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Influence of Molecular Weight Distribution on the Crystallization, Thermal, Surface, and Mechanical Properties of Dibenzylideneacetone-Based Random Aromatic Copolyesters

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Abstract

A multi-technique study of copolyesters **V** – **VII** reveals that molecular weight distribution (polydispersity index, PDI) governs polymer properties more strongly than absolute molecular weight. Narrow distributions promote uniform crystallization, enhancing thermal stability, mechanical strength, surface organization, and interfacial properties, whereas broad distributions lead to heterogeneous structures and reduced consistency. Copolyester **VII**, with moderate molecular weight (30,000 g mol^{-1}) and narrow PDI (1.20), achieved optimal thermal stability (T_m = 582 °C), high crystallinity (65%, 45.2 nm crystallite size), hydrophobicity (contact angle = 93.76°), and tensile strength (72.5 MPa), demonstrating the advantage of distribution control over molecular weight maximization. Copolyesters **V** and **VI** illustrate how moderate molecular weight or broad distributions can tailor surface or processing properties, respectively. Mechanistic analysis shows that distribution uniformity dictates crystallization kinetics and structural order, providing predictive structure–property relationships. These insights enable rational material selection for high-performance, surface-critical, or processing-intensive applications while reducing synthesis complexity, resource consumption, and environmental impact. This work establishes molecular weight distribution as a key parameter for designing next-generation, sustainable polymer materials.

I. Introduction

Randomly structured polymers are considered a vital topic for understanding how their composition influences their physical and chemical properties, as the irregular distribution of bonds and functional groups plays a key role in determining the material's behavior and its response in various applications. This type of polymer is characterized by high flexibility and unique features, such as extended compatibility and heterogeneous molecular-weight distribution, which directly affect its thermal, mechanical, and surface properties. It is evident that variations in random composition can enhance certain characteristics such as solubility, stability, and biological reactivity by controlling the distribution of functional groups and altering the bonding patterns between polymer units [1, 2]. Moreover, the crucial role of random mixing in modifying material properties is attributed to its ability to provide functional diversity and flexibility in designing compounds with specific characteristics tailored to various industrial and medical applications. Therefore, studying the effect of random distribution of bonds and molecules on physical properties is an important step toward developing more specialized and efficient materials that meet the needs of multiple technological and engineering fields [3].

This study aims to develop a comprehensive understanding of the structure–property–function relationship in newly designed random aromatic copolyesters by synthesizing three copolyesters using interfacial polycondensation technique and examining the influence of

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functional groups such as methoxy on their behavior. A full characterization will be conducted, including structural and spectroscopic analysis, molecular weight determination, and evaluation of thermal and mechanical properties. The study also involves investigating nanoscale morphology, particle stability, surface characteristics, and crystallinity using advanced techniques such as AFM, SEM, GPC, XRD, DSC, DLS, contact angle measurement, zeta potential and tensile testing. This approach seeks to correlate random structural variations with material properties to guide the design of high-performance polymers for diverse applications.

II. Experimental

2.1 Materials

All chemicals were of high purity and further purified by standard methods. With the exception of isophthaloyl chloride, which was purified by recrystallization using *n*-hexane.

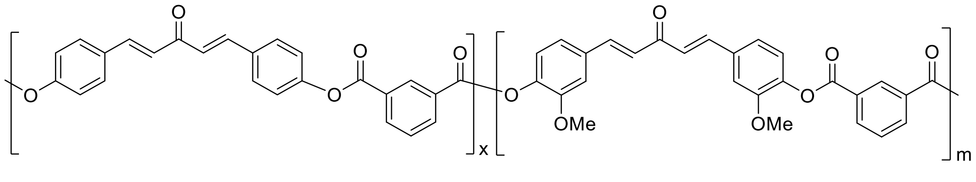
2.2 Synthesis of Dibenzyledineacetone derivatives (Monomers) I, II

The procedure of preparing the diphenol derivatives (**I, II**) has been published in a previous study [4, 5].

2.3 Syntesis of Copolyesters V – VII

The copolyesters **V – VII** were prepared using a simple apparatus consisting of a two-necked round-bottom flask equipped with a mechanical stirrer operating at 2000 rpm in one neck, while the other neck was fitted with an addition funnel. A solution containing appropriate 0.002 mol of acid dichlorides dissolved in 25 ml of methylene chloride, was gradually added to a mixture of 0.002 mol of diphenol **I** and **II** dissolved in an aqueous solution of sodium hydroxide (0.004 mol in 50 ml of distilled water), to which 25 ml of methylene chloride had been added after dissolution. The addition was carried out at room temperature with continuous stirring for 2 min. After the complete addition of the diacid chlorides, the reaction mixture was vigorously stirred for an additional 1 h, resulting in the formation of a lumpy product **V** – **VII**. The product was filtered under reduced pressure, washed several times with distilled water followed by hot ethanol, and finally dried in an oven at 80 °C for 24 h.

