Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Structural, Optical, Dielectric and Nonlinear Properties of PVA/Na-Alg/ITO Nanocomposite Films

Martin Ouma Osemba

mouma@associates.mku.ac.ke

Mount Kenya University https://orcid.org/0009-0007-2045-4746

Adrián Chávez Huerta

Zulian Institute of Technological Research (INZIT), Venezuela

justin Kambale Maghanga

TTU

Research Article

Keywords: Polyvinyl alcohol, Sodium alginate, Indium tin oxide, Optical band gap, Dielectric properties, Nonlinear optics, Nanocomposites

Posted Date: April 10th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9366243/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Structural, Optical, Dielectric and Nonlinear Properties of PVA/Na-Alg/ITO Nanocomposite Films

Dr. Martin Osemba1*[1], Prof. Justin Maghanga*[2] & Dr. Adrián Chávez Huerta[3]

1. Mount Kenya University, Department of Natural Sciences

2. Taita Taveta University, Chemistry Department, Kenya

3. Zulian Institute of Technological Research (INZIT), Venezuela

ABSTRACT

Flexible and optically active polymer nanocomposites have attracted significant attention for next-generation optoelectronic and photonic applications. In this study, PVA/Na-Alg/ITO nanocomposite films were successfully fabricated via a solution casting method, and the effect of indium tin oxide (ITO) nanoparticle incorporation (2–5 wt%) on their structural, optical, dielectric, and nonlinear optical properties was systematically investigated. X-ray diffraction (XRD), Fourier-transform infrared (FTIR), and Raman analyses confirmed good miscibility between polyvinyl alcohol (PVA) and sodium alginate (Na-Alg), along with uniform dispersion of ITO nanoparticles with an average crystallite size of 21.7 nm. Morphological analysis revealed homogeneous films with minimal agglomeration. UV–visible spectroscopy showed a red shift in the absorption edge accompanied by a systematic reduction in optical band gap from 3.59 eV (pristine PVA) to 3.18 eV (5 wt% ITO), indicating enhanced electronic interactions and charge delocalization. The refractive index increased from 1.47 to 1.78, while the dispersion energy (Ed) improved from 8.28 eV to 12.17 eV with increasing ITO content, reflecting enhanced electronic polarizability. The dielectric constant ($\varepsilon\infty$) also increased from 2.37 to 3.46, confirming strengthened interfacial polarization effects. Photoluminescence (PL) analysis revealed significant quenching of emission intensity with increasing ITO concentration, indicating efficient charge transfer and suppression of radiative recombination. Furthermore, the nonlinear refractive index (n_2) increased from 0.675×10^{-12} to 4.83×10^{-12}, while the third-order nonlinear susceptibility ($\chi^{(3)}$) increased from 0.314×10^{-13} to 2.84×10^{-13} (esu) as ITO content increased from 0 to 5 wt%. These results demonstrate that controlled incorporation of ITO nanoparticles significantly enhances the structural disorder, optical tunability, dielectric response, and nonlinear optical performance of PVA/Na-Alg films. The developed nanocomposites show strong potential as environmentally friendly, flexible materials for advanced optoelectronic, photonic, and nonlinear optical device applications.

Keywords: *Polyvinyl alcohol; Sodium alginate; Indium tin oxide; Optical band gap; Dielectric properties; Nonlinear optics; Nanocomposites*

1.0 INTRODUCTION

Polymer-based materials have become essential in the advancement of modern optoelectronic and photonic technologies due to their low cost, mechanical flexibility, ease of processing, and tuneable physicochemical properties (Aziz et al., 2015; Mutuku, Diana et al., 2025). In recent years, significant attention has been directed toward polymer systems capable of meeting the demands of flexible and transparent electronic devices, including optical waveguides, sensors, light-emitting devices, and energy-related applications (Osemba, Martin, & Maghanga, Justin, 2025). Compared to inorganic counterparts, polymers offer important advantages such as lightweight structures, solution processability, and compatibility with large-area fabrication methods, making them highly attractive for next-generation optoelectronic platforms (Estefanía et al., 2020). Among these materials, polyvinyl alcohol (PVA) has attracted considerable interest due to its excellent film-forming ability, high optical transparency, chemical stability, and strong intermolecular hydrogen bonding (Filimon et al., 2025). PVA is a water-soluble, semi-crystalline polymer with good mechanical integrity and optical clarity, which are essential for flexible optoelectronic applications (Al Hashedi et al., 2025). Furthermore, PVA is non-toxic, biodegradable, and environmentally friendly, making it highly relevant for sustainable material development (Al-Saleem et al., 2025). Despite these advantages, pristine PVA exhibits poor electrical conductivity and limited optical tunability, which restrict its direct use in high-performance electronic and photonic devices (Al-Yaari et al., 2025). To address these limitations, polymer blending and nanocomposite engineering have been widely employed as effective strategies for tailoring material properties. In particular, blending PVA with naturally derived biopolymers such as sodium alginate (Na-Alg) has gained increasing attention (Estefanía et al., 2025). Sodium alginate is a polysaccharide extracted from brown algae and is characterized by abundant hydroxyl and carboxylate functional groups. When combined with PVA, these functional groups enhance intermolecular hydrogen bonding,

improve film flexibility, and introduce ionic characteristics into the polymer matrix (Sadiku et al., 2025). Consequently, the PVA/Na-Alg blend exhibits improved structural homogeneity, mechanical stability, and functional versatility compared to single-polymer systems, making it an excellent host matrix for functional nanofillers (Osemba et al., 2024). In addition to polymer blending, the incorporation of inorganic nanofillers is an effective approach for tuning the optical, electrical, and dielectric properties of polymer matrices (Piegari, 2018). Polymer–nanofiller composites often exhibit properties that are not present in the individual components, arising from interfacial interactions, charge transfer processes, and modifications in electronic structure (Osemba, M. O., 2019). Among various fillers, transparent conductive oxides (TCOs) have emerged as particularly promising due to their unique combination of high optical transparency and electrical conductivity. Indium tin oxide (ITO) is one of the most widely studied TCO materials, possessing high carrier concentration, low resistivity, and excellent optical transparency in the visible and near-infrared regions (Chougle et al., 2025). Owing to these properties, ITO has been extensively utilized in applications such as flat-panel displays, photovoltaic devices, touch panels, and transparent electrodes (M. Osemba et al., 2024). When incorporated into polymer matrices, ITO nanoparticles can significantly modify charge transport behavior, optical band structure, refractive index, and dielectric response, enabling the development of multifunctional flexible materials (Dannert et al., 2019). Despite extensive research on ITO thin films and inorganic systems, limited studies have explored the role of ITO as a nanofiller in biopolymer-based polymer blends, particularly in PVA/Na-Alg systems. The interaction between ITO nanoparticles and polymer matrices introduces complex structure–property relationships governed by filler dispersion, interfacial bonding, and local electronic environments (Noha et al., 2016). Achieving uniform nanoparticle dispersion without compromising optical transparency and mechanical flexibility remains a major challenge (M. O. Osemba, Ojwang et al., 2024). Furthermore, the influence of ITO loading on linear and

nonlinear optical properties, dielectric behavior, and photoluminescence characteristics in such hybrid systems has not been comprehensively investigated. A fundamental understanding of how ITO nanoparticles affect structural arrangement, electronic transitions, optical band gap, refractive index dispersion, and polarization mechanisms is essential for rational material design (Rebecchi et al., 2023). From an application perspective, this understanding is crucial for optimizing nanocomposites for use in flexible optoelectronic devices, optical limiters, sensors, and nonlinear optical components. Therefore, the present study focuses on the fabrication and systematic characterization of PVA/Na-Alg/ITO nanocomposite films prepared via a solution casting technique. The effect of varying ITO concentration (2–5 wt%) on structural, morphological, optical, photoluminescence, dielectric, and nonlinear optical properties is comprehensively investigated. Structural characterization is performed using X-ray diffraction (XRD), Fourier-transform infrared (FTIR), Raman spectroscopy, and electron microscopy, while optical behavior is analyzed through UV–visible spectroscopy and photoluminescence measurements (Ouma, O., Martin, 2025). In addition, dispersion parameters, dielectric constants, and nonlinear optical coefficients are evaluated to establish detailed structure–property relationships (Tăchiță et al., 2025). This study provides new insights into environmentally friendly, flexible, and optically active nanocomposites by integrating biodegradable polymer blends with technologically important transparent conductive oxides. The findings highlight the potential of PVA/Na-Alg/ITO systems for advanced applications in optoelectronic devices, photonic systems, and nonlinear optical technologies.

2. Experimental Techniques

2.1 Materials

Polyvinyl alcohol (PVA) with a purity of 99% and an average molecular weight of 23,000 $g \cdot mol^{-1}$ was used as the primary polymer matrix due to its excellent film-forming properties. Sodium alginate (Na-Alg), a naturally derived biopolymer, was employed as a blending agent to enhance intermolecular interactions and mechanical flexibility. Indium tin oxide (ITO) nano-powder was selected as the functional inorganic filler owing to its high optical transparency and electrical conductivity. All chemicals were used as received without further purification, and deionized (DI) water was used as the solvent throughout the preparation process.

2.2 Preparation of PVA/Na-Alg/ITO Nanocomposite Films

PVA/Na-Alg blend films and PVA/Na-Alg/ITO nanocomposite films were prepared using a solution casting method, ensuring high compositional homogeneity and uniform film morphology as shown in figure 1 below. Initially, 10 wt% PVA was dissolved in 100 mL of deionized water under continuous stirring at 75 °C until a clear and homogeneous solution was obtained. Separately, 2 wt% sodium alginate was dissolved in 100 mL of deionized water at room temperature with constant stirring to ensure complete hydration of polymer chains. The Na-Alg solution was then added dropwise into the PVA solution under continuous stirring to form a uniform PVA/Na-Alg blend. The mixture was further stirred to promote strong intermolecular hydrogen bonding between hydroxyl (–OH) and carboxylate ($–COO^-$) functional groups, ensuring molecular-level homogeneity. For nanocomposite preparation, ITO nanoparticles were incorporated into the PVA/Na-Alg blend at concentrations of 2, 3, 4, and 5 wt% relative to the total polymer weight. Prior to incorporation, ITO nanoparticles were ultrasonically dispersed in deionized water to minimize agglomeration. The suspension was then gradually introduced into the polymer blend under continuous magnetic stirring. The

resulting mixtures were subjected to combined magnetic stirring and ultrasonication to ensure uniform dispersion of nanoparticles and strong interfacial interaction between the polymer matrix and ITO filler.

