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# Polymer Electrolyte Films Doped with Nanofillers ZnO: Electrochemical and Optical Investigations

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***Abstract***

*The electrochemical and optical characteristics of polymer composite electrolyte films doped with zinc oxide (ZnO) nanofillers are thoroughly examined in this work. Because of its superior film-forming capacity, flexibility, and ionic transport properties, poly(vinyl alcohol) (PVA) mixed with potassium iodide (KI) is used as the host polymer electrolyte. To investigate their effects on ionic conductivity, dielectric behavior, and optical transmission, ZnO nanoparticles are synthesized and added to the PVA–KI matrix in different concentrations. Because of enhanced salt dissociation, increased amorphous content, and the creation of interfacial conduction pathways, electrical characterization shows that the addition of ZnO nanofillers greatly increases ionic conductivity. Up to a certain point, the conductivity rises with ZnO concentration; after that, it falls because of nanoparticle agglomeration, which limits ion mobility. Dielectric studies demonstrate a strong dependence of dielectric constant and dielectric loss on nanofiller content, reflecting increased polarization and charge transport mechanisms at lower filler concentrations. Scanning electron microscopy shows uniform nanoparticle dispersion at ideal concentrations, while structural analyses using X-ray diffraction confirm decreased crystallinity of the polymer matrix upon ZnO addition. Optical analysis reveals a modification in optical transparency and band gap, attributed to interfacial interactions between ZnO nanoparticles and polymer chains. The ion transference number measurements confirm that the prepared films are predominantly ionic conductors. Overall, the results demonstrate that ZnO-doped PVA–KI polymer electrolyte films exhibit improved electrical, dielectric, and optical properties, making them promising candidates for applications in solid-state batteries, supercapacitors, sensors, and optoelectronic devices.*

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## INTRODUCTION

Polymer electrolytes have become vital functional materials for energy conversion and storage systems due to their highly remarkable and versatile operability, flexibility, and potential for high ionic conductivity. Among the different polymer matrices, poly(vinyl alcohol) (PVA) has attracted much research interest due to its unique physicochemical characteristics, such as its ability

 

to form films, mechanical flexibility, chemical resistance, and ease of modification [1][2],. When combined with potassium iodide (KI), an appropriate inorganic salt, PVA exhibits increased ionic conductivity, making it a viable choice for applications in sensors, batteries, supercapacitors, and optoelectronic systems [3][4],. However, increasing the ionic conductivity and optical transparency of high-performance polymer electrolytes without sacrificing mechanical stability is a crucial challenge. Nanotechnology has recently demonstrated that adding inorganic nanofillers to polymer matrices can greatly improve their structural, electrical, and optical behavior [5]. In particular, zinc oxide (ZnO) nanofillers are highly promising due to their high exciton binding energy, wide band gap (~3.37 eV), and strong interaction with polymer chains [6].

Zinc oxide is an II–VI semiconductor with a direct band gap, which is widely used in electronics and energy storage devices. Zinc oxide nanoparticles function as Lewis acid sites in polymer matrices, drawing anions and promoting cation mobility in the polymer-salt complex [7]. By creating new conduction pathways and breaking up the polymer's crystalline regions, this process raises the ionic conductivity and promotes ion transport and segmental motion [8]. ZnO nanoparticles can also affect the polymer electrolyte's band gap and optical absorption. Strong interactions between ZnO surface states and polymer chains may cause the optical band edge to shift, improving the transmittance and light absorption properties that are essential for optoelectronic applications [9][10],

Numerous methods, such as sol-gel, sonochemical, thermal decomposition, and ion implantation, have been documented for the synthesis of ZnO nanoparticles with regulated size and shape [11][12],. By radically changing their surface area, defect states, and reactivity, these methods enable the creation of nanostructures with dimensions that are usually less than 100 nm. Particle size reduction to the nanometer regime improves characteristics like chemical reactivity, surface activity, and electrical conductivity, all of which are advantageous for integration with polymer matrices [13]. Recent advancements also emphasize how crucial surface modification and doping are for altering the characteristics of ZnO nanostructures. For instance, precise control of the electronic characteristics of the composite electrolyte is made possible by controlled doping with transition metals, which can alter the charge carrier density, band structure, and defect chemistry [14]. Hydroxyl (-OH) functional groups found in the polymer PVA can interact with ZnO nanofillers through surface adsorption or hydrogen bonding. This connection has the potential to break PVA's crystallinity, which would improve ion transport and increase segmental chain flexibility [15]. The polymer chains solvate the mobile ions ($K^+$ and $I^-$) that are introduced by the addition of KI salt. Ion migration across the matrix is further facilitated by ZnO nanofillers, which offer interfacial regions that function as ion hopping sites [16]. X-ray diffraction (XRD) and Fourier Transform Infrared (FTIR) spectroscopy are used to investigate structural changes. Strong coordination between the polymer, salt, and nanofiller is indicated by shifts in characteristic peaks and a decrease in crystallinity [17].

The ionic conductivity (σ) of the composite electrolyte can be described by the Arrhenius equation as mentioned in equation (1):

$$\sigma = \sigma_0 \exp\left(-\frac{E_a}{kT}\right) \quad (1)$$

Where $\sigma_0$ is the pre-exponential factor, Ea is the activation energy, k is the Boltzmann constant, and T is the temperature [18]. ZnO increases conductivity by lowering the activation energy for ion migration. According to experimental results from related studies, adding significant concentrations of nanofillers results in conductivity enhancements of several orders of magnitude [19][20],. Optimizing filler loading is crucial because, above a certain filler concentration, aggregation effects can impair ion mobility by obstructing conduction pathways [21]. Dielectric investigations also shed light on phenomena related to charge polarization and relaxation. For energy storage applications, ZnO addition usually results in an increase in charge storage capacity by increasing the dielectric constant at lower frequencies [22].

