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*Original Article*

# Optical analysis of the electrospinning based polyvinyl alcohol (PVA) nanofibrous mats

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## Abstract

Aim of the present research is to examine the optical characteristics of the electrospinning based nanofibrous membranes or mats of polyvinyl alcohol (PVA). Influence of fiber shape and diameter on the transmission spectra obtained from these nanofibrous mats is investigated in detail in the spectral range from 400 to 800 nm. Optical properties and functionality of nanofibrous membranes are strongly dependent on the refractive index values of the membranes. Refractive index also plays a crucial role in understanding the structure and designing optically sensitive materials and devices. Hence, the present analysis is also targeted to compute and evaluate the refractive index of fabricated PVA mats, for better demonstration of these concepts.

**Keywords**: polyvinyl alcohol, nanofibrous mats, electrospinning, transmittance, refractive index

## 1. Introduction

Transparent polymer thin films are now the most utilized in the manufacture of optical devices, either when they are used in their pure form or when they are doped with other materials. The widespread adoption of these materials is due to their low cost, rapid production and high mechanical resilience. Solar cell (Herrero & Guillén, 2002), selective optical filter (Khalil, El-Sayed, Masoud, Mahmoud, & Hamad, 2021), thin-film organic lasers (Quintana, 2017) and Light-Emitting Diode (Kalyani & Dhoble, 2012) are devices that use films of this type. Concurrently, the optical properties of nanofiber polymer membranes or mats have gained a lot of attention over the past years, owing to the prospective uses in photonics, UV protection, and solar energy harvesting. The performance of these nanofibrous membranes on the basis of optical analysis critically relies on the structural features of these membranes, especially imperfections and distribution of fiber diameters (Damberga *et al*., 2020). When confronted with other methods, electrospinning is an easy and inexpensive approach for the production of nanofibers with an extensive array of organic polymers (Wang & Hsiao, 2016). There are a lot of beneficial characteristics of polymer nanofibers that can be modified and enhanced through the electrospinning process to address a specific application. This can be done by manipulating the process parameters like DC voltage, flow rate, and the gap between needle and collector, along with the factors conductivity and viscosity of the polymer (Kumbar, James, Nukavarapu, & Laurencin, 2008). Today, the most prominent polymer used is PVA, for the reason that it is admittedly unique in that it has water solubility, biodegradability, and non-toxicity. Additionally, in comparison to many other polymers, PVA stands out owing to its distinct abilities, which include better mechanical strength, oxygen barrier performance, transparency, and biocompatibility (Abdullah, Dong, Han, & Liu, 2019; Kim *et al*., 2018). Such features of PVA make it a worthy choice for fabrication of films, hydrogels, fibers, and other materials (Abral *et al*., 2020; Assaedi *et al*., 2019; Khalil, El-Desouky, Sobhy, & El-Mansy, 2023; Khan, Masroor & Rizvi, 2023; Wang *et al*., 2022; Wu *et al*., 2019).

In the last few years, the optical properties of PVA and their combination with nanoparticles or their composites

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have been the main interest of researchers. Charradi *et al*. (2022) discovered that the optical features of oxide PVA membranes are far better than those of pure PVA membranes. These membranes were found to be highly effective in the absorption of UV and visible light, with blue emission occurring at 415 nm, which suggests the possibility of their use in applications that require specific optical properties. In a different work, Rasheed, Hashim, and Abass (2023) incorporated silver nanoparticles in PVA nanofibers for optical characterization. They identified that the extinction coefficient, refractive index, and absorption coefficient were altered, and possibly these nanofibers could be used in solar cells. Ahmadpoor, Nateri, and Motaghitalab (2013) carried out research on PVA/TiO2 nanofibers and concluded that on increasing the diameter of fibers and the concentration of TiO2, the reflectance and lightness go down. This signifies that the reported work will be very useful in designing optical devices based on the accurate control and management of light. The study of Anitha and Natarajan (2015) revealed clearly that the composite membranes from PVA/ZnO were more effective than the pure membrane of PVA in blocking UV rays. Consequently, this investigation brings to light that the mats they made exhibited greater efficacy and manageability in light-protection applications. Furthermore, Kumar, Jain, Singh, and Dhakate (2020) were able to prepare nano-sized electrospun Eu+3/PVA composite fibers. These fibers showed a bright red flash at 724 nm when they were irradiated at 239 nm, which is an indication of uniform dispersion and the ability to be tuned. Moreover, the optical characteristics of electrospun nanofiber substrates, such as transmittance and reflectance, can be adjusted by modifying variables like fiber diameter, morphology, and packing density. Davis *et al*. (2009) provided an overview of these factors and emphasized the importance of controlling them to meet practical requirements for light management in nanofiber substrates.

Several works have been reported in which PVA is used to create thin films and mats for various applications, often in combination with other polymers and composites (Ali, Hassan, Emshary, & Sultan, 2020; Biju *et al*., 2024; Khan, Masroor & Rizvi, 2023). However, to the best of our knowledge, till todate, the literature is devoid of thorough studies that address the optical characteristics of pure polyvinyl alcohol (PVA) nanofiber mats or membranes made at different concentrations in solutions. Therefore, our study's focus is enticed by this identified gap in the academic literature. Although PVA fiber mats or membranes are widely used and have many applications, it is very important to advance our knowledge in understanding their optical behaviors, especially with regard to fluctuations in solution concentration. So, this endeavor aims to fill this knowledge gap and hopefully will make a significant and remarkable contribution in this regard, which will ultimately affect and influence a number of scientific and industrial fields.

