



Tailoring the Electrical and Thermal Response of PVA Nanofibers Through Metal Oxide Incorporation via Electrospinning

Maryam A. Abood^{1*} and Isam M. Ibrahim²

^{1,2}Department of Physics, College of Sciences, University of Baghdad, Baghdad, Iraq

*Corresponding Author

Received:28/January/2026

Accepted:14/June/2026

Published:20 /October/2026

<https://doi.org/10.30526/39.4.4444>



© 2026. The Author(s). Published by College of Education for Pure Science (Ibn Al-Haitham), University of Baghdad. This is an open-access article distributed under the terms of the [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/)

Abstract

This study investigates the structural, thermal, and electrical properties of polyvinyl alcohol (PVA) nanofibers doped with a ZnO–CoO binary oxide, synthesized via a controlled electrospinning process at an applied voltage of 16 kV and a flow rate of 0.8 mL/h. FESEM analysis revealed a systematic morphological transition from smooth, uniform fibers to a bead-on-string structure as the dopant concentration increased from 1 wt% to 5 wt%. Moreover, quantitative analysis revealed fine fiber morphologies, with the minimum diameters reaching 17 nm, 23 nm, and 26 nm of different concentration ratios, respectively. X-ray diffraction (XRD) analysis confirmed the amorphous nature of both the pristine and doped nanofibers. The absence of metallic crystalline peaks suggests that the dopants were uniformly distributed throughout the polymer matrix, which is consistent with established literature. Fourier Transform Infrared (FTIR) spectra demonstrated an increasing shift in the vibrations of the hydroxyl (–OH) functional groups, signifying strengthened intermolecular interactions. Thermal analysis via TGA/DSC indicated that while low-level doping (1 wt%) enhances thermal stability, higher dopant concentrations result in a reduction of the characteristic degradation temperatures. Electrical characterization revealed that the conductivity follows an Arrhenius-type behavior, in which the activation energy (E_a) was significantly reduced with increasing dopant concentration. The lowest E_a value of 0.031 eV was attained for the composite containing 4 wt% of the ZnO–CoO hybrid. These results suggest that the charge transport mechanism is thermally activated and that the incorporation of metal oxide dopants effectively lowers the energy barrier for carrier hopping. Consequently, the synthesized hybrid nanofibers demonstrate a high degree of tailoring capability for tunable electronic applications.

Keywords: Electrospinning, Poly (vinyl alcohol), Hybrid nanofibers.

1. Introduction

The synthesis of one-dimensional (1D) nanostructures has gained significant interest in recent years, finding applications in manufacturing flexible electronics and novel optoelectronic devices¹. Materials with particular electrical and optical responses can be produced by combining a flexible organic matrix with semiconducting inorganic fillers, according to recent research on metal-oxide-decorated polymers². Among the various synthesis routes, electrospinning is widely regarded as the most versatile and efficient method for producing ultrafine fibers with a remarkably high surface-area-to-volume ratio, a parameter critical for maximizing active sites in sensing and light-matter interactions^{3,4}.

Poly (vinyl alcohol) (PVA) is often used as a structural support for these hybrid systems because it possesses superior mechanical properties, can make films better, and is chemically stable^{5,6}. Nonetheless, PVA exhibits intrinsic insulating properties, requiring the addition of functional inorganic dopants to facilitate semiconductive behavior and photosensitivity⁷. Zinc oxide (ZnO) and cobalt oxide (CoO) are especially excellent choices for this kind of integration. ZnO is a

well-known wide-bandgap semiconductor with a high exciton binding energy, which makes it great for absorbing photons. CoO, on the other hand, has unique magnetic and catalytic properties that can change how carriers move through the polymer matrix^{8,9}.

Numerous studies have examined single-oxide polymer composites; however, the synergistic effect of a binary ZnO-CoO system within a PVA matrix necessitates thorough investigation, especially concerning morphological stability and thermal degradation kinetics at elevated weight percentages⁹. In the present study, the impact of binary metal oxide loading, ranging from 1% to 5% wt.%, on the morphological, structural, and thermal properties of electrospun PVA nanofibers is systematically investigated. The interfacial interactions and the change from smooth to bead-on-string morphology were described using Field Emission Scanning Electron Microscopy (FESEM), (FTIR) spectroscopy, and TGA/DSC analysis^{10,11}. This thorough profiling provides a crucial benchmark for the optimization of polymer-inorganic interfaces and validates the potential of these hybrid mats as active layers for upcoming flexible, low-cost conductometric applications^{12,13}.

The current investigation addresses existing gaps in the field of binary metal oxide nanofibers through the accomplishment of three key objectives. The study shows that it is possible to create ultrafine ZnO-CoO/PVA hybrids with a specific size of 17 nm. Furthermore, it illustrates the critical role that p-n heterojunctions play in tuning the electrical and optical behavior of the polymer matrix.

2. Materials and Methods

2.1. Materials

High molecular weight poly (vinyl alcohol) (PVA) was used to create the polymeric matrix. The binary metal oxide dopants were made up of Zinc Acetate Dihydrate: $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ and Cobalt (II) Chloride Hexahydrate: $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ powder. Distilled water and 70% ethanol were employed as primary solvents. All chemicals were used as received from commercial sources without further purification, following standard protocols for nanocomposite preparation¹³.

2.1.1. Preparation of the Blend Solution

The first step in making the product was to make a 6% (w/v) poly (vinyl alcohol) (PVA) solution. In this case, 10 mL of distilled water was used to dissolve 0.6 g of PVA powder. For 6 hours, the mixture was stirred with a magnet at a temperature between 50 and 60 °C until it became a clear, even precursor. Once the solution was homogeneous, a certain amount of 70% ethanol was added to it to make the surface tension and viscosity just right for the electrospinning process¹⁴. The binary metal oxide dopants were prepared as two separate suspensions. 0.1 g of Zinc Acetate Dihydrate: $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ and 0.1 g of Cobalt (II) Chloride Hexahydrate: $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, were each placed into 20 mL of 70% ethanol. Both suspensions were stirred for 30 minutes which allowed for even distribution of metal particulates throughout the alcohol.