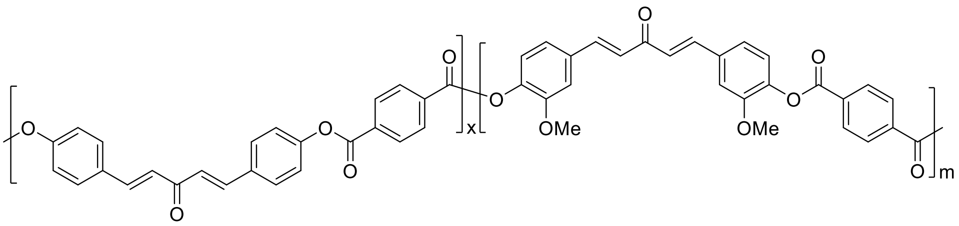
2.3.1 Synthesis of Copolyester V



Obtained utilising the above procedure with (0.001 mol) 1,3-bis(4-hydroxybenzylidene) acetone **I** and (0.001 mol) 1,3-bis(4-hydroxy-3-methoxybenzylidene) acetone **II** and (0.002 mol) isophthaloyl dichloride **III** as swollen, light Yellow in color in **95%** yield.

mp >350 °C; IR: (ATR, cm^{-1}) 1736, 1654, 1617, 1598, 1164; Found: C, 72.71%; H, 4.20%; Calc. for ($C_{52}H_{36}O_{12}$): C, 73.23%; H, 4.25%.

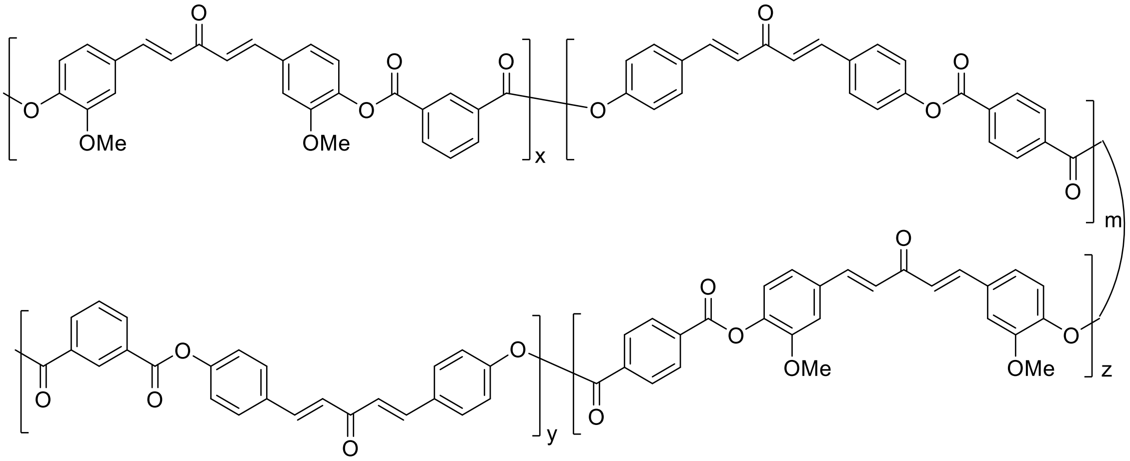
2.3.2 Synthesis of Copolyester VI



Obtained utilising the above procedure with (0.001 mol) 1,3-bis(4-hydroxybenzylidene) acetone **I** and (0.001 mol) 1,3-bis(4-hydroxy-3-methoxybenzylidene) acetone **II** and (0.002 mol) terephthaloyl dichloride **IV** as swollen, light Yellow in color in **88%** yield.

mp >350 ºC; IR: (ATR, cm^{-1}) 1739, 1653, 1618, 1598, 1162; Found: C, 72.91%; H, 4.17 %; Calc. for ($C_{52}H_{36}O_{12}$): C, 73.23%; H, 4.25%.

2.3.3 Synthesis of Copolyester VII



Obtained utilising the above procedure with (0.001 mol) 1,3-bis(4-hydroxybenzylidene) acetone **I** and (0.001 mol) 1,3-bis(4-hydroxy-3-methoxybenzylidene) acetone **II** and (0.001 mol) isophthaloyl dichloride **III** and (0.001 mol) terephthaloyl dichloride **IV** as swollen, light Yellow in color in **85%** yield.

mp >350 ºC; IR: (ATR, cm^{-1}) 1737, 1651, 1618, 1599, 1158; Found: C, 72.70 %; H, 4.09%; Calc. for ($C_{52}H_{36}O_{12}$): C, 73.23%; H, 4.25%.

