ISSN: 0975-8585

Research Journal of Pharmaceutical, Biological and Chemical Sciences

Synthesis and Thermal Performance of a Copolymer Engineered for High-Temperature Applications.

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ABSTRACT

A novel functional copolymer was synthesized via polycondensation of 2, 4-dihydroxybenzoic acid, acrylamide, and formaldehyde in a 2:1:3 molar ratio under acidic conditions. The structure of the synthesized copolymer was confirmed through various spectrographic analysis encompassing elemental characterization, Fourier-transform infrared spectroscopy, UV-Vis, Proton NMR spectroscopy, which revealed the formation of methylene bridges and characteristic functional groups. The surface topography of the synthesized copolymer led to examined using Scanning Electron Microscopy (SEM), revealing insights into its textural features and microstructural characteristics. Crystallinity was assessed through X-ray Diffraction (XRD) examination, which confirmed the presence of an ordered crystalline phase within the polymer matrix. Furthermore, Gel Permeation Chromatography (GPC) was utilized to evaluate the molecular weight distribution and determine the polydispersity index, providing essential information about the polymer's molecular uniformity and structural consistency. The thermal actions of the synthesized copolymer was systematically analyzed utilizing. Thermogravimetric Analysis (TGA), which revealed a multi-step decomposition pattern, indicating a high degree of thermal stability. Activation energy values were determined through both the Freeman–Carroll and Sharp–Wentworth kinetic models, ensuring reliable thermal decomposition kinetics. The copolymer's notable resistance to thermal degradation highlights its potential applicability in high-temperature environments, making it a promising candidate for advanced polymeric systems requiring enhanced thermal endurance.

Keywords: Functional copolymer, Spectral, Surface morphology, Thermal behavior, Activation energy.

https://doi.org/10.33887/rjpbcs/2025.16.6.2

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INTRODUCTION

Copolymers, composed of two or more distinct monomer units, represent a versatile class of polymeric materials with adjustable structural and functional properties. By incorporating different monomeric species into the polymer backbone, copolymers offer the advantage of combining desirable features such as mechanical strength, chemical resistance, processability, and thermal stability within a single material. This molecular tunability makes them highly suitable for advanced material design in sectors ranging from coatings and adhesives to biomedical devices and electronic components.

Temperature stability is a critical parameter for performance of polymeric substance, especially in applications subjected to elevated temperatures. The incorporation of aromatic structures, crosslinked networks, and thermally stable linkages into copolymer chains significantly enhances their resistance to thermal degradation. As a result, thermally stable copolymers are increasingly being developed for use in aerospace, automotive, electronics, and industrial insulation, where materials are expected to maintain structural integrity and function under heat stress [1-2]. Gurnule et al. examined degradation process at relative high temperature of a newly prepared copolymer derived from 1, 5-diaminonaphthalene, 2-hydroxy-4-methoxybenzophenone, and formaldehyde, revealing significant findings related to its thermal stability and decomposition profile [3]. A thermally stable copolymer was synthesized via bulk polymerization of phenylhydrazine, 2, 4-dihydroxybenzoic acid, and formaldehyde in a 3:1:5 molar ratio, using an acid catalyst to facilitate the reaction. Its thermal behavior was thoroughly characterized to evaluate structural resilience under heat stress [4-6]. Copolymers and their polychelates, renowned for their outstanding thermal endurance, play a vital role in advancing high-performance polymeric materials for modern technological applications [7]. Rathod and co-workers demonstrated that the integration of metal ions into a Copolymer resin led to a marked decline in its thermal stability, highlighting the influence of metal coordination on polymer degradation behavior [8-10]. Rahangdale conducted a detailed investigation into the thermogravimetric analysis of copolymer prepared from 2-hydroxy-4-methoxybenzophenone, 1, 5-diaminonaphthalene, and formaldehyde, providing valuable insights into its thermal stability profile [11]. Thermal decomposition examination of the 2-amino-6-nitrobenzothiazole-oxamide-formaldehyde copolymer revealed that significantly improved thermal stability. This enhancement is attributed to the increased carbonized residue content, as confirmed by the TGA data for both materials [12-13]. Thermal studies at relatively at high temperature polymer was systematically examined using thermogravimetric analysis offering detailed insights into its decomposition profile and heat-resistance characteristics [14-15].

The current research involves the preparation and interpretation of a novel copolymer, 2, 4-Dihydroxybenzoic acid–Acrylamide–Formaldehyde (2, 4-DBAF-II), synthesized via the polycondensation method. Its thermal behavior was evaluated using thermogravimetric analysis (TGA), while elemental analysis and various spectroscopic techniques were employed for structural elucidation. Scanning electron microscopy was utilized to observe surface topography, and X-ray diffraction analysis was performance to explore the crystalline or amorphous nature of the copolymer. Furthermore, activation energy along with other kinetic and thermodynamic parameters was calculated to gain deeper insights into its thermal stability.

EXPERIMENTAL

Starting Materials

All compound and chemicals used in this study were of analytical grade and were utilized devoid of any additional purification. Comprehensive details regarding their specifications and suppliers are provided in Table 1.