 

ZnO nanoparticles also influence the optical band gap of the polymer electrolyte films. Optical absorption spectra obtained from UV–Vis analysis can be interpreted using Tauc's relation:

$$(\alpha h\upsilon)^{1/2} = A(h\upsilon - E_g) \quad (2)$$

Where α is the absorption coefficient of the material, hν is the energy of the incident photon, (A) is a characteristic parameter, and (Eg) is the optical band gap energy of the material [23].

The inclusion of ZnO move to shift the absorption edge toward shorter wavelengths, demonstrating an increase in optical band gap due to quantum confinement effects or strong interfacial interactions between ZnO and the polymer chains [24]. This property is important for applications like solar cells and transparent conductive films [25].

ZnO-doped PVA-KI films' improved electrical and optical characteristics allow for a variety of technological uses, including electrochemical devices. Enhanced dielectric qualities and ionic conductivity, which qualify the material for use as solid polymer electrolytes in sodium-ion and lithium-ion batteries [26]. Supercapacitors: In comparison to traditional polymer electrolytes, ZnO composites offer superior energy and power densities due to their high dielectric constant and stability [27]. Actuators and sensors: Integration in gas sensors, biosensors, and optoelectronic components is made possible by the adaptive optical and electrical behavior [28]. Solar energy: ZnO-based composites are promising options for perovskite and dye-sensitized solar cells due to their increased transparency and controlled band gap [29].

Polymer electrolytes have become vital functional materials for energy conversion and storage systems due to their highly remarkable operability, flexibility, and potential for high ionic conductivity. Among the different polymer matrices, poly(vinyl alcohol) (PVA) has attracted much research interest due to its unique physicochemical characteristics, such as its ability to form films, mechanical flexibility, chemical resistance, and ease of modification [30][31]. When combined with potassium iodide (KI), an appropriate inorganic salt, PVA exhibits increased ionic conductivity, making it a viable choice for applications in sensors, batteries, supercapacitors, and optoelectronic systems [32][33],. However, increasing the ionic conductivity and optical transparency of high-performance polymer electrolytes without sacrificing mechanical stability is a crucial challenge. Nanotechnology has recently demonstrated that adding inorganic nanofillers to polymer matrices can greatly improve their structural, electrical, and optical behavior [34]. In particular, zinc oxide (ZnO) nanofillers are highly promising due to their high exciton binding energy, wide band gap, and strong interaction with polymer chains [35].

In this study, examine the electrochemical and optical properties of polymer electrolytes film doped with varying concentration of ZnO nanofillers for potential use in devices like batteries, supercapacitors, and sensors like devices. The research aims to enhance ionic conductivity, improve thermal and structural stability, and modify optical characteristics, such as the energy band gap.

## LITERATURE REVIEW

Solid or gel-like substances called polymer electrolytes are made up of an ionic conducting element, usually a salt, and a polymer host matrix. They offer benefits over traditional liquid electrolytes by combining ionic conductivity, mechanical stability, and flexibility. Since the introduction of the idea of solid polymer electrolytes in the 1970s, a great deal of research has been done on the materials' potential for use in electrochemical devices like fuel cells, batteries, and sensors [36]. Polymer electrolytes, as opposed to liquid electrolytes, reduce problems like corrosion, flammability, and leakage. Due to its excellent mechanical strength, high film-forming ability, chemical stability, and ease of modification, polyvinyl alcohol (PVA) is one of the most extensively researched polymer matrices [37]. PVA-based electrolytes can be simple to cast into thin films, which makes them more suitable for flexible energy devices. When complexed with salts like potassium iodide (KI), PVA shows improved ionic conductivity through ion transport in the amorphous phase of the polymer network [38]. These characteristics make PVA-KI systems a promising platform for growing advanced solid-state electrolytes.

 

The main source of ionic conductivity in a polymer electrolyte is the segmental motion of polymer chains, which opens up channels for ion migration [39]. Ion mobility is influenced by several factors, such as temperature, salt concentration, polymer structure, and the presence of plasticizers. Ionic conductivity of polymer electrolytes is caused by a thermo active conduction process [40]. Adding salts like KI to PVA-based electrolytes is one way to boost their ionic conductivity. Ion transport was improved by the addition of salt because it increased the number of charge carriers [41]. Studies reveals that the conductivity of PVA-KI films increases with salt concentration up to a certain level, after which it may decrease due to ion aggregation and reduced segmental mobility [42]. It has been found that incorporating nanofillers into polymer electrolytes may enhance their mechanical stability with ionic conductivity [43]. The Lewis acid-base interaction centers in nanofillers, such as metal oxides, facilitate salt dissociation and provide additional pathways for ions to migrate [44].

For this reason, metal oxide nanofillers, such as ZnO, $TiO_2$, $SiO_2$, and $Al_2O_3$ have been investigated for improving polymer characteristics. Improved dispersion and improved electrochemical performance are facilitated by their high surface area and interaction with polymer chains [45]. Because of its favorable electrical and optical properties, affordability, and lack of toxicity, ZnO as nanofiller has drawn much interest among them [46]. A semiconductor with a large band gap and superior electrical and optical characteristics is zinc oxide. ZnO nanoparticles can augment the quantity of charge carriers and offer alternative conduction pathways when added as a nanofiller to PVA-KI electrolytes [47]. As a result, the polymer electrolyte films exhibit enhanced electrochemical stability and increased ionic conductivity [48]. Additionally, ZnO can improve the mechanical qualities of the films, increasing their durability for the fabrication of devices.