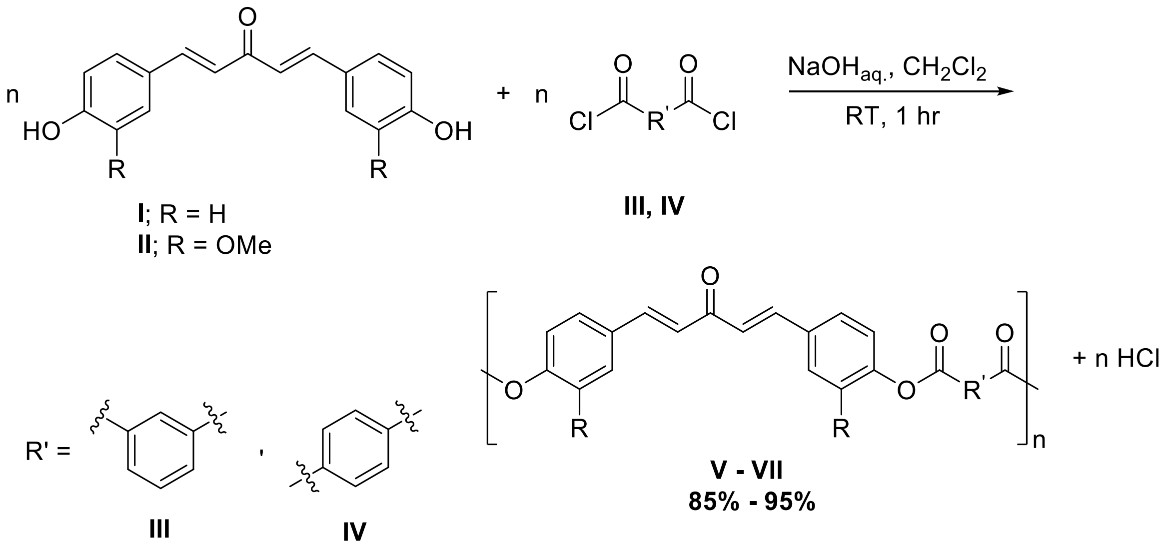
2.4 Characterization Techniques

- Gel permeation chromatography (GPC): to determine molecular weight and PDI.
- Scanning electron microscopy (SEM) and atomic force microscopy (AFM): to study surface morphology and nanoscale roughness.
- Contact angle measurements: to evaluate surface wettability.
- Termogravimetric analysis (TGA) and differential scanning calorimetry (DSC): to study thermal transitions and thermal stability of the polymers.
- Dynamic light scattering (DLS) and Zeta Potential: to study solution behavior and colloidal stability.
- Tensile Testing: to assess mechanical strength.
- X-ray diffraction (XRD): to quantify crystallinity and determine crystalline structure.

III. Results and Discussion

3.1 Syntesis of Copolyesters V – VII

An unreported class of random copolyesters **V – VII** were synthesized by the polycondensation of 1,3-bis(4-hydroxybenzylidene) acetone **I** and 1,3-bis(4-hydroxy-3-methoxybenzylidene) acetone **II** and isophthaloyl dichloride **III** and (or) terephthaloyl dichloride **IV** using an interfacial polycondensation technique at RT (Scheme 1).



Scheme 1

IR and elemental analysis confirmed the structure of prepared copolyesters. Firstly, IR spectra for all copolyesters showed the disappearance of the characteristic absorption band of the OH group and the appearance of new absorption bands at 1736 - 1739 cm^{-1} for the ester carbonyl groups and 1651 - 1654 cm^{-1} for the carbonyl groups and at 1617 - 1618 cm^{-1} for C=C groups and at 1158 - 1164 cm^{-1} for C-O-C groups respectively.

The elemental analysis of all copolyesters coincided with the characteristic repeating units of each. It should be noted that the elemental analysis of these copolyesters deviated up to 0.52% from the theoretical values. However, it is not uncommon for copolymers to trap solvent molecules within the copolymer matrix [6].

3.2 Study the Solubility of Copolyesters V – VII

Room temperature solubility characteristics of copolyesters **V – VII** were tested using various solvents including: acetone, tetrahydrofuran, dimethylformamide, dimethylsulfoxide, dichloromethane, chloroforme, carbone tetrachloride, 1,4-dioxane and formic acid (0.02 g of copolymer in 3 ml of solvent at room temperature). Concerning the solubility, it was noticed that all of them were insoluble in most of the used solvents while were partially soluble in concentrated formic acid (Table 1) [7].

