Original Article

Enhancement of optical and electrical properties of PVC/PMMA blend films doped with Li$_4$Ti$_5$O$_{12}$ nanoparticles

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ABSTRACT

Nanocomposite films of polyvinyl chloride/polymethyl methacrylate (PVC/PMMA)/lithium titanium oxide (Li$_4$Ti$_5$O$_{12}$) were prepared through a casting method. The structural features of the prepared films were investigated using XRD, TEM, FTIR, SEM, and UV/Vis. spectroscopy techniques. XRD pattern reveals the formation of the crystalline phase of lithium titanium oxide of average crystallite size 40 nm embedded in the amorphous polymeric matrix. The average crystallite size observed from TEM images is in good agreement with the XRD results. The physical interaction between the PVC/PMMA blend and Li$_4$Ti$_5$O$_{12}$ NPs was confirmed by FTIR through the formation of a hydrogen bond. SEM micrographs showed partial compatibility between the polymer blend and the Li$_4$Ti$_5$O$_{12}$ NPs. UV/Vis. analysis displayed that the values of the optical energy gap are decreased with increasing the concentration of Li$_4$Ti$_5$O$_{12}$ NPs, this means that charge transfer complexes are arising between the polymer blend and Li-ions. The DC conductivity results are explained in the light of an intrachain one-dimensional interporlaron hopping model. The obtained results recommend the choice of Li$_4$Ti$_5$O$_{12}$ NPs as dopants to enhance the electrical properties of virgin PVC/PMMA blend. Also, nanocomposite films can be employed in different electrochemical and industrial fields such as Li-ion batteries.

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1. Introduction

Polymer research remains a growing field in which blends play an important role due to their relatively simple preparation and the diverse resulting properties [1]. The important advantages of polymer blending are versatility, simplicity, inexpensiveness, and the properties of the final product, which can be tailored to requirements of applications that cannot be achieved by a single polymer [2].

Polyvinyl chloride (PVC) is one of the most important and extensively used thermoplastics polymer owing to its many significant features such as low flammability, chemical resistance, and low cost [3]. PVC has disadvantages such as low thermal stability at processing temperatures, low
impact strength and large melt viscosity [4]. This deficiency is overcome by adding plasticizers or processing aids in PVC. Especially, polymethyl methacrylate (PMMA) is used as processing aids for PVC [5]. The purpose of the PVC modification by blending is the production of new polymers that combine the desired physical properties at a low cost.

Li$_4$Ti$_5$O$_{12}$ NPs is particularly attractive in electronic applications because it is cheaper, environmental friendliness [6], and has excellent lithium-ion mobility [7]. Also, the properties of Li$_4$Ti$_5$O$_{12}$ are hardly expanded by the overcharge and high stability in cycles of discharging and charging [8]. These properties make it a good nanofiller to enhance the electrical and optical properties of polymers and polymer blends [9]. The incorporation of nanofiller within the polymeric matrix has gained significant research interest since it introduces new materials with improved optical and electrical properties. There are numerous applications of polymeric nanocomposites based on their electrical, mechanical, optical, and magnetic properties [10–12].

Morsi et al. [13] investigated the effect of Li$_4$Ti$_5$O$_{12}$ NPs on the structural, optical, thermal and electrical properties of the PEO/CMC blend. FTIR results show the interaction between the PEO/CMC blend and Li$_4$Ti$_5$O$_{12}$ NPs via the formation of a hydrogen bond. The decrease of the optical energy gap, $E_g$, for the nanocomposite samples compared to that of pure PEO/CMC blend and the determination of the type of electronic transitions were demonstrated by UV/Vis. absorption results. The influence of Li$_4$Ti$_5$O$_{12}$ NPs on structural, optical, and thermal properties of PVDF/PEO blend was investigated by Abd El-Kader et al. [8]. Elashmawi et al. [9] studied the changes in spectroscopic, electrical, and thermal properties of the PVDF/PEO containing lithium nanoparticles using several analytical techniques. The results of FTIR, XRD, thermal, and SEM studies indicated that the addition of Li$_4$Ti$_5$O$_{12}$ can reduce the degree of crystallinity due to suppression of recognition of polymeric chains by Li$_4$Ti$_5$O$_{12}$ nanoparticles. Abdelrazek et al. [14] prepared samples of different mass fractions (PMMA/PVC) and their physical properties were studied by ordinary FTIR, XRD, UV/Vis., and SEM with a different glimpse. A new route for inquest the degree of miscibility was introduced depending on a spectroscopic quantitative measurement. All results suggested that the ratio (70/30 wt.%) of PVC/PMMA blends was preferred to be used in some practical applications to add appropriate dopant on it. To the best of our knowledge, the embedded of Li$_4$Ti$_5$O$_{12}$ NPs within PVC/PMMA polymer matrix has never been reported.