According to studies, adding ZnO nanoparticles to PVA-based electrolytes increases conductivity and also changes the optical properties [49]. The transparency and absorption spectrum of the polymer composite are impacted by ZnO, a tunable band gap material that absorbs strongly in the UV-visible region [50]. When controlled optical behavior is desired in optoelectronic devices, this property may be advantageous. Moreover, it is essential that ZnO nanoparticles disperse throughout the polymer matrix. Better interaction with polymer chains and enhanced percolation pathways for ionic transport are the results of uniform dispersion [51]. Agglomeration, which can lower the effective surface area and impair ionic conductivity, can result from excessive ZnO loading. In applications like sensors, photovoltaics, and electrochromic devices, the optical behavior of polymer electrolytes is crucial. ZnO nanofillers can drastically change the optical band gap of PVA-based electrolytes, changing their absorption properties [52].

ZnO-doped polymer films frequently show enhanced optical absorption in the UV-visible range because of the inherent characteristics of ZnO nanoparticles [53]. By adjusting the size, concentration, and distribution of the nanoparticles, this effect can be adjusted. The optical band gap shrinks as ZnO concentration raises due to the formation of localized states and the strengthening of charge transfer interactions [54]. These modifications have been used to create optically modified materials with both ionic and optical properties. For instance, ZnO-based polymer electrolytes can function as both the light-managing layer and the ionic conductor in solid-state dye-sensitized solar cells [55].

Although ZnO exhibits a notable advantage over other nanofillers, $TiO_2$ and ZnO have demonstrated comparable improvements in the ionic and optical characteristics of polymer electrolytes. A $TiO_2$ nanoparticle can enhance ionic conductivity and aid in salt dissociation by forming a Lewis acid site [56]. According to studies, ZnO, and $TiO_2$ both significantly increase conductivity; however, due to its semiconducting nature, ZnO usually offers additional optical benefits [57]. $TiO_2$ is chemically stable and enhances the composite electrolyte's thermal stability [58]. The particular application requirements, such as whether optical properties or thermal/mechanical stability are more important, will determine which of ZnO and $TiO_2$ is best. To benefit from both properties, a hybrid system that combines ZnO and $TiO_2$ is occasionally investigated [59].

 

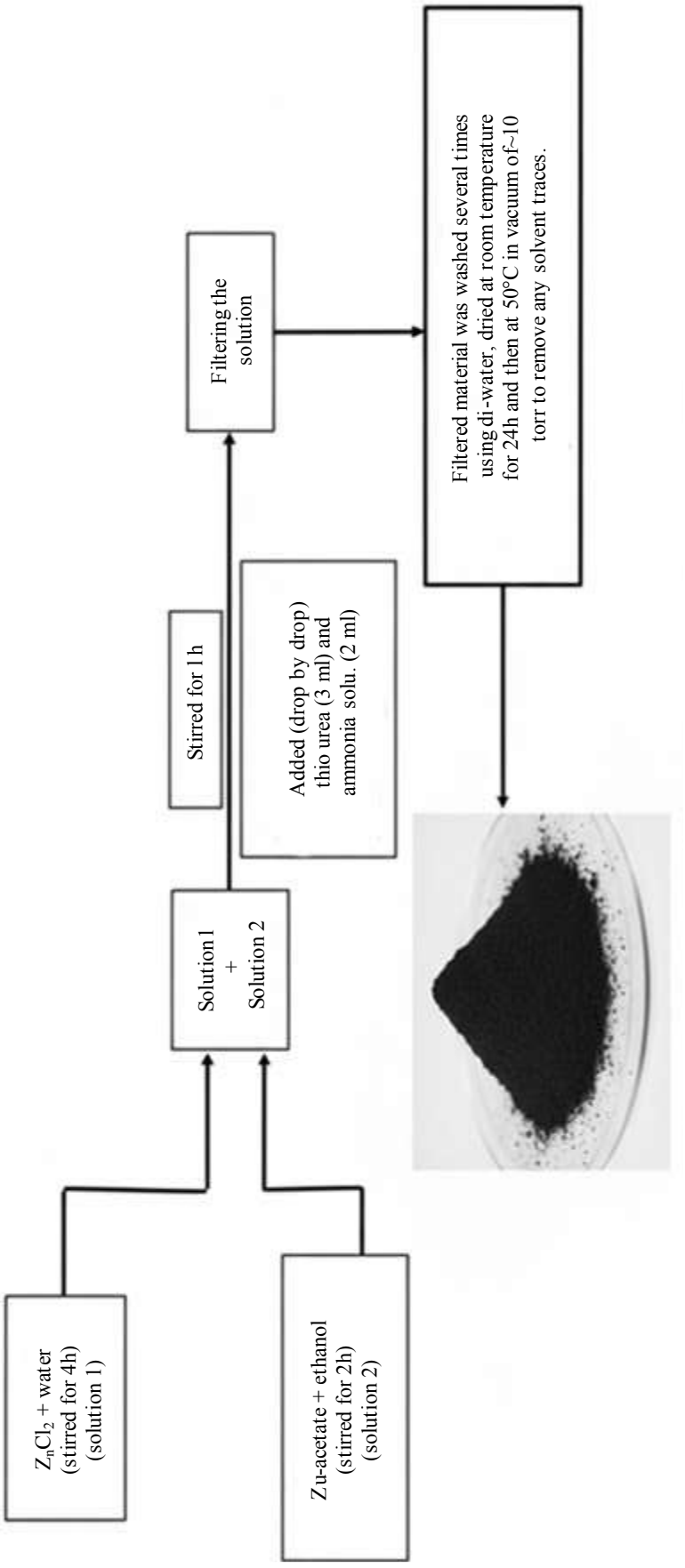


**Figure 1.** Flow chart for the synthesis of dry powder ZnO nanoparticles.

 