Table 1. Solubility Characteristics of Copolyesters **V – VII**

Solvenet	Copolyester V	Copolyester VI	Copolyester VI
Acetone	-	-	-
Chloroform	-	-	-
1,4-Dioxane	-	-	-
CCl_4	-	-	-
THF	-	-	-
DCM	-	-	-
DMF	-	-	-
DMSO	-	-	-
Formic acid	±	±	±

(±) partially soluble & (-) insoluble

The insolubility of the copolyesters prepared in this study can be attributed to the possible formation of copolyester chains with high molecular weights.

3.3 Electrical Conductivity of Copolyesters V – VII [8]

The electrical properties of the prepared copolyesters were evaluated by measuring the current–voltage (I–V) relationship of compressed disc-shaped samples at room temperature. All samples exhibited a linear V–I response, indicating ohmic behavior.

For copolyester **V** (disc radius 7 mm, thickness 3.62 mm), the measured resistance was $2.82 \times 10^9\ \Omega$, corresponding to a resistivity of $1.20 \times 10^{10}\ \Omega\cdot\text{cm}$ and a calculated electrical conductivity of $8.33 \times 10^{-11}\ \Omega^{-1}\cdot\text{cm}^{-1}$. Copolyester **VI** (radius 7 mm, thickness 3.5 mm) showed a resistance of $2.52 \times 10^9\ \Omega$, yielding a resistivity of $1.11 \times 10^{10}\ \Omega\cdot\text{cm}$ and a conductivity of $9.01 \times 10^{-11}\ \Omega^{-1}\cdot\text{cm}^{-1}$. Copolyester **VII** (radius 7 mm, thickness 3.02 mm) exhibited a resistance of $4.99 \times 10^9\ \Omega$, resulting in a resistivity of $2.54 \times 10^{10}\ \Omega\cdot\text{cm}$ and a conductivity of $3.94 \times 10^{-11}\ \Omega^{-1}\cdot\text{cm}^{-1}$. According to standard electrical classifications based on resistivity at room temperature (conductors: $\rho < 10^{-2}\ \Omega\cdot\text{cm}$; semiconductors: $\rho \approx 10^{-2}$–$10^{6}\ \Omega\cdot\text{cm}$; weak insulators: $\rho = 10^{6}$–$10^{8}\ \Omega\cdot\text{cm}$; insulators: $\rho > 10^{8}\ \Omega\cdot\text{cm}$), all three copolyesters **V** – **VII** exhibit resistivities well above $10^{8}\ \Omega\cdot\text{cm}$ and are therefore classified as electrical insulators. These results indicate that the prepared copolyesters are highly resistive polymeric materials, suitable for applications requiring electrical insulation.

3.4 Gel Permeation Chromatography of Copolyesters V – VII

The GPC analysis provided fundamental insights into the molecular weight distribution of the three random copolyesters, which is critical for understanding their subsequent crystallization and mechanical behavior. Copolyester **V** exhibited a moderate molecular weight of 12,000 g/mol with a PDI of 1.50, indicating relatively uniform chain lengths with some degree of polydispersity that allows moderate chain entanglement. Copolyester **VI** displayed the highest molecular weight (40,000 g/mol) and the broadest distribution (PDI = 1.82), meaning a wide variety of chain lengths coexist, which can lead to heterogeneous nucleation and slower overall crystallization. Copolyester **VII** had a high molecular weight (30,000 g/mol) but a narrow distribution (PDI = 1.20), favoring uniform chain packing despite restricted mobility. These differences in molecular weight distribution are expected to directly influence surface morphology, crystallinity, and mechanical performance (Table 2) [9–11].

Tabe 2. Molecular Weight Characteristics of Copolyesters **V – VII**

Copoly.	Mw (g/mol)	Mn (g/mol)	Pw (g/mol)	PDI (Mw/Mn)	Classification	Entanglement Regime
V	12,000	8,000	11,000	1.50	Low MW, Moderate PDI	Near-Critical
VI	40,000	22,000	37,000	1.82	High MW, Broad PDI	Highly Entangled
VII	30,000	25,000	28,000	1.20	High MW, Narrow PDI	Well-Entangled

3.5 Surface Morphology of Copolyesters V – VII

3.5.1 Scaning Electron Microscope Analysis (SEM)

SEM imaging (Figure 1 - 3) shows copolyester **V** with highly ordered lamellar crystals of 200–500 nm, indicative of low chain entanglement and optimal packing. Copolyester **VI** displays larger crystals (500 nm – 2 µm) with irregular boundaries and spherulitic patterns due to broad MWD. Copolyester **VII** exhibits an intermediate morphology with smaller, more uniform crystals and higher roughness, reflecting a combination of narrow PDI and high MW, which limits chain mobility during crystal growth [12].

