid byproducts than solid or vapor byproducts. When compared to the fast pyrolysis process, the slow pyrolysis method has a much longer gas residence period (450-550 s) and a lower heating rate (0.1-1°C/s). When comparing slow pyrolysis to fast pyrolysis, it is clear that the former yields more solid vapor and less liquid vapor [4, 5]. Patterns of polypropylene pyrolytic product formation at temperatures ranging from (200-600)^{o}C are investigated. From room temperature, samples are heated at 100oC min^{-}1 with argon flow (40-50 ml min-1). At 200-300 °C pyrolysis, the yield of light liquid hydrocarbons (C_5-C_{10}) is minimal; it increased consistently until 446 °C, at which point it declined [6]. Ethylene, propylene, butylene, and other light hydrocarbons were the principal components of the product at higher temperatures, which was mostly a gas. Furthermore, researchers discovered certain aromatics such as benzene and toluene, along with aliphatic compounds [7]. Thermal pyrolysis turns plastic and thermoplastic waste plastics into high-quality compounds and lubricants. It also handles unsorted, disorganized, and untreated trash without polluting. It sustainably solves the complex municipal refuse management problem [8]. Furthermore, to produce large-scale catalysts, the commercial-scale process is expensive, requires extensive feasibility assessment, and may require specialized equipment. Also, the plastic waste is mixed trash and may require sorting to obtain the target waste plastic. The process of managing this diversity of waste plastic and selecting the appropriate catalyst can be challenging [9]. Thus, thermal pyrolysis requires extensive studies for all aspects of the plastic waste targeted by the designer, such as the type of plastic waste, the technology of pyrolysis, the kinetics of the degradation of the plastic waste, and the economic feasibility of the process. It turns trash into useful energy products such as bio-oil, charcoal, and syngas, it provides an efficient and ecologically beneficial waste disposal solution. This not only helps to minimize garbage transported to landfills, but it also lessens our dependency on fossil fuels. Furthermore, thermal pyrolysis is a relatively clean process that helps to reduce air pollution and greenhouse gas emissions, making it an ecologically friendly choice [10]. Despite the existence of several researched and patented methods for converting waste plastic into biodiesel, their practical implementation remains limited [11]. Studies have revealed that among the various recycling methods, only four achieve the technology readiness level (TRL) of level 8. These four methods include plastic energy, Enerkem, Brightmark, and JEPLAN [12]. Some countries like China, where industrial solid waste significantly contributes to environmental pollution [13], have shifted their focus to the catalytic thermal conversion of carbon-rich feedstock into solid, liquid, and gaseous fuels [14]. Italy has designed a molecular dissociation pilot plant to convert unsorted municipal solid waste into syngas. Similarly, the UK and France have devised various methods to produce gas from solid wastes [38, 39].

The effectiveness of these catalysts is influenced by parameters such as reaction circumstances, feedstock composition, and desired product requirements. The primary challenges that need to be overcome are scaling up production and ensuring economic feasibility. The present study aims to explore the feasibility of cost-effective green biodiesel production from polypropylene waste using thermal pyrolysis. The study examined the kinetics model of thermal degradation to assess the process. By optimizing the experimental design, this study seeks to promote sustainability and find viable solutions for addressing environmental challenges associated with plastic waste.

2. Materials and Methods

2.1. Materials

The feedstock in the present work is polypropylene that is obtained from North Refineries Company in Iraq. Table (1) displays the specifications of the water polypropylene.

Table (1): Specifications of the water polypropylene.