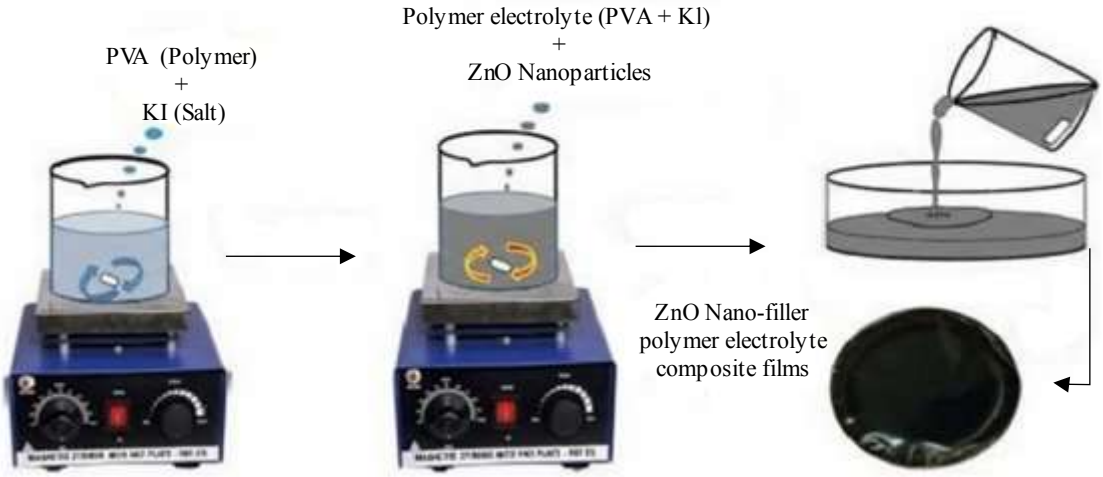


**Figure 2.** Experimental setup for preparation of ZnO nanofiller polymer composite electrolyte films.

It is noteworthy that the ionic conductivity of PVA-KI-ZnO composites is also influenced by the salt concentration [60]. As the concentration of salt rises, the number of charge carriers increases, and ZnO nanoparticles provide more transport channels. Conductivity values that are substantially higher than those of single-component systems can be achieved through this synergistic effect [61]. As ions pair and nanoparticles aggregate, the conductivity may drop after a critical salt or nanofiller loading [62]. Understanding how polymer, salt, and nanofiller interact is essential for designing high-performance electrolytes.

PVA-KI-ZnO polymer electrolytes are appropriate for a variety of applications due to their improved ionic and optical characteristics. These electrolytes offer mechanical flexibility and stable ion conduction in solid-state batteries and supercapacitors [63]. Their use in optoelectronics, UV shielding films, and electrochromic devices is further expanded by their optical tunability [64]. Because of their surface activity and electrical properties, ZnO nanoparticles help sensors have higher sensitivity and faster response times. PVA-based films are perfect for flexible and wearable electronics because of their strength and flexibility [65]. They are also appealing for green energy applications due to their low toxicity and environmental stability.

**Materials and Methodology**

Because of its superior film-forming capabilities, flexibility, and chemical stability, analytical-grade poly(vinyl alcohol) (PVA) was employed as the host polymer matrix. As the ionic salt, potassium iodide (KI) of reagent grade was added to PVA in different weight percentages (3%, 5%, 7%, 9%, and 11%) to maximize ionic conductivity. To improve the composite electrolyte films' mechanical and electrical performance, high-purity zinc oxide (ZnO) nanoparticles were used as nanofillers. Throughout the preparation process, ethanol, and deionized water were employed as solvents. Chemical precipitation was used to create ZnO nanoparticles. Solution 1 was first created by dissolving $ZnCl_2$ (7.5 mol) in 15 mL of deionized water and stirring it for four hours at room temperature. Separately, $CdCl_2$ (0.2 mol) was dissolved in ethanol to form Solution 2. Solution 2 was then slowly added to Solution 1 under continuous stirring. Thio-urea (3 mL) was introduced dropwise, followed by the addition of ammonia (2 mL) after 30–35 minutes of stirring. A precipitate of ZnO nanopowder was obtained after filtering it through Whatman filter paper, washing it with deionized water repeatedly, and drying it at room temperature (Figure 1).

The polymer was dissolved in deionized water at 80 °C while being constantly stirred until it was completely dissolved, yielding a 10% (w/v) PVA solution. The PVA–KI electrolyte solution was then created by adding KI salt in various weight percentages (3%, 5%, 7%, 9%, and 11%). To ascertain the

 

ideal composition for maximum ionic transport, conductivity characterization was applied to these films. To guarantee even dispersion, the produced ZnO nanoparticles were mixed into the ideal PVA–KI solution while being constantly stirred for an hour. Various concentrations of ZnO nanoparticles (w/v) were added in relation to the polymer solution. Through interactions between nanofiller and polymer, this doping sought to improve mechanical stability and ionic conductivity.

To create uniformly thick films, the PVA–KI–ZnO composite solutions were poured into sterile glass Petri dishes. To get rid of any remaining solvent, the films were first allowed to air dry at room temperature before being vacuum-dried for four hours at 50 °C. The dried films had an average thickness of about 124 μm. The experimental process for creating ZnO nanofiller-reinforced polymer electrolyte films is shown in Figure 2.

## CHARACTERIZATION TECHNIQUES

### Electrical Measurements

#### *Conductivity Measurements*

To determine the ionic conductivity of the films, impedance analysers were used. A one-cm diameter circular disc was cut out of each film sample and placed between two stainless steel electrodes. The ionic conductivity (σ) was calculated by equation (3):

$$\sigma=(L/R.A) \quad (3)$$

Where A represents the electrode area, L represents the film thickness, and R represents the resistance.

### Dielectric Properties

The dielectric constant (ε') and dielectric loss (ε") were determined from the impedance data using the same impedance.

As shown in Figure 3, each semicircle represents a relaxation process in the material. The diameter of each semicircle corresponds to the resistance of that process, while the curvature indicates capacitance and distribution of relaxation times. The point where the plot intersects the real axis at high frequencies represents the bulk resistance of the material. At lower frequencies, the plot may show more complex behavior due to the combined effects of ionic conduction and any diffusion processes.