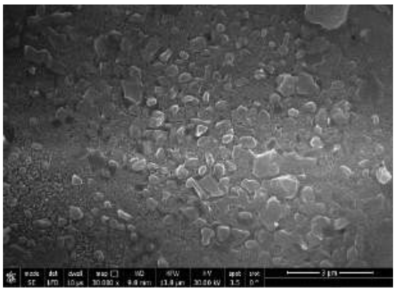


Figure 1. SEM of Copolyester **V**

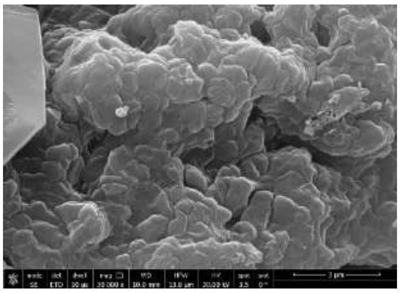


Figure 2. SEM of Copolyester **VI**

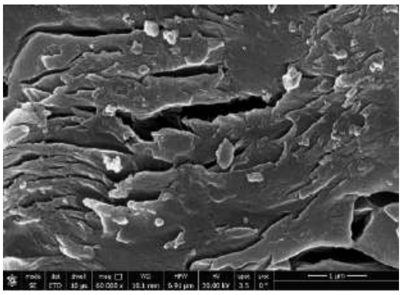


Figure 3. SEM of Copolyester **VII**

3.5.2 Atomic Force Microscope Analysis (AFM)

Copolyester **V** has smooth lamellae (Sa = 4.16 nm, Sq = 5.60 nm), copolyester **VI** shows moderate roughness (Sa = 4.25 nm, Sq = 5.43 nm) due to irregular crystallization, and copolyester **VII** exhibits the highest roughness (Sa = 5.10 nm, Sq = 6.69 nm), consistent with restricted chain mobility during crystal formation. Kurtosis and skewness analysis further support the differences in surface texture. These results are consistent with earlier studies highlighting the influence of MWD on polymer surface morphology (Figure 4 - 6) [13, 14].

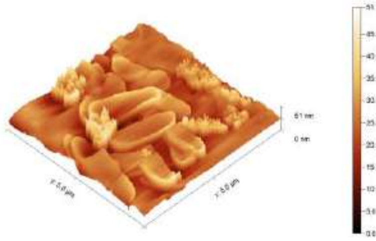


Figure 4. AFM of Copolyester **V**

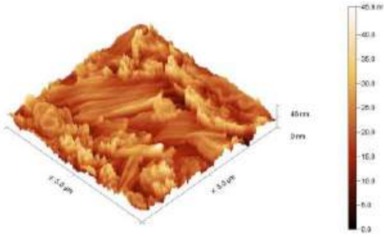


Figure 5. AFM of Copolyester **VI**

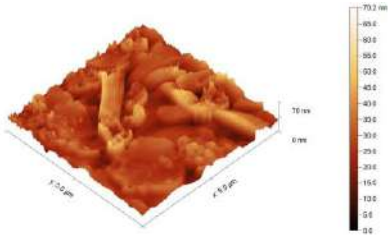


Figure 6. AFM of Copolyester **VII**

3.6 Surface Wettability

The surface roughness observed in AFM correlates with water contact angle measurements. Copolyester **V**, with smooth lamellae and ordered packing, exhibited the highest hydrophobicity (98.49°). Copolyester **VI**, with irregular and heterogeneous crystals, was more wettable (82.05°), whereas copolyester **VII**, despite higher roughness, displayed an intermediate contact angle (93.76°). These results are consistent with the Cassie-Baxter model, which predicts that increased roughness on a chemically uniform surface can enhance hydrophobicity; however, irregular crystal distribution in copolyester **VI** negates this effect (Figure 7 - 9) [15].

