



Fabrication and Boosting the Features of PCL-PS/ZnO-MWCNTs Multifunctional Films for Optoelectronics and Photonics Applications

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Abstract

Polymer blend nanocomposites are advanced materials formed by combining two or more polymers with nanoscale fillers to enhance mechanical, thermal, and barrier properties. These materials offer tailored performance for applications in the automotive, packaging, electronics, and biomedical fields. The aim of this research is to fabricate PCL/PS polymer blends doped with (ZnO/MWCNTs) and investigate their optical and some morphological features. PCL/PS polymer blend/(ZnO/MWCNT) nanocomposites were prepared by using a casting technique with various concentrations of (ZnO/MWCNT) nanoparticles. Optical microscopy images show a good distribution of (ZnO/MWCNTs) in the polymer blend matrix. The optical features were investigated at wavelengths ranging from 200–1100 nm. An analysis revealed that when the ZnO/MWCNT nanoparticle ratio increased, the absorption value of the PCL/PS blend/(ZnO/MWCNT) nanocomposites increased, whereas the transmittance value decreased. When the ZnO/MWCNTs ratio increased, the band gap decreased from 3.8 eV to 3.18 eV for the allowed transition and from 3.62 eV to 3.11 eV for the forbidden transition. Other optical features of the polymer blend/(ZnO/MWCNTs) have been improved. The optical characteristics of the polymer blend/(ZnO/MWCNTs) reveal the possibility of its application in biomedical devices, sensors and flexible electronics.

Keywords:

PCL, Optical features, PS, ZnO, Polymer blend, MWCNTs.

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Introduction

Polymer nanocomposites are advanced materials formed by dispersing nanofillers into a polymer matrix, resulting in significantly enhanced mechanical, thermal, and electrical properties (Gobena ST & Woldeyannes AD, 2024). Their performance depends on how well the fillers are distributed and

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bonded within the polymer (Zafar et al., 2024). These materials are used in a wide range of applications, including electronics, automotive, aerospace, and medical devices. Overall, they provide lightweight, robust, and multipurpose solutions across industries. In recent years, the use of polymer-based nanocomposites has emerged as a viable technique for creating multifunctional materials with improved physical, chemical, and biological properties (Ahmed Hashim et al., 2017; Akbas et al., 2018). These hybrid materials combine the inherent benefits of polymer matrices, such as processability, flexibility, and biocompatibility, with the superior features of nanostructured fillers (Sirelkhatim et al., 2015).

Among the wide range of polymers, polycaprolactone (PCL) and polystyrene (PS) have received considerable attention because of their complementary characteristics (Zhang et al., 2020). PCL is a semicrystalline, biodegradable, and biocompatible polyester widely used in the biomedical field, including tissue engineering and drug delivery. Its low melting point and excellent blend compatibility make it suitable for composite formation (Manakhov et al., 2017; Jabbar et al., 2019). On the other hand, polystyrene is a rigid, hydrophobic thermoplastic that offers excellent mechanical strength and chemical resistance, making it valuable for industrial applications such as packaging, insulation, and lightweight structures (Singh, 2019).

ZnO is a well-known n-type semiconductor with significant photocatalytic activity, UV blocking capability, and broad-spectrum antibacterial characteristics. These properties make ZnO very useful for the development of materials for biological, environmental, and electrical applications (Tiwari et al., 2018).

MWCNTs, on the other hand, possess unique one-dimensional nanostructures with exceptional electrical conductivity, mechanical strength, and thermal stability (Musa et al., 2025).

Doping a dual-polymer matrix of PCL and PS with ZnO nanoparticles and MWCNTs results in a multiphase nanocomposite with tailored functionalities (Sirelkhatim et al., 2015). By carefully engineering these composites through optimized fabrication techniques such as electrospinning, solution blending, or in situ polymerization, it is possible to achieve a balanced material system with improved tensile properties, controlled degradation rates, electrical conductivity, and antimicrobial behavior (Ng CT et al., 2017; MK Salman et al., 2023).

These improved nanocomposites have enormous potential in a wide range of cutting-edge applications (Madhumitha et al., 2016). In biomedicine, they can be used as wound dressings, tissue regeneration scaffolds, or controlled-release drug delivery systems (Aditya A et al., 2018). Because of their large surface area and active filler components, they have potential in environmental applications such as membranes for water purification and gas filtration. Furthermore, their electrical and thermal properties make them suitable for flexible electronics and sensor technology (Yaqoob et al., 2025).

Several obstacles remain, particularly those related to the uniform dispersion of nanofillers, interface compatibility, and scalability of synthetic approaches. Furthermore, understanding the long-term stability, toxicity, and environmental impact of these hybrid materials is still an important focus of continuing research (Buzea et al., 2007). NPs have been added to polymers to improve their optical properties (Ahmed Hashim et al., 2017; Hussien et al., 2024; Hashim et al., 2023; Jaafar et al., 2023; Majeed Ali Habeeb et al., 2017). The goal of this research is to create polycaprolactone (PCL)/polystyrene (PS)-doped ZnO/MWNT films and investigate their optical and morphological properties for use in advanced applications.