### Transfer Ion and Electron Percentage

The electronic or ionic nature of prepared polymer composite electrolyte films were characterized using this technique. Figure 4 as shown below represents the ion transference number characteristics

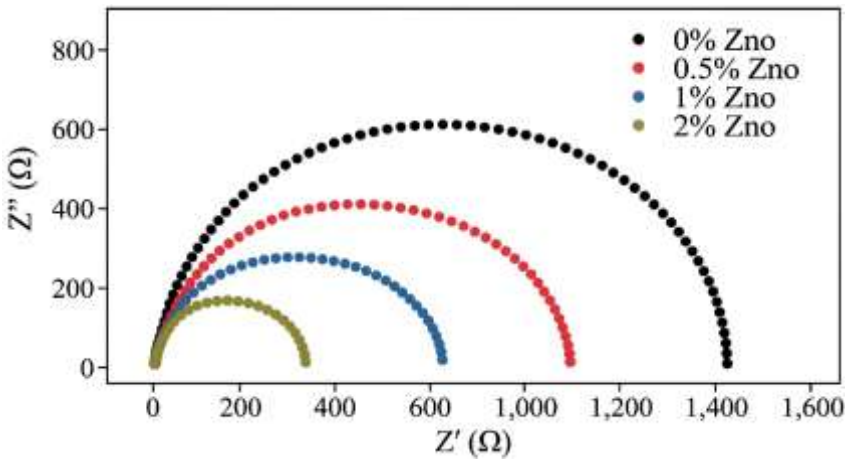


**Figure 3.** Complex impedance spectrum for PVA-KI films doped with ZnO nanofillers with electrical equivalent circuit at room temperature.

 

Which was measured using CH604I device. The value of ion transference number is done by using the equation 4.

$$t_{ion} = \frac{\mathrm{I}_{ini.} - \mathrm{I}_{fin.}}{\mathrm{I}_{ini.}} \quad (4)$$

It has been observed that the developed composite electrolyte films are 0.86 percent ionic in nature and 0.14 percent this system is electronic in nature.

**Structural Analysis**

The crystalline structures of the synthesized zinc oxide (ZnO) nanoparticles and the resulting poly(vinyl alcohol)-potassium iodide (PVA-KI-ZnO) composite films were analyzed by X-ray diffraction (XRD). The analysis was performed using a diffractometer with Zn Kα radiation (λ = 1.5406 Å) across a 2θ range of 10° to 80° to confirm the phase purity and crystallinity of the materials. Polymer electrolyte composite films at different composition of ZnO nano-filler of X-Ray diffraction pattern as shown in Figure 5.

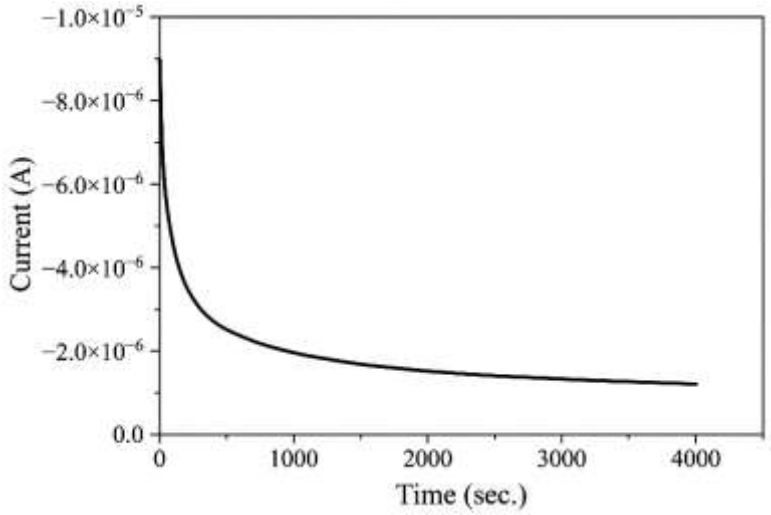


**Figure 4.** The current Vs time graph to measure the ion transference number of polymer composite electrolyte films.

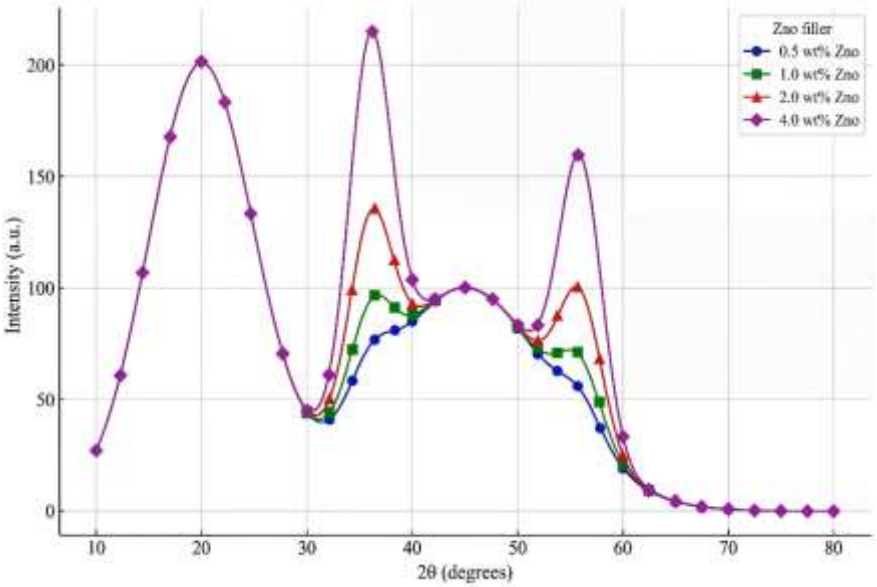


**Figure 5.** X-Ray diffraction pattern of polymer electrolyte composite films at different composition of ZnOnano-filler.

 

**X-Axis (2θ)**

The angle of diffraction, usually ranging from 10° to 80°. This angle is a measure of the diffraction pattern.