Presented work aims to study the structural role of Li$_4$Ti$_5$O$_{12}$ NPs dopant level on the optical, and electrical characteristics of the PVC/PMMA/Li$_4$Ti$_5$O$_{12}$ polymer nanocomposite for possible use in lithium-ion batteries.

2. Materials and methods

2.1. Materials

High molecular weight poly(vinyl chloride) (PVC), (Fluka, Romania), and polymethyl methacrylate (PMMA) with molecular weight $M_n = 25,000$ gm/mol, (Poly Science, Warrington, PA), were used as the basic polymeric materials. Lithium titanium oxide (Li$_4$Ti$_5$O$_{12}$) nanopowder with particle size < 100 nm is the other basic material was used as a dopant and supplied by Sigma-Aldrich (USA). Tetrahydrofuran (THF) with purity 99.5% from (Central Drug House, New Delhi, INDIA) was used as a solvent.

2.2. Preparation of PVC/PMMA/ Li$_4$Ti$_5$O$_{12}$ nanocomposite films

Nanocomposite films were prepared by ordinary casting methods as follows: first, both PVC and PMMA were dissolved separately in THF for 2 h at room temperature until a homogeneous solution was obtained for each polymer. Second, the two polymers were added together for 2 h to obtain (PVC/PMMA) blend with weight percentage (70/30 wt.%). Third, the required masses (0.1, 0.2, 0.4, and 0.8 wt.% of Li$_4$Ti$_5$O$_{12}$ NPs were loaded within the solution of PVC/PMMA under stirring for 2 h at room temperature to inhibit any agglomerations. Fourth, probe sonicator model Q500-Sonicator, USA, was placed in the mixture until the completely dispersion of Li$_4$Ti$_5$O$_{12}$ NPs with polymer blend mixture occurs. Finally, the resulting solution with suitable viscosity was cast to a glass dish and kept at room temperature for 2 days to remove any solvent traces. The prepared films were peeled from Petri dishes and kept in a vacuum desiccator until use. The thickness of the obtained films was in the range of 0.04–0.10 mm.

2.3. Characterization methods

FTIR absorption spectra were carried out for different films using the single beam spectrometer Nicolet iS10, USA. The X-ray pattern was recorded on PANalytical X’Pert Pro XRD system using Cu-K$_\alpha$ radiation (where, $\lambda = 1.540$ Å). The tube operated at 30 kV, scans were collected over a 28 range of 5–80$. UV–vis absorption spectra were measured in the wavelength range of 200–900 nm using a JASCO 630 spectrophotometer, USA. Morphology of prepared films was investigated by using a scanning electron microscope (SEM) model JSM-6510LV JEOL, USA, at 20 kV accelerating voltage, magnification 500×. To determine the size, shape, and distribution of the Li$_4$Ti$_5$O$_{12}$ NPs, transmission electron microscope (TEM) model JEM-2100 JEOL, Japan, was used. DC electrical conductivity was measured using auto-ranging multi-meter KETHLEY 6517B, USA, with an accuracy of $\pm$ 0.5%.

3. Results

3.1. XRD analysis

Fig. 1 depicts the XRD spectrum of Li$_4$Ti$_5$O$_{12}$ NPs. The peak position and Miller indices ($h$ $k$ $l$) to each peak of Li$_4$Ti$_5$O$_{12}$ NPs were estimated. Seven sharp diffraction peaks can be seen at 2θ values of 18.24, 35.57, 43.24, 47.36, 57.21, 62.83, and 66.07, which correspond to the (111), (311), (400), (331), (551), (440) and (531), respectively, reveal the crystalline behavior of Li$_4$Ti$_5$O$_{12}$ NPs. This is consistent with the values in the standard card.
and intensity is reduced upon the addition of Li$_4$Ti$_5$O$_{12}$ NPs. This significant disorder induces a more flexible polymer backbone and thus enhancing ionic transportation, which is useful for lithium batteries [9]. In doped films with 0.1 and 0.2 wt.%, the main peaks of Li$_4$Ti$_5$O$_{12}$ NPs have disappeared owing to the small amount of Li$_4$Ti$_5$O$_{12}$ NPs. For the film with a concentration of $\geq$ 0.4 wt.%, new peaks were observed and attributed to Li$_4$Ti$_5$O$_{12}$ NPs. Also, their intensities increase with increasing Li$_4$Ti$_5$O$_{12}$ NPs content in the blend sample.