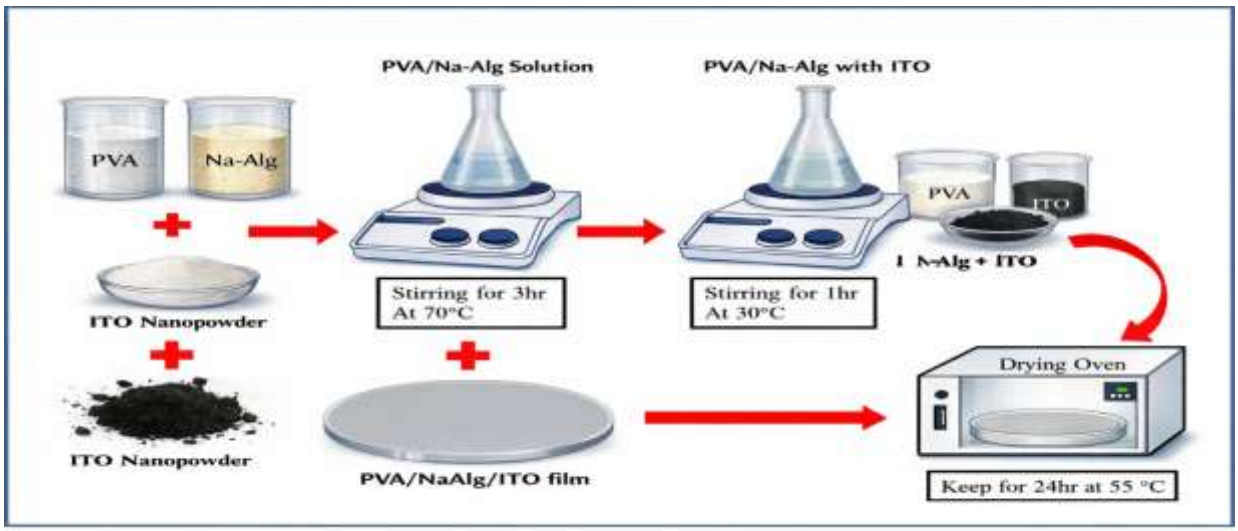


Figure 1. Schematic illustration of the preparation of PVA/Na-Alg/ITO nanocomposite films via the solution casting method.

The homogeneous solutions were cast onto clean glass substrates or Petri dishes and dried in a controlled-temperature oven to allow slow solvent evaporation. After complete drying, flexible and optically uniform films were carefully peeled off and stored in a desiccator prior to characterization. Film thickness was measured at multiple points, and the average thickness value was used in subsequent optical and dielectric calculations. The weight fraction of ITO nanoparticles was calculated using the relation:

$$ITO\ wt\% = \frac{W_{ITO}}{W_{PVA}+W_{Na-Alg}+W_{ITO}} \times 100 \quad \text{.....Eq.1}$$

Where,

W_{ITO} is the weight of ITO nanoparticles

W_{PVA} and $W_{Na\text{-}Alg}$ are the weights of PVA and sodium alginate, respectively.

This equation would guarantee regulated loading of the filler and reproducibility of the nanocomposite films.

2.3 Material Characterization

The structural properties of the prepared PVA, PVA/Na-Alg blend, and PVA/Na-Alg/ITO nanocomposite films were investigated using X-ray diffraction (XRD) with Cu–Kα radiation (λ = 1.5406 Å). Diffraction patterns were recorded over an appropriate 2θ range (10–80°) at room temperature to evaluate the semi-crystalline nature of the polymer matrix and the crystalline phases of ITO nanoparticles. Microstructural parameters, including crystallite size, microstrain, and dislocation density, were estimated using standard line-broadening methods. Fourier-transform infrared (FTIR) spectroscopy was carried out in the spectral range of 400–3500 cm^{-1} to identify functional groups and analyze intermolecular interactions within the films. Peak positions and shifts were examined to confirm hydrogen bonding and polymer–filler interactions. Complementary Raman spectroscopy was performed to further verify the incorporation of ITO nanoparticles and to probe changes in the local chemical environment of the polymer matrix. Raman spectra were recorded over a suitable wavenumber range to detect characteristic vibrational modes of both the polymer blend and the inorganic filler. The surface morphology and dispersion state of ITO nanoparticles were examined using scanning electron microscopy (SEM). Both surface and cross-sectional images were acquired to assess film uniformity, thickness distribution, and nanoparticle dispersion. Elemental composition and spatial distribution of ITO within the polymer matrix were confirmed using energy-dispersive X-ray spectroscopy (EDX) attached to the SEM system. Optical properties were analyzed using UV–visible spectroscopy over a wide wavelength range of 200–800 nm. Transmittance (T) and reflectance (R) spectra were recorded, and the absorption coefficient (α) was calculated. The optical band gap (E_g) was determined using Tauc's relation by plotting $(\alpha h\nu)^n$ versus photon energy $(h\nu)$, where $n = 2$ corresponds to allowed direct transitions. Photoluminescence (PL)

measurements were performed at room temperature using a fixed excitation wavelength to investigate emission characteristics and charge recombination behavior of the films. The optical constants, including refractive index (n) and extinction coefficient (k), were derived from the UV–visible spectral data using standard relations. Dispersion behavior was analyzed using the Wemple–DiDomenico single-oscillator model, allowing determination of the oscillator energy (E_0) and dispersion energy (E_d). The dielectric properties were evaluated by calculating the real (ε_1) and imaginary (ε_2) parts of the dielectric constant from the optical constants. These parameters were used to analyze polarization mechanisms and charge carrier dynamics within the nanocomposite system. Finally, the nonlinear optical properties were assessed by estimating the third-order nonlinear optical susceptibility ($\chi^{(3)}$) and the nonlinear refractive index (n_2) using empirical relations based on the linear optical parameters and band gap values.

Results and Discussion

3.0 Structural Analysis:

3.1 X-ray Diffraction (XRD) Studies

The X-ray diffraction (XRD) patterns of the PVA/Na-Alg blend and PVA/Na-Alg/ITO nanocomposite films with varying ITO concentrations (1–4 wt%) are presented in Figure 2, along with the reference pattern of pure ITO. The analysis was carried out to evaluate the effect of polymer blending and ITO incorporation on the structural ordering of the matrix. The diffraction profile of the PVA/Na-Alg blend exhibits a broad characteristic peak centered at 2θ approximately 20°, which is attributed to the semi-crystalline nature of PVA arising from intermolecular hydrogen bonding between polymer chains. The broad halo indicates the coexistence of amorphous and ordered domains within the polymer matrix. The absence of distinct crystalline peaks corresponding to sodium alginate suggests good miscibility between PVA and Na-Alg, resulting in a homogeneous polymer blend without phase separation. This observation confirms strong intermolecular interactions, primarily hydrogen bonding between hydroxyl (–OH) groups of PVA and carboxylate ($–COO^-$) groups of Na-Alg. Upon incorporation of ITO nanoparticles, noticeable structural modifications are observed. In addition to the broad polymer peak, weak diffraction peaks corresponding to crystalline ITO begin to emerge, particularly at higher filler loadings (≥ 2 wt%). These peaks can be indexed to the characteristic planes of cubic ITO, such as (222), (400), (440), and (622), confirming the successful incorporation of the inorganic filler within the polymer matrix. The relatively low intensity of these peaks indicates that the nanoparticles are well-dispersed at the nanoscale and present in low concentrations, which is essential for maintaining optical transparency. A gradual decrease in the intensity and slight broadening of the main polymer diffraction peak with increasing ITO content from 1 to 4 wt% is observed. This behavior suggests partial disruption of the polymer chain ordering due to the presence of nanoparticles. The ITO

nanoparticles act as physical barriers that hinder close packing of polymer chains, leading to an increase in the amorphous fraction of the nanocomposite films. Such an increase in structural disorder is beneficial for enhancing charge carrier mobility and interfacial polarization, which directly influence the optical and dielectric properties. The average crystallite size of the embedded ITO nanoparticles, calculated using the Scherrer equation, was found to be approximately 21.7 nm, confirming the nanoscale nature of the filler. Additionally, the microstrain and dislocation density were observed to increase with increasing ITO loading, indicating enhanced lattice distortion. This can be attributed to interfacial stress arising from the mismatch between the rigid inorganic nanoparticles and the flexible polymer chains. Overall, the XRD results demonstrate that the PVA/Na-Alg blend serves as an effective host matrix for the uniform dispersion of ITO nanoparticles.

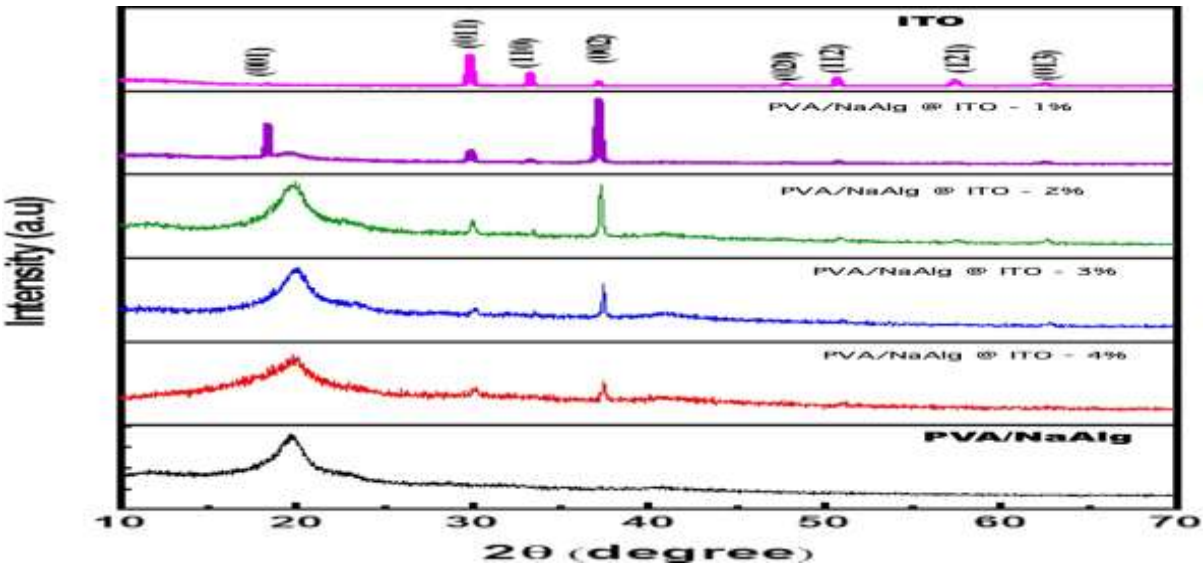


Figure 2. XRD patterns of PVA/Na-Alg/ITO nanocomposite films with varying ITO concentrations (1–4 wt%) along with pure ITO reference.