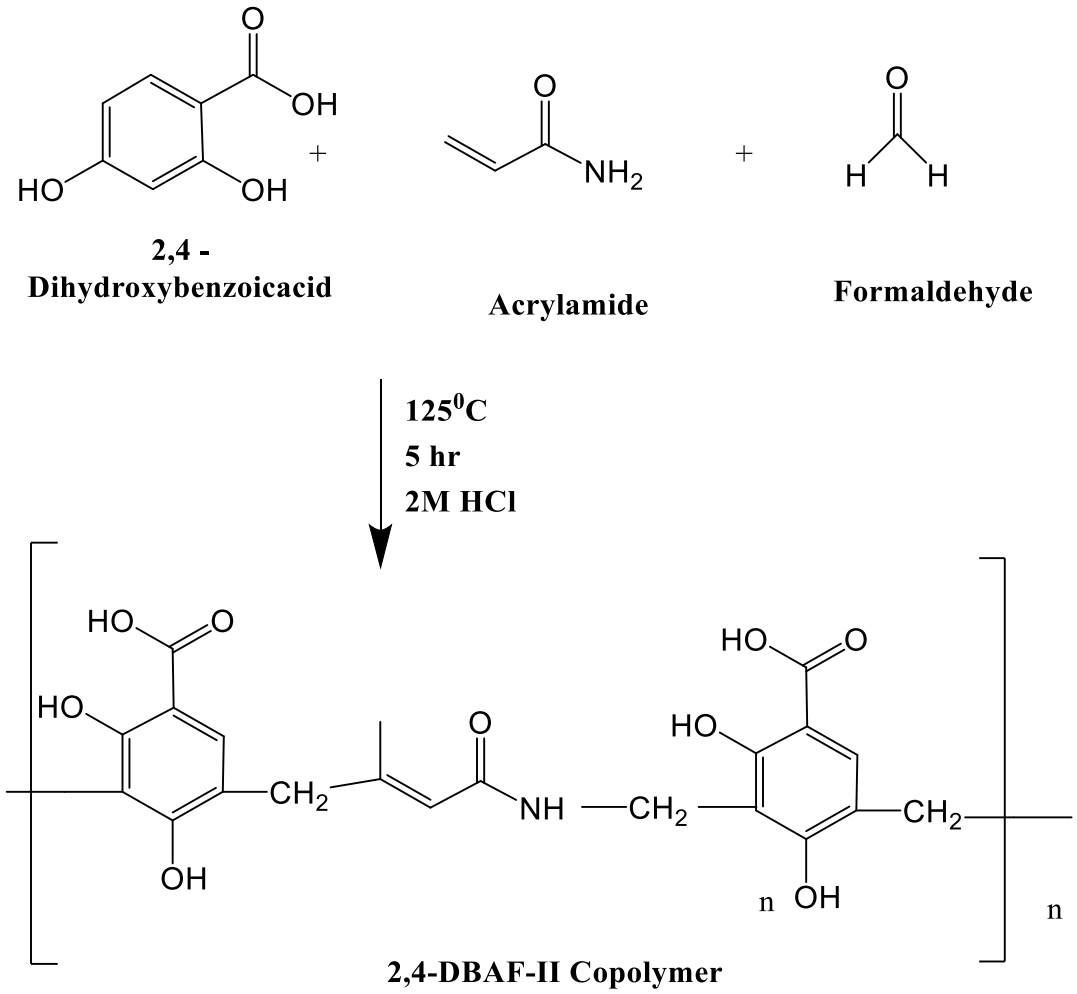
Table 1: Summary of the purity, analytical grade, and sources of the chemicals utilized in this study.

Chemicals	Source
2,4-Dihydroxidebenzoic acid	SD fin, Central Scientific Company, Nagpur.
Acrylamide	SD fin, Central Scientific Company, Nagpur
Formaldehyde	SD fin, Central Scientific Company, Nagpur
Dimethyl sulfoxide	Himedia, Central Scientific Company, Nagpur
N, N-dimethylformamide	Himedia, Central Scientific Company, Nagpur
Hydrochloric acid	Himedia, Central Scientific Company, Nagpur

ISSN: 0975-8585

Synthesis of Copolymer

The 2, 4-DBAF-II copolymer was synthesized via a controlled polycondensation reaction involving 2, 4-dihydroxybenzoic acid, acrylamide, and formaldehyde, catalyzed by 2 M hydrochloric acid. The chemical blend was refluxed at 125 °C for 5 hours, yielding a yellow resinous product. The crude material underwent initial purification through successive washes with diethyl ether and distilled water. To enhance purity, the product was dissolved in 8% (w/v) sodium hydroxide, followed by gradual reprecipitation using a concentrated HCl water mixture. The resulting solid was finely ground and sieved to obtain a uniform powder. The copolymer demonstrated excellent solubility in polar aprotic solvents such as DMSO, DMF, and THF, indicating strong compatibility with organic media. In contrast, its poor solubility in mineral acids reflects limited interaction under strongly acidic conditions, further supporting the structural integrity and stability of the copolymer. The reaction sequence of the newly prepared of 2, 4-DBAF-II copolymer is shown in Scheme 1.



Scheme 1. Configuration and suggested structure of 2, 4-DBAF Copolymer

Instruments

Comprehensive physicochemical and structural characterization of the synthesized copolymer was undertaken using a suite of advanced analytical strategy. Elemental composition was analyzed using a Perkin Elmer 789N QP-2010 instrument. Molecular weight and distribution were examine by Gel Permeation Chromatography (GPC), employing tetrahydrofuran (THF) as the mobile phase at a constant rate of flow 1 mL/min. The apparatus was standardized with polystyrene standards to ensure accurate molecular weight estimation. UV–Visible spectral studied was employed in DMSO across a 200–800 nm wavelength range to probe electronic transitions within the polymer. FTIR analysis was conducted using KBr pellets in the 4000–500 cm^{-1} region to identify key functional groups. Structural elucidation was further supported by ^{1}H NMR spectra, recorded in DMSO-d_6 on a 400 MHz Bruker spectrometer. The

polymer's surface architecture was visualized via Scanning Electron Microscopy (SEM), while its crystalline characteristics were examined through X-ray Diffraction (XRD). Thermal stability and degradation kinetics were systematically analyzed using a Perkin Elmer TGA thermal analyzer.

Physico-chemical characteristics

Key physicochemical parameters of the synthesized copolymer including void volume fraction, solid content, true density, moisture content, and sodium exchange capacity were systematically evaluated using well-established literature-based methods. These assessments provided valuable information for structural integrity of the resin, highlighting its potential for applications in separation and purification processes.