3.2. Morphological properties

Fig. 3(a,b) illustrate the TEM micrograph for the Li$_4$Ti$_5$O$_{12}$ NPs and its histogram, respectively. The TEM image shows a nearly cubic-shaped of Li$_4$Ti$_5$O$_{12}$ NPs. The particle size is in the range of 30–60 nm as observed from the histogram. Fig. 3c shows the electron diffraction pattern of Li$_4$Ti$_5$O$_{12}$ NPs. It can be observed that the Li$_4$Ti$_5$O$_{12}$ NPs have a polycrystalline phase. These results are in good agreement with XRD findings.

SEM image can only provide the surface morphology of the sample without giving a fair judgment of the internal structure or phase separation. It just gives an initial indication for the homogeneity or saturation processes. To understand the phase morphology and the effect of Li$_4$Ti$_5$O$_{12}$ NPs incorporation within the PVC/PMMA polymer matrices, the surface morphology of the prepared films was investigated by using SEM technique. Fig. 4a-g depicts the SEM micrograph of the surface of virgin blend and the blend doped with different concentrations of Li$_4$Ti$_5$O$_{12}$ NPs. As shown in Fig. 4a, the virgin film has a better crater and pore surface distribution due to the evaporation of THF solvent during the preparation process [18]. As a result, the charge carriers can be transported easily and quickly without the presence of the blocking phase [19]. Fig. 4b-g illustrates the distribution of Li$_4$Ti$_5$O$_{12}$ NPs inside the PVC/PMMA blend. It can be noticed that the pores are re-shape and disappearance owing to the presence of structural reorganizations after the incorporation of Li$_4$Ti$_5$O$_{12}$ NPs inside the blend. This behavior is nearly similar to the literature [17–19]. Also, the small white spots are dispersed on the surface of the blend with some agglomerations. By increasing the Li$_4$Ti$_5$O$_{12}$ NPs content the agglomerations are increased. In the case of Li$_4$Ti$_5$O$_{12}$ NPs = 0.8 wt.%, Fig. 4e shows a high agglomeration of the Li$_4$Ti$_5$O$_{12}$ NPs at the surface, which indicates a close state of saturation. These results are also correlated with XRD results.

3.3. FTIR analysis

To establish the interactions between PVC/PMMA matrices and Li$_4$Ti$_5$O$_{12}$ NPs, FTIR spectroscopy is a very important tool for this purpose. Fig. 5 illustrates the FTIR spectrum of Li$_4$Ti$_5$O$_{12}$ NPs. It can be observed that the band at about 3435 cm$^{-1}$ is attributed to O–H bending vibration mode [20], the band at 686 cm$^{-1}$ is due to Ti–O stretching vibration [20], and the shoulder at about 462 cm$^{-1}$ is assigned to the Li–O vibration [8]. Fig. 6 depicts the FTIR absorption spectra of virgin PVC, virgin PMMA, virgin blend, and the blend doped with different concentrations of Li$_4$Ti$_5$O$_{12}$ NPs. The bands of the virgin films are assigned and interpreted in light of the literature [21–24]. FTIR spectrum of the virgin PVC illus-