Materials and procedures

The solution-casting process was used at room temperature to create the nanocomposite. First, polycaprolactone (PCL) and polystyrene (PS) were weighed at a 1 g (9PS:1PCL) ratio and dissolved in 25 ml of chloroform under continuous magnetic stirring to guarantee complete dissolution and homogeneity of the polymer blend. Separately, specified amounts of zinc oxide (ZnO) nanoparticles and multiwalled carbon nanotubes (MWCNTs) (0.1, 0.2, and 0.3 wt%) were dispersed in chloroform using ultrasonication for 30–60 minutes to achieve uniform dispersion and prevent agglomeration. After both solutions were ready, the ZnO/MWCNT dispersion was gradually added to the PCL/PS polymer solution under continuous stirring. The resulting mixture was stirred for several additional hours to ensure the even distribution of the nanofillers within the polymer matrix. The homogeneous nanocomposite solution was then poured into a clean, flat glass Petri dish and left to dry slowly at room temperature, allowing the chloroform solvent to evaporate gradually. Once the solvent had completely evaporated, the resulting nanocomposite film was peeled off and stored in a desiccator for further characterization. The sample thickness was measured using a micrometer and was found to be within 40 μm . A UV-18000A Shimadzu spectrophotometer was used to determine the optical characteristics of

the polymer blend/(ZnO/MWCNT) nanocomposites.

Results and Discussion

Morphological investigations

The surface morphology images of the polycaprolactone (PCL)/polystyrene (PS)-doped ZnO/MWNT films are shown in Figure 1. Optical microscopy clearly reveals that the polymer blend has been dissolved perfectly in the solution, as illustrated in Figure 1, and that the ZnO/MWCNTs are well distributed on the surface of the polymer blend with a uniform density, which is related to the interfacial interactions between the nanomaterials and the polymer phases, as well as the processing techniques employed (Zhang et al., 2024).

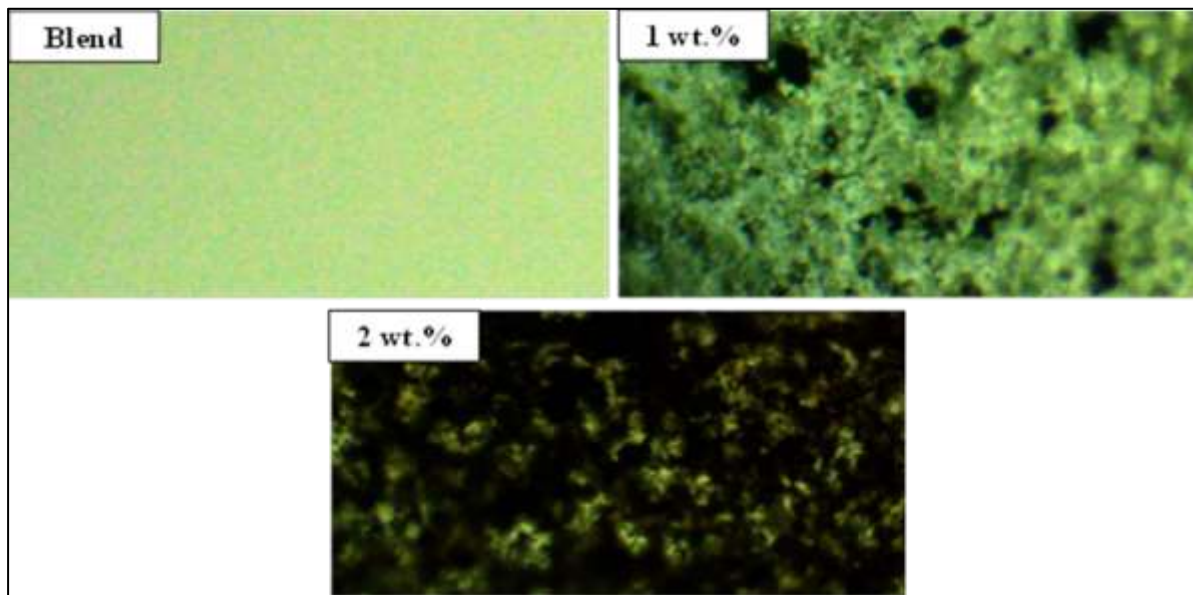


Figure 1: Optical microscopy images of PCL-PS/ZnO-MWCNT films.

Optical property investigations

In this section, the optical properties of the polymer blend films were systemically examined and studied. The variation in the optical absorbance spectra of the polymer blend and polymer blend (ZnO/MWCNT) films against the photon wavelength for different concentrations of MWCNT nanoparticles in the wavelength range of 260–860 nm is shown in Figure 2. As illustrated in Figure 2, the absorbance decreases with increasing wavelength, and the absorbance is greatest in the UV region because of the high photon energy at these energies. It increases with increasing ZnO/MWCNT ratio, which is due to enhanced light absorption from the nanomaterials related to an increase in charge carriers, leading to improved optical properties (Popa et al., 2023; Falah Ali Jasim et al., 2013; Falah Ali Jasim et al., 2013; Ahmed Hashim & Aseel Hadi, 2017).