Finally, the metal oxide suspensions were combined with the PVA precursor at specific volumetric ratios to formulate samples B2- B6 at 1 wt% to 5 wt% loadings¹⁵.

2.1.2. Electrospinning Procedure

A 50 mL plastic syringe with a 30-gauge stainless steel needle was filled with the prepared solutions. The electrospinning apparatus, depicted in **Figure 1**, was optimized in accordance with existing literature on PVA-based systems^{16,17}.

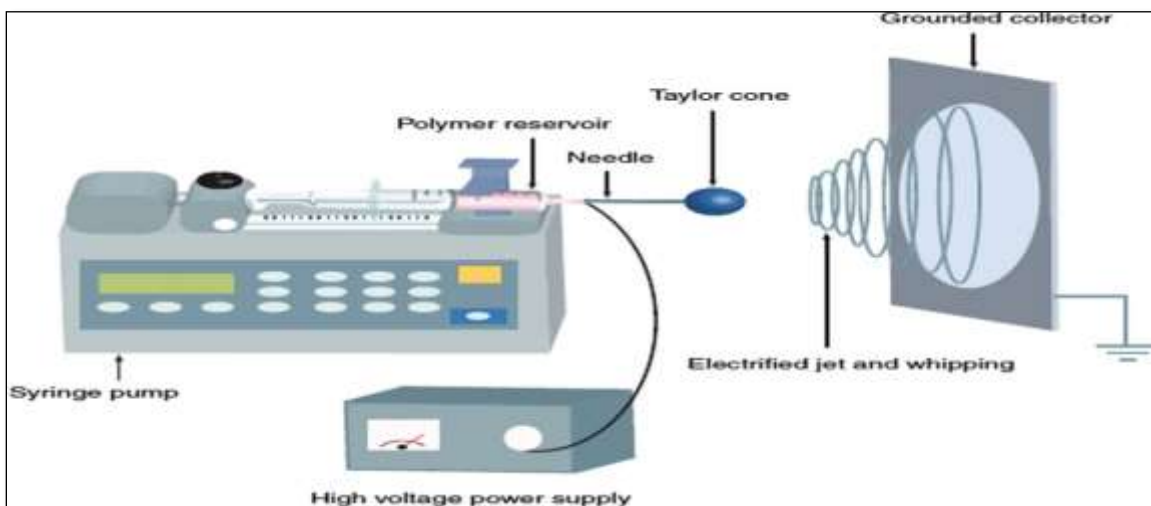


Figure 1. Schematic representation of the electrospinning setup¹⁸.

The following process parameters were upheld:

Applied Voltage: 16 kV

Flow Rate: 0.8 mL/h

Tip-to-Collector Distance: 13 cm

Collector: Rotating drum covered with aluminum foil.

These parameters were fixed based on preliminary optimization to ensure a stable Taylor cone and consistent fiber morphology for a controlled comparative study. The nanofiber mats that were made were collected at room temperature and put in a cell-culture dish to keep them clean and dry before they were tested¹⁹.

3.Results

In order to emphasize the importance of the technique utilized for this purpose, the morphological and structural aspects of the fabricated ZnO-CoO/PVA nanofibers have been compared to different PVA-based nanocomposites obtained using alternative techniques. The comparison between the electrospinning method used in the present investigation and the other methods reported in recent literature, such as solution casting, spin coating, and chemical spray pyrolysis, is presented in **Table 1**. It is evident from **Table 1** that the electrospinning method offers distinct advantages over other conventional techniques due to its ability to fabricate 1D nanostructures with ultra-thin diameters and high surface-to-volume ratios.

Table 1. Comparative study of different synthesis techniques and their effects on the morphological characteristics of PVA-based nanocomposites.

Morphology	Preparation Method	Material System	Reference
1D Nanofibers	Electrospinning	PVA/ZnO-CoO	Present Study
2D Thin Film	Solution Casting	PVA/ZnO-Au	Abdel-Fattah (2026) ²⁰
Micro-thick Film	Spin Coating	PVA/Au-NRs	Tarpataki (2025) ²¹
2D Smooth Film	Chemical Spray	ZnO films	Al-Dahash (2024) ²²

3.1.Morphological Characterization (FESEM)

Field Emission Scanning Electron Microscopy (FESEM) was used to look at the surface morphology and structural evolution of the electrospun nanofibers, as shown in **Figure 2**. Sample B1, composed of unadulterated PVA nanofibers, demonstrated a remarkably uniform, smooth, and bead-free cylindrical morphology with a random orientation in **Figure 2a**. The creation of this stable porous network shows that the electrospinning settings, like the 16 kV applied potential and 0.8 mL/h flow rate, were set up in the best way to break the surface tension of the pure polymer solution. Adding the binary salt system, which is made up of zinc acetate

and cobalt chloride, caused significant changes in the fiber's diameter and surface. The fibres kept their linear continuity at a 1 wt% loading concentration (Sample B2), the fibers maintained their linear continuity, yet a discernible reduction in average diameter was observed compared to the undoped PVA in **Figure 2b**. This reduction in diameter is attributed to the increased net charge density of the precursor solution. Upon increasing the dopant concentration to 3 wt% (Sample B4) and 5 wt% (Sample B6), the morphology transitioned to a "bead-on-string" structure in **Figure 2c-d**. The interaction of the solution's surface tension and electrostatic repulsion forces largely drives this structural change. The high ion concentration at these high loadings drastically changes the rheological characteristics of the solution.