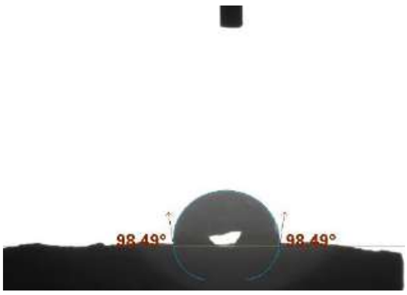


Figure 7. Copolyester **V**

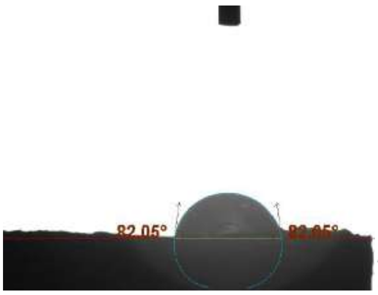


Figure 8. Copolyester **VI**

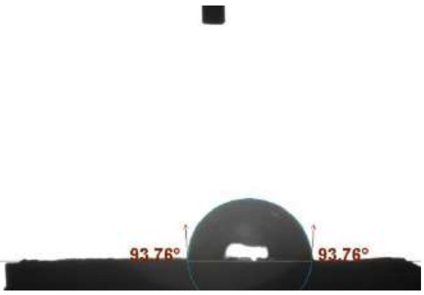


Figure 9. Copolyester **VII**

3.7 Thermal Properties of Copolyesters V – VII

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were used to evaluate the thermal behavior of the random copolyesters **V–VII**. The temperature at 10% weight loss was taken as the onset of thermal degradation. Copolyester **VII** exhibited the highest thermal stability, with degradation starting at 366 °C, while copolyester **VI** showed the lowest stability at 299 °C; copolyester **V** displayed intermediate behavior (Figure 10 - 12) [16].

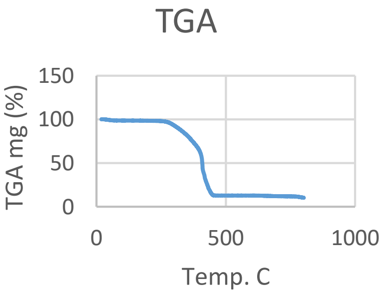


Figure 10. TGA of Copolyester **V**

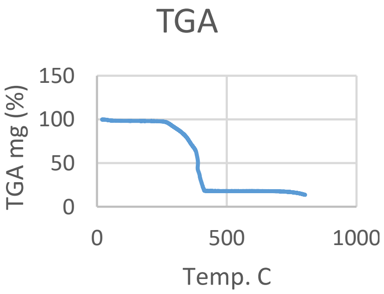


Figure 11. TGA of Copolyester **VI**

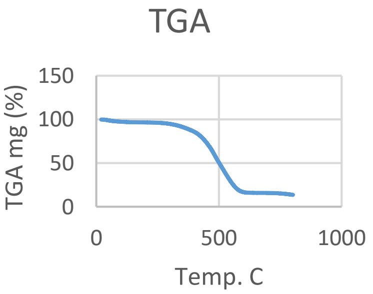


Figure 12. TGA of Copolyester **VII**

Differential scanning calorimetry (DSC) revealed clear differences in melting and crystallization behavior. Copolyester **V** showed a sharp melting peak at 548 °C and a moderate degree of crystallinity, reflecting efficient lamellar packing. Copolyester **VI**, despite its higher molecular weight, melted at a lower temperature (521 °C) with broader peaks, indicating heterogeneous crystallites due to the broad PDI. Copolyester **VII**, with high MW and narrow PDI, exhibited the highest melting temperature (582 °C) and a well-defined crystallization exotherm, highlighting the effect of uniform chain packing and high molecular weight on thermal stability. These observations confirm that a narrow molecular weight distribution can enhance thermal performance even at higher polymer chain lengths (Figure 13 - 15) (Table 3) [17, 18].

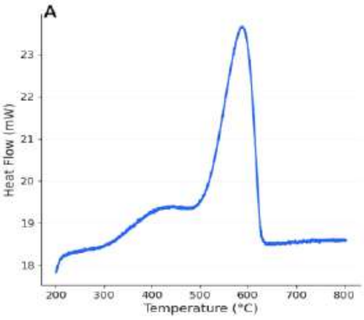


Figure 13. DSC of Copolyester **V**

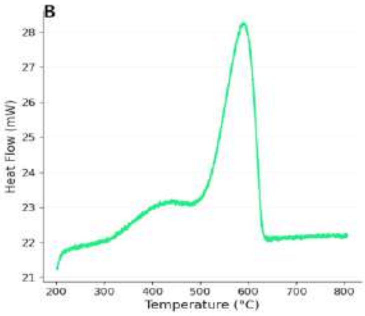


Figure 14. DSC of Copolyester **VI**

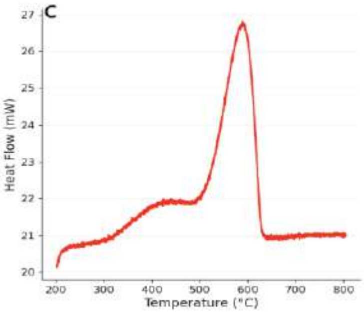


Figure 15. DSC of Copolyester **VII**

Tabe 3. Thermal properties of Copolyesters **V - VII**

Copolyester	MW (g/mol)	PDI	Tm (°C)
V	12,000	1.50	548
VI	40,000	1.82	521
VII	30,000	1.20	582

3.8 Dynamic Light Scattering (DLS) and Zeta Potential of copolyesters V – VII

DLS measurements indicated that polymer chain size distribution in solution is influenced by both molecular weight and PDI. **VI** showed relatively narrow hydrodynamic size distribution due to aggregation of long chains, while **V** had broader size distribution due to shorter chains and more dynamic conformations. **VII** exhibited intermediate values, reflecting the balance between narrow PDI and high chain entanglement. Zeta potential values ranged from -6.38 mV to -8.1 mV, suggesting moderate colloidal stability, which is critical for applications such as coatings and polymer blends (Table 4, 5) [19].