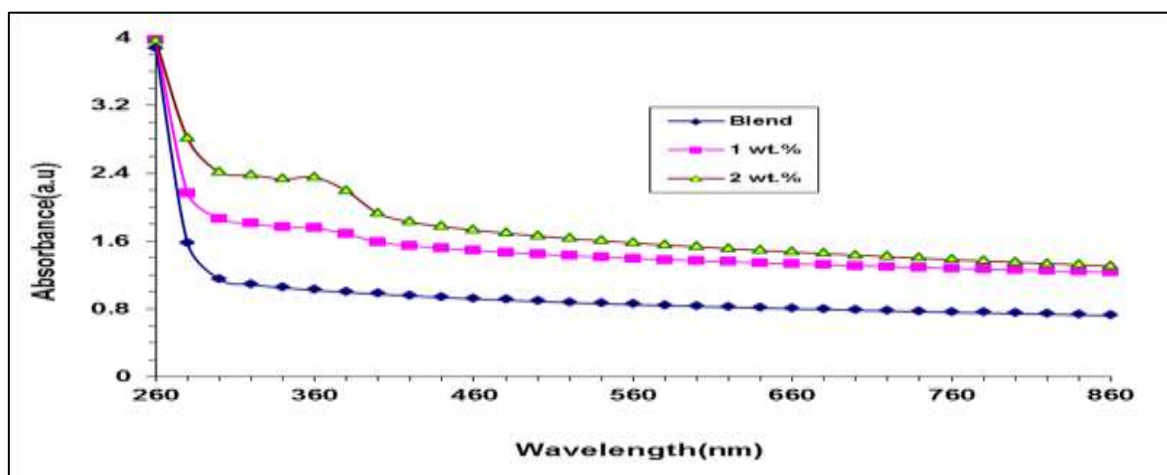


Figure 2: Absorbance versus wavelength of PCL-PS/ZnO-MWCNT films.

The transmittance spectra of the polymer blend and polymer blend/(ZnO/MWCNT) films as a function of wavelength are shown in Figure 3. The transmittance (T) was calculated as follows (M-H Lin et al., 2021):

$$A = \log\left(\frac{1}{T}\right) \quad (1)$$

As illustrated in Figure 3, the transmittance increased with increasing wavelength and decreased with increasing ratio of ZnO/MWCNT ZnO nanoparticles when ZnO was added to the polymer matrix, which reduced the transmittance by increasing light absorption and scattering, especially in the UV region. Similarly, the inclusion of MWCNTs can further decrease the transmittance because of their high absorption and scattering properties (Yakubu et al., 2015).

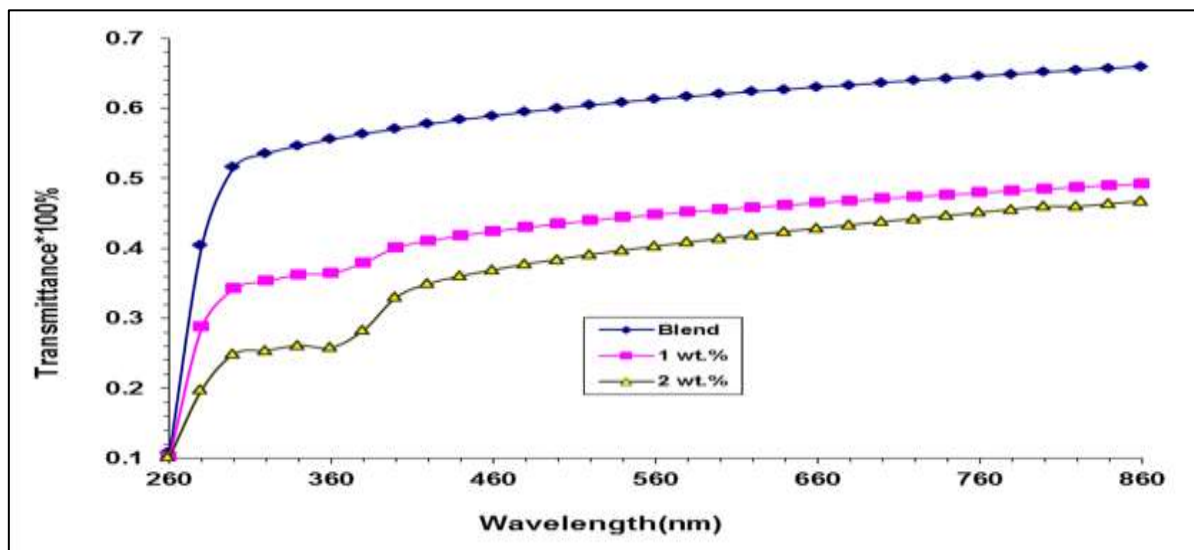


Figure 3: Transmittance versus wavelength of PCL-PS/ZnO-MWCNT films.