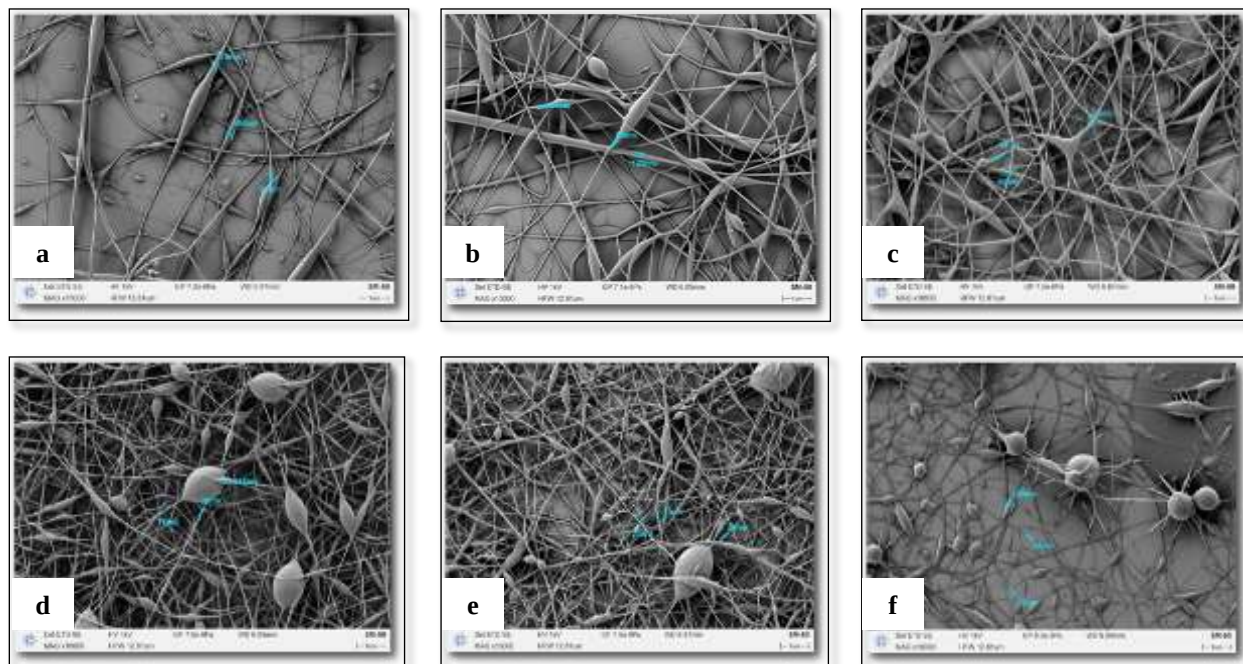


Figure 2. FESEM micrographs illustrating the morphological evolution of PVA/zinc acetate/cobalt chloride hybrid nanofibers: a. pure PVA (B1), b. 1 wt% (B2), c. 2 wt% (B3), d. 3 wt% (B4), e. 4 wt% (B5), and f. 5 wt% (B6).

3.2. Structural Analysis (XRD)

The crystalline structure of the pure PVA and ZnO-CoO/PVA hybrid nanofibers was investigated using XRD analysis, as shown in Figure 3. It is evident from the plots that there is a single broad peak around $2\theta = 19.6^\circ$, indicative of the (101) semi-crystalline plane of the PVA matrix (**Figure 3**).

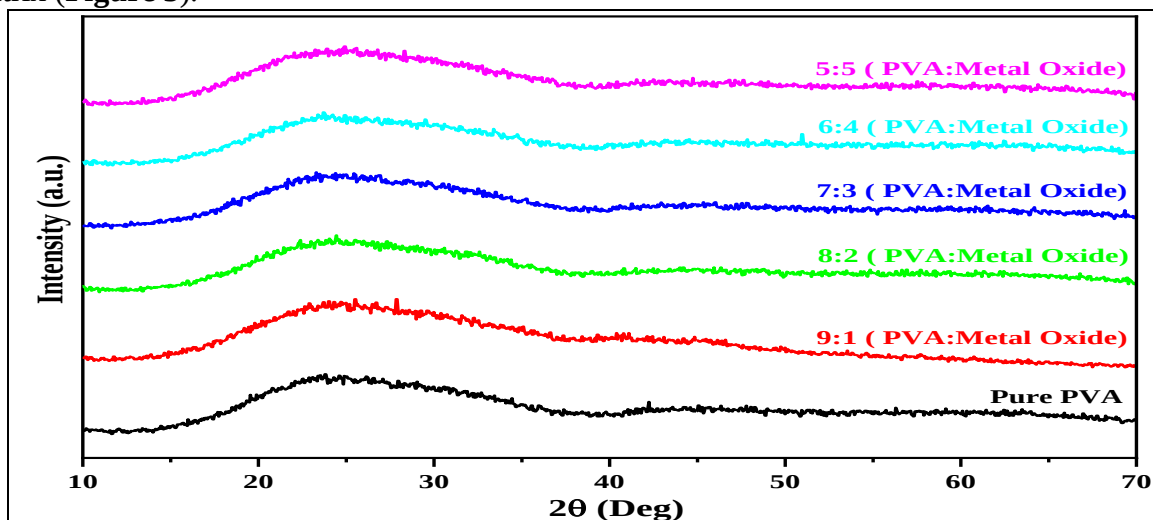


Figure 3. X-ray Diffraction Analysis of Pure and Hybrid ZnO-CoO/PVA Electrospun Nanofibers.

Interestingly, there were no sharp peaks corresponding to the hexagonal structure of ZnO and the cubic structure of CoO observed for the doped samples. The lack of such metallic characteristic peaks indicates that the metal oxides are present in an amorphous form or as ultrafine clusters, which is below the coherence length necessary for X-ray diffraction. This phenomenon is attributed to the "quenching" effect associated with the electrospinning technique, where the solvent evaporates rapidly and the jets elongate at very high speeds, thereby immobilizing the precursor components within the PVA molecular chains.

3.3.FTIR Analysis and Chemical Interaction

The chemical interactions and interfacial dynamics between the zinc acetate/cobalt chloride binary dopant system and the polyvinyl alcohol (PVA) polymeric matrix were clarified using FTIR spectroscopy. **Figure 4** displays the spectra of the pristine and hybrid nanofibers side by side. The spectrum of pure PVA (Fig. 4a) shows peaks at 3320 cm^{-1} (O-H stretching), 2924 cm^{-1} (C-H asymmetric stretching), 1732 cm^{-1} (C=O stretching), and 1088 cm^{-1} (C-O stretching). When the binary salts are added (Fig. 4b–f), the O-H band gets a lot wider and shifts to the red. Furthermore, the higher peak intensities in the $1560\text{--}1410\text{ cm}^{-1}$ range are linked to the vibrations of the carboxylate (COO^-) group in Zinc acetate. These changes, along with those at 1088 cm^{-1} , show that the metallic ions work as cross-linking nodes in the polymer matrix. This molecular integration stabilizes the hybrid structure and matches the changes in shape seen in FESEM. Table 2 displays the peak assignments and the observed shifts.