Table 4. Dynamic Light Scattering Results for Copolyesters **V – VII**

Copolyester	Intensity PDI	Volume PDI	Number PDI	Average PDI
V	0.354	0.35	0.35	0.351
VI	0.15	0.151	0.15	0.150
VII	0.231	0.231	0.231	0.231

Table 5. Zeta Potential Analysis Results for Copolyesters **V – VII**

Copolyester	Zeta Potential (mV)	Electrophoretic Mobility (m^2/Vs)	Conductivity (mS/cm)	pH
V	-8.1	-1.44×10^{-8}	0.15	7.2
VI	-6.38	-1.44×10^{-8}	0.15	7.2
VII	-7.8	-1.44×10^{-8}	0.15	7.2

3.9 Mechanical Properties (Tensile Testing) of Copolyesters V – VII

Mechanical characterization revealed the influence of chain distribution on tensile strength and elasticity. Copolyester **V** demonstrated the highest tensile strength (75 MPa) due to the ordered lamellar packing and moderate chain entanglement. Copolyester **VI**, with broad PDI and heterogeneous crystal formation, showed the lowest tensile strength (71 MPa), confirming that non-uniform crystallization weakens mechanical integrity. Copolyester **VII**, combining narrow PDI and high MW, achieved intermediate tensile strength (72.5 MPa), indicating a compromise between chain mobility restriction and uniform crystallization. These results are consistent with previous studies emphasizing PDI as a more critical determinant than absolute molecular weight for mechanical properties (Table 6) [20].

Table 6. Mechanical properties of Copolyesters **V – VII**

Copolyester	Tensile Strength (MPa)	Remarks
V	75	Optimal lamellar packing
VI	71	Heterogeneous crystals
VII	72.5	Balanced properties

3.10 X-Ray Diffraction (XRD) of Copolyesters V – VII

X-ray diffraction (XRD) analysis provided detailed insight into the crystalline structure of the three random copolyesters **V – VII**, complementing the surface morphology and thermal analyses. The XRD patterns revealed a series of characteristic diffraction peaks at 2θ ≈ 15.2°, 30.4°, 38.6°, 45.8°, 55.2°, 65.4°, and 75.8°, corresponding to the (010), (020), (011), (021), (030), (031), and (040) crystal planes, respectively. These reflections confirm that all copolyesters retain the characteristic crystalline structure of polyester-based materials.

A systematic variation in peak sharpness and intensity was observed among the copolyeaters, reflecting differences in crystallite size, lattice regularity, and molecular weight distribution. Copolyester **V** exhibited sharp and well-defined diffraction peaks, indicating the presence of small, highly ordered crystallites.

This behavior is consistent with SEM and AFM observations showing uniform platelet-like lamellae and supports the relatively high degree of crystallinity inferred from DSC measurements. The sharp diffraction features suggest efficient chain packing enabled by a moderate polydispersity index (PDI), leading to regular crystal lattice formation and contributing to the superior tensile strength of copolyester **V**. In contrast, copolyester **VI** displayed broader and less intense diffraction peaks, particularly at the major reflections around 2θ ≈ 30.4° and 45.8°, indicating the formation of larger but more imperfect crystalline domains. This behavior can be attributed to its broad molecular weight distribution, where longer polymer chains tend to form larger crystallites while shorter chains occupy interstitial regions in a less uniform manner. Such structural heterogeneity correlates well with the spherulitic growth patterns observed in SEM and AFM images and explains the slightly reduced thermal stability and mechanical performance compared to copolyester **V**. Copolyester **VII** exhibited intermediate peak sharpness but significantly enhanced peak intensities, consistent with its combination of high molecular weight and narrow PDI. The narrow molecular weight distribution promotes uniform chain packing and ordered crystallization, while the high molecular weight partially restricts chain mobility, limiting the growth of perfectly ordered crystallites. As a result, copolyester **VII** demonstrates a balanced crystalline structure characterized by small, uniform crystallites and higher overall crystallinity. This structural balance is in good agreement with the higher melting temperature observed in DSC analysis and the moderate surface roughness measured by AFM.

Overall, the XRD results demonstrate that molecular weight distribution plays a more dominant role than absolute molecular weight in controlling crystalline order and lattice regularity in random copolyesters, directly influencing their thermal and mechanical properties. (Figure 16) [21, 22].