The absorption coefficient (α) can be determined by using the following relation (Naik GV et al., 2012):

$$\alpha = 2.303\left(\frac{A}{d}\right) \quad (1)$$

where A is the value of absorbance and d is the thickness value. The absorption coefficients of the polymer blend and polymer blend/(ZnO/MWCNT) nanocomposite are shown in Figure 4. The α provides information on the nature of the transition. It is observed that $\alpha > 104 \text{ cm}^{-1}$; therefore, the indirect transition is dominant, and generally, the absorption coefficient decreases with increasing wavelength because of the reduced photon energy, which becomes insufficient to excite electrons across the band gap of ZnO and to interact effectively with the π -electron system in the MWCNTs. This leads to diminished light absorption, especially beyond the UV region (Feng C et al., 2019).

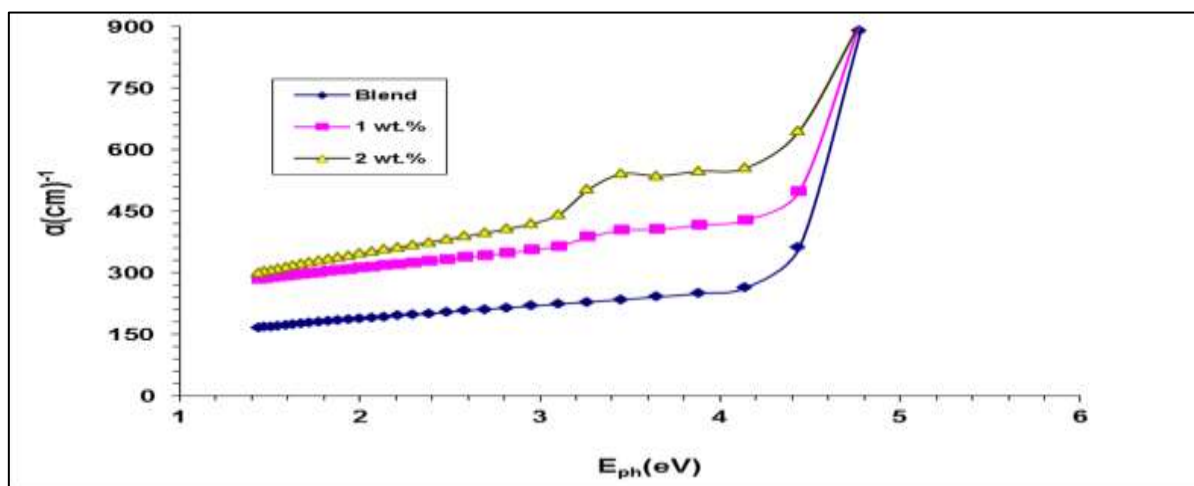


Figure 4: Absorption coefficient of PCL-PS/ZnO-MWCNT films

The value of the energy gap is given bt by the following relation (Abdel-Baset T et al., 2016):

$$\alpha h\nu = B(h\nu - E_g)^m \quad (2)$$

B is a constant, $h\nu$ represents the photon energy, E_g is the band gap energy, and m can take values of 2 or 3 for both allowable and forbidden alterations. The values of the allowed and forbidden energy gaps of the PCL/PS polymer blend and polymer blend/(Zno/MWCNTs) films are illustrated in Figures 5 and 6, respectively. In PCL/PS blends doped with ZnO/MWCNTs, the energy gap decreases from 3.8 eV to 3.18 eV for allowed transition and from 3.62 eV to 3.11 eV for forbidden transition as the filler ratio increases because of defect states, charge transfer, and electronic delocalization. These effects enable lower-energy electronic transitions, enhancing optical absorption in the visible range (Anku et al., 2020; A. Hashim et al., 2017).