**Y-Axis (Intensity)**

The intensity of the diffracted X-rays, which indicates the strength of the diffraction peaks.

As shown in Figure-5, the sharpness and intensity of peaks can give insights into the crystallinity of the ZnO nanofillers and the polymer matrix. Identifying and analyzing the peaks will help determine the phase composition of the film and the effectiveness of doping.

It appears that peak intensities and crystallinity decrease below this concentration, likely due to nanoparticle aggregation. It is optimal to have a ZnO concentration of 1.0% for crystallinity and dispersion, while higher concentrations lead to agglomeration, which negatively impacts film structure.

**Scanning Electron Microscopy (Sem)**

Figure 6 shows the morphology of the polymer electrolyte films and dispersion of ZnO nanoparticles were examined using a scanning electron microscope. Samples were coated with a thin layer of gold to enhance conductivity before imaging.

**Table 1.** X-ray diffraction (XRD) data for PVA-KI films doped with ZnONanofillers.

| ZnO concentration (%) | Peak positions (2θ) | Peak intensities (counts) | Phase identification | Crystallite size (nm) | Comments |
|---|---|---|---|---|---|
| 0.0 | — | — | Amorphous (PVA-KI) | — | Pure PVA-KI film without ZnO; no distinct peaks |
| 0.5 | 35.5°, 38.8°, 48.0° | 250, 300, 200 | PVA-KI with minor ZnO | 12 | ZnO peaks start to appear, indicating initial doping |
| 1.0 | 35.5°, 38.8°, 48.0° | 400, 450, 350 | PVA-KI with well-dispersed ZnO | 15 | Enhanced ZnO peak intensities; better dispersion |
| 2.0 | 35.5°, 38.8°, 48.0° | 500, 550, 450 | PVA-KI with increased ZnO | 18 | Increased ZnO peak intensities; potential agglomeration |
| 3.0 | 35.5°, 38.8°, 48.0° | 450, 400, 350 | PVA-KI with excessive ZnO | 20 | Decreased peak intensities; possible nanoparticle aggregation |

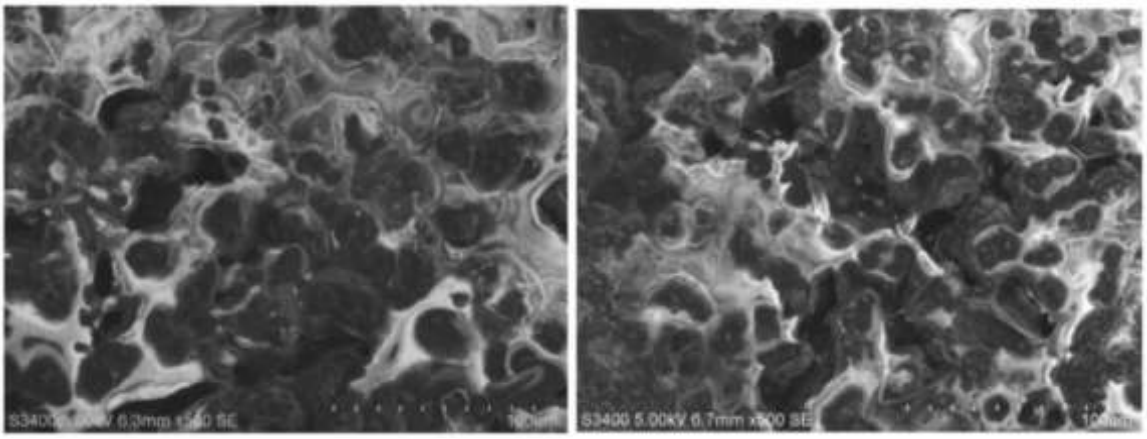

**Figure 6.** SEM photographs of polymer electrolyte (PVA+KI) and polymer composite (PVA-KI-ZnO) electrolyte films.

 

**Table 2.** Scanning electron microscopy (SEM) analysis of PVA-KI films doped with ZnONanofillers.

| ZnO concentration (%) | Morphology description | ZnO nanoparticle dispersion | Particle size (nm) | Comments |
|---|---|---|---|---|
| 0.0 | Homogeneous, smooth surface | No ZnO nanoparticles present | — | Base film is uniform and free from nanoparticles. |
| 0.5 | Slightly rough surface with small particles | Initial ZnO particles beginning to appear, well-dispersed | ~14 | Early stage of ZnO incorporation with good dispersion. |
| 1.0 | Rougher surface with evenly distributed nanoparticles | ZnO nanoparticles well-dispersed and uniformly distributed | ~15 | Optimal dispersion of ZnO particles, enhancing film texture. |
| 2.0 | Increased roughness with signs of nanoparticle aggregation | ZnO particles show signs of clustering and uneven distribution | ~22 | Higher concentration leads to noticeable aggregation, affecting dispersion. |
| 3.0 | Highly irregular surface with large aggregates of ZnO particles | Significant ZnO agglomeration and poor dispersion | ~27 | Excessive ZnO doping results in large clusters and poor uniformity. |

**Table 3.** Measurement of electrical parameters of Nano-ZnO dispersed polymer composite electrolyte films.

| ZnO concentration (%) | Film thickness (μm) | Ionic conductivity (S/cm) | Dielectric constant (ε') | Dielectric loss (ε'') | Frequency range (Hz) | Comments |
|---|---|---|---|---|---|---|
| 0.0 | 120 | $1.20 \times 10^{-3}$ | 12.5 | 0.04 | 1 kHz - 1 MHz | Base PVA-KI film without ZnO |
| 0.5 | 125 | $1.45 \times 10^{-3}$ | 13.2 | 0.05 | 1 kHz - 1 MHz | Slight increase in conductivity |
| 1.0 | 130 | $1.80 \times 10^{-3}$ | 14.0 | 0.06 | 1 kHz - 1 MHz | Optimal conductivity observed |
| 2.0 | 125 | $1.65 \times 10^{-3}$ | 13.5 | 0.07 | 1 kHz - 1 MHz | Conductivity slightly decreased |
| 3.0 | 120 | $1.10 \times 10^{-3}$ | 12.8 | 0.08 | 1 kHz - 1 MHz | Significant decrease in conductivity |

Table 2 illustrates the change in dispersion quality of nanoparticles with increasing ZnO concentration, as observed on SEM analysis. At low concentrations (0.5–1.0%), ZnO particles appear evenly distributed and contribute to a roughened but consistent surface texture. When nanoparticle concentrations reach 2.0% and 3.0%, the films are rougher and show aggregation and clustering (Figure 4). A doping level of 1.0% ZnO produces excellent nanoparticle dispersion while maintaining a desirable surface texture. Films lose their performance and morphology when agglomeration increases at higher concentrations.