3.2 Fourier Transform Infrared (FTIR) Spectral Analysis

FTIR spectroscopy was employed to investigate the chemical structure and intermolecular interactions within the PVA/Na-Alg/ITO nanocomposite films. The FTIR spectrum of pristine

PVA (Figure 3a) shows a broad absorption band at 3269 cm^{-1}, corresponding to O–H stretching vibrations due to extensive hydrogen bonding. Peaks at 2906 cm^{-1} (C–H stretching), 1711 cm^{-1} (C=O stretching of residual acetate groups), 1417 cm^{-1} (CH_2 bending), 1325 cm^{-1} (C–H bending), 1141 cm^{-1} (C–O–C stretching), and the fingerprint region peaks at 1087, 916, and 843 cm^{-1} confirm the chemical integrity of the polymer. Upon blending PVA with Na-Alg (Figure 3a and 3b), noticeable changes in both peak positions and intensities are observed. The O–H stretching band broadens and shifts slightly to lower wavenumbers, suggesting stronger hydrogen bonding between PVA hydroxyl groups and Na-Alg carboxylate groups. Additional absorption bands corresponding to asymmetric and symmetric stretching of $-COO^-$ groups from Na-Alg appear, confirming successful incorporation of sodium alginate into the polymer matrix. The addition of ITO nanoparticles (3–5 wt%) to the PVA/Na-Alg blend (Figure 3a and 3b) does not introduce new chemical bonds but slightly affects the transmittance and intensity of the characteristic peaks. This indicates physical interactions between ITO and the polymer matrix, likely via hydrogen bonding, without altering the primary chemical structure. The gradual decrease in peak intensity with increasing ITO content suggests uniform dispersion of nanoparticles within the PVA/Na-Alg matrix. Overall, the FTIR results (Figure 3) confirm the formation of a homogenous PVA/Na-Alg polymer blend and successful incorporation of ITO nanoparticles while maintaining the chemical integrity of the matrix.

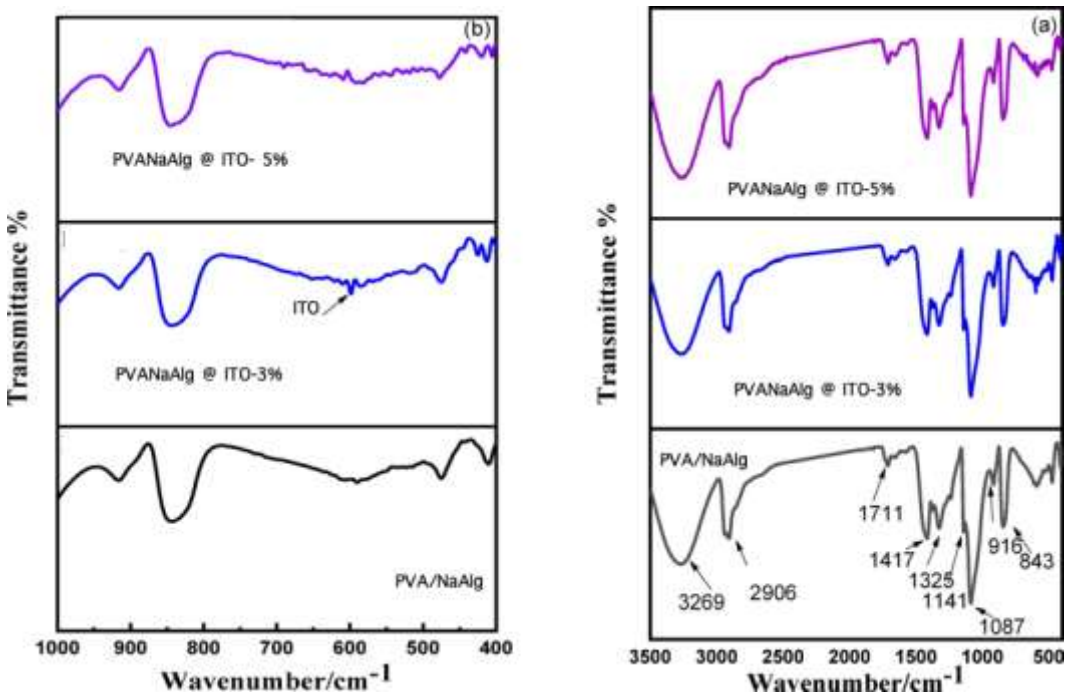


Figure 3. FTIR spectra of (a) PVA/Na-Alg blend and (b) PVA/Na-Alg/ITO nanocomposite films with varying ITO content of 3 and 5 wt%.

Analysis using Raman Spectroscopy

Raman spectroscopy was applied as the complementary technique in order to further investigate the structural properties of the nanocomposite films. The Raman spectrum of the PVA/Na-Alg blend is dominated by the broad bands due to polymer backbone vibrations, indicating amorphous nature of PVA/Na-Alg blend. Upon incorporation of the ITO nanoparticles, other Raman-active modes typical of ITO become visible especially for higher filler concentrations.

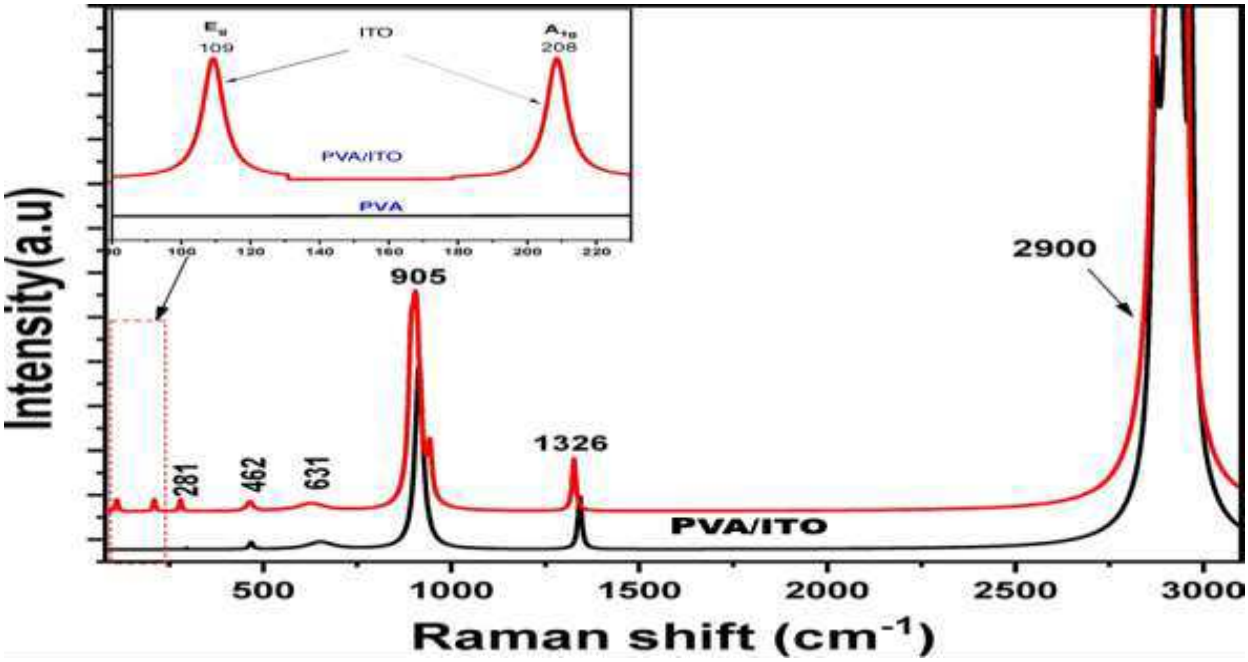


Figure 1 . Raman spectra for pure PVA and PVA/ITO (5%) film.

The existence of these modes is a confirmation of the preservation of the crystalline structure of ITO in the polymer matrix. Slight variation of the intensity of bands and their linewidth indicates the phonon confinement effects and interfacial interaction of the nanoparticles and polymer chains. The lack of new Raman bands is an indication that no chemical degradation or unwanted phase formation occurs during nanocomposite preparation.

Structural Implications

The XRD, FTIR and Raman analyses together confirm the formation of a structurally compatible host matrix for ITO nanoparticles in case of PVA/ Na-Alg blend. The nanocomposites have a controlled structural disorder, good interfacial interactions, and dispersion of the nanoscale filler. These features are expected to have a significant effect on the optical transitions, dielectric polarization and nonlinear optical response.

Morphological Analysis and Elemental Analysis

Scanning Microscopy Electron Microscopy (SEM)

The surface morphology of pristine PVA, PVA/Na-Alg blend, and PVA/Na-Alg/ITO nanocomposite films was studied by using scanning electron microscope in order to study the uniformity of the film, dispersion of filler and influence of the ITO incorporation on polymer matrix. The SEM micrograph of pure PVA shows a relatively smooth and homogenous surface without visible crack or phase separated regions, which suggest a good film-forming capability of PVA and uniform solvent evaporation during the solution-casting process.

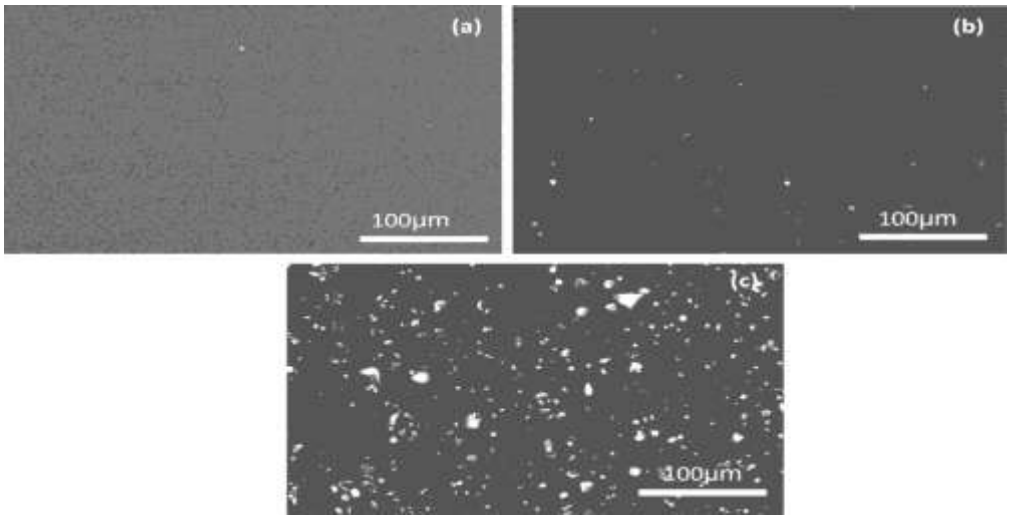


Figure 5 SEM images for PVA (a), PVA/ITO − 3% (b) and PVA/ITO − 5% (c).