Moisture Content Determination (in %)

To evaluate the moisture content, the copolymer 0.30 g was soaked in 35 mL of distilled water for 46 hours to attain full swelling. The swollen polymer was then filtered, and excess surface water was carefully blotted with filter paper. The sample was weighed in its swollen state, followed by dehydrating in a hot air oven at 90–98 °C for 8 hours. After cooling to room temperature, the dry weight was recorded. Moisture content (%) was calculated based on the weight difference between the swollen and dried samples.

The solid content (%)

$$\text{Solid content (\%)} = (W_d/W_b) \times 100 \text{---------- (1)}$$

Where:
Wd = Dried material (g)
Wb = Material before drying (g)

Moisture Content Calculation

The moisture content in percentage was examine using this equation

$$\text{Moisture content percentage} = 100 - \text{Solid (\%)} \text{ ---------- (2)}$$

True density

$$\text{True density} = \frac{Wp-W}{(Ww-Wpw)+(Wp-Ww)} \text{ ---------- (3)}$$

Where:
W = mass of empty bottle
Wp = mass of bottle with sample
Ww = mass of bottle with water
Wpw = mass of bottle with polymer and water

Volumetric Density

$$\text{Volumetric density} = \frac{\text{Weight of sample}}{\text{Volume of sample}} \text{ ---------- (4)}$$

Assessment of Physical Properties

The core physical properties of the synthesized copolymer—including solid content, moisture content, true density, and volumetric density were systematically evaluated using standardized methods. These procedures, adopted from established literature protocols, ensured methodological uniformity and enhanced the reliability and reproducibility of the results.

Thermal analysis

Thermogravimetric Analysis (TGA) was accompany to examine the thermal resistance and stepwise degradation behavior of the synthesized copolymer. The analysis provided comprehensive insights into its degradation profile over a controlled temperature range. Key kinetic and thermodynamic boundary,

including activation energy and entropy change, were extracted from the TGA data using two established non-isothermal kinetic models: the Freeman–Carroll (FC) and Sharp–Wentworth (SW) methods, ensuring accurate evaluation of the copolymer's thermal behavior. These complementary models enabled an in-depth evaluation of the copolymer's thermal performance, highlighting its suitability for applications requiring elevated thermal resistance.

RESULTS & DISCUSSION

Elemental Analysis of 2, 4-DBAF-II Copolymer

Elemental composition analysis of the synthesized 2, 4-DBAF-II copolymer was conducted using micro analytical techniques, focusing on the quantification of carbon (C), hydrogen (H), nitrogen (N). This evaluation validated the stoichiometric accuracy and structural fidelity of the copolymer as per its proposed molecular architecture. The experimentally measured elemental percentages closely matched the theoretically predicted values, confirming the successful synthesis of the target structure. Based on the obtained experimental outcomes, the empirical formula of the copolymer was established, and the molecular weight of one repeating structural unit was precisely evaluated. A comparative summary of theoretical and experimental elemental data is provided in Table 2, reinforcing the structural consistency of the polymer.

Table 2: Elemental Analysis of 2, 4-DBAF-II Copolymer

Copolymer	Carbon (%) Experimental Theoretical	Hydrogen (%) Experimental Theoretical	Nitrogen (%) Experimental Theoretical	Empirical Formula (Per Structural Unit)	Molecular Weight of Structural Unit (g/mol)
2, 4-DBAF-II	58.68 (58.16)	4.67 (4.32)	3.34 (2.85)	$C_{25}H_{21}N_3O_9$	9611

Molecular Weight Characterization of 2, 4-DBAF-II Copolymer

The molecular weight of the synthesized copolymer was accurately measured using Gel Permeation Chromatography (GPC), a dependable analytical approach that govern molecular weight dissemination by segregating polymer chains based on their size and behavior in solution. Tetrahydrofuran (THF) served as the mobile phase, maintained at a consistent rate of flow by 1 mL/min throughout the analysis. Calibration was achieved using a set of polystyrene calibered with accurately known molecular weights, facilitating the development of a precise calibration curve. The molecular weight of the synthesized copolymer was then assessed by referencing this standard curve. Key parameters such as the number-average molecular weight (Mn) are outlined in Table 3, providing essential information regarding the copolymer's molecular architecture and distribution profile.

Table 3: Molecular Weight determination of 2, 4-DBAF-II Copolymer

Copolymer	Molar Mass of Repeating Unit (g/mol)	Number average molecular weight ($\bar{}_{Mn}$)
2, 4-DBAF-II	570	9611

Spectral studies

UV–Visible Spectroscopic Analysis of 2, 4-DBAF-II Copolymer

The UV–Visible absorption spectrum of the 2, 4-DBAF-II copolymer, recorded in pure DMSO (Fig. 2), was scanned over a wavelength range of 200 to 850 nm at a scanning rate of 100 nm/min. The spectrum revealed two distinct absorption peaks—one prominent band in the range of 360–370 nm and another between 240–260 nm. The more intense peak is attributed to $\pi \rightarrow \pi$ electronic transitions, typical of aromatic ring systems. The less intense band corresponds to $n \rightarrow \pi$ transitions, associated with the presence of –OH and –NH functional groups on the side chains. A hypochromic shift was observed, which can be attributed to these groups functioning as auxochromes, thereby enhancing the absorption intensity [16].