Property	Value
Density	901.24 kg/cm^3
Impact resistance at 23°C	47.57 J/m
Tensile strength	36.54 MPa
Flexural modulus	1357.1 MPa
Deflection temperature	80.38 °C
Specific volume	30 cm^3/Ib
Melting point	163 °C

2.2. Pyrolysis Experiments

Initially, a pre-wash is performed to eliminate the most superficial residues. A 'pre-washing tank' may also be employed at this stage to eliminate heavy contamination from plastic materials. The plastic type determines whether the actual washing process is hot or cold, with water or dry. Next, a plastic crusher machine crushes the plastic waste before shaping it into polypropylene granules. The plastic waste is crushed using a granule shredder machine (electric, capacity: 50 to 500 kg, China), located in Tikrit City, with a size of 25 mm, as shown in Figure (1). Temperature significantly influences the type and quantity of products formed during the thermal degradation of polymers. To investigate the pattern of degradation that occurs in the plastic materials when subjected to the reaction conditions that would be employed for pyrolysis, TGA studies were conducted. Consequently, the TGA analysis was conducted at a moderate reaction temperature of 900 °C for a duration of 30 minutes while being agitated with nitrogen flow (purity is 99%.). The experiment's goal was to predict the plastic's weight reduction to time and temperature. A thermogravimetric analyzer comprises two fundamental elements: a data recorder and a controlled ceramic furnace that is microbalance [15].

Fig. (1): Granules Shredder machine.

The thermal degradation characteristics of the plastics were ascertained through thermos gravimetric analysis (TGA) of the samples using the TGA Q5000 instrument in the Petroleum Research and Development Center, Oil Ministry, Baghdad, as shown in Figure (2) and specifications in Table (2). Measuring the weight loss of the plastic samples as the temperature rose allowed for this. The process included heating about 10 mg of the polypropylene (in nitrogen) at a rate of 5 °C min^{-1} to a final temperature of 900 °C. The sample spent thirty minutes at that temperature. To create a homogenous and representative sample for the analysis, polypropylene samples were ground to 500 nm particles in a cryogenic mill before the TGA. The goal of this investigation was to construct a polypropylene thermal model.

Table (2): Specifications of the TGA Q5000 instrument.

Property	Value
Dynamic Range	100 mg
Isothermal Stability	± 0.1 °C
Humidity Range	0-98%
Crucibles Capacity	20-180 μL
Weighting Accuracy	± 0.1%
Sensitivity	0.1 μg
Drift of the Baseline	5μ / 24 hours

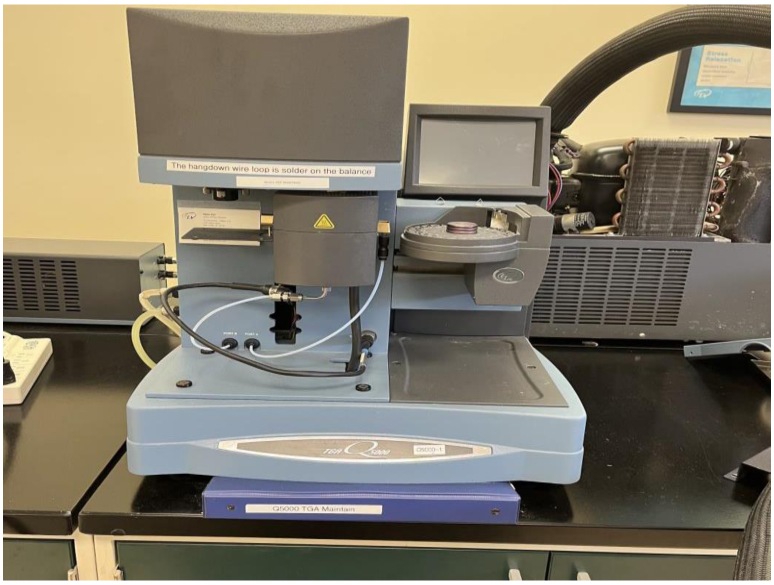

Fig. (2): TGA Q5000 instrument.

2.3. Specifications of the Biodiesel

2.3.1. Specific Gravity

The specific gravity of a material is a comparative indication of its density. The term "density ratio" refers to the relationship between a material's density and a reference density. A pycnometer, a standard test method for density and relative density (specific gravity) of liquids was used by Bingham Pycnometer to determine the density of the sample.