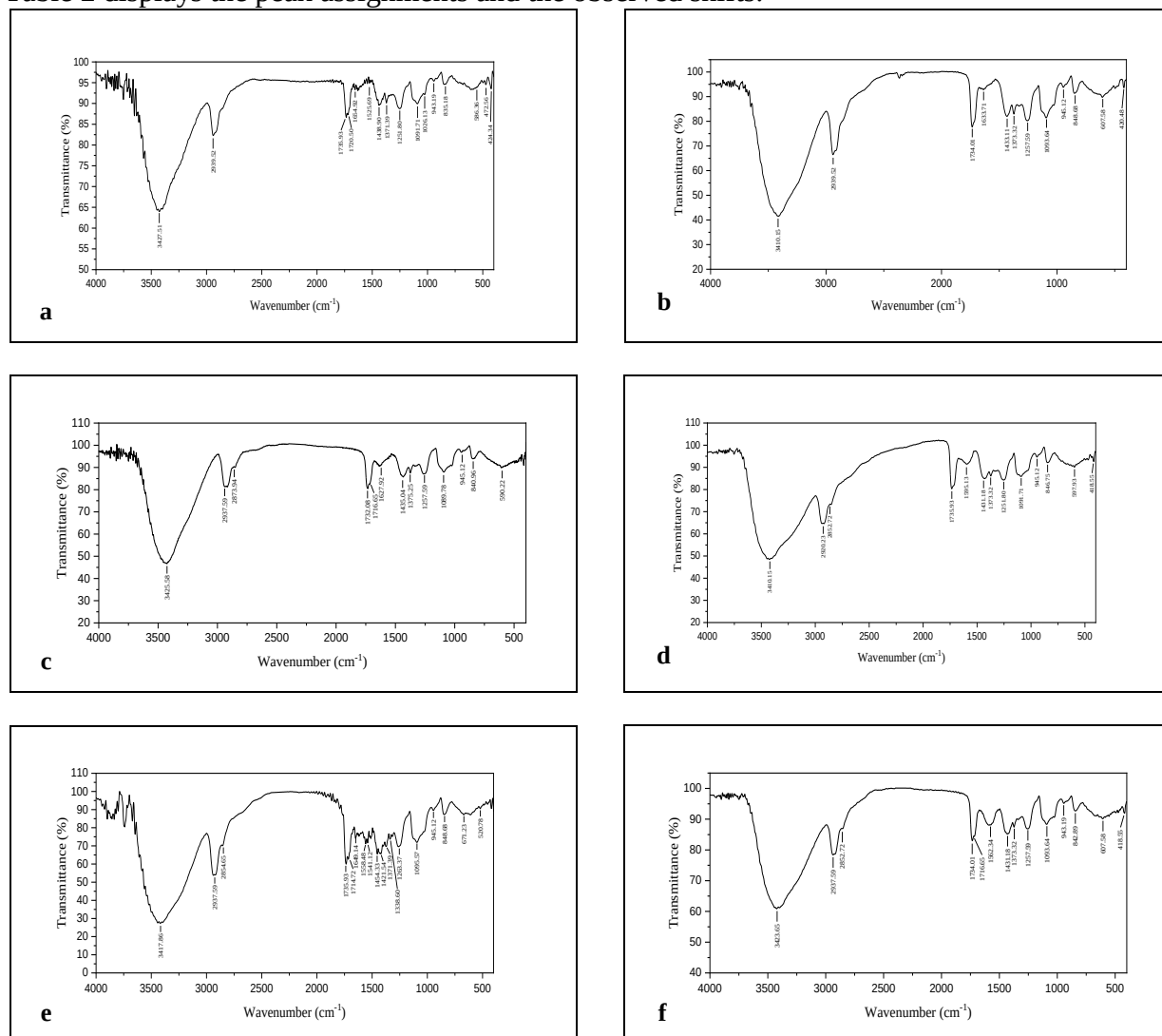


Figure 4. FTIR spectra of the hybrid nanofibers illustrating the chemical functional group distributions for: a. pure PVA (B1), b. 1 wt% (B2), c. 2 wt% (B3), d. 3 wt% (B4), e. 4 wt% (B5), and f. 5 wt% (B6).

Table 2. Vibrational Band Assignments and Peak Positions (cm⁻¹).

Functional Group / Assignment	B1 (Pure)	B2: 1 wt%	B3: 2 wt%	B4: 3 wt%	B5: 4 wt%	B6: 5 wt%
O-H Stretching (Hydrogen Bonding)	3427.51	3410.15	3425.58	3410.15	3417.86	3423.65
C-H Stretching (Aliphatic)	2939.52	2939.52	2937.59	2920.23	2937.59	2937.59
C=O Stretching (Residual Acetate)	1735.93	1734.01	1732.08	1735.93	1735.93	1734.01
C-H Bending (CH ₂ groups)	1438.90	1433.11	1435.04	1431.18	1421.54	1431.18
C-O Stretching (Crystalline phase)	1091.71	1093.64	1089.78	1091.71	1095.57	1093.64
M-O Stretching (Zn-O / Co-O)	--	420.48	590.22	418.55	520.78	418.55

3.4. Thermal Analysis (TGA/DSC)

Figure 5 illustrates how TGA and DSC were used to examine the heat stability and state changes of the hybrid nanofibers. This analysis shows how the polymer breaks down and how the two-salt system affects the polymer's structure and ability to resist heat.