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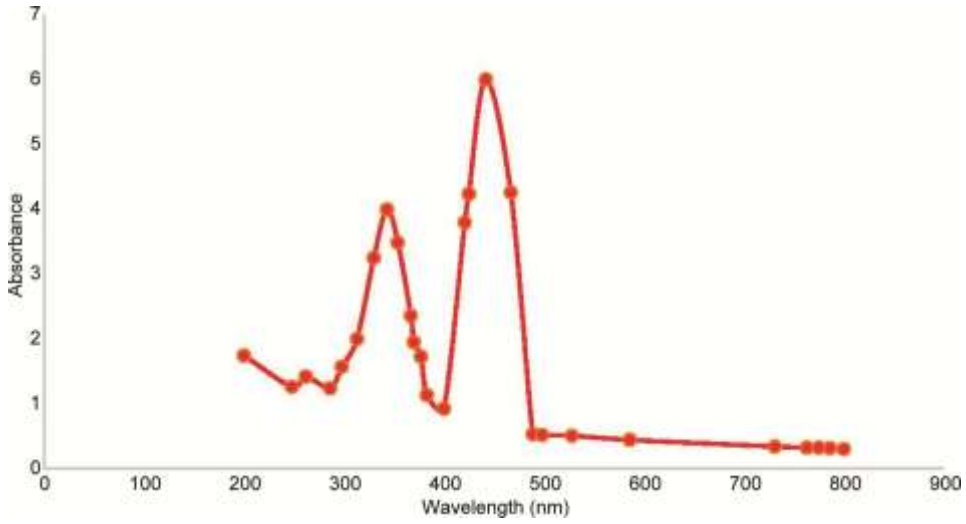

Figure 2. Ultraviolet–Visible Absorption Spectrum of 2, 4-DBAF-II Copolymer

FTIR Spectroscopic Analysis of 2, 4-DBAF-II Copolymer

The FTIR spectrum of the synthesized copolymer (Fig. 5), along with its corresponding absorption band assignments, is detailed in Table 4. A broad absorption band observed in the 3506–3508 cm^{-1} region corresponds to O–H stretching vibrations of phenolic hydroxyl groups, indicating possible intramolecular hydrogen bonding [17]. A sharp, intense peak in the 1556–1626 cm^{-1} range is associated with aromatic skeletal vibrations. The characteristic methylene ($-CH_2$) bridging linkages are confirmed by absorption bands in the 1210–1230 cm^{-1} region [18]. Additional medium-to-weak intensity bands appearing at 953–970 cm^{-1}, 1046–1145 cm^{-1}, 1182–1188 cm^{-1}, and 1320–1321 cm^{-1} are consistent with 1, 2, 3, 5-substitution patterns on the benzene ring. Moreover, a distinct band between 3393–3402 cm^{-1} indicates the presence of –NH bridging groups, which likely overlap with the broad O–H stretch, further confirming the coexistence of phenolic and amino functionalities.

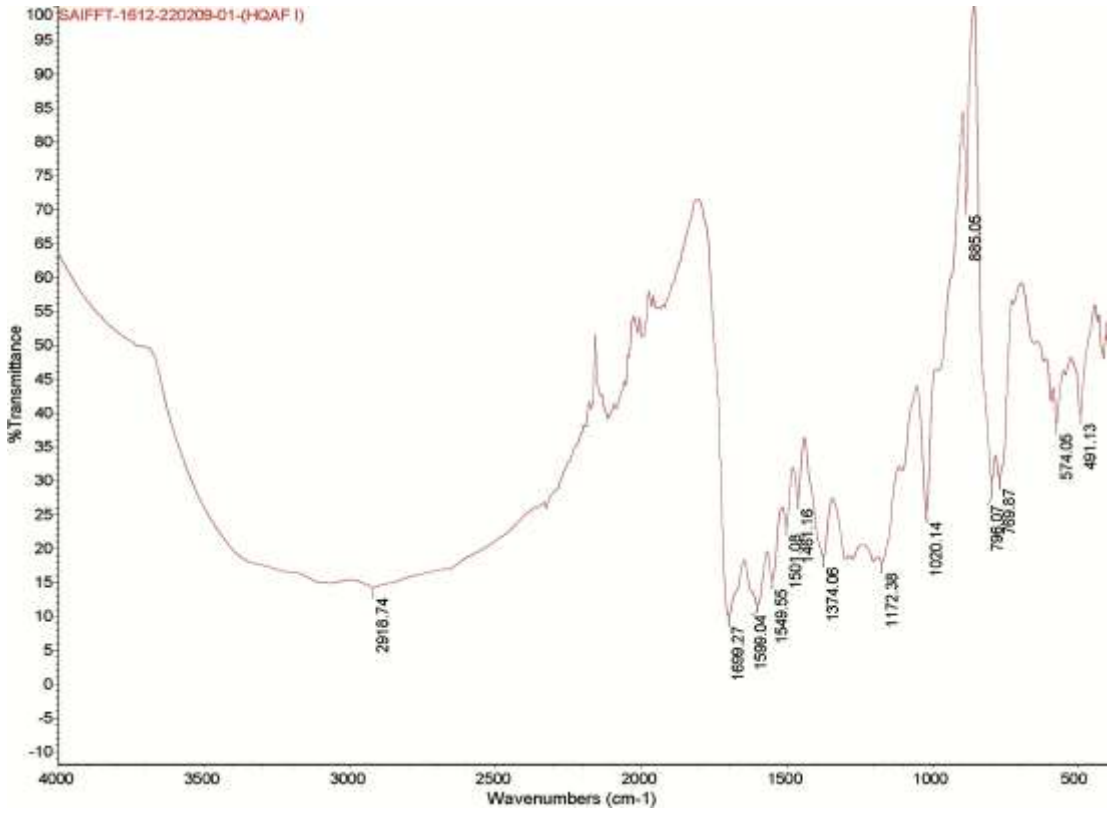

Figure 3: FTIR Spectroscopic Characterization of 2, 4-DBAF-II Copolymer

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Table 3: FT- IR spectral data of 2, 4-DBAF-II Copolymer

Assignment	Predicted Vibrational Frequency (cm^{-1})	Measured IR Band Position (cm^{-1})
Ph-OH	3100-3500	3506-3508 (broad, strong)
-NH (bridge)	3500-3300	3393-3402 (sharp, strong)
Phenyl ring	1445-1485	1556-1626 (sharp, medium)
$>CH_2$ (methylene bridges)	1250-1360	1210-1230 (weak, medium)
1,2,3,4,5 substitution in benzene skeleton	557.9-900	953-970, 1046-1145, 1182-1188, 1320-1321 (broad ,strong)

^{1}H NMR Spectral Analysis of 2, 4-DBAF-II Copolymer

The ^{1}H NMR spectrum of the synthesized 8-HQAF copolymer (Fig. 4), along with corresponding spectral assignments, is outlined in Table 4 and supported by literature references. The spectrum was recorded in DMSO-d_6 as the deuterated solvent. The chemical shift values (δ, ppm) were interpreted based on established data [19–20]. A singlet observed at δ 4.96–4.98 ppm is attributed to methylene (–CH_2–) protons adjacent to the Ph–CH_2–N linkage. Resonances between δ 7.35–7.41 ppm correspond to –NH bridging protons. Weak, unsymmetrical multiplets appearing at δ 8.20–8.25 ppm are assigned to aromatic (Ar–H) protons. Additionally, signals in the δ 9.02–9.06 ppm range represent phenolic –OH protons. The pronounced downfield shift of these hydroxyl signals suggests strong intramolecular hydrogen bonding involving –OH groups [21–22].