\[ \text{Size} = \frac{k \lambda}{\beta \cos \theta} \]
The wagging CH−1329 can be observed at 2951 cm\(^{-1}\). The band at 1430 cm\(^{-1}\) is attributed to the wagging of methylene groups in PVC. The bands at 1329 cm\(^{-1}\), 1249 cm\(^{-1}\), 1065 cm\(^{-1}\), and 959 cm\(^{-1}\) represent the \(–\text{CH}_2\) deformation, C–H rocking and C–C bonds, and trans C–H wagging group of PVC. The bands at 691 cm\(^{-1}\) and 630 cm\(^{-1}\) are attributed to the C–Cl stretching and cis C–H wagging vibrations. The FTIR spectrum of virgin PMMA shows the bands at 2994 cm\(^{-1}\) and 2948 cm\(^{-1}\) may be due to the stretching of \(–\text{CH}_2\) and \(–\text{CH}_3\) groups of PMMA. The bands at 1732 cm\(^{-1}\), 1444 cm\(^{-1}\), 1161 cm\(^{-1}\), and 1264 cm\(^{-1}\) may be attributed to the C=O stretching, CH\(_2\) stretching, absorption of \(–\text{OCH}_3\), and C–O–C stretching vibration mod of PMMA. Spectra of the films after adding \(\text{Li}_4\text{Ti}_5\text{O}_{12}\) NPs have some changes in band intensities and band positions (shift) as compared to that of the pure blend. This indicates the considerable interaction between the blend and \(\text{Li}_4\text{Ti}_5\text{O}_{12}\) NPs takes place. Also, the C–Cl stretching mode at 686 cm\(^{-1}\) for the pure blend indicates a decreasing in intensity with increasing amount of dopant. This implies that there is an interaction between Cl in the PVC with Li\(^{+}\) ion from the \(\text{Li}_4\text{Ti}_5\text{O}_{12}\) NPs as shown in the Scheme 1. The band at 1161 cm\(^{-1}\) due to OCH\(_3\) in the virgin blend is shifted to 1148 cm\(^{-1}\). The band at 1721 cm\(^{-1}\) due to C=O is shifted to 1732 cm\(^{-1}\). These shifts are expected to be due to the interaction between Li\(^{+}\) ion and the oxygen atoms in PMMA (Scheme 1).

### 3.4 UV/Vis analysis

Fig. 7 depicts the UV/vis. absorption spectra of the prepared virgin blend and blend/\(\text{Li}_4\text{Ti}_5\text{O}_{12}\) NPs in the wavelength range 190–800 nm at room temperature. The observed spectrum of virgin blend film has two absorption bands at 208 nm, which is mainly assigned as \(n→\pi^*\). While the absorption
Fig. 4 – SEM images of PVC/PMMA blend sample doped with: (a) 0.0, (b) 0.1, (c) 0.2, (d) 0.4, and (e) 0.8 wt.% of Li$_4$Ti$_5$O$_{12}$ nanoparticles.

band (shoulder) is observed at 278 nm, indicating the presence of unsaturated bonds of the type C=O, confirmed at about 1732 cm$^{-1}$ and assigned to π-π* transition [25,26], which is responsible for electrical conduction in the films. The main absorption band around 208 nm and the band at about 278 nm for all curves were shifted towards longer wavelengths with increasing Li$_4$Ti$_5$O$_{12}$ NPs content. This may be attributed to the complexation between the dopants and the polymer blend and the change in crystallinity [27].

The investigation of optical absorption provides information about the band structure of the organic materials. The process of light absorption occurs only when an electron moves from a lower to higher energy state through the absorption of specified energy in the form of photons. The types of possible electronic transitions can be determined by the changes in the absorbed radiation. A sudden change in the fundamental absorption can be defined as an absorption edge. The absorption is expressed in terms of an absorption coefficient (α) that represent the relative rate of decrease in light intensity given by:

$$\alpha = \frac{2.303 A}{d}$$

(2)

where (A) is the value of absorbance and (d) is the thickness of the sample [28]. The absorption coefficient of amorphous materials can be related to the energy of the incident photon as follows [29-31]:

$$\alpha h\nu = C(h\nu - E_g)^r$$

(3)

where $E_g$ is the optical energy gap, C is the band tailing parameter and $r=2$ for indirect electronic transition and $r=1/2$ for direct electronic transition in the k space.
Fig. 5 – FTIR spectrum of Li$_4$Ti$_5$O$_{12}$ NPs.

Fig. 6 – FTIR absorption spectra for virgin PVC, virgin PMMA, virgin blend, and the blend doped with different concentrations of Li$_4$Ti$_5$O$_{12}$ NPs.

Scheme 1 – Possible mechanism of hydrogen bond formation between PVC/PMMA polymer blend and Li$_4$Ti$_5$O$_{12}$ NPs.

Fig. 7 – UV/vis. absorption spectra of prepared blend before and after doping with different mass fractions of Li$_4$Ti$_5$O$_{12}$ NPs.

Fig. 8 – Variation between the calculated values of (a) indirect and (b) direct band gap versus the Li$_4$Ti$_5$O$_{12}$ NPs content.