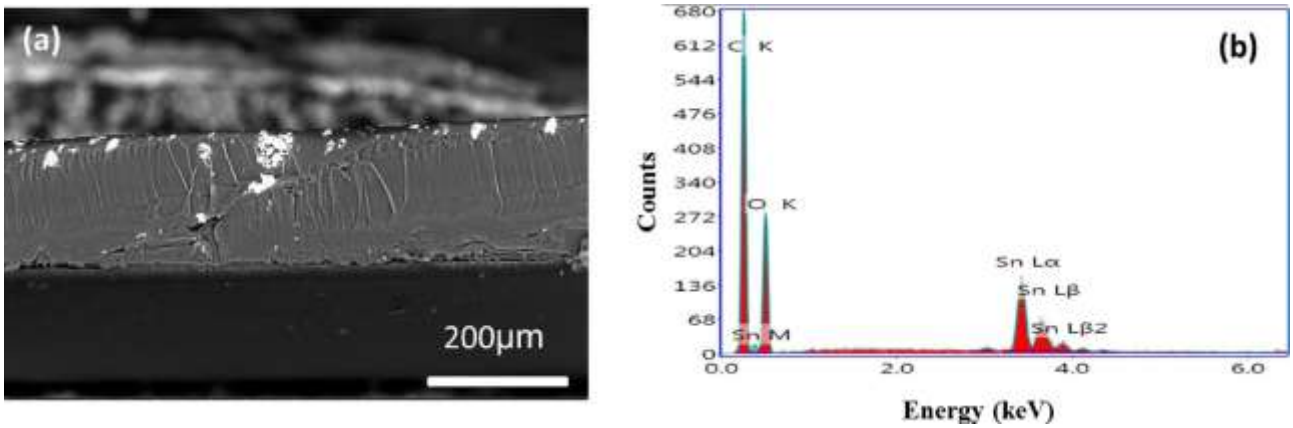


Figure 6 (a) SEM cross-sectional image of PVA/ITO − 5% film and its EDX (b).

The PVA/Na-Alg blend has a slightly textured and continuous surface morphology in comparison to pristine PVA. This change can be attributed to the improved intermolecular

interactions among the chains of PVA and sodium alginate, resulting in the subtle microstructural rearrangements in the blend. Importantly, no evidence of phase segregation, nor agglomeration, is evidenced, which confirms the good miscibility and compatibility between the two polymer components. Upon ITO nanoparticles incorporation, different morphological features can be observed for the nanocomposite films. At reduced ITO concentrations, the nanoparticles are dispersed homogeneously in the polymer blend, and the surface of the film is smooth and without defects. The ITO nanoparticles are not dispersed in the polymer matrix as separate clusters but are incorporated into the polymer matrix, indicating the existence of high interfacial adhesion between the filler and the polymer blend. This homogenous dispersion is the most important to maintain optical transparency and mechanical flexibility. As the ITO loading increases a gradual increase in the surface roughness is observed which is accompanied by the appearance of fine granular features corresponding to embedded nanoparticles. However, even at high filler concentrations, large scale agglomeration is very low, indicating that the combination of polymer blending and ultrasonication is effective in suppressing the clustering of the nanoparticles. The lack of cracks or voids is another hint on the fact that the solution-casting process produces mechanically stable films despite the use of rigid inorganic fillers. Cross-sections of these films by SEM verify the deposition of films of uniform thickness over the entire surface. The ITO nanoparticles are dispersed in the film thickness, not near the film surface, indicating the good filler incorporation in the casting process. This homogenous distribution is beneficial for obtaining the uniformity of the optical and dielectric behaviour throughout the material.

Energy-Dispersive X-ray spectroscopy (EDX).

Elemental analysis was conducted on the energy dispersive X-ray spectroscopy to confirm the existence and distribution of ITO nanoparticles in the PVA/Na-Alg matrix. The EDX spectra

of the nanocomposite films clearly showed the characteristic peaks of In, Sn and O elements as well as C and O from the polymer blend.

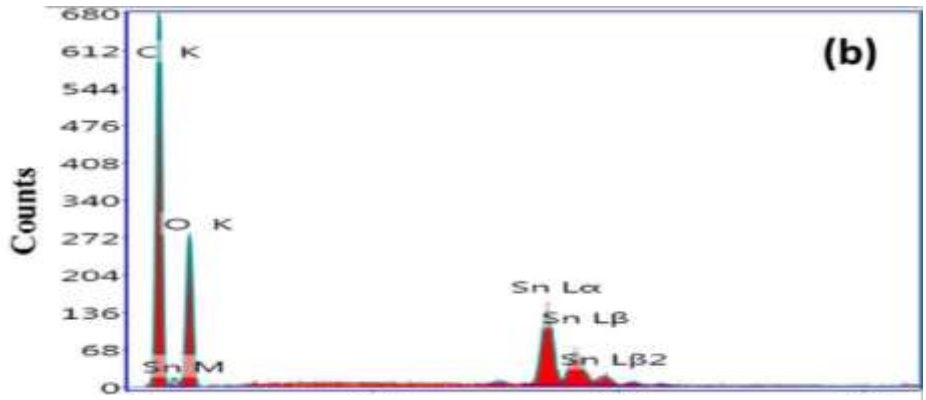


Figure 2 PVA/ITO EDX (b − 5% film

The presence of indium and tin elements gives direct proof of the successful incorporation of ITO into the polymer matrix. The relative intensities of both the In and Sn peaks increase as more ITO is added, in agreement with the controlled variation in filler loading during the preparation of nanocomposites. Elemental mapping is also used to confirm the homogeneous spatial distribution of ITO nanoparticles over the surface of the film without localized areas of high filler concentration. The lack of extraneous elemental peaks in the EDX spectra shows that the nanocomposite films do not contain any unwanted impurities or contaminants. The homogeneity of elemental composition between different parts of the film is proof of the reproducibility of the fabrication process and the stability of the polymer-filler system.

Morphological Implications

The combination of the SEM and EDX analyses shows that the PVA/Na-Alg blend is an effective matrix for the uniform dispersion of ITO nanoparticles. The good interfacial compatibility of the polymer mixture and the inorganic filler reduce agglomeration and improves the homogeneity of the structure. These morphological characteristics are of great importance to control the light-matter interactions, the charge transport pathways and the

polarization mechanism, which are discussed in detail in the optical and dielectric analyses that follow.

Optical Properties

Analysis Using UV-Visible Spectral

The optical properties of pristine PVA, PVA/Na-Alg blend and PVA/Na-Alg/ITO nanocomposite films were studied with the help of UV-visible spectroscopy over the wide wavelength range. The pristine PVA film has high optical transparency in the visible region with a sharp absorption edge in the ultraviolet region, which is typical for wide band gap polymeric materials. The high transparency results from the lack of prolonged conjugation and dominance of electronic transitions in the polymer backbone. The PVA/Na-Alg blend shows a similar profile of the transmittance with small variation in absorbance intensity and edge position. The small variation that is found can be explained by enhanced intermolecular interactions and the introduction of ionic functional groups originating from sodium alginate. Importantly, the blend is transparent to light with great transparency, thus proving its suitability as a host matrix for optically active fillers. With the addition of ITO nanoparticles significant changes in the UV-visible absorption spectra are seen. The absorbance of the nanocomposite films as a whole gradually increases with increasing content of ITO, especially in the ultraviolet region. This enhancement is related to electronic transitions within the ITO nanoparticles and enhanced light scattering that is caused by the presence of nanoscale fillers. In spite of this increase in absorption the nanocomposites have relatively high transparency in the visible region at lower filler loadings, which is a desirable characteristic for transparent optoelectronic applications. A systematic red shift in absorption edge is observed with the increase of ITO concentration. This shift reflects changes in the electronic structure of the polymer matrix caused by the interactions between the polymer and the filler, and also localized states here introduced by the ITO nanoparticles. Such behavior implies the improvement of charge transfer

and the density of states near the band edges which affect the optical transitions within the nanocomposite system.

Determination of Optical Bands Gap.

The optical band gap energy (E_g) of the films was determined by using Tauc's relation that relates the absorption coefficient as a function of photon energy. By taking the plot between $(\alpha hn)^n$ and hn where n is a function of the nature of the electronic transition, the optical band gap was extracted from the linear part of the plots as shown in figure 8 below demonstrating plots for the PVA and PVA films doped with ITO: (a) transmittance vs. wavelength and (b) reflectance versus wavelength. The best linear fitting was found for allowed direct transitions suggesting that the predominant optical transitions in the films under study are of the direct type.

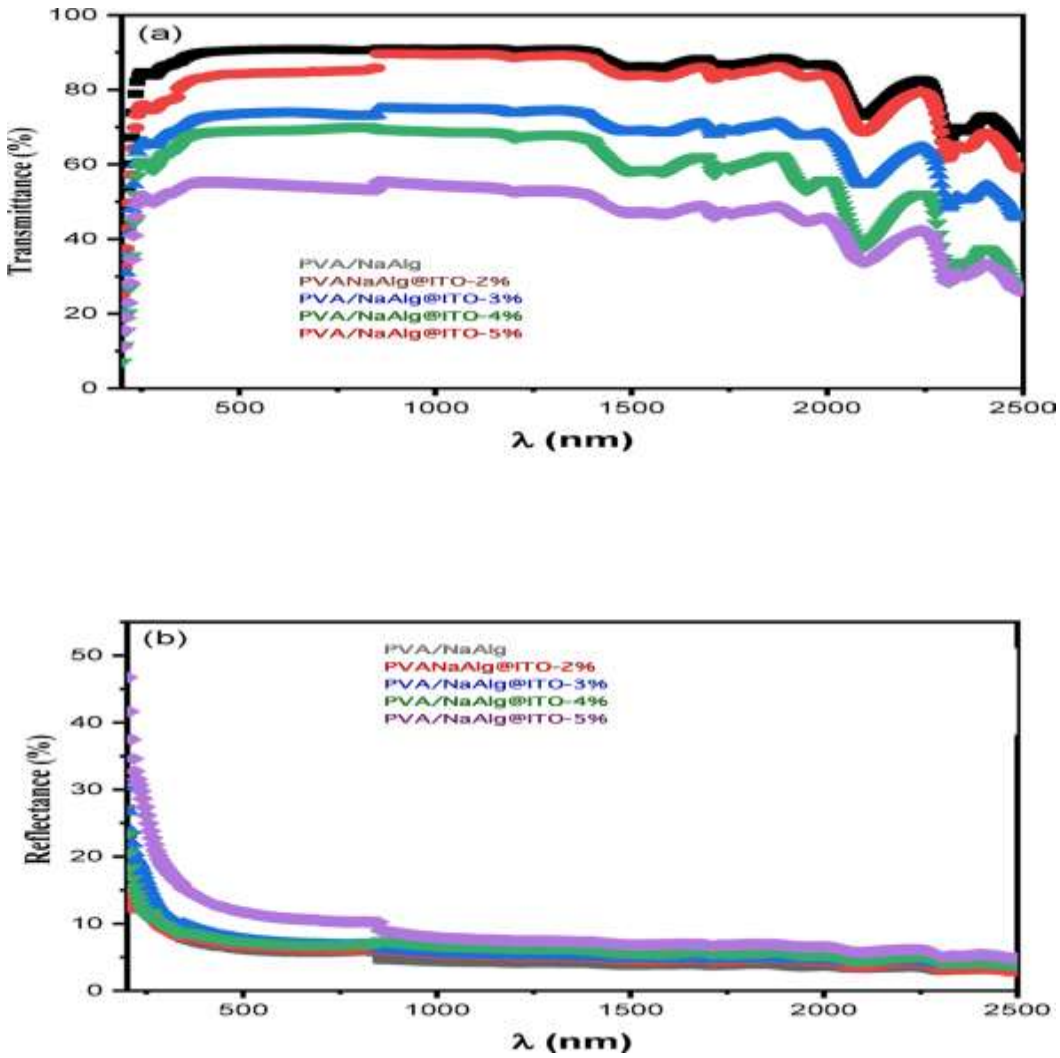


Figure 3 Plots for the PVA and PVA films doped with ITO: (a) transmittance vs. wavelength and (b) reflectance versus wavelength.