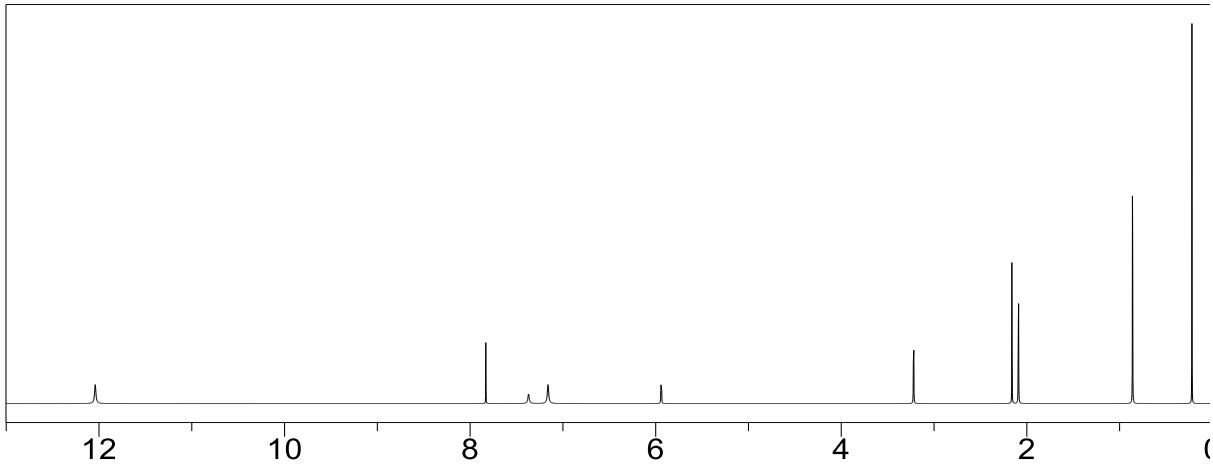

Figure 4: ^{1}H NMR Characterization of 2, 4-DBAF-II Copolymer

Table 4: Assigned ^{1}H NMR Signals of 2, 4-DBAF-II Copolymer

Proton assigned	Assigned ^{1}H NMR Chemical Shifts for 2, 4-DBAF-II Copolymer
Protons of Aromatic Ring (Appearing as Unsymmetrical Multiplies)	8.20-8.25
Amine Bridging Proton (–NH)	7.35-7.41
Proton of the –CH_2– Group Linking Phenyl and Amine Units	4.96-4.98
Proton of Ar-OH	9.02-9.06

Morphological Analysis of 2, 4-DBAF-II Copolymer by Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) was accompany to explore the surface morphology of the synthesized 2, 4-DBAF-II copolymer, as illustrated in Figure 5. The micrograph reveals the development of well-defined spherical structures (spherules) with a smooth, polycrystalline surface, indicative of the

polymer's semi-crystalline nature [23]. The appearance of fringed textures on the surface suggests a heterogeneous microstructure comprising both amorphous and crystalline regions. The observed crystallinity appears to be modulated by the acidic nature of the monomer units, emphasizing the influence of monomer composition on the internal architecture of the copolymer. Densely packed amorphous domains interspersed with deep surface pits may serve as active sites for ion-exchange processes. The yellow coloration and textured fringes further reflect transitional zones between ordered and disordered phases. Additionally, the presence of microvoids and surface cracks likely originating from air entrapment during polymerization or drying—could contribute to an increased effective surface area, enhancing the copolymer's adsorption and ion-exchange performance [24]. The detection of crystal-like formations in the polymer matrix also suggests a significant degree of molecular ordering, with spherulitic structures extending up to several millimeters, characteristic of semi-crystalline polymers capable of self-organization during solidification.

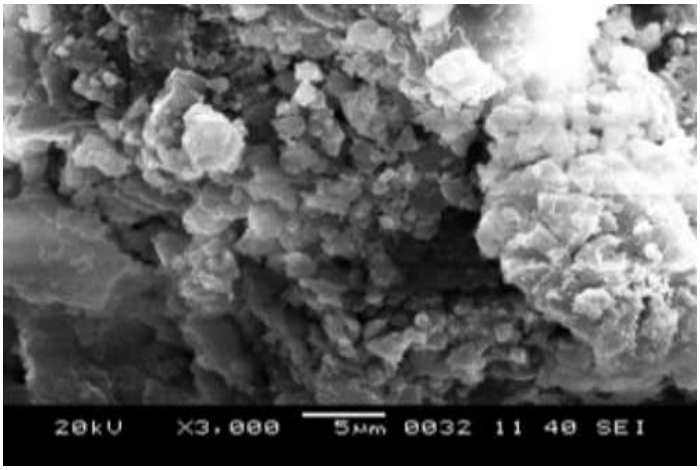

Figure 5: SEM images of 2, 4-DBAF-II Copolymer

X-ray Diffraction Analysis of 2, 4-DBAF-II Copolymer

The crystalline properties of the synthesized 2,4-DBAF-II copolymer were evaluated using X-ray Diffraction (XRD), with the resulting diffraction pattern illustrated in Figure 6.The diffraction pattern exhibited prominent peaks at 2θ values near 32°, 47°, and 57°, confirming the presence of well-ordered crystalline domains within the polymer matrix. The sharpness and high intensity of these peaks reflect a substantial degree of molecular organization, indicative of significant crystallinity [25]. This well-ordered structure offers valuable insight into the copolymer's physicochemical behavior and highlights its potential for applications where crystallinity plays a key role such as in separation technologies, adsorption systems, and electroactive materials.