Fig. 8 illustrates $(\alpha h\nu)^2$ versus $(h\nu)$ for virgin film and the film doped with Li$_4$Ti$_5$O$_{12}$ NPs. By the extrapolated linear part of the plot of $(\alpha h\nu)^2$ and $(h\nu)^{1/2}$ versus photon energy to $h\nu = 0$, the values of the direct and indirect band gaps are determined. The obtained values of direct and indirect band gap for the prepared films are listed in Table 1. It is showed that the direct and indirect band gap values are decreased after the incorporation of Li$_4$Ti$_5$O$_{12}$ NPs as compared to that of the virgin blend. This can be explained in light of the charge transfer complexes (CTC) occurring between Li$_4$Ti$_5$O$_{12}$ NPs dopant and the PVC/PMMA blend and may be due to the formation of defects in the polymeric chain resulting in the localized states in the energy gap [8,32]. These localized states overlaps and broadens with increasing the Li$_4$Ti$_5$O$_{12}$ NPs content [13]. Hence, the degree of disorder of the virgin polymer increases by doping...
in the conductivity is interpreted based on the free volume theory [33], where this improvement can be attributed to the thermal movement of polymeric chains and the dopants dissociation as a result of the temperature effect. Further, the movement of segments in the polymer chain either provides a pathway for the Li-ions to move easily in amorphous regions and/or permits the Li-ions to hop from one site to another. As shown in Fig. 9, the dependence of $\sigma_{DC}$ on the reciprocal of the temperature for all the prepared films follows the Arrhenius equation given by [34]:

$$\sigma = \sigma_0 \exp\left(-\Delta E_a / k_B T\right)$$

(5)

where $\sigma_0$ is the pre-exponential factor, $\Delta E_a$ is the activation energy, $k_B$ is the Boltzmann constant and $T$ is the absolute temperature. From the estimated values of the slope and the intercept of the straight lines in Fig. 9, the activation energy ($\Delta E_a$) and pre-exponential factor ($\sigma_0$) can be determined. Fig. 10 shows the variation of pre-exponential factor and activation energy versus Li$_4$Ti$_5$O$_{12}$ NPs with the content of Li$_4$Ti$_5$O$_{12}$ NPs. It can be seen that the $\Delta E_a$ values are decreased while $\sigma_0$ values are increased with increasing Li$_4$Ti$_5$O$_{12}$ NPs content. This indicated that higher ionic conductivity is due to the amorphous region in the polymer matrix. Besides, the adding of Li$_4$Ti$_5$O$_{12}$ NPs disrupts the interaction between the Li$^+$ and the polymer backbone. Consequently, less energy is required to reform and break the coordination bond in the polymer matrix. As a result, ion diffusion is favorable during the hopping process [18].

Furthermore, the presence of double-bond segments (detected by FTIR analysis) in the present system are considered as suitable sites for polaron and/or bipolarons creation in the polymeric nanocomposite. The modified interpolaron hopping model of Kuivalainen et al. [35] is used to explain the present conductivity results as follows:

$$\sigma = \frac{Ae^2}{KT} \frac{\gamma_p \gamma_{hp}}{\left(\gamma_p + \gamma_{hp}\right)^2} \exp\left(\frac{-2BR}{\zeta}\right)$$

(6)

with Li$_4$Ti$_5$O$_{12}$ NPs. This result is in good agreement with the XRD analysis result.

### 3.5. DC conductivity

The values of DC conductivity were obtained from the following equation:

$$\sigma_{DC} = \frac{L}{RTA}$$

(4)

where $L$ is the thickness of the sample, $R$ is the resistance, which directly measured as a relation with an increase of temperature, and $A$ is the surface area. Fig. 9 illustrates the plot of log ($\sigma_{DC}$) versus (1000/$T$) of the virgin blend and blend/Li$_4$Ti$_5$O$_{12}$ NPs. It can be observed that the values of $\sigma_{DC}$ are gradually increased with increasing the temperature for all films and the behavior of conductivity does not display any peaks with increasing temperature. The estimated values of conductivity are changed from $1.68 \times 10^{-11}$ S/cm of the virgin film to $6.29 \times 10^{-9}$ S/cm of the doped films at room temperature and at a higher temperature from $1.54 \times 10^{-10}$ S/cm of the virgin film to $2.39 \times 10^{-7}$ S/cm of the doped films. These results suggest that the Li$_4$Ti$_5$O$_{12}$ NPs is a good filler to enhance the electrical conductivity of PVC/PMMA films. This enhancement