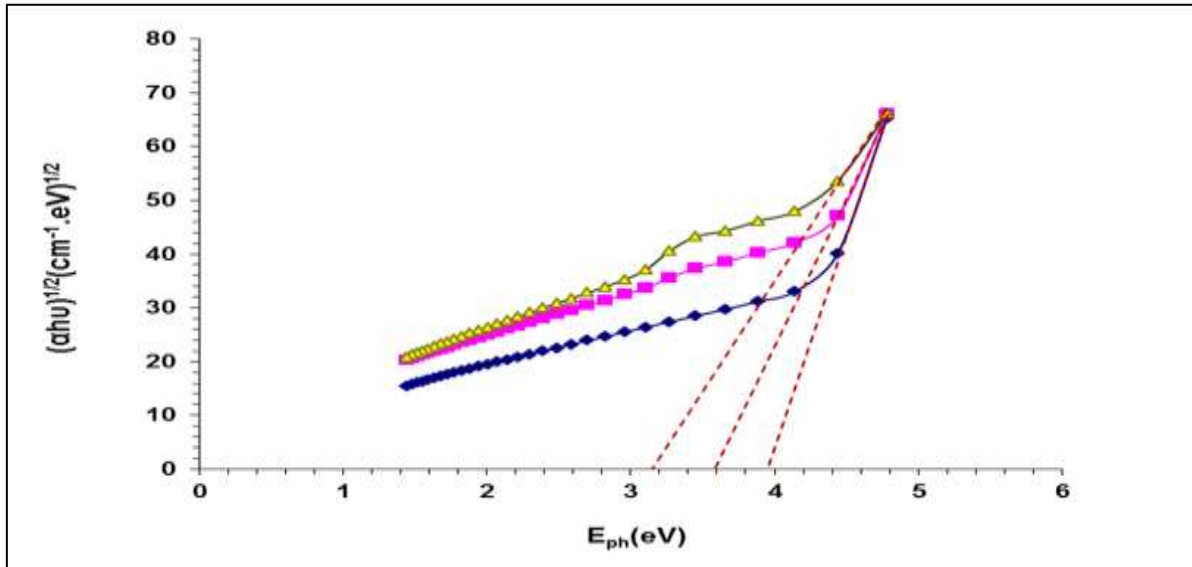


Figure 5: E_g values of PCL-PS/ZnO-MWCNT films for allowed transition.

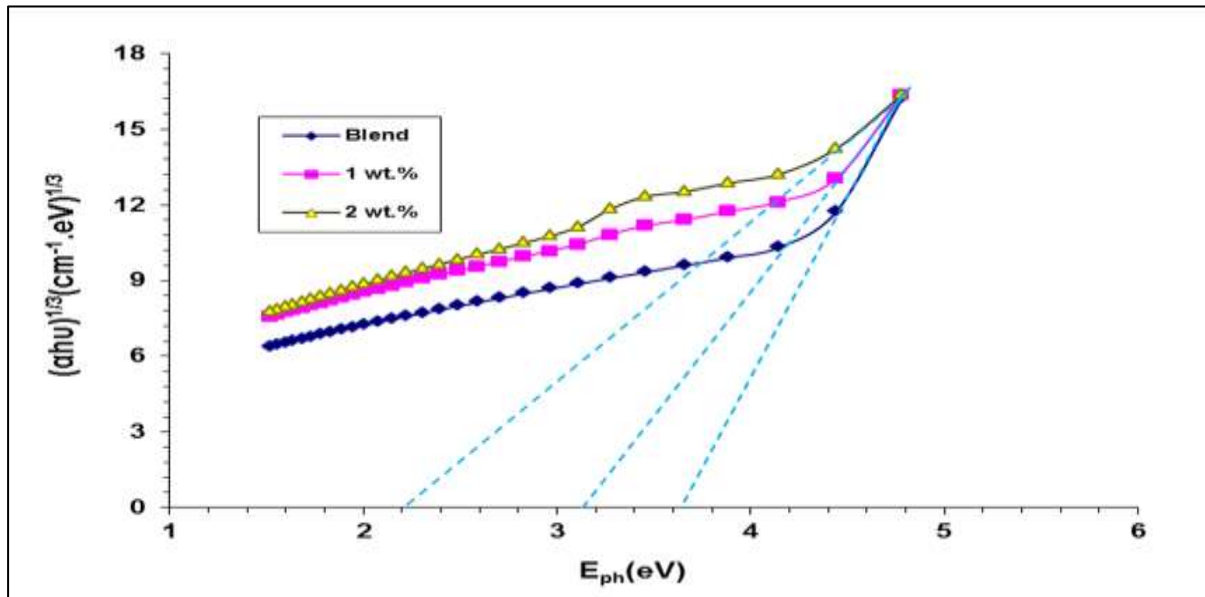


Figure 6: E_g values of PCL-PS/ZnO-MWCNT films for forbidden transition.

The refractive index (n) is calculated by the following relation (Amin et al., 2021):

$$n = \frac{1+R^{1/2}}{1-R^{1/2}} \quad (3)$$

where R is the reflectance, and the extinction coefficient (K) is obtained by the following relation (Amin et al., 2021):

$$k = \frac{\alpha\lambda}{4\pi} \quad (4)$$

where λ is the wavelength and the n and k values of the PCL/PS polymer blend and polymer blend/(ZnO/MWCNT) films are shown in Figures 7 and 8, respectively. Both the value of the refractive index (n) and the value extinction coefficient decrease as the wavelength increases, as illustrated in the figures. due to reduced electronic polarizability and lower absorption at longer wavelengths. This behavior reflects normal dispersion and diminishing electronic transitions in the UV–visible range (Shahin et al., 2019).