2.3.2. Heating value

The heat output of a fuel at ambient temperatures determines its energy content. Complete combustion generates water; hence, the heat of combustion equals the energy difference between liquid and vaporized water. If all the water in exhaust products is believed to be liquid, the heat has a greater heating value. Secondly, heat has a reduced heating value if all water is vapor [16]. Calorimetric or elemental analysis may determine the fuel heating value. Differential scanning calorimetry (DSC) generates fuel calorific values by calculating heat flow as a function of temperature [17]. The setup for conducting this experiment is an Oxygen Calorimeter (XRY-1A Digital Oxygen Bomb Calorimeter, China) located in the laboratory of Graduates Research, Chemical Engineering, Tikrit University.

2.3.3. Viscosity

The physical property of viscosity serves as an indicator of the internal resistance encountered by a flowing fluid. The fluid is deformation resistant. The identification of finalized or semi-completed products is a critical function of this index. The viscosity of the product was determined utilizing a rotary viscometer (ATO, NDJ-8T, China).

2.3.4. Spectra of the biofuel constituents

The liquid products were analyzed using a Perkin Elmer GC-MS with an FID detector (GC/MS Perkin Elmer) at Ondokuz Mayıs University in Turkey. The GC auto system XL with FID, automatic sampling 82 positions, and two injectors that are split, mass spectrometer (MS) detection system Turbomass Improve alone the quadrupole, and vacuum pump rotary Edwards RV3 were used. The product sample was diluted with hexane for examination. The GC/MS had a FI detector and Optima FFAP column with a 30 m length, 0.25 mm internal diameter, and 0.25 mm film thickness of 95% Dimethylpolysiloxane. A 1µl diluted sample was injected into the GC/MS with a split ratio of 15 and Helium as the carrier gas at 1 ml/min. Maintaining 275°C inlet temperature. The oven was preheated at 60°C for 10 minutes, then 230°C. Then scheduled to rise 25°C every minute to 280°C for 5 minutes. The total run time was 60 minutes.

3. Results and Discussion

3.1. Kinetics of the thermal pyrolysis

TGA instruments may operate isothermally or non-isothermally. In this study, non-isothermal TGA is used because of its shorter duration and convenience at higher temperatures for significant heat-up and cool-down periods[18]. The behavior of polyproblen during thermal pyrolysis is predicted by the kinetic model via the computation of the reaction rate. Equation (1) The rate of a reaction that occurs in the solid state is given by ($d\alpha/dt$), which for polyproblen pyrolysis is the amount of reacted material at any given time:

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \tag{1}$$

Where:

α: Reacted fractional or conversion.

k(T): Expression of temperature mathematically.

f (α): a conversion expressed mathematically known as a kinetic model.

The temperature function denoted by Equation (1) adheres to the Arrhenius law, which is defined by Equation (2):

$$k = A * e\left(-\frac{Ea}{RT}\right) \tag{2}$$

Where:

k: is the reaction rate constant (s^{-1}),

A: Arrhenius constant (s^{-1}),

Ea: the activation energy (J/mol),

R: the universal gas constant (8.314 J/mol.^{o}C)

T: Temperature (^{o}C).

Regarding an isothermal process with a constant rate of heating (β = dT/dt = constant), Equation (2), convert to Equation (3):

$$\frac{d\alpha}{dT} = \frac{A}{\beta} * e\left(-\frac{Ea}{RT}\right) f(\alpha) \tag{3}$$

Where:

$\frac{d\alpha}{dT}$: The reaction rate under non-isothermal conditions.

β: The heating rate (K/s).

The model-free techniques (FR, FWO, KAS, and STK) and model-fitting methods are derived. Table (3) displays the kinetic equations of the four generally used model-free methods and the two model-fitting methods.

Table (3): Equations for four model-free methods.