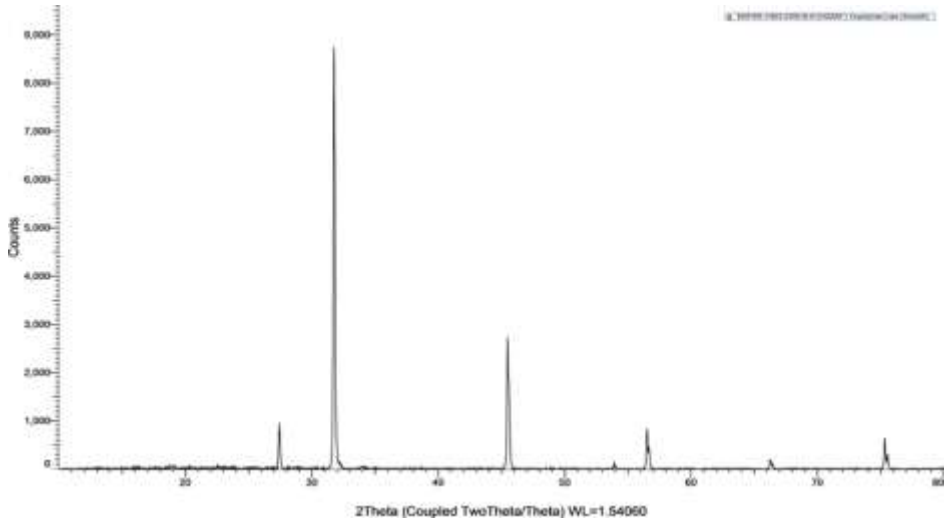

Figure 6: XRD Spectra of 2, 4-DBAF-II Copolymer

Thermal Degradation Study of 2, 4-DBAF-II Copolymer

The thermal behavior of the 2, 4-DBAF-II copolymer was investigated using thermogravimetric analysis (TGA), with the resulting thermogram depicted in Figure 7. The decomposition profile exhibited a distinct multi-step degradation pattern. The initial temperature in between of 40 °C to 160 °C, a minor weight deprivation of approximately 2.01% (experimental) and 2.08% (theoretical) was recorded [26]. This early-stage mass reduction is evaporation by physically adsorbed or crystallization-bound water entrapped within polymer matrix. Following the initial moisture loss, the TGA thermogram revealed a three-step thermal degradation pattern. The first degradation stage, intervening between 160 °C and 290 °C, is assign to the breakdown of three phenolic –OH groups attached to the aromatic quinoline units. This step resulted in an experimental weight loss of 37.12%, comparable the hypothetical value of 36.98%. The gradual mass reduction in this phase is likely due to thermal activation of the polymer backbone, which induces cross-linking and internal stress, ultimately causing partial fragmentation as the structure shifts toward thermodynamic equilibrium. The second major degradation stage happened between 290 °C and 520 °C, with a significant weight loss of 82.95% (observed) versus 83.00% (calculated) [27-28]. This abrupt decline is associated with the decomposition of the three quinoline aromatic rings, likely driven by depolymerization, unzipping of cross-linked segments, and thermal-induced molecular strain.In the final degradation stage, spanning 520 °C to 800 °C, further mass loss was observed due to increased cross-linking density and thermal tension, leading to complete structural disintegration. This phase accounted for an almost total weight loss of 99.68% (experimental) and 100% (theoretical), indicating near-complete thermal decomposition. The minimal residual char confirms the polymer's high decomposition efficiency under elevated thermal conditions [29-30].

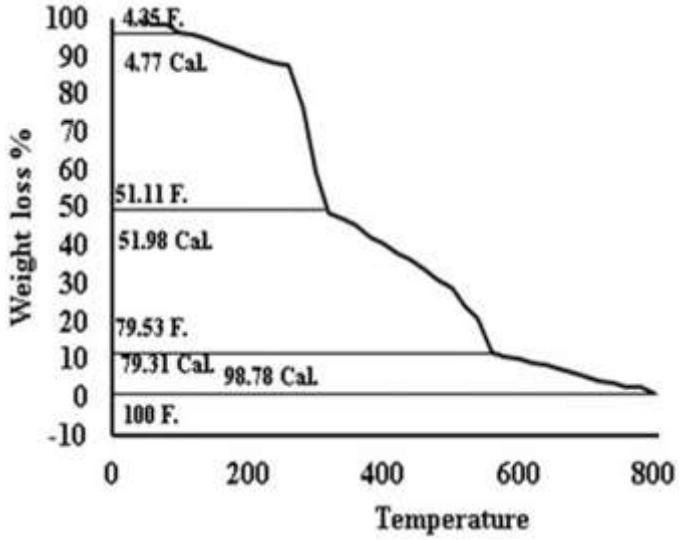

Figure 7. Thermogravimetric curve of 2, 4-DBAF-II Copolymer

Evaluation of Activation Energy Using Sharp–Wentworth Approach

Sharp–Wentworth (SW) method was utilized to evaluate the activation energy (Ea) corresponding to the thermal degradation of the synthesized polymer. This analytical approach enables the determination of kinetic parameters by interpreting thermogravimetric data. The activation energy was examine using the following equation.

$$\text{Log}\left[\frac{\frac{dc}{dt}}{1-c}\right] = \log\left(\frac{A}{\beta}\right)\frac{-Ea}{2.303\,R}\cdot\frac{1}{T} \text{ ------- (11)}$$

Where:

$\frac{dc}{dt}$ = Change in Weight Loss Fraction as a Function of Temperature

C = Degradation extent at time t

B = Linear heating rate

R = Gas constant

T = temperature

A = Frequency factor

Ea = Activation energy (kJ/mol)

A plot of

$$\text{Log}\frac{(\frac{dc}{dt})}{1-c} / \frac{1}{T} \text{ ------- (12)}$$

Generate a straight line to evaluated the activation energy from the slope

$$\text{Slope} = \frac{-Ea}{2.303R} \text{ -------- (13)}$$

This graphical approach, depicted in Figure 8, offers a dependable estimation of the activation energy associated with the thermal degradation process, thereby providing deeper insight into the kinetic behavior of the copolymer.