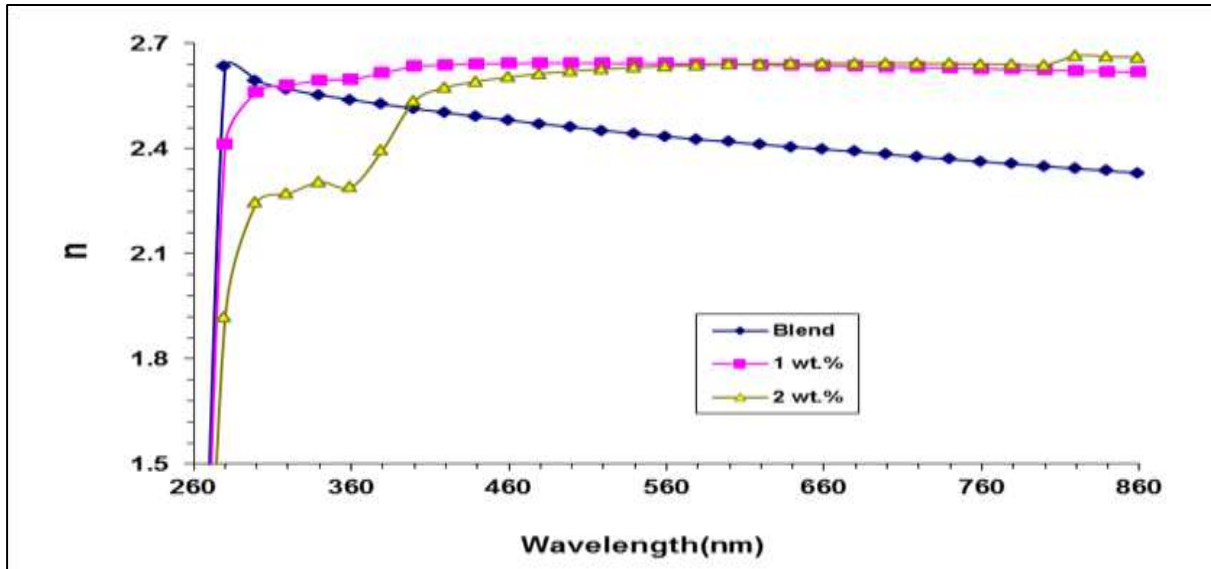


Figure 7: Performance of n for PCL-PS/ZnO-MWCNT films.

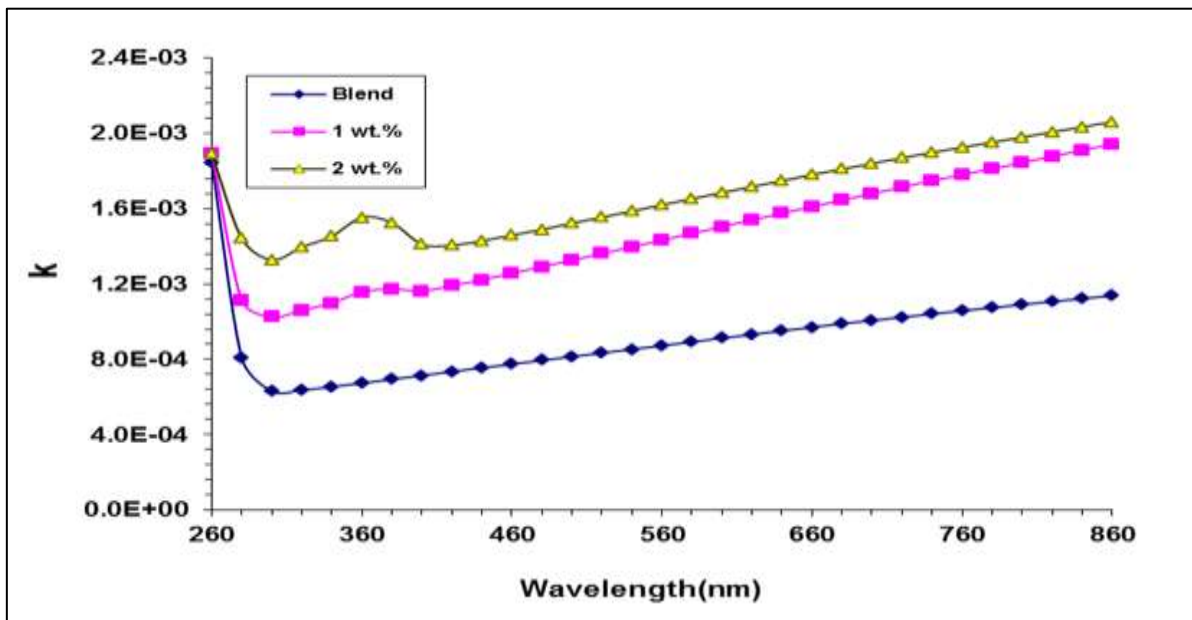


Figure 8: Variation in the extinction coefficient with wavelength for PCL-PS/ZnO-MWCNT films.