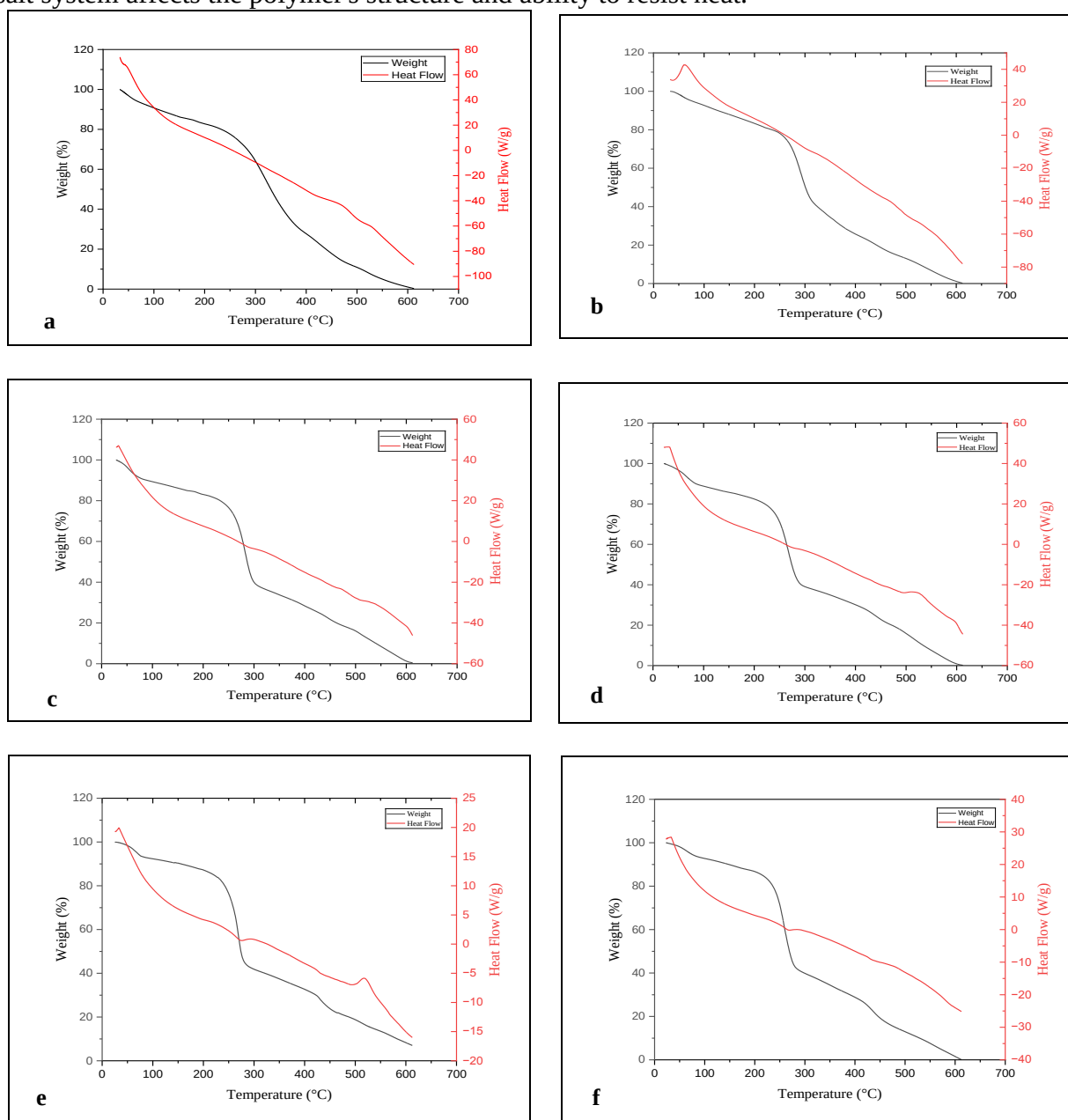


Figure 5. Thermal analysis of the hybrid nanofibers: a. pure PVA (B1), b. 1 wt% (B2), c. 2 wt% (B3), d. 3 wt% (B4), e. 4 wt% (B5), and f. 5 wt% (B6).

There are three different stages of weight loss during thermal degradation. The first stage (50–150 °C) is caused by the evaporation of water and leftover solvents that are physically adsorbed. The main degradation stage (250–450 °C) is when the PVA side chains lose water and the acetate groups break down. The hybrid samples (B2–B6) show a slight shift in the onset temperature of degradation and an increase in the final char yield.

The DSC thermograms reveal both melting behavior and the glass transition temperature (T_g). The incorporation of binary salts results in a gradual increase in T_g , corroborating that the metallic ions restrict the segmental motion of the PVA chains through the cross-linking effect observed in the FTIR analysis. Additionally, the melting temperature (T_m) slightly decreases, and the melting enthalpy (H_m) diminishes for samples with higher loadings (B4–B6). This suggests a reduction in the degree of crystallinity, as the elevated concentration of ions disrupts the orderly packing of the polymer chains, which aligns with the transition to the beaded morphology observed in FESEM.

3.5. D.C. Electrical Conductivity and Activation Energy Analysis

The temperature-dependent DC electrical conductivity (σ_{dc}) and corresponding activation energies (E_a) for the hybrid nanofibers (B2–B6) were investigated to determine the charge transport mechanisms. Pristine PVA (B1) was excluded from electrical characterization as it acts as a typical insulator with a high bandgap; its insulating behavior is well-documented in existing literature. **Figure 6** presents the Arrhenius plots ($\ln \sigma$ vs. $1000/T$) for the doped samples.