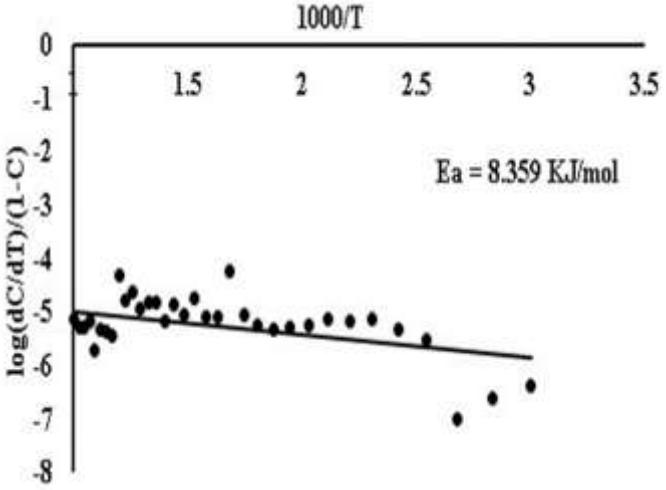

Figure 8. Graphical Determination of Activation Energy via SW Method for 2, 4-DBAF-II Copolymer

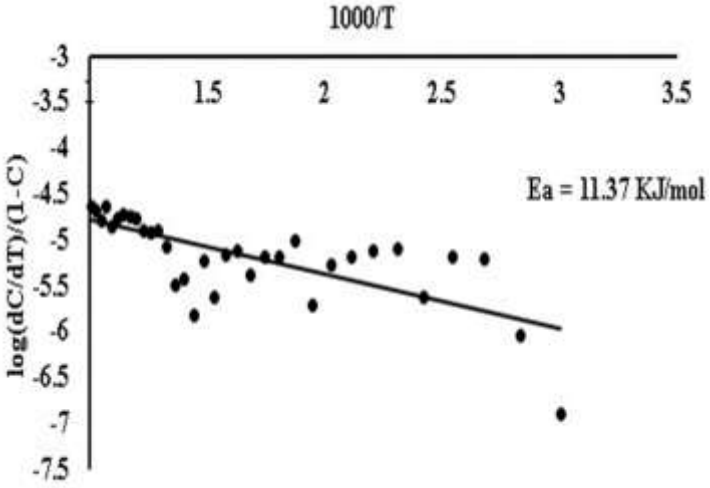

Figure 9. Sharp-Wentworth graph of 2, 4-DBAF-II Copolymer

Kinetic Evaluation Using the Freeman–Carroll Method

The further analyze the thermal decomposition behavior of the polymer the Freeman–Carroll (FC) practice was applied to detrrmine the activation energy (Ea) as well as the reaction order (n). This approach adopts a differential methodology, relying on thermogravimetric data to extract kinetic parameters. The computations were carried out using the following mathematical expression:

ISSN: 0975-8585

$$\frac{\Delta \log\left(\frac{dw}{dt}\right)}{\Delta \log Wr} = \frac{Ea}{2.303R} \cdot \frac{\Delta\left(\frac{1}{T}\right)}{\Delta Log\ Wr} + n \text{ ---------- (14)}$$

Where:
$\frac{dw}{dt}$ = Mass Accumulation Rate as a Function of Time
$W_r = W_C - W$
Wc= Decreased Mass Observed Upon Completion of the Reaction
W = Decrease in Sample Mass at a Given Time t
Ea= Activation energy (kJ/mol)
R = Gas constant
T = temperature (K)
n = Reaction rate

The activation energy of the polymer resin was determined by evaluating thermogravimetric data through the application of both the Sharp–Wentworth (SW) method (Figure 10) and the Freeman–Carroll (FC) approach (Figure 11). Values obtained from these two independent approaches were found to be closely aligned, reinforcing the reliability and accuracy of the kinetic parameters associated with the polymer's thermal degradation behavior.