Method	Equation	Plot	ref
Friedman	$\ln(\beta\frac{d\alpha}{dT}) = \ln[Ao\ f(\alpha)] - \frac{Ea}{RT}$	$\ln(\beta\frac{d\alpha}{dT})vs\ (\frac{1}{T})$	[19]
Flynn–Wall–Qzawa (FWO)	$\ln(\beta) = \ln\left[\frac{Ao * E}{Rg(a)}\right] - 5.331 - 1.052 - \frac{Ea}{RT}$	$\ln(\beta)\ vs\ (\frac{1}{T})$	[20]
Kissinger–Akahira–Sunose (KAS)	$\ln(\frac{\beta}{T^2}) = \ln\left[\frac{Ao * R}{Eg(a)}\right] - \frac{Ea}{RT}$	$\ln(\frac{\beta}{T^2})\ vs\ (\frac{1}{T})$	[21]
Starink	$\ln(\frac{\beta}{T^{1.92}}) = C - 1.008\frac{Ea}{RT}$	$\ln(\frac{\beta}{T^{1.92}})\ vs\ (\frac{1}{T})$	[22]

The Friedman method is a differential isoconversional method. To ascertain the activation energy, it evaluates the rate of reaction at various temperatures. The FWO is a fundamental isoconversional technique. The method is contingent upon the temperature at which non-isothermal heating achieves a particular conversion. The KAS method is an integral isoconversional method that is similar to FWO; however, it employs a distinct method of data analysis. Another integral method is the Starink method, which provides an approximation for the activation energy without assuming a specific reaction model. TGA results for the pyrolysis of PP polymers with the specified heating rate are shown in Figure (3). There was no differentiation between the thermograms and the thermal decomposition features, which included commencement, maximum, and final temperatures. At a heating rate of 5^{o}C/min, the onset temperature is 350^{o}C, the peak temperature is 420 ^{o}C, and the ultimate temperature is 450^{o}C. This figure illustrates a single reaction region during PP polymer pyrolysis. This discovery is entirely consistent with various published data [23, 24].

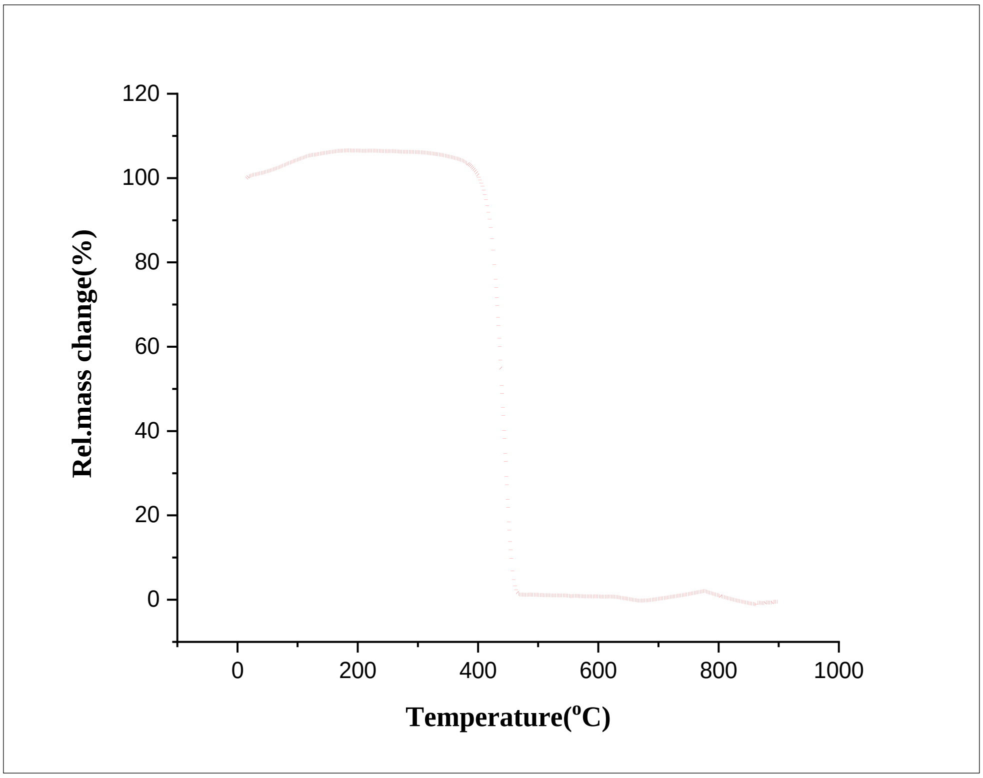

Fig. (3): Weight loss (%) against temperature (◦C) for PP.