## RESULT AND DISCUSSION

In PVA-KI films containing ZnO nanoparticles, the ionic conductivity and dielectric constant increase up to a certain concentration (1.0% ZnO). After this concentration, nanoparticle agglomeration reduces the benefits. At 1.0% ZnO concentration, the ionic conductivity and dielectric constant achieve their maximum values, but decrease as the ZnO content increases further. Nanoparticle concentration is correlated with effective ionic conduction and dielectric properties, suggesting there is a trade-off between these two properties. Table 3 summarizes the changes in ionic conductivity, dielectric constant, dielectric loss, and film thickness with varying concentrations of ZnO nanofiller. Table 3 makes it clear that adding ZnO increases ionic conductivity up to an ideal concentration of 1.0%, after which agglomeration of nanoparticles causes a decrease.

 

In excess amounts of ZnO doping, the dielectric loss increases with increasing ZnO concentration, reaching its peak at 1.0% ZnO and then rising. This indicates that while polarization effects are enhanced with ZnO doping, excessive amounts result in higher losses.

**Conductivity With Optimal Concentration**

As a result of well-dispersed nanoparticles, this increment is due to improved ion transport up to concentration of nanofillers is 1%. As ZnO concentrations exceed 1.0%, agglomeration occurs in electrolytes, affecting ion pathways and further reducing conductivity i.e less ion movements. In terms of enhancing ionic conductivity, ZnO concentrations of 1.0% are optimal, providing the best performance without any significant drawbacks.

**Doping Limitations**

As the concentration of ZnO exceeding 1.0%, that reduce conductivity as nanoparticles aggregate, emphasizing the importance of carefully controlling doping levels in electrolytes.

## CONCLUSION

The synthesized ZnO nanoparticles' size characterization using XRD and SEM shows consistent results, confirming successful synthesis. The ZnO-doped polymer electrolyte films exhibit enhanced ionic conductivity, increasing up to an optimal ZnO concentration, beyond which conductivity declines due to nanoparticle agglomeration. The ion transference number of 0.86 indicates that the films are predominantly ionic conductors, making them promising candidates for electrochemical device applications. The study comprehensively elucidates the effects of ZnO doping on the electrical, optical, and structural properties of PVA-KI polymer electrolyte films. These findings provide valuable insights for tailoring polymer electrolyte properties to meet specific application requirements. Future research should focus on further optimization of nanofiller concentration, exploring different nanoparticle sizes and types to maximize performance, and assessing long-term stability and mechanical properties for practical device integration.

## REFERENCES

1. Chaurasia SK, Thakur AK. Electrical conductivity of polymer electrolytes. J Mater Sci. 2013;48(12):4160–7.
2. Careem MA, Dahlan ASA. Polymer electrolytes for electrochemical devices. Solid State Ionics. 2016;86–88:785–9.
3. Rajendran S, Sivakumar M. Ionic conductivity studies in PVA–KI polymer electrolytes. Mater Chem Phys. 2002;74:52–7.
4. Stephan AM. Review on polymer electrolytes for lithium batteries. Eur Polym J. 2006;42:21–42.
5. Subba Reddy CV, et al. Effect of nanofillers on polymer electrolytes. Electrochim Acta. 2010;55:7000–5.
6. Susan MABH, Noda A, Mitsushima S. ZnO nanofiller-based polymer electrolytes. J Power Sources. 2008;183:724–30.
7. Minami T. ZnO transparent conducting oxide semiconductors. Semicond Sci Technol. 2005;20(4):S35–44.
8. Poizot P, Laruelle S, Grugeon S. Nanosized transition-metal oxides as negative-electrode materials. Nature. 2000;407:496–9.
9. Sahoo SK. Optical properties of polymer nanocomposites. J Phys D Appl Phys. 2011;44:1–10.
10. Look DC. Recent advances in ZnO materials and devices. Mater Sci Eng B. 2001;80:383–7.
11. Yao BD, Chan YF. ZnO nanostructures synthesis. Appl Phys Lett. 2002;81:757–9.
12. Wang ZL. Zinc oxide nanostructures: growth, properties and applications. J Phys Condens Matter. 2004;16:R829–58.
13. Liu CH, et al. Sol-gel derived ZnO nanoparticles. Appl Phys Lett. 2005;86:1–3.
14. Ellmer K. Resistivity of polycrystalline zinc oxide films. J Phys D Appl Phys. 2001;34:3097–108.
15. Silva MM, et al. Structure and ionic conductivity of PVA-based electrolytes. Electrochim Acta. 2006;52:1016–21.