The real (ϵ_1) and imaginary (ϵ_2) parts of the dielectric constant are given by (Amin et al., 2021):

$$\epsilon_1 = n^2 - k^2 \quad (5)$$

$$\epsilon_2 = 2nk \quad (6)$$

The real and imaginary dielectric constants of the PCL/PS polymer blend and polymer blend/(ZnO/MWCNT) films are shown in Figures 9 and 10, respectively, which reveal that when the ratio of (ZnO/MWCNTs) increased, both the dielectric constant increased and generally decreased with increasing wavelength, which was due to enhanced interfacial polarization. Both constants decrease

with increasing wavelength, indicating typical dielectric dispersion. This behavior confirms the improved dielectric properties resulting from the addition of a nanofiller (Kumar V, et al., 2023).

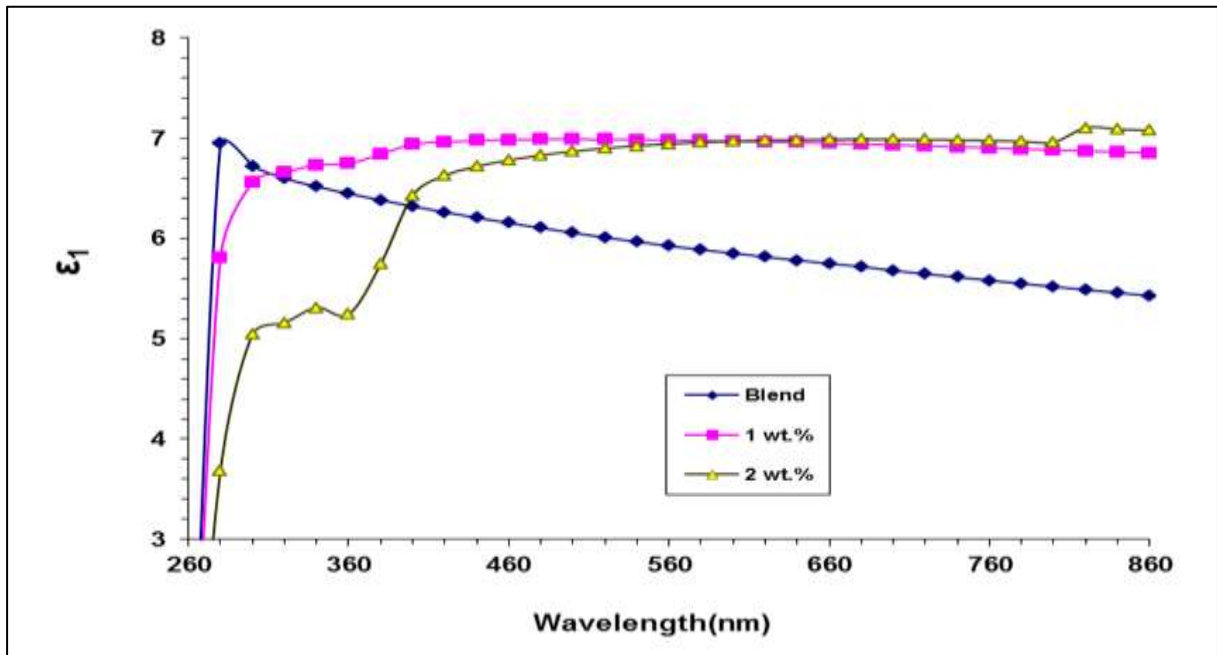


Figure 9: Real part of the dielectric constant (ϵ_1) for PCL-PS/ZnO-MWCNT films.