The present study collected data on the thermal degradation of waste polypropylene plastic. These data were collected by heating the plastic waste in the absence of oxygen and measuring the weight loss of the waste sample with time and against temperature progression. These data were utilized for the development of the kinetic model and the determination of the Arrhenius equation model parameters (pre-exponential factor and activation energy):

$$\mathrm{logk} = \mathrm{logA} - \frac{\mathrm{E}}{2.303\mathrm{RT}} \tag{4}$$

The rate expression for a non-isothermal degradation reaction Equation (3) will become as follows:

$$\frac{\mathrm{dx}}{\mathrm{dT}} = \mathrm{A} * \mathrm{e}\left(-\frac{\mathrm{Ea}}{\mathrm{RT}}\right) * \mathrm{f}\,(\mathrm{x}) \tag{5}$$

Where x represents the sample's fractional conversion at time t. Using the following expression, the fractional conversion of the material at a specific temperature X_T was determined:

$$\mathrm{X_T} = \left(\frac{\mathrm{W_i - W_T}}{\mathrm{W_i - W_f}}\right) \tag{6}$$

Where:

W_i: initial weight(g).

W_f: final weight(g).

W_T: weight at a particular temperature(g).

If $f(x) = (1-x)^n$ (with a constant heating rate and the order of the degradation reaction denoted by n). Following this, the Arrhenius equation can be expressed as follows using the Coats-Redfern method [25]:

$$\log\left(\frac{1-(1-x)^{1-n}}{T^2(1-n)}\right) = \log\left(\frac{AR}{aE}\left(1-\frac{2RT}{E}\right)\right) - \frac{E}{2.303RT} \qquad n \neq 1 \tag{7}$$

$$\log\left(\frac{-\log(1-x)}{T^2}\right) = \log\left(\frac{AR}{aE}\left(1-\frac{2RT}{E}\right)\right) - \frac{E}{2.303RT} \qquad n = 1 \tag{8}$$

$$Y = -\log\left(\frac{1-(1-x)^{1-n}}{T^2\,(1-n)}\right) \qquad n \neq 1 \tag{9}$$

$$Y = -\log\left(\frac{-\log(1-x)}{T^2}\right) \qquad n = 1 \tag{10}$$

The Coats-Redfern method achieves a harmonious equilibrium between dependability and simplicity. It necessitates a reduced number of experimental data points and offers a straightforward, uncomplicated method for determining pre-exponential factors and activation energy. Furthermore, its linearity facilitates its application and interpretation, rendering it the preferred option in numerous thermal analysis investigations. To approximate the order of degradation kinetics, various values of 'n' were substituted into Equations (7) or (8). From the TGA data, the values of 'Y' were estimated and plotted against the reciprocal of the degradation temperature. For the degradation of polypropylene when n equals zero, Coats-Redfern plots were generated; the corresponding plots are depicted in Figure 4. It is evident from Figure (4) that the thermal degradation of polypropylene exhibits a predominantly zero order. The values of activation energy (E) and pre-exponential factor (A) were calculated from the slope (-E/2.303R) and intercept log [(AR/aE (1-2RT/E)] of the linear equation by using trial and error with temperature. The Coats-Redfern approach [26] is used to obtain the parameters of the kinetics of thermal degradation. The estimated values of degradation reaction order, activation energy, and pre-exponential factor obtained from the Coats-Redfern plot as shown in Figure (4) are 128.74 kJ/mol and 2.603. The activation energy value for polypropylene indicates the average activation energy values in other literature, in agreement with other similar reports [23, 27, 28].