The clean PVA film has a relatively wide optical band gap as would be expected for an insulator. The PVA/Na-Alg blend exhibits a small decrease in band gap energy, that can be attributed to the increase of structural disorder and to the enhancement of intermolecular interactions in the blended polymer matrix. More significant reduction of optical band gap is recorded upon the incorporation of ITO nanoparticles. Increasing ITO contents result in an increased importance of the band gap narrowing as a consequence of the introduction of localized energy states and improved electronic coupling between the polymer matrix and the inorganic filler. The presence of ITO nanoparticles helps in the delocalization of charge carrier and alters the

electronic environment thus leading to reduced transition energy requirements. This band gap tuning behaviour is especially important for optoelectronic applications, because it allows the modulation of the light absorption characteristics to be controlled without seriously affecting the optical transparency. The possibility of adjusting the band gap by the filler concentration is important in terms of the versatility of the PVA/Na-Alg/ITO nanocomposite system.

Coefficient of Absorption and Optical Transitions.

The absorption coefficient of nanocomposite films shows a systematic increase with respect to the ITO content, which can be considered to demonstrate the enhanced photon absorption and improved light-matter interaction. This behavior can be explained by the combined influence of intrinsic absorption of ITO, interfacial polarization and enhancement of the density of electronic states. The improved absorption in the low wavelengths area implies the potential use of these nanocomposites in UV-blocking and photonic filtering devices.

Optical Implications

The UV-visible and band gap analysis shows that the introduction of ITO nanoparticles in the PVA/Na-Alg matrix has an effective modulation effect on the optical characteristics of the films. The red shift in absorption edge, band gap narrowing and a higher absorption coefficient that were observed suggest the presence of strong interactions between polymer and filler, as well as enhancement of electronic coupling. These optical modifications, realized while maintaining acceptable transparency, making the PVA/Na-Alg/ITO nanocomposites good candidates for flexible optoelectronics and photonic applications.

Optical Constants and the Dispersion Analysis

Refractive Index/ Extinction Coefficient

The optical constants of the PVA, PVA/Na-Alg blend, and PVA/Na-Alg/ITO nanocomposite films were calculated from the UV-Visible spectral data to obtain further insight into the light matter interactions and electronic polarization mechanism. The refractive index (n) and

extinction coefficient (k) values were determined as a function of photon energy by using standard relations using the measured absorption and reflectance.

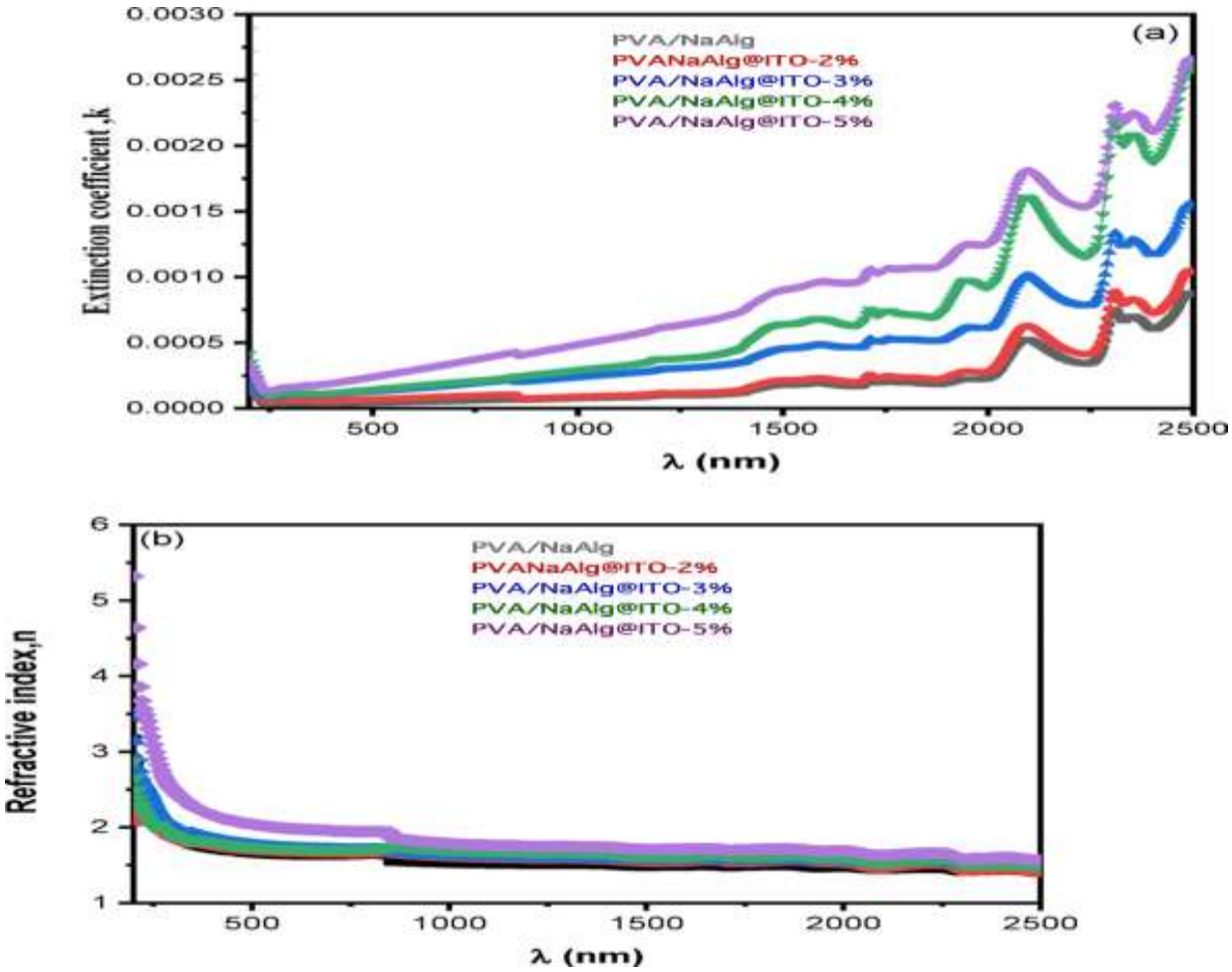


Figure 4 Extinction coefficient, k (a), and Reflective index n (b) for PVA/ITO films.

The pristine PVA film shows a rather low refractive index across the visible region which can be attributed to its low density of electronic states and low electronic polarizability. The PVA/Na-Alg blend exhibits a slight rise in the refractive index and this can be explained by the enhanced intermolecular interactions and the higher packing density due to polymer blending. The presence of sodium alginate gives rise to ionic functional groups that produce local polarization effects, and hence an enhancement in the refractive index of moderate strength. With the incorporation of ITO nanoparticles, a strong enhancement of the refractive index is obtained at the wavelength region studied. The enhancement is more significant with the higher

ITO content, indicating the improved electronic polarizability of nanocomposite system. The high carrier concentration and dielectric property of ITO nanoparticles play an active role in increasing light refraction and especially in the lower photon energy region. This effect is useful in applications where it is necessary to tune the refractive indices, e.g. optical coatings and waveguides.

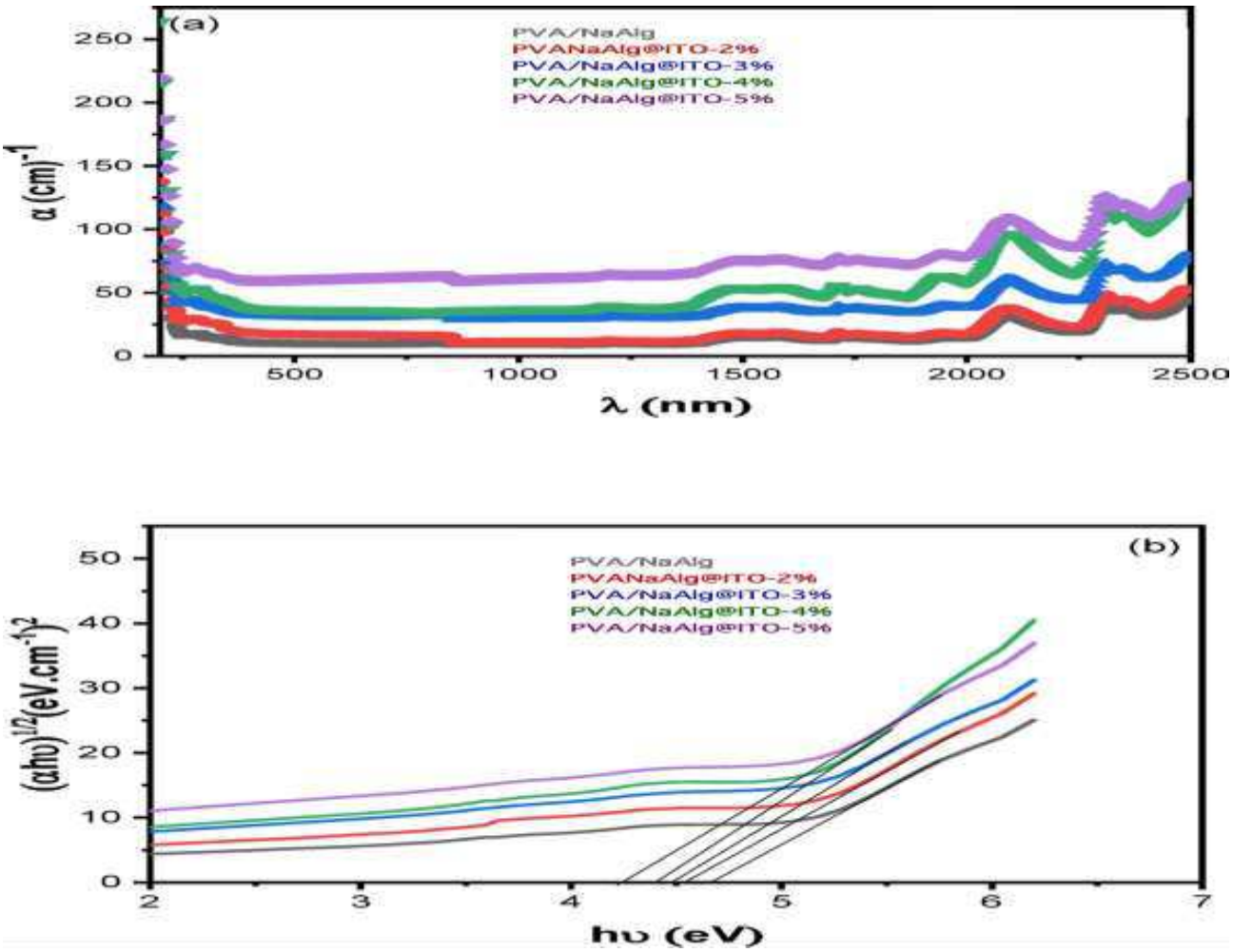


Figure 5 Absorbance coefficient (α) vs. wavelength and (αhv) 1/2 vs. hv of nanocomposite PVA/ITO film.