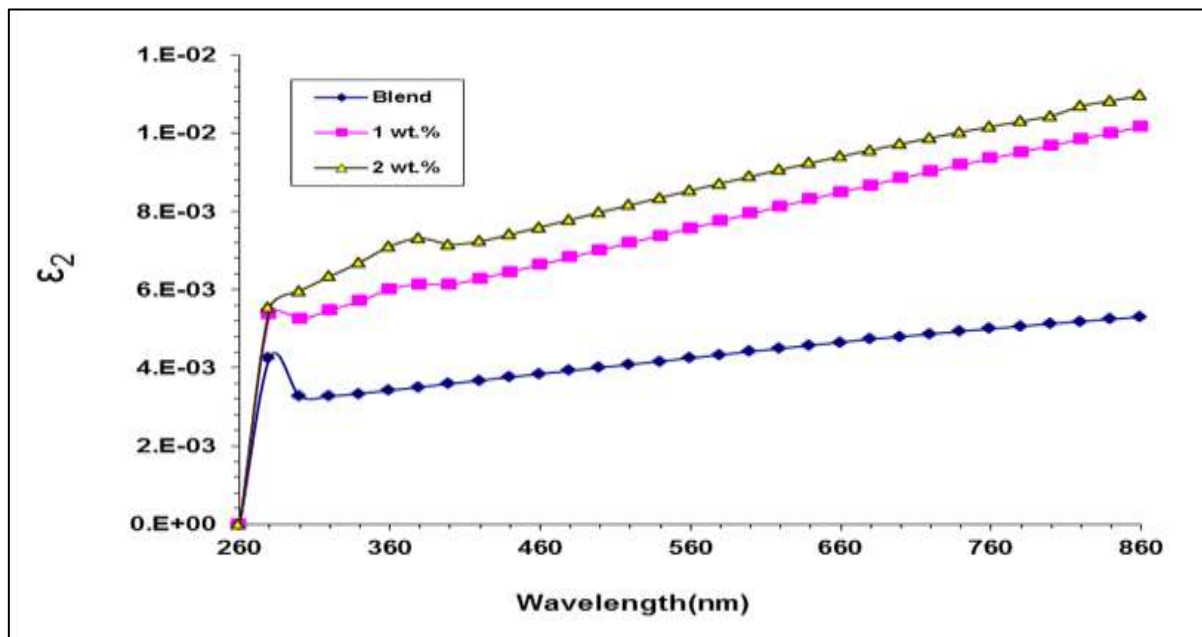


Figure 10: Imaginary parts of the dielectric constant (ϵ_2) for the PCL-PS/ZnO-MWCNT films.

$$\sigma_{op} = \frac{\alpha n c}{4\pi} \quad (7)$$

The optical conductivity as a function of the wavelength for PCL/PS polymer blend and polymer blend/(ZnO/MWCNT) films (Al-Shawabkeh AF et al., 2023) is shown in Figure 11. As shown in the figure, the optical conductivity at high photon energy (low wavelength) increased and vice versa at high wavelength; generally, it increased with increasing ratio of (ZnO/MWCNTs). This behavior is attributed to enhanced charge carrier excitation and transport facilitated by the incorporation of ZnO and MWCNTs, which provide conductive pathways and increase interfacial polarization (El-Naggar AM et al., 2023).

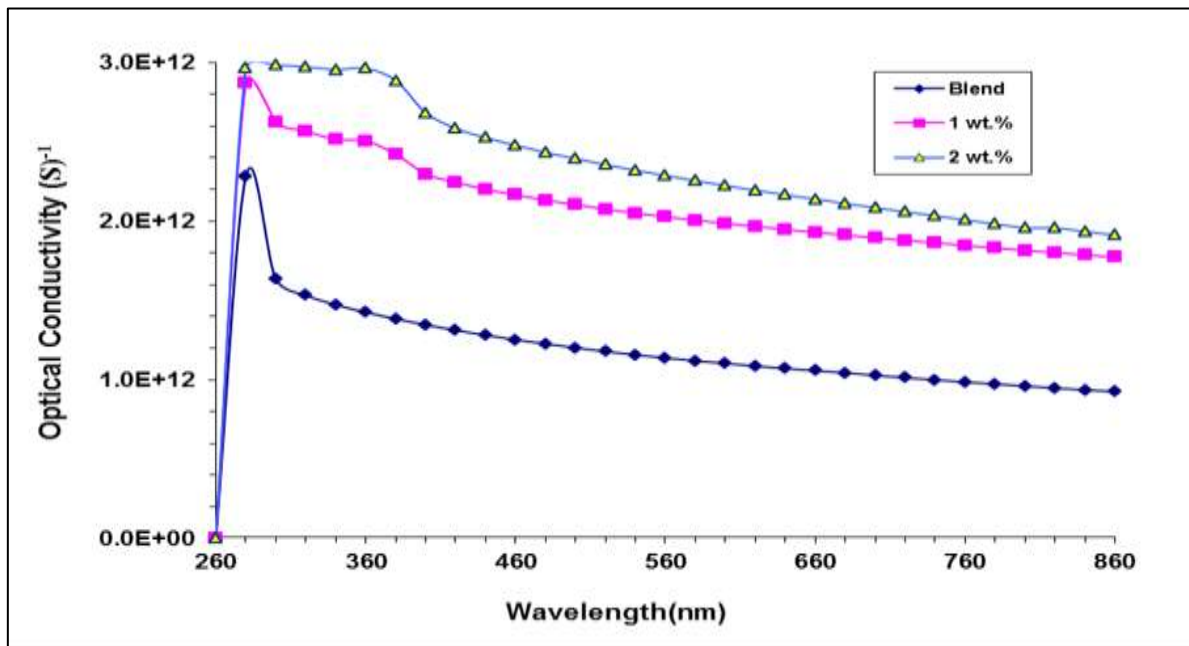


Figure 11: Optical conductivity of PCL-PS/ZnO-MWCNT films.

Conclusion

PCL/PS polymer blend and polymer blend/(ZnO/MWCNT) nanocomposite films were successfully prepared by the traditional casting technique. Optical microscopy images revealed that the (ZnO/MWCNTs) were homogeneously diffused within the matrix of the polymer blend. An increase in optical properties, such as the absorbance, transmittance, optical conductivity, refractive index, and energy gap, was observed for the (ZnO/MWCNT) nanocomposite. The energy gap decreased from 3.8 eV to 3.18 eV for the allowed transition and from 3.62 eV to 3.11 eV for the forbidden transition. Optical characterization revealed that the PCL/PS polymer blend/(ZnO/MWCNT) nanocomposite can be used in biomedical, sensor and flexible electronics.

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Conflict of Interest

The authors declare that there are no conflicts of interest.

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