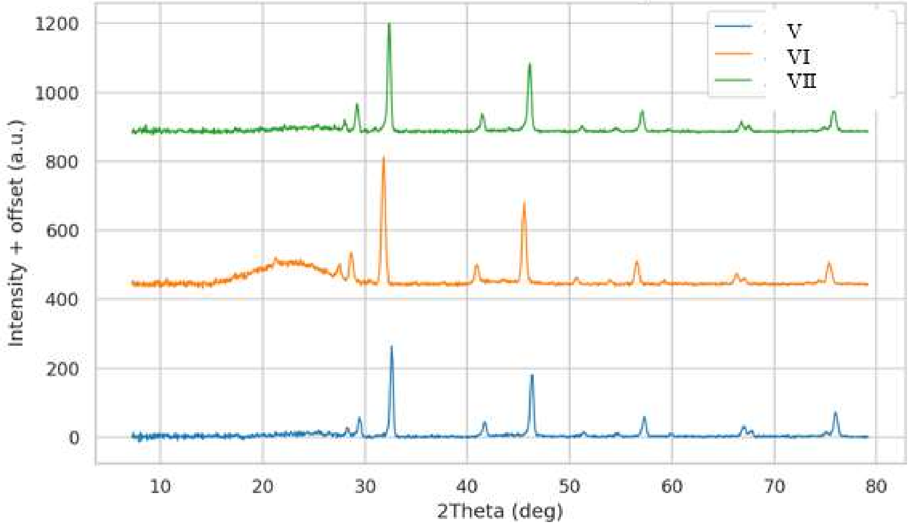


Figure 16. X-ray Diffraction Patterns of Copolyesters **V – VII**

IV. Conclusions

Novel random copolyesters **V–VII** were successfully synthesized via interfacial polycondensation and structurally confirmed by FTIR and elemental analysis. The results demonstrate that molecular weight distribution plays a decisive role in controlling the crystallization behavior, surface morphology, thermal stability, mechanical properties, and wettability of the prepared copolyesters. Electrical measurements revealed semiconducting behavior at room temperature, while XRD analysis confirmed the presence of crystalline polyester structures with varying degrees of crystallinity. Overall, the combination of tunable structural properties, thermal robustness, and semiconducting characteristics highlights the potential of these copolyesters for applications in functional coatings and advanced polymer materials.

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Influence of Molecular Weight Distribution on the Crystallization, Thermal, Surface, and Mechanical Properties of Novel Random Copolyesters

تأثير توزيع الوزن الجزيئي على خصائص التبلور، الحرارية، السطحية والميكانيكية لكوبولي إسترات أروماتية عشوائية معتمدة على ثنائي بنزيليدين الأسيتون

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الملخص

تكشف دراسة متعددة التقنيات للكوبولي إسترات **V–VII** أن توزيع الوزن الجزيئي (مؤشر التعددية، PDI) يتحكم في خصائص البوليمر بدرجة أقوى من الوزن الجزيئي المطلق. إذ تعزز التوزيعات الضيقة تبلورًا متجانسًا، مما يؤدي إلى تحسين الاستقرار الحراري، والمتانة الميكانيكية، والتنظيم السطحي، وخصائص الواجهات البينية، في حين تؤدي التوزيعات الواسعة إلى بنى غير متجانسة وانخفاض في الاتساق. وقد حقق الكوبولي إستر**VII** ، ذو الوزن الجزيئي المتوسط (30,000 جم·مول$^{-1}$) ومؤشر تعددية ضيق (1.20)، أفضل استقرار حراري (T_m = 582°م) ، ودرجة تبلور مرتفعة (65% مع حجم بلوري قدره 45.2 نانومتر)، وخواص كارهة للماء (زاوية تلامس 93.76°)، وقوة شد عالية (72.5 ميغاباسكال)، مما يبرز ميزة التحكم في توزيع الوزن الجزيئي مقارنة بمجرد تكبير الوزن الجزيئي. توضح الكوبولي إسترات **V** و **VI** كيف يمكن للوزن الجزيئي المتوسط أو التوزيعات الواسعة أن تُستخدم، على التوالي، لتفصيل الخصائص السطحية أو خصائص المعالجة. ويبيّن التحليل الآلي أن تجانس التوزيع هو العامل الحاكم لحركية التبلور والنظام البنيوي، مما يوفر علاقات تنبؤية بين البنية والخاصية. وتتيح هذه الرؤى اختيارًا رشيدًا للمواد للتطبيقات عالية الأداء، أو الحساسة للسطح، أو كثيفة المعالجة، مع تقليل تعقيد التخليق واستهلاك الموارد والأثر البيئي. وتؤسس هذه الدراسة توزيع الوزن الجزيئي بوصفه معاملًا رئيسيًا في تصميم مواد بوليمرية مستدامة من الجيل القادم.