### Table 1 – The calculated values of direct and indirect band gap for the prepared films.

<table>
<thead>
<tr>
<th>Li$_4$Ti$<em>5$O$</em>{12}$ NPs wt.%</th>
<th>$E_g$ (eV)</th>
<th>$E_g$ (eV)</th>
<th>$E_g$ (eV)</th>
<th>$E_g$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>$E_{g1}$</td>
<td>$E_{g2}$</td>
<td>$E_{g1}$</td>
<td>$E_{g2}$</td>
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<tr>
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<td>1.84</td>
<td>3.38</td>
<td>4.81</td>
<td>3.69</td>
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Fig. 9 – Plot of log ($\sigma_{DC}$) versus reciprocal absolute temperature (1000/$T$) of the virgin blend and blend/Li$_4$Ti$_5$O$_{12}$ NPs.

Fig. 10 – Variation of pre-exponential factor and activation energy versus Li$_4$Ti$_5$O$_{12}$ NPs.
where, \( A = 0.45 \), \( B = 1.39 \), \( R_i \) is the typical separation between impurities, \( y_p \) and \( y_{bp} \) are the polaron and bipolaron concentration \([36]\), respectively, \( \zeta = (\zeta_1\zeta_2)^3 \) is the average decay length of a polaron and bipolaron wave function, \( \zeta_1 \) is the decay lengths parallel and \( \zeta_2 \) is the decay lengths perpendicular to the polymer chain, respectively. Bredas et al. \([37]\) explained that polaron and bipolarons induce defects of the same extension. The rate of electronic transition between the states of polaron and bipolaron is given by \([37]\):

\[
\gamma(T) = 1.2 \times 10^{12}(T/300K)^n
\]  

(7)

where \( n \) is a constant \( \approx 11 \). The order of magnitude of \( \sigma \) for the prepared films was determined by using a computer-based program and adjusted with a fitting parameter. The estimated parameters of \( \zeta_1 \) and \( \zeta_2 \) are found to be 1.06 and 0.22 nm, respectively. This result depends on the interchain distance and the interchain resonance energy \([38]\). By using Eq. (6) and (7), the values of the hopping distance \( (R_b) \) are calculated. Fig. 11 illustrates the variation of \( R_b \) versus \( Li_4Ti_5O_{12} \) NPs content at various temperatures. It can be observed that the \( R_b \) is linearly decreased with increasing the temperature for the various concentrations of \( Li_4Ti_5O_{12} \) NPs. This evidences the concentration of thermally activated polaron and/or bipolaron (act as hopping sites for the charge carriers) increase with increasing the temperature. The estimated values of \( R_b \) are in the range of 1.4–5.6 nm for the virgin film and the doped film with 0.8 wt.% at a higher temperature. Considering the length of the monomer unit is 0.25 nm \([39]\), the evaluated average hopping distance between two sites is in the range of 5.6–22.40 times the monomer unit lengths. This suggests that the intrachain one-dimensional hopping conduction mechanism takes place \([40]\) and indicates the choice of \( Li_4Ti_5O_{12} \) NPs as dopants to enhance the electrical conductivity of PVC/PMMA films.

### 4. Conclusion

PVC/PMMA films doped with \( Li_4Ti_5O_{12} \) were prepared by ordinary casting technique. The prepared films were examined by using different techniques such as XRD, TEM, FTIR, SEM, and UV/Vis. spectroscopy. TEM images of \( Li_4Ti_5O_{12} \) NPs illustrate nano size with an average of 40 nm, cubic shape, and non-monodispersed. FTIR indicated the good complexation between the PVC/PMMA blend and \( Li_4Ti_5O_{12} \). XRD results showed that the addition of \( Li_4Ti_5O_{12} \) NPs can reduce the degree of crystallinity for the doped films. Optical measurements indicated the presence of a well-defined \( \pi \rightarrow \pi^* \) transition, which comes from unsaturated bonds, \( \text{C}=\text{O} \), and the optical band gap is decreased with increasing the \( Li_4Ti_5O_{12} \) NPs content. Moreover, it has been observed that charge transfer complexes are arising inside the prepared films. DC electrical conductivity depends on temperature as well as \( Li_4Ti_5O_{12} \) NPs dopants. The enhancement of DC conductivity was ascribed to an increase in the amorphous nature of polymer blend as well as the increasing of the mobile charge carriers of \( Li_4Ti_5O_{12} \). The obtained values of the energy gap and DC conductivity suggest that the prepared films with a high content of \( Li_4Ti_5O_{12} \) NPs can be used in lithium-ion battery and electronic devices.

### Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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