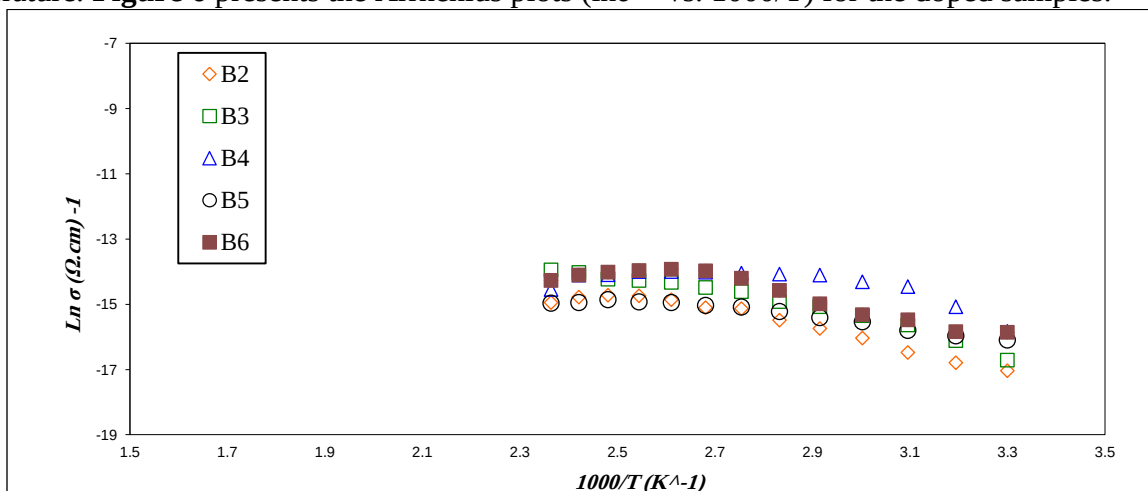


Figure 6. Arrhenius plots of $\ln \sigma_{dc}$ vs. $1000/T$ for hybrid samples B2–B6.

The hybrid nanofibers act like semiconductors, meaning that their conductivity goes up as the temperature rises. The plots show that all of the samples have a dual-stage conduction mechanism. Conduction is controlled by the hopping of charge carriers between localized states at lower temperatures (303–383 K), where the activation energy (E_{a1}) varies from 0.153 eV for B5 to 0.382 eV for B4. As seen in the above figure, there is a phase change that occurs as the temperature increases (432 K). This increase in temperature allows for the energy barrier (E_{a2}) to drastically reduce. Sample B5 plateaus at a lowest energy of 0.031 eV while sample B4 decreases steeply to 0.055 eV past 343 K. Charge migration can occur with greater ease as Zn^{+2} and Co^{+2} ions have greater freedom of movement within the polymer matrix as it thermally expands. Hence, we see an increase in conductivity at elevated temperatures. While the binary salt system still requires less energy to transport ions when compared to the pure polymer, we can see this relationship in the decrease in E_a throughout the hybrid series. Ionic mobility increases in the thermally expanded matrix, causing a decrease in energy barrier (E_{a2}) as temperature increases (up to 432 K). The precise figures derived from these plots are displayed in **Table 3**.

Table 3. Pre-exponential factors (σ_0) and activation energies for hybrid samples B2–B6.

Sample name	E_{a1} (eV)	E_{a2} (eV)	$\sigma_{01} (\Omega \cdot \text{cm})^{-1}$	$\sigma_{02} (\Omega \cdot \text{cm})^{-1}$
B2	0.305 (303–363 K)	0.105 (373–423 K)	0.004 (303–363 K)	8.113E-06 (373–423 K)
B3	0.330 (303–373 K)	0.141 (383–432 K)	0.019 (303–373 K)	4.220E-05 (383–432 K)
B4	0.382 (303–343 K)	0.055 (353–423 K)	0.367 (303–343 K)	1.410E-07 (353–423 K)
B5	0.153 (303–383 K)	0.031 (393–432 K)	3.596E-05 (303–383 K)	1.354E-07 (393–432 K)
B6	0.280 (303–373 K)	0.115 (383–432 K)	0.004 (303–373 K)	2.839E-08 (383–432 K)

4. Discussion

A notable change in the electrohydrodynamic characteristics of the solution is responsible for the transition from smooth, homogeneous nanofibers at low salt concentrations (1-2 wt%) to a beaded-string structure at higher concentrations (3-5 wt%). Increasing the binary salt concentration first improves the polymer jet's charge density, allowing for more stretching and producing finer fibre diameters. In comparison to recently established parameters for binary oxide/PVA-based composites, the resulting fiber diameter (17 nm) is remarkably lower, as average values typically range between 50 and 120 nm⁹. Such an improvement in diameter is attributed to the enhanced charge density within the precursor solution. The presence of metallic ions enhances electrical conductivity, thereby increasing the whipping instability and the longitudinal stretching forces acting on the jet, which culminates in the production of finer fibers²³. However, a Taylor cone instability could be caused by an excessive ion loading of more than 3 wt%. When the repulsive electrostatic forces outweigh the surface tension of the solution, beads form as a structural adaptation to accommodate the excess charge¹⁶. While the strong electrical forces continue to lengthen the fibre segments between them, the surface tension attempts to reduce surface energy by pulling the jet into spindle-shaped beads²⁴. The resulting morphological changes can be correlated to the matrix's chemical landscape; FTIR results verify that Zn^{+2} and Co^{+2} cations serve as centers of coordination. This change to lower wavenumbers shows that strong intermolecular hydrogen bonds have formed between the PVA hydroxyl groups and the metallic cations (Zn^{+2} , Co^{+2}) or acetate anions²⁵. The metal cations are bonding directly with the lone pair of electrons on the oxygen in PVA's hydroxyl groups. This is evidenced by the concerted shift of the O-H stretch bands, as well as the emergence of M-O vibration bands located at 450-600 cm^{-1} ²⁶. Such observation suggests that the dopants are chemically bonded into the network as cross-linking nodes along the polymer chain². Electrical measurements on the hybrid nanofibers also support this interpretation, as they exhibit a transition from insulating to semiconductor-like behavior. Activation energies determined from Arrhenius plots indicate a two-step thermally activated conduction process dominated by hopping of carriers between localized metallic states²⁷. The lower temperature limitation is probably due to lower segmental mobility of the PVA chains, thus requiring higher E_a . Increasing the temperature allows the matrix to expand, increasing the efficiency of hopping. The decrease in activation energy with loading is lowest (0.031 eV) for the 4 wt% sample. This suggests the establishment of a continuous percolation network. At this critical concentration, the coordination sites are densely packed, facilitating rapid charge movement and significantly reducing the energy barrier for conduction. The enhanced DC conductivity of this binary system represents a significant advancement over previously investigated single-doped PVA/ZnO fibers²³. This property is advantageous for application in photodetection systems due to the increased density of defect centers²⁴. This elevated conductivity of the current composite material can be explained by the formation of heterojunctions at the interface of n-type zinc oxide and p-type cobalt oxide. These junctions serve to minimize the charge transfer barrier within the polymer matrix, a finding that is consistent with recent investigations on 1D hybrid systems^{2,28}. Regarding thermal behavior, the coordination between the metallic cations (Zn^{+2} , Co^{+2}) and the PVA hydroxyl groups enhances the thermal stability of the composite and