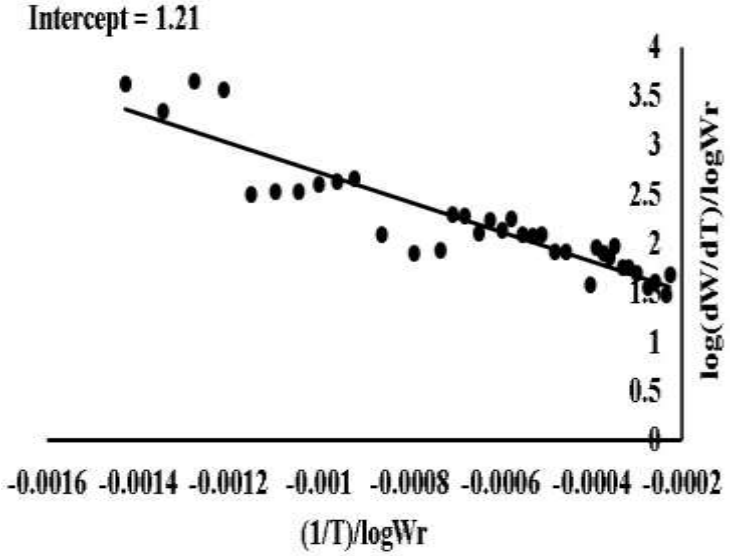

Figure 10. Freeman-Carroll Activation energy graph of 2, 4-DBAF-II Copolymer

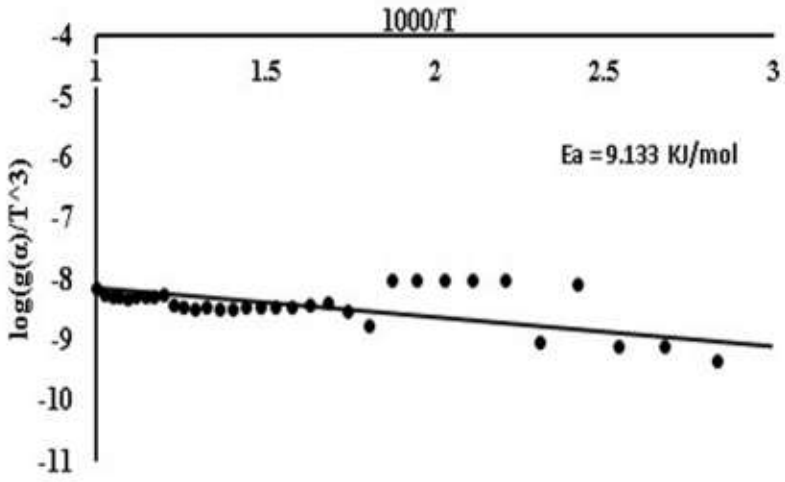

Figure 11. Graphical Analysis of Activation Energy and Reaction Order via FC Method

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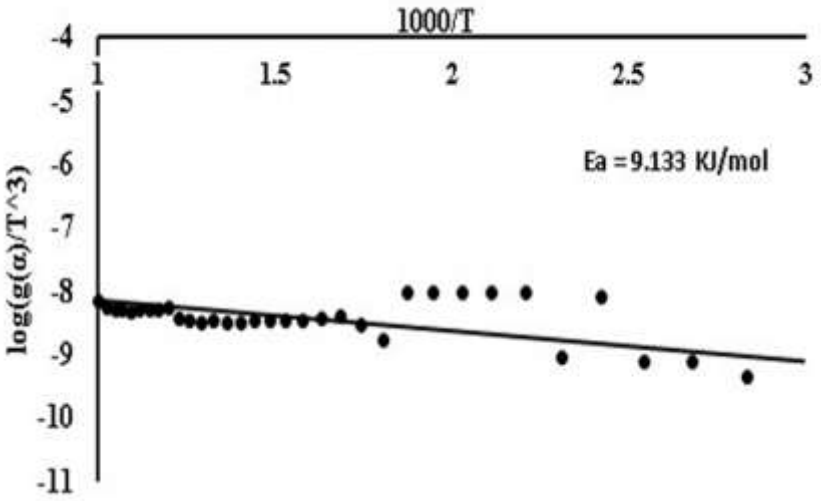

Table: 6. Study of Kinetic Profiles and Thermodynamic Variables of the Polymer System

Polymer	Activation KJ mol^{-1} (Freeman-Carroll)	Energy[Ea] (Sharp-Wentworth)	Entropy Change (ΔS), (J)	Free energy change(ΔF), KJ	Frequency Factor (Z) Sec^{-1}	Apparent Entropy change (S*)	Order of reaction (n)
2, 4-DBAF-II	26.3	28.42	-216.91	113.57	559	-61.33	0.8

The thermal decomposition behavior of the 2, 4-DBAF-II copolymer was further elucidated by calculating key thermodynamic parameters, including Gibbs free energy change (ΔF), entropy change (ΔS), apparent entropy (S*),* and the frequency factor (Z), as summarized in Table 6. The activation energy (Ea) values obtained from both the Freeman–Carroll (FC) and Sharp–Wentworth (SW) methods showed close agreement, underscoring the reliability and consistency of the kinetic analysis. The relatively low value of the frequency factor (Z) suggests that the degradation proceeds through a comparatively slow reaction mechanism, likely governed by the intrinsic thermal stability and molecular architecture of the copolymer. Furthermore, the negative entropy change (ΔS) indicates that the transition state is more ordered than the initial state, implying the formation of a more structured activated complex during the decomposition process.

A comprehensive comparison of the activation energy values for each stage of thermal decomposition, calculated using both the Freeman–Carroll and Sharp–Wentworth methods, is presented in Table 7. The consistency between the two sets of data reinforces the validity of the kinetic model and provides strong evidence for the thermal stability of the 2, 4-DBAF-II copolymer.

Polymer	Stages	Temp. variation	Functional group depletion	Weight reduction (%)	Activation (Ea)(KJ/mol) (SW)	Activation (Ea)(KJ/mol) (FC)
2,4-DBAF-II	1th	40.0-150	H_2O molecule entrapped	3.29	85.03	25.38
2,4-DBAF-II	2nd	150-320	degradation two -OH groups	36.70	28.99	28.39
2,4-DBAF-II	3th	320-480	Reduction of phenyl ring along with two $-CH_2$ groups	59.20	12.18	12.31
2,4-DBAF-II	4th	480-710	Loss of acrylamide moiety.	85.03	86.16	86.02

CONCLUSION

Based on the presented results, the synthesized copolymer 2, 4-DBAF-II, derived from the condensation of 2, 4-dihydroxybenzoic acid, acrylamide, and formaldehyde in the existence of an acid catalyst, demonstrates promising structural and thermal characteristics. The copolymer exhibited considerable thermal stability, as evidenced by the onset of decomposition occurring at relatively high temperatures, making it suitable for applications where resistance to thermal degradation is essential, such as in high-temperature ion-exchange systems or thermally stable membranes. Moreover, the low value of the frequency factor (Z) derived from kinetic analysis suggests that the thermal decomposition of 2,4-DBAF-II proceeds via a slow reaction mechanism, which is beneficial for materials required to maintain integrity under prolonged thermal exposure. These findings collectively underscore the copolymer's potential in practical and industrial environments demanding durable, heat-resistant polymeric materials.

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