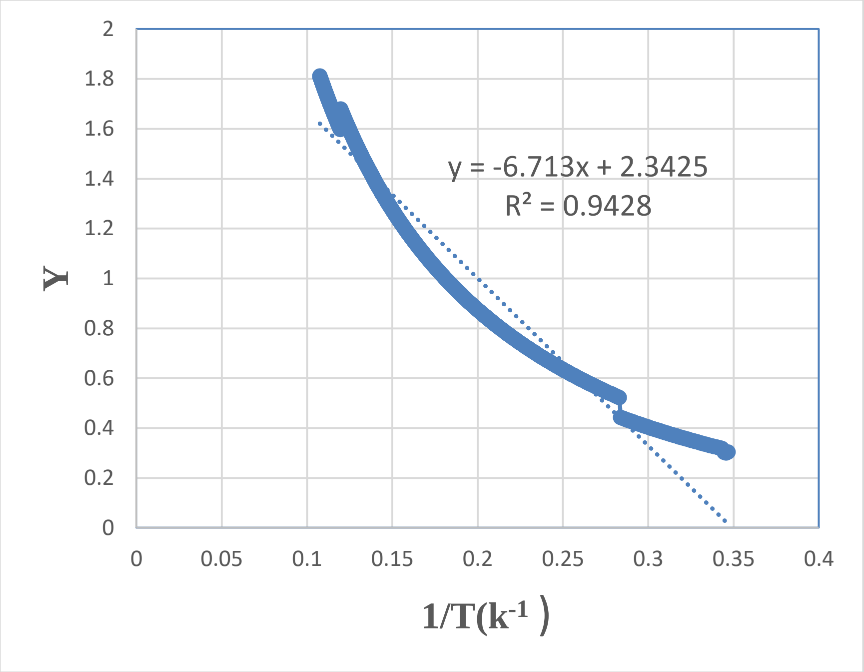

Fig. (4): Coats-Redfern plot for polypropylene.

3.2. Specifications of the product (biofuel)

The quality of biofuel is assessed based on many metrics that indicate its chemical and physical characteristics. The quality of biofuel may be influenced by many aspects, including the quality of the feedstock (polyproblem), analysis of the compounds, production method, materials used in the process, parameters, and handling and storage. Table (4) presents a comparison between the specifications of the prepared biofuel and petroleum diesel fuel.

Table (4): Specifications of the biofuel.

Property	diesel	Test	Biofuel
Flashpoint (ºC)	66	ASTM D93	73
API	35	Calculated	32
Kinematic Viscosity@40°C (mm²/s)	1.2	ASTM D975	1.57
Calorific value (HHV) kJ/kg	46	ASTM D4294	39
Sulfur content, (ppm)	5	ASTM D4294-03	nill
Cetane number	45 to 55	ASTM D613-03a	46-48
Boiling point range(°C)	150 to 380	ASTM D86	141-346

According to Table (4), it is evident that the HHV value of the biofuel produced in this research is almost identical to the HHV value of petroleum fuel. GC-MS analyzed the thermal pyrolysis of polypropylene into biofuel. The liquid fuel sample, specifically plastic oil, undergoes examination using GS-MS (gas chromatography-mass spectrometry). This analytical technique is based on the principle of catalytic pyrolysis, which enables the identification and quantification of the various chemicals present in the sample. The results of this analysis provide a clear depiction of the composition of the liquid fuel sample. Figure (5) The Total Ion Chromatogram (TIC) displays the peaks of several substances, including Nonane, Decane, Undecane, Dodecane, Tridecane, Pentadeance, Hexadecane, Heptadecane, Octadecane, Eicosane, Heneicosane, Heptadecane, so hexadecane and Eicosane are indicated the sample biodiesel. The conclusions are derived from this. The sample exhibits longer hydrocarbon chains, similar to the molecular bonding seen in alkenes and alkanes. This chemical structure allows the fuel to have a higher fire point, making it more suitable for burning. The production of harmful polyaromatic hydrocarbons, such as carcinogens, mutagens, and teratogens, is nonexistent. However, there is a partial formation of benzene rings, which are not harmful. These benzene rings can be oxidized with alkanes and alkenes when an emulsion is added, reducing the formation of hydrocarbon chains in the combustion chamber [29]. The peaks found in the GC-MS analysis correspond to distinct hydrocarbons that are present in the sample. Analyzing the structure of these peaks aids in assessing the suitability of the feedstock for biodiesel synthesis. The detection of nonane to eicosane peaks suggests the existence of diverse hydrocarbons that may be transformed into biodiesel using methods such as transesterification.