Table 1 The dispersion, dielectric and nonlinear parameters pva/ito films.

Estimated parameters	PVA film	PVA − 2% SnO film	PVA − 3% SnO film	PVA − 4% SnO film	PVA- 5% SnO film
(E^{Opt}) eV g	3.59	3.47	3.3	3.25	3.18
(Eo) eV	5.28	5.05	4.86	4.75	5.53
(Ed) eV	8.28	11.21	10.25	11.25	12.17
ϵ *WD* ∞	2.37	2.58	2.81	3.12	3.46
no	1.47	1.62	1.72	1.74	1.78
So (m−2) x 1013	0.47	0.41	1.8	4.03	4.53
λo(nm)	381	328	41.16	39.76	31.24
ϵ_L	2.33	2.64	2.65	267	2.29
$\frac{N}{m\hbar}$ **x1049**	5.597	11.293	12.64	13.304	16.34
$n2$ **x** 10^{-12} **(hυ → 0)**	0.675	1.29	2.01	2.88	4.83
χ (3) **x 10−13 (hυ → 0)**	0.314	0.543	0.826	1.42	2.84

The extinction coefficient shows a similar tendency with relatively low value for pristine PVA and PVA/Na-Alg blend in accordance with their high transparency. The nanocomposite films exhibit the increasing of K values with an increase of ITO content, especially in the ultraviolet region, corresponding to the improvement of absorption and the electronic transition due to the filler. Nevertheless, the extinction coefficient is low enough in the visible light at moderate filler loading to maintain optical clarity.

Parameters of Dispersion Behavior and Oscillator.

The dispersion behaviour of the refractive index has been analyzed by Wemple-DiDomenico single oscillator model which describes the dependence of refractive index on photon energy in terms of effective oscillator energy (E_o) and dispersion energy (E_d). Linear fitting of the experimental data allows these parameters to be extracted, which gives an insight on the strength of the interband optical transitions. The pristine PVA film has low values of dispersion energy indicating low interband transition strength and low electronic polarizability. The E_d is slightly enhanced in PVA/Na-Alg blend suggesting a better structural order and increase in oscillator strength due to blending of polymer.

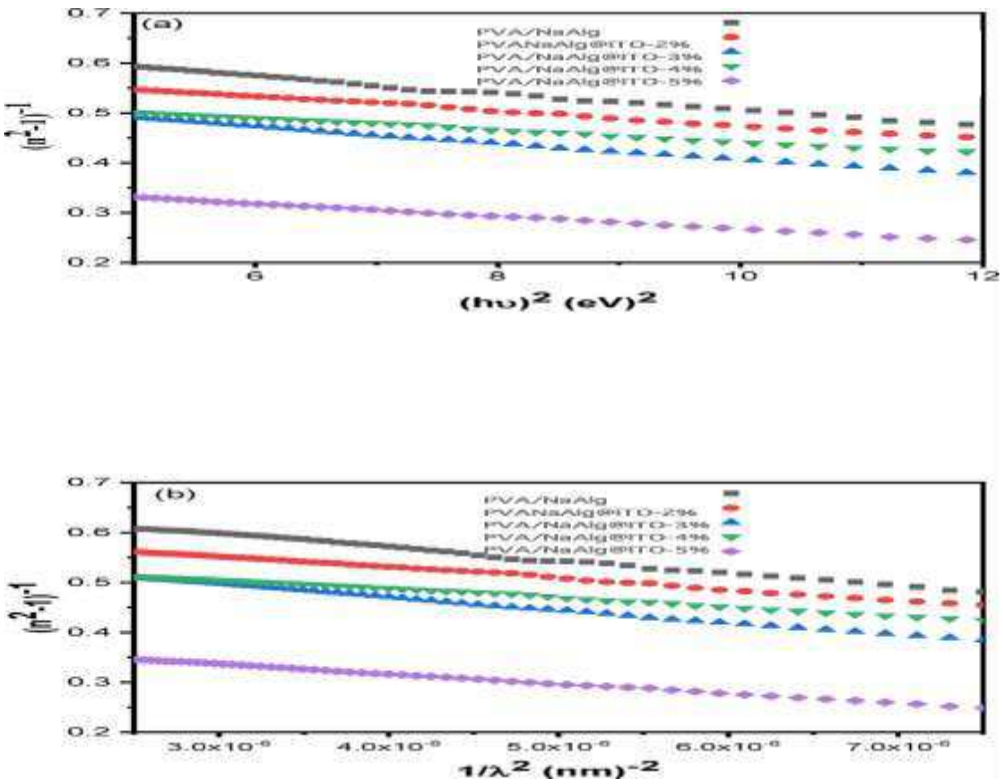


Figure 6 a) Plots of (n2−1) −1 vs. (hv)2(b) Plots of (n 2−1) −1 vs. λ−2 for PVA-ITO films.

In contrast, the PVA/Na-Alg/ITO nanocomposites have much higher dispersion energy values which systematically increase with the ITO content. This enhancement is reflected in an increase in interband transitions and an increase in electronic coupling between the polymer matrix and the ITO nanoparticles. The effective oscillator energy shows a slight decrease with increasing filler concentration which is in agreement with the observed reduction in optical band gap and red shift in absorption edge. These results suggest that the introduction of ITO nanoparticles alters the electronic environment of the polymer blend by increasing the charge carrier density and improving the polarization effects and thus influence the dispersion characteristics of the nanocomposites.

Dielectric Function and the Polarizability

The real (*ε1*) and imaginary (*ε2*) components of the dielectric function were calculated using the refractive index and extinction coefficients values that were obtained from the calculations. The real part of the dielectric constant is increased with the increase of the ITO content, which

indicates the improvement of energy storage capacity and the increase of electronic polarization. This trend is in accord with the high dielectric nature of ITO and its high interaction with the polymer blend. The imaginary component of the dielectric function which reflects the dissipation of energy in the material also increases with the amount of filler, especially with higher photon energies. This behaviour has been related to enhanced optical absorption and charge carrier transitions induced by the ITO nanoparticles.

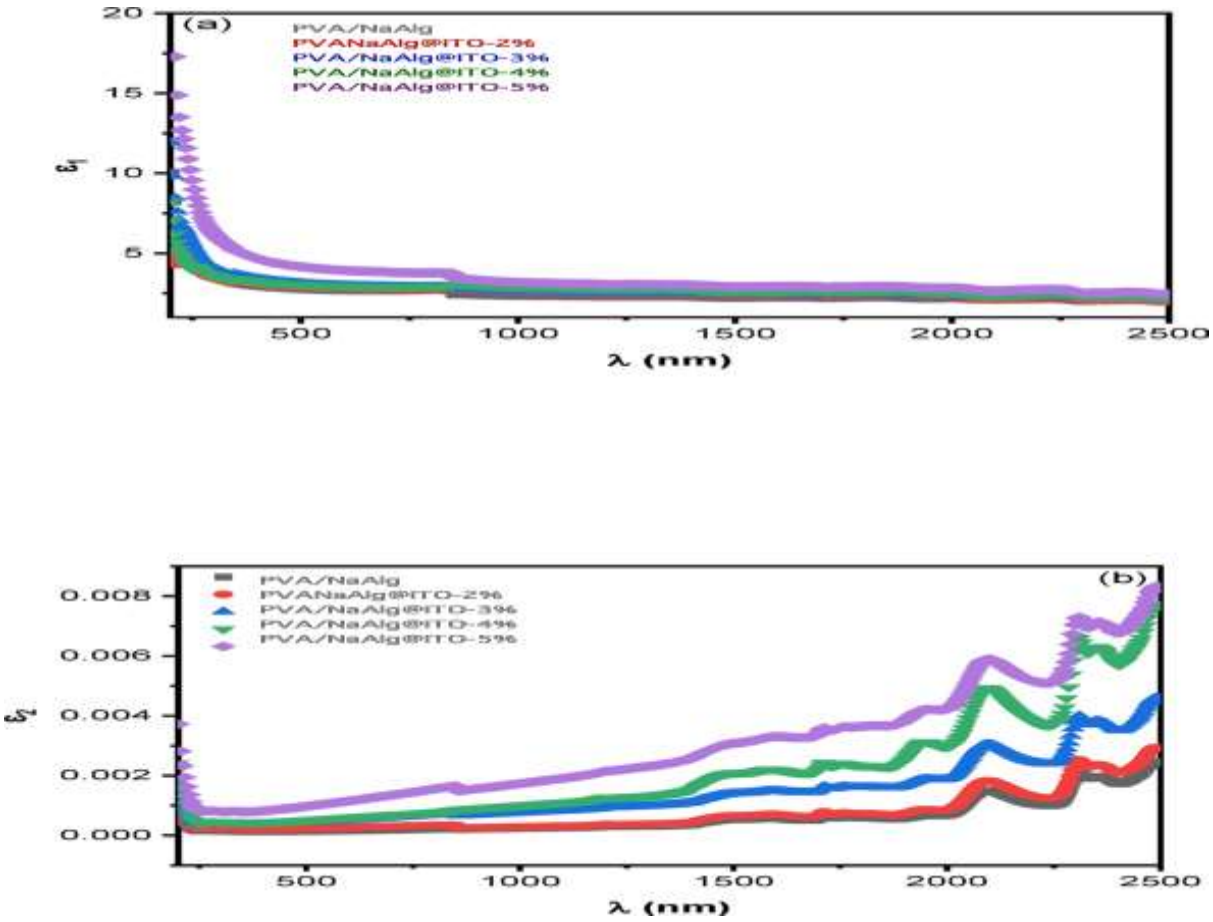


Figure 7 The variation of (a) real (ε1) and (b), imaginary (ε2) parts of the dielectric constant vs. the wavelength for PVA/ITO films.