promotes the formation of a stable carbonaceous residue²⁸. The interaction of morphological evolution, chemical coordination, and enhanced charge transport renders these hybrid nanofibers as exceptional materials for advanced flexible electronics and sensing applications.

5. Conclusion

The current research clearly showed how to make PVA/zinc acetate/cobalt chloride hybrid nanofibers using the electrospinning method. Morphological examination using FESEM showed that when the concentration of the binary salt reached 3 wt% or higher, the fibers changed from a smooth and uniform appearance to a beaded-string formation. This transformation is attributed to the interaction between the surface tension and electrical conductivity of the spinning solution. FTIR structural analysis verified the molecular incorporation of metallic dopants, as indicated by the appearance of M–O stretching bands and notable changes in the vibrational regions of hydroxyl and acetate groups. Thermal analysis demonstrated that the interaction between metallic cations and the polymer backbone improved the composite's thermal stability. Compared to pure PVA samples, the hybrids resulted in greater char formation. Electrical characterization showed that the material exhibited a dual-stage conduction mechanism and semiconducting properties. Activation energy significantly decreased at elevated temperatures, reaching as low as 0.031 eV and 0.055 eV for samples B5 and B4, respectively. This suggests charge migration and ionic hopping facilitated by the binary salt system, aligning with our understanding of hopping conduction in polymer electrolytes. Overall, these findings indicate that these hybrid nanofibers have the potential for use in advanced technologies such as ion-conductive membranes and flexible electronics. To extend these findings, future research should focus on varying the Zn:Co molar ratios to precisely tune the optical energy gap and charge carrier density required for advanced flexible optoelectronic devices. Furthermore, evaluating long-term stability, specifically regarding mechanical integrity and photo-sensitivity, is essential for the practical implementation of such ultrafine fibers. The gas-sensing potential of these nanofibers, leveraged by the formed p-n heterojunctions and high surface area, represents a promising avenue for further investigation.

Acknowledgment

We express our gratitude to the University of Baghdad and the College of Science for their invaluable support. We extend special thanks to the staff of the Physics Department for granting access to the necessary facilities and laboratories essential for the execution of this research.

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethical Clearance

This study did not involve human participants or animal experiments; therefore, ethical approval was not required.

Funding

None.

References

1. Rasheed MH, Mousa MH, Kadhim QS, Abdelmoula N, Khalfallah A, Benzarti Z. Novel Electrospun PVA-PVP-PAAm/TiO₂ Nanofibers with Enhanced Optoelectrical, Antioxidant and Antibacterial Performances. *Polymers*. 2025;17(18):2487. <https://doi.org/10.3390/polym17182487>
2. Ambrosio R, Carrillo A, Mota ML, de la Torre K, Torrealba R, Moreno M, Vazquez H, Flores J, Vivaldo I. Polymeric Nanocomposites Membranes with High Permittivity Based on PVA-ZnO