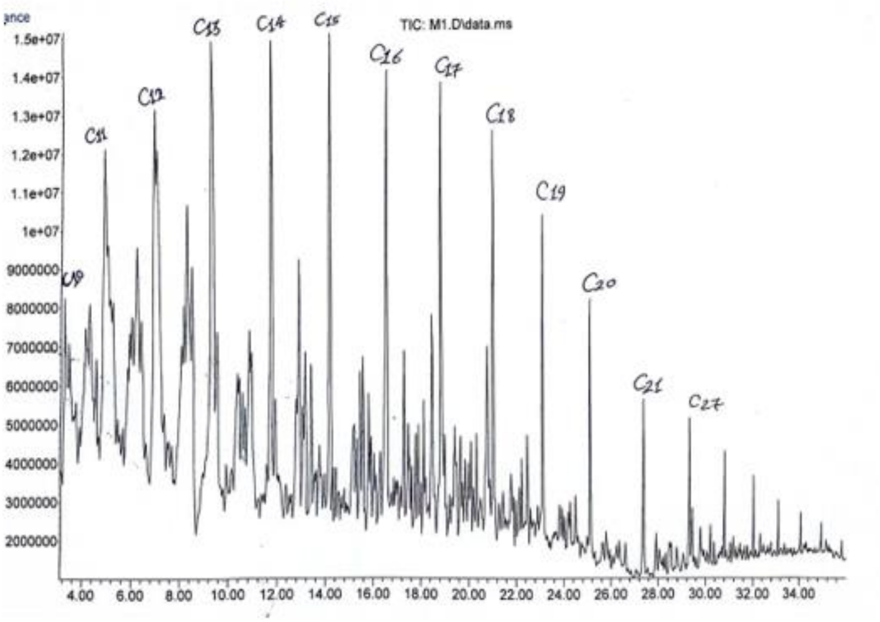

Fig. (5): GC-MS spectrum of the waste plastic oil as biodiesel.

4. Conclusions

The study utilized non-isothermal TGA for its efficiency in providing rapid results at higher temperatures, crucial for analyzing polypropylene (PP) pyrolysis. Equation (1) accurately predicted the thermal behavior of PP by stating that the reaction rate ($d\alpha/dt$) is dependent on temperature (T), conversion (α), and a mathematical expression ($f(\alpha)$). A comprehension of solid-state processes such as PP pyrolysis necessitates an understanding of the Arrhenius equation, which provides additional details regarding the rate constant (k) that varies with temperature. Similar to previous investigations, the TGA analyses revealed a solitary reaction region throughout the pyrolysis of PP. The Coats-Redfern technique was employed to determine the thermal degradation kinetics of PP, which revealed a predominantly zero-order deterioration. The biofuel produced through the pyrolysis process exhibited chemical similarities to diesel fuel derived from petroleum. GC-MS analysis identified various hydrocarbons suitable for biodiesel synthesis; fuel stability was enhanced by longer hydrocarbon chains. Environmentally sustainable, the fuel is devoid of any hazardous polyaromatic hydrocarbons. The comprehension of the kinetics of thermal processes can result in the more efficient design and optimization of industrial processes, such as those used in the production of advanced materials, pharmaceuticals, and chemicals. Precise kinetic parameters facilitate improved control over reaction conditions, resulting in a reduction in energy consumption and an increase in yield. In the future, research should concentrate on enhancing the economic feasibility of thermal processes. This may entail the investigation of alternative raw materials, the optimization of energy consumption, and the integration of renewable energy sources into thermal processing operations.

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