The higher dielectric constant and polarizability of nanocomposite films make these films potential candidates for use in optoelectronic devices, capacitive devices, and photonic structures where materials with tuning dielectric properties are needed.

Dispersion Implications

The systematic improvement of refractive indices, dispersion energies and dielectric parameters with the increasing amount of ITO proves that the optical constants of the PVA/Na-Alg blend can be efficiently adjusted by nanofiller incorporation. The observed dispersion behavior reveals the strong interfacial interaction and electronic coupling between polymer matrix and ITO nanoparticles, which are very important for advanced photonic and optoelectronic applications.

Photoluminescence Analysis

The photoluminescence behaviour of pristine PVA, PVA/Na-Alg blend and PVA/Na-Alg/ITO nanocomposite films were investigated to understand the effect of polymer blending and ITO incorporation on radiative recombination processes and the defect related emission behaviour. Photoluminescence spectroscopy offers useful information about electronic transitions, trapping of charge carriers and energy transfer processes in polymer-based nanocomposites.

The PL spectrum of pristine PVA shows a wide emission band in the near-ultraviolet to blue region that is usually explained by intrinsic defect states, localized excitons and recombination of charge carriers belonging to hydroxyl-related functional groups. The broad nature of the emission is indicative of the amorphous regions and structural disorder of polymeric materials.

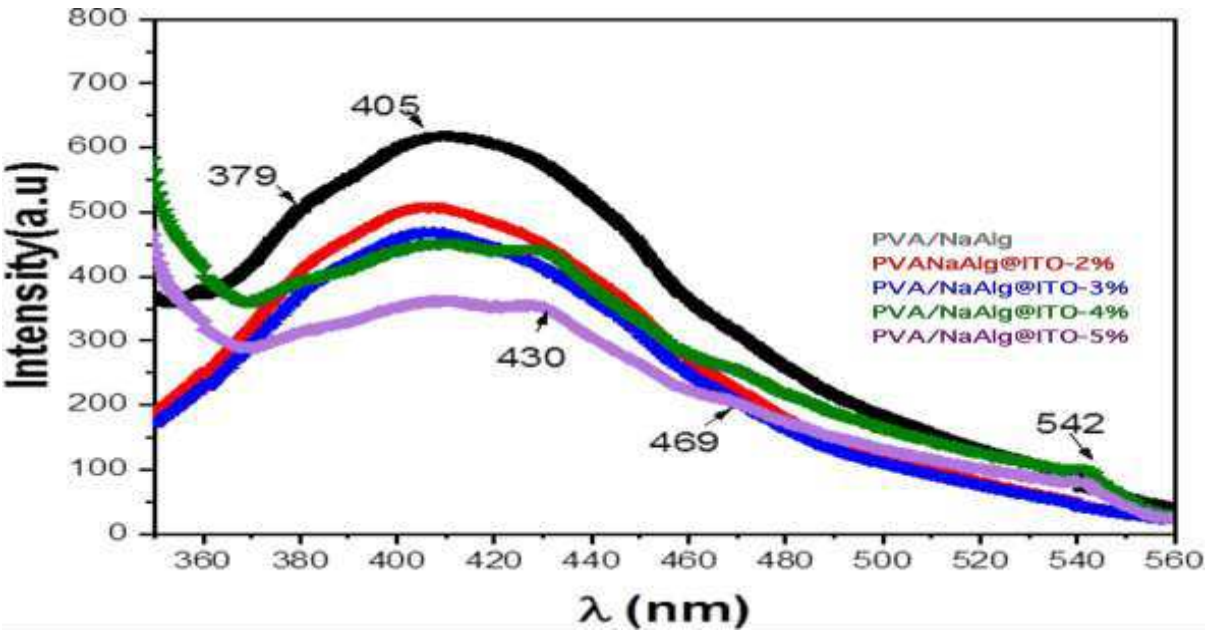


Figure 8 PL vs. wavelength (nm) for nanocomposite PVA/ITO film.

Upon mixing PVA and sodium alginate a prominent change in PL intensity and emission profile are observed. The PVA/Na-Alg blend exhibits a slight decrease in the emission intensity with a minor peak broadening. This behaviour can be explained by improved intermolecular hydrogen bonding and increased non-radiative relaxation routes introduced by the ionic functional groups of Na-Alg. The enhanced structural homogeneity of the blend decreases the localized defect states, so the recombination dynamics is affected. The incorporation of ITO nanoparticles causes significant modification of photoluminescence characteristics of nanocomposite films. A systematic quenching of PL intensity is observed with increasing concentration of ITO indicating effective charge transfer from polymer matrix to ITO nanoparticles. The high carrier concentration and conductive nature of ITO allow non-radiative recombination mechanisms which lessen the intensity of the radiative emission. In addition to intensity quenching, small changes are observed in the emission peak position in the nanocomposite films. These shifts are a good indication of changes in the local electronic environment and formation of interfacial states at the polymer-ITO interface. The interaction between the polymer chains and ITO nanoparticles changes the distribution of the defect states

and energy levels and so it affects the emission behavior. The observed PL quenching behavior strongly implies the enhanced separation of the photo-generated charge carriers which is a desirable feature for optoelectronic applications such as photodetectors and photovoltaic devices. The decrease in the radiative recombination suggests that the charge transport efficiency is enhanced and the carrier mobility increases in the nanocomposite system. Overall, the results of photoluminescence confirm the existence of strong interfacial interactions between the PVA/Na-Alg matrix and ITO nanoparticles. The ability to tune emission intensity and recombination dynamics based on filler concentration puts the nanocomposite system into focus from the perspective of tunability and potential applications of the nanocomposites in the optoelectronic and photonic domains.

Nonlinear optical analysis and Dielectric Properties.

Dielectric Properties

The dielectric properties of pristine PVA, PVA/Na-Alg blend and PVA/Na-Alg/ITO nanocomposite films were examined to gain an insight into polarization mechanism and charge carrier dynamics through the material system. The dielectric parameters were then determined from optical constants and analyzed as functions of the photon energy, which gives an insight into electronic and interfacial polarization processes. The real part of the dielectric constant ($\varepsilon 1$) for the pristine PVA shows fairly low values which is consistent with the insulating nature of the material along with a low electronic polarizability. The PVA/Na-Alg blend exhibits a moderate increment of $\varepsilon 2$, which could be explained by the improved intermolecular interactions and the existence of ionic functional groups induced by sodium alginate. These groups contribute towards the dipolar polarization within the polymer matrix.

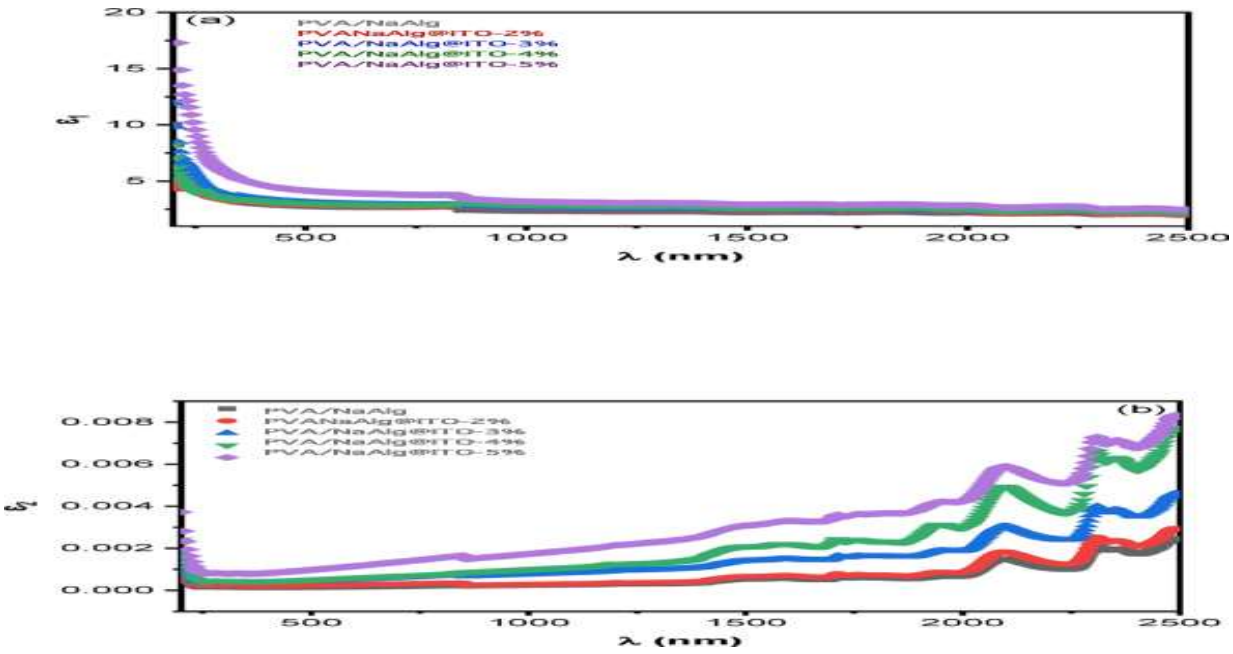


Figure 9 The variation of (a) real (ε1) and (b), imaginary (ε2) parts of the dielectric constant vs. the wavelength for PVA/ITO films.

A high increase in the dielectric constant is observed with the incorporation of ITO nanoparticles. The improvement in *ε1* is higher with higher filler concentration indicating the high dielectric properties and charge carriers in ITO. The presence of nanoscale fillers presents both more polarization centers and additional interfacial polarization of the polymer-filler boundaries. The application is especially useful in applications that need a material with a higher dielectric response and energy storage property. The imaginary portion of the dielectric constant (e2), which is related with dielectric loss, is also found to increase with ITO content in the case of the case of higher photon energies. This increase can be attributed to an improved charge carrier hopping, localized electronic transitions, and filler-induced increased absorption. However, under moderate filler concentration, dielectric losses are kept within acceptable limits, and mechanical performance of the nanocomposites is not affected.