 

16. MacCallum JR, Vincent CA. Polymer Electrolyte Reviews. Elsevier; 1989.
17. Dyre JC, Schroder TB. Universality of ac conduction in disordered solids. Rev Mod Phys. 2000;72:873–92.
18. Lanje AS, et al. ZnO nanoparticles: synthesis and properties. J Phys Chem Solids. 2010;71:1234–9.
19. Skotheim TA, Elsenbaumer RL. Ionic transport in polymer nanocomposites. Science. 1988;240:1645–52.
20. West AR. Solid State Chemistry and Its Applications. Wiley; 2014.
21. Sluiter MHF, et al. Effect of filler concentration on composite properties. J Appl Phys. 2004;96:381–7.
22. Rajendran S, Sivakumar M. Dielectric properties of PVA electrolytes. J Power Sources. 2002;112:313–7.
23. Tauc J. Amorphous and Liquid Semiconductors. Plenum Press; 1974.
24. Klingshirn C. ZnO: from fundamentals to novel applications. Phys Status Solidi B. 2007;244:3027–73.
25. Goetzberger A, Hoffmann VU. Photovoltaic Solar Energy Conversion. Springer; 2005.
26. Armand M, Tarascon JM. Building better batteries. Nature. 2008;451:652–7.
27. Conway BE. Electrochemical Supercapacitors. Springer; 1999.
28. Baskoutas S, Sarantopoulou ES. ZnO nanostructures for sensors. IEEE Sens J. 2013;13:1245–51.
29. Rühle S. ZnO applications in solar cells. Sol Energy Mater Sol Cells. 2011;95:1293–300.
30. Palanisamy S, et al. Characterization of Acacia caesia bark fibers. J Nat Fibers. 2021;19(15):1–15.
31. Palanisamy S, et al. Use of hemp waste for mycelium-grown biocomposites. BioResources. 2023;18(4):8771–80.
32. Padmanabhan RG, et al. Mechanical properties of aluminum-DMEM WFMLs. Ain Shams Eng J. 2024;15(7):102759.
33. Aruchamy K, et al. Enhancement of mechanical properties of hybrid polymer composites. BioResources. 2024;20(1):698–724.
34. Ayrilmis N, et al. Reinforcing fillers for thermoplastic composites. J Reinf Plast Compos. 2024;44(17–18):1108–18.
35. Ramasubbu R, et al. Epoxy composites reinforced with areca fibers. BioResources. 2024;19(2):2353–70.
36. Scrosati B, Garche J. Lithium batteries: status and future. J Power Sources. 2010;195:2419–30.
37. Arof AK, Shukur MF. PVA-based polymer electrolytes: a review. Ionics. 2013;19:1017–25.
38. Shukur MF, Yusof RH, Arof AK. Electrical characterization of PVA–KI polymer electrolyte. Electrochim Acta. 2013;88:212–9.
39. Armand M. Polymer solid electrolytes: an overview. Solid State Ionics. 1983;9–10:745–54.
40. Bruce PG. Solid-State Electrochemistry. Cambridge University Press; 1995.
41. Baskaran R, et al. Conductivity enhancement in PVA:KI polymer electrolytes. J Power Sources. 2004;134(2):235–40.
42. Stephan AM. Review on polymer electrolytes for lithium batteries. Eur Polym J. 2006;42(1):21–42.
43. Rhoo H, Kim YH, Oh SM. Nanofiller effect on ionic conductivity. Electrochim Acta. 2000;45:1487–93.
44. Hema M, et al. Structural and electrical studies of PVA nanocomposites. J Non-Cryst Solids. 2007;353:84–90.
45. Thakur AK, Chandra S. Role of metal oxides in polymer electrolytes. Solid State Ionics. 2005;176:2035–40.
46. Klingshirn C. ZnO: from basics towards applications. Phys Status Solidi B. 2007;244:3027–73.
47. Mahadeva MA, Kim KY, Kim J. ZnO nanofiller enhanced polymer electrolytes. J Power Sources. 2011;196:4026–32.
48. Han SC, et al. ZnO/PVA composite electrolytes for energy devices. Electrochim Acta. 2011;56:8335–41.

 

49. Singh J, Singh RK, Chandra S. Optical studies of ZnO nanofiller polymer films. Physica B. 2011;406:78–83.
50. Pearton SJ, Norton DP, Ren F. ZnO thin films: properties and applications. J Appl Phys. 2005;98:1–10.
51. Kuila T, et al. Interfacial phenomena in polymer nanocomposites. Prog Polym Sci. 2010;35:1350–75.
52. Shukla S, Kumar A. Optical band gap studies of ZnO-doped PVA films. J Mater Sci. 2009;44:3896–901.
53. Wang Y, et al. UV–vis optical properties of ZnO-polymer nanocomposites. J Nanopart Res. 2011;13:975–83.
54. Karak N. Fundamentals of Nanomaterials. Elsevier; 2019.
55. Zhang H, et al. ZnO nanostructured electrolytes for solar cells. Sol Energy Mater Sol Cells. 2011;95:2755–60.
56. Sudhakar T, Selvin R. $TiO_2$ nanofiller enhanced electrolytes. Ionics. 2012;18:165–73.
57. Mandal BK. Comparative study of ZnO and $TiO_2$ fillers. Solid State Ionics. 2013;252:87–93.
58. Chandra S, Singh J. Thermal behavior of $TiO_2$-polymer composites. Thermochim Acta. 2013;564:16–22.
59. Biesheuvel RGM. Hybrid ZnO–$TiO_2$ nanofillers in polymer electrolytes. Electrochim Acta. 2016;210:47–54.
60. Nair SK, et al. Synergistic effects of ZnO nanofillers and KI salt in PVA. J Power Sources. 2008;177:550–6.
61. Tripathi AK. Salt and nanofiller interplay in polymer electrolytes. Ionics. 2010;16:867–73.
62. Croce F, Appetecchi GB, Scrosati B. Nanocomposite polymer electrolytes. Nature. 1998;394:456–8.
63. Tarascon JM, Armand M. Challenges facing rechargeable lithium batteries. Nature. 2001;414:359–67.
64. Poizot P, et al. Nano-sized transition-metal oxides for lithium-ion batteries. Nature. 2000;407:496–9.
65. West AR. Solid State Chemistry and Its Applications. Wiley; 2014.

 