- Nanoparticles for Potential Applications in Flexible Electronics. *Polymers*. 2018;10(12):1370. <https://doi.org/10.3390/polym10121370>
3. Oncheurn K, Infahsaeng Y. Electric field effect on electrospun fiber alignment using a parallel electrode plate. *J Phys Conf Ser*. 2021;1719(1):012064. <https://doi.org/10.1088/1742-6596/1719/1/012064>
 4. Moin TS, Sarkar MR, Chowdhury MFM, Rahman MM, Khan MN. Electrospun Poly(vinyl alcohol)/Chitosan Nanofibers Embedded with a CuO-GO Nanocomposite for pH-Sensitive Adsorption. *ACS Omega*. 2025;10(19):19294–19313. <https://doi.org/10.1021/acsomega.4c08836>
 5. Iskalieva A, Yesmurat M, Al Azzam KM, Ainakulova D, Yerbolat Y, Negim ES, Ibrahim MNM, Gulzhakhan Y. Effect of Polyethylene Glycol Methyl Ether Methacrylate on the Biodegradability of Polyvinyl Alcohol/Starch Blend Films. *Polymers*. 2023;15(15):3165. <https://doi.org/10.3390/polym15153165>
 6. Abd AL-Aziz DS, Hamdan SA. Enhancement of Optoelectronic Properties of Electrospun PVA Fibers by Adding Zinc and Cobalt Ions for Photodetection Applications. *Iraqi J Appl Phys*. 2026;22(1):137–144. <https://doi.org/10.2025/5xza8056>
 7. Flores-García E, González-Hernández J, Ramírez-Bon R, Castillo-Pérez R, Espinosa-Magdaleno MA. Simple fabrication of a UV photodetector based on electrospun ZnO crystalline nanofibers. *Nano Express*. 2025;6(4):045003. <https://doi.org/10.1088/2632-959X/ae104a>
 8. Noori AJ, Ali IM. An Investigation on the Rectifying Characteristics of PVA/Y2O3 Nanofibers. *Iraqi J Phys*. 2025;23(1):103–113. <https://doi.org/10.30723/ijp.v23i1.1359>
 9. Kailasa S, Reddy MSB, Maurya MR, Rani MS, Rao KV, Sreedhar B. Electrospun Nanofibers: Materials, Synthesis Parameters, and Their Role in Sensing Applications. *Macromol Mater Eng*. 2021;306(10):2100310. <https://doi.org/10.1002/mame.202100310>
 10. Liu Z, Ju K, Wang Z, Li J, Zhao H, Liu Y. Electrospun Jets Number and Nanofiber Morphology Effected by Voltage Value: Numerical Simulation and Experimental Verification. *Polymer*. 2020;210:123019. <https://doi.org/10.1016/j.polymer.2020.123019>
 11. Duygulu NE, Altınbay A, Çiftçi F. Antibacterial, Mechanical, and Thermal Properties of Ag, ZnO, TiO2 Reinforced PVA Nanocomposite Fibers. *ChemistrySelect*. 2024;9(30):e202402311. <https://doi.org/10.1002/slct.202402311>
 12. Tsiopstias C, Fardis D, Ntampou X, Kehagias N, Tsivintzelis I. Thermal Behavior of Poly(vinyl alcohol) in the Form of Physically Crosslinked Film. *Polymers*. 2021;13(18):3012. <https://doi.org/10.3390/polym13183012>
 13. Tebyetekerwa M, Ramakrishna S. What Is Next for Electrospinning? *Matter*. 2020;2(2):279–283. <https://doi.org/10.1016/j.matt.2020.01.004>
 14. Virginia C, Khasanah A, Munir MM, Khairurrijal K. Electrospinning and characterization nanofibers and nanoparticle of Polyvinylpyrrolidone. *IOP Conf Ser Mater Sci Eng*. 2020;902:012053. <https://doi.org/10.1088/1757-899X/902/1/012053>
 15. Farahani AH, Moghadam RZ, Marandi M. Electrospinning of nanofibers and the functional potential of starch: a comprehensive review. *Discover Nano*. 2026;21(1):24. <https://doi.org/10.1186/s11671-026-04434-8>
 16. Ciarleglio G, Capuccilli N, Toto E, Santonicola MG. Poly(Vinyl Alcohol)/Hyaluronic Acid Nanofibers for Biomedical Use Under Physiological Conditions: Electrospinning Fabrication and Stabilization via Solvent-Free Citric Acid Crosslinking. *Polymers*. 2020;12(10):2289. <https://doi.org/10.3390/polym12102289>
 17. Borowczak M, Sobczyk K, Leluk K. The influence of multi-solvent systems on the electrospinning process. *Sci Rep*. 2026;16(1):8666. <https://doi.org/10.1038/s41598-026-42574-0>
 18. Eatemadi A, Daraee H, Zarghami N, Melikov R, Adibzadeh M, Hasanzadeh M. Nanofiber: Synthesis and biomedical applications. *Artif Cells Nanomed Biotechnol*. 2016;44(1):111-121. <https://doi.org/10.3109/21691401.2014.922538>
 19. Korotcenkov G. Current trends in nanomaterials for metal oxide-based conductometric gas sensors: Advantages and limitations. Part 1: 1D and 2D nanostructures. *Nanomaterials*. 2020;10(7):1392. <https://doi.org/10.3390/nano10071392>
 20. Abdel-Fattah EM, Elnemr AM, Elsharkawy WB, Fahmy T. Multifunctional PVA-CMC/ZnO-Au Nanocomposite Films with Enhanced UV Shielding, Thermal Stability, and Antibacterial Performance. *Polymers*. 2026;18(6):718. <https://doi.org/10.3390/polym18060718>

21. Tarpataki N, Keczánné-Üveges A, Szalóki M, Bonyár A. Preparation of Few-Micron-Thick Free-Standing Au-Nanorod/UDMA-TEGDMA Nanocomposite Films by Using PVA Sacrificial Layers. *Polymers*. 2025;17(10):1391. <https://doi.org/10.3390/polym17101391>
22. Al-Dahash G, Salman QM, Haddawi SF. Investigation of Structural, Optical and Electrical Properties of MnO Doped with Cu Thin Films Prepared by PLD Technique for Solar Cell Applications. *J Mater Sci Mater Electron*. 2024;35(2):142. <https://doi.org/10.1007/s10854-023-11854-w>
23. Prabhu NN, Rajendra BV, Anandhan S, Murthy K, Jagadeesh Chandra RBJ, George G, Kumar BS, Shivamurthy B. Understanding the interplay of solution and process parameters on the physico-chemical properties of ZnO nanofibers synthesized by sol-gel electrospinning. *Mater Res Express*. 2023;10(8):085001. <https://doi.org/10.1088/2053-1591/acead4>
24. Nguyen AD, Lim ST, Kim JH, Kim Y, Yoon G, Mirzaei A, Kim HW, Kim SS. Electrospun Amorphous Indium Gallium Zinc Oxide (IGZO) Nanofibers for Highly Selective H₂S Gas Sensing. *Sensors*. 2026;26(6):1936. <https://doi.org/10.3390/s26061936>
25. Shah SA, Ali H, Inayat MI, Mahmoud EE, Garalleh HA, Ahmad B. Effect of carbon nanotubes and zinc oxide on electrical and mechanical properties of polyvinyl alcohol matrix composite by electrospinning method. *Sci Rep*. 2024;14(1):28107. <https://doi.org/10.1038/s41598-024-79477-x>
26. Jiang J, Sun Z, Chen J, Chen H, Zheng G, Wang X, Ye R, Li W. Real-time monitoring and closed-loop control system for multi-jet electrospinning with coaxial laser. *Sci Rep*. 2026;16(1):8225. <https://doi.org/10.1038/s41598-026-39655-5>
27. Xiao Y, Luo H, Tang R, Hou J. Preparation and applications of electrospun optically transparent fibrous membrane. *Polymers*. 2021;13(4):506. <https://doi.org/10.3390/polym13040506>
28. Macartney RA, Fricker ATR, Tajalla GUN, Smith AM, Kishida S, Fedele S, Roy I, Knowles JC. Optimisation of electrospinning parameters to successfully obtain high ratios of medium chain length polyhydroxyalkanoate in electrospun fibres with drug loading for wound healing applications. *J Mater Sci Mater Med*. 2026;37(1):56. <https://doi.org/10.1007/s10856-026-07030-5>