Nonlinear Optical Properties

The nonlinear optical behavior of the PVA/Na-Alg/ITO nanocomposite films was evaluated by estimation of the third-order nonlinear optical susceptibility $\chi^{(3)}$ and nonlinear refractive index

(n2). These parameters were assessed by means of well-known empirical relations based on linear optical constants and band gap values. Pristine PVA has relatively low nonlinear susceptibility, which is associated with its wide band gap and low electronic polarizability [13]. The PVA/Na-Alg mixture exhibits a slight improvement in nonlinear response, because of the increased structural disorder and higher dipolar interactions, which are introduced by polymer blending.

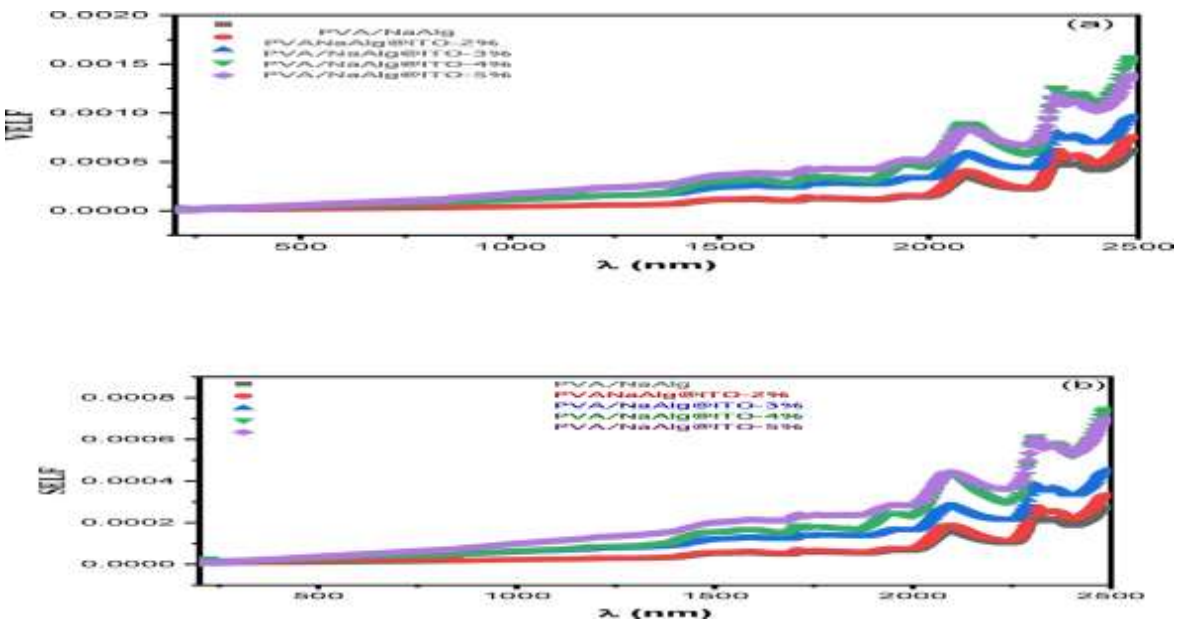


Figure 10 The variation of (a) VELF & (b) SELF vs. the wavelength for PVA/ITO films

A huge enhancement in third order nonlinear susceptibility is observed with the introduction of ITO nanoparticles. The increase in $\chi^{(3)}$ is explained by an increase in charge carrier density, a higher degree of electronic delocalization and a strong interfacial polarization effect at the polymer-ITO interface. The nonlinear refractive index shows a similar trend, that is, it shows a systematic increase with filler concentration. The observed enhancement in the nonlinear optical parameters points out the suitability of PVA/Na-Alg/ITO nanocomposites for applications in optical switching, optical limiting and photonic modulation devices. One of the most important advantages of using fillers is the ability to tune the nonlinear response by

controlled filler loading which offers a versatile approach for the design of functional optical materials.

Conclusion

In this work, flexible and optically active PVA/Na-Alg/ITO nanocomposite films were successfully developed by the solution casting technique. The structural, morphological, optical, dielectric, and nonlinear optical properties of the nanocomposites were systematically studied as a function of the concentration of ITO nanoparticles. Structural analyses confirmed good miscibility between PVA and sodium alginate and showed that the polymer blend provides a good matrix host for the homogeneous dispersion of ITO nanoparticles. XRD, FTIR and Raman studies showed strong intermolecular and interfacial interaction, resulting in controlled structural disorder and improved amorphous features. Good filler distribution and good film integrity were further confirmed by SEM and EDX analyses. Optical studies revealed that the incorporation of ITO nanoparticles causes a red shift of the absorption edge accompanied by systematic reduction of the optical band gap, increase in absorption, and tuneable refractive index. Dispersion analysis showed that there is higher electronic polarizability, and stronger interband transition effects with higher filler content. Photoluminescence measurements showed that there is great quenching of emission intensity because of efficient charge transfer and decreased radiative recombination. Dielectric and nonlinear optical analyses showed a significant improvement in dielectric constant, third-order nonlinearity and nonlinear refractive index when ITO was incorporated. These improvements are attributed to the enhanced charge carrier density, interfacial polarization and high electronic coupling between the polymer blend and ITO nanoparticles. Overall, the results make PVA/Na-Alg/ITO nanocomposite films good candidates for flexible optoelectronic, photonic and nonlinear optical applications. The environmentally friendly nature of the polymer blend as

well as the functional advantages of the transparent conductive oxide fillers is a viable pathway towards sustainable and high-performance optical materials.

REFERENCES

Al Hashedi SA, Abd El-latif AM, Al-Muntaser AA, Al-Zoreky NS, Ramadan KMA, Alosabi AQ. Effect of disodium phthalocyanine on the structural, optical, electrical, and dielectric properties of PVA/CMC blend towards optoelectronic applications. *International Journal of Biological Macromolecules*. 2025; 307:141840.

Al-Saleem NK, Al-Naghmaish A, Madani M, 2025; Multifunctional roles and advances of polymers in solar cell technologies: a review. *RSC Advances*. 15(43):35998-36049. Doi: https://doi.org/10.1039/d5ra05820a.

Al-Yaari M, Alosabi AQ. Enhancement of the optical, electrical, and dielectric properties of PEO/CMC matrix via Na2Pc dye additive for optoelectronic devices. *International Journal of Biological Macromolecules*. 2025; 328:147510.

Aziz SB. Modifying Poly (Vinyl Alcohol) (PVA) from Insulator to Small-Bandgap Polymer: A Novel Approach for Organic Solar Cells and Optoelectronic Devices. *Journal of Electronic Materials*. 2015;45(1):736-745. doi: https://doi.org/10.1007/s11664-015-4191-9

Chougle A, Rezk A, Afzal SUB, Mohammed AK, Shetty D, Nayfeh A. Evolving Role of Conjugated Polymers in Nanoelectronics and Photonics. *Nano-Micro Letters*. 2025;17(1). doi: https://doi.org/10.1007/s40820-025-01748-7

Dannert C, Stokke BT, Dias RS. Nanoparticle-Hydrogel Composites: From Molecular Interactions to Macroscopic Behavior. *Polymers*. 2019;11(2):275. doi: https://doi.org/10.3390/polym11020275

Estefanía Baigorria, Cano L, Sánchez LM, Álvarez VA, Ollier RP. Bentonite-composite polyvinyl alcohol/alginate hydrogel beads: Preparation, characterization and their use as arsenic removal devices. *Environmental Nanotechnology, Monitoring and Management*. 2020; 14:100364-100364. doi: https://doi.org/10.1016/j.enmm.2020.100364

Filimon A, Dobos AM, Onofrei MD, Serbezeanu D. Polyvinyl Alcohol-Based Membranes: A Review of Research Progress on Design and Predictive Modeling of Properties for Targeted Application. *Polymers*. 2025;17(8):1016. doi: https://doi.org/10.3390/polym17081016

Mutuku, Diana *et al.* (2025) "Effect of chitosan coating on the efficiency and degradation of solar panels," *Mount Kenya University* [Preprint]. Available at: https://erepository.mku.ac.ke/handle/123456789/7865.

Noha, El M, Hafez RS. Synthesis, structural and optical properties of tin oxide nanoparticles and its CMC/PEG–PVA nanocomposite films. *Polymer Science Series A*. 2016;58(6):1004-1016. doi: https://doi.org/10.1134/S0965545X16060055

Osemba, M., Muriuki-Hutchins, M., Karenga, S., & Keru, G. (2024). Chitosan Coupled Silver Nanoparticles Electrocatalyst Synthesis and Characterization. *International Journal of Pure and Applied Chemistry*, *2*(1), 1–12.

Osemba, M. O. (2019). *Electrochemical Degradation and Chemical Assessment of Azo Dyes in the Textile Waste Water* [PhD Thesis, Pwani University]. https://elibrary.pu.ac.ke/handle/123456789/826

Osemba, M. O., Muriuki-Hutchins, M., Karenga, S., & Keru, G. (2024). Production of Chitosan from Crab Shells. *International Journal of Advanced Research*, *7*(1), 244–250.

Osemba, M. O., Ojwang, L., & Maghanga, J. (2024). Electrochemical Color Removal of Azo Dyes Using Boron-Doped Diamond Electrodes and Silver Nanoparticles as Electrocatalyst. *International Journal of Advanced Research*, *7*(1), 251–265.

OSEMBA, M. O. (2019). ELECTROCHEMICAL DEGRADATION AND CHEMICAL ASSESSMENT OF AZO DYES IN THE TEXTILE WASTE WATER (Doctoral dissertation, Pwani University).

Othmani, B., Gamelas, J. A., Rasteiro, M. G., & Khadhraoui, M. (2020). Characterization of two cactus formulation-based flocculants and investigation on their flocculating ability for cationic and anionic dyes removal. *Polymers*, *12*(9), 1964.

Ouma, O., Martin. (2025). Synthesis and characterization of silver Nanoparticle elecrocatalyst embedded onto indium tin oxide electrodes for degradation of azo dyes. *Mount Kenya University*. https://erepository.mku.ac.ke/handle/123456789/7870

Piegari A, Flory F. *Optical Thin Films and Coatings*. Woodhead Publishing; 2018.

Rebecchi L, Petrini N, Maqueira Albo I, Curreli N, Rubino A. Transparent conducting metal oxides nanoparticles for solution-processed thin films optoelectronics. *Optical Materials: X*. 2023; 19:100247. doi: https://doi.org/10.1016/j.omx.2023.100247

Sadiku R, Agboola O, Kokkarachedu Varaprasad, Mapula Lucey Mavhungu. *Design of Functional Polymer Nanocomposites*. Woodhead Publishing; 2025.

Tăchiță Vlad-Bubulac, Serbezeanu D, Perju E, et al. Multifaceted Nanocomposites Combining Phosphorylated PVA, MXene, and Cholesteric Liquid Crystal: Design and

Application Insights. *Nanomaterials*. 2025;15(16):1251-1251. Doi:

https://doi.org/10.3390/nano15161251