The rest of the paper is organized as follows; Section 2 discusses the procedure for making the eleropspun nanofibrous PVA mats. Section 3 provides the results and discussion. This section is composed of three subsections that shed light on the morphology and diameters of the fabricated nanofibrous mats following the spectral and refractive index analyses, respectively. Finally, section 4 concludes the paper.

## **2**. **Fabrication of PVA Mats**

In this work we fabricate three different samples of PVA mats or membranes using electrospinning. These samples are differentiated on the basis of PVA concentration used in solution. Particularly, we made solutions of 6%, 10% and 15% of PVA by weight in distilled water by following a standard procedure (Khan, Mahmood, Raees, & Rizvi, 2021). Once the solution is prepared and stabilizes at room temperature, we start the electrospinning procedure for making PVA mats on aluminum foil. For this purpose, a high voltage of about 13kV is provided via a copper electrode linked to the syringe (containing solution) needle, with a feed rate of 0.01ml/h. This experiment utilizes the 5ml syringe with a needle diameter of 0.64mm. The distance between the needle and the collector is kept at around 120mm. Once the experiment starts, we make sure that the process continuous for 15minutes to create fiber on an aluminum foil sheet that serves as a collector. After that span of time, the apparatus is switched off, and the sample is ready for SEM and spectral analysis. Figure 1 shows the simplest setup of electrospinning. In our case we use cylindrical rotating drum with a constant 300RPM instead of a flat collector.

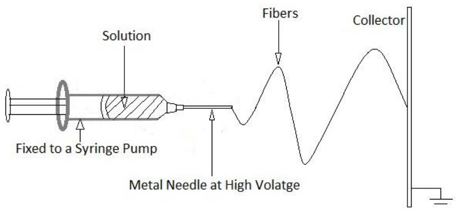


Figure 1. Basic electrospinning setup

## **3**. **Results and Discussion**

### **3**.**1 Morphology of the fabricated fibers**

Using a high-resolution scanning electron microscope (SEM), JEOL-SEM DEVICE, a thorough analysis of the morphology of PVA nanofiber was conducted. Figure 2 shows the SEM pictures of the three samples of PVA fibers fabricated at 6%, 10%, and 15% solution concentrations. From these scans we estimated that the fibers had average diameters of around 216 nm, 408 nm, and 872 nm in the above samples, respectively. The nanofibers didn't seem to align even though a drum collector was used throughout the electrospinning procedure. The reason behind this misalignment is the low-speed rotation mechanism that was inadequate to properly position the fibers into a uniform configuration (Bakar, Fong, Eleyas, & Nazeri, 2018). Furthermore, the size and shape of the nanofibers are closely related to the solution concentration used in the electrospinning process (Khan, Mahmood, Raees, & Rizvi, 2021; Kirecci, Özkoç, & İçoğlu, 2012). Our results also indicate that fibers with a reduced diameter are produced by lower solution concentrations. Conversely, bigger diameter nanofibers were produced at increased solution concentrations, suggesting a denser fiber network. Further, the upcoming subsections discuss in depth the impact of the morphology of these PVA fibers on their optical properties.

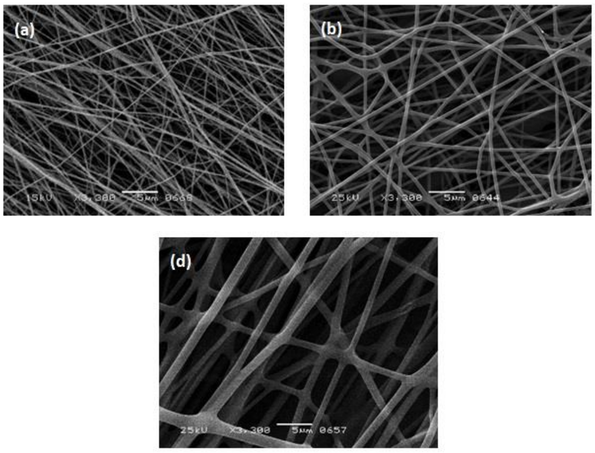


Figure 2. SEM images of the three types of samples made by using three alternative concentrations of PVA, namely (a) 6%, (b) 10%, and (c) 15%

## 3.2 Spectral analysis of pva fibers mats

All the spectral analysis in this work was done by using a spectrometer (Avaspec-2048-3-DT) that detects light of wavelengths between 325 and 1,100 nm. The graphical representation of wavelength (λ) against transmittance (T) along with absorbance (A) is displayed in Figure 3, which illustrates the spectral characteristics of the electrospun PVA mats or membranes created while utilizing the PVA at different concentrations in solution. To be more precise, transmittance and absorbance patterns for PVA mats composed of solution concentrations of 6%, 10%, and 15%, respectively, are shown in Figures 3(a), 3(b), and 3(c) covering the spectral range from 400 to 800nm. Considering all the three sample membranes, it is noteworthy that longer wavelengths exhibit the highest transmittances. As an example, the highest transmittance for the nanofiber mats made using a 6% solution concentration is 73%, while the peaks observed for the mats created from 10% and 15% solutions are at 78% and 90%, respectively. Furthermore, it is clear from Figure 3(b) and Figure 3(c) that the transmittance remains stable between 500 and 800 nm, whereas Figure 3(a) demonstrates a steady transmittance level above 670 nm. Distinct patterns at different wavelength intervals are also revealed by a thorough examination of transmittance. For instance, transmittance increases by a noteworthy 20% between 400 and 455 nm (see Figure 3(a)). This elevated level lasts until around 635 nm, after which it rises by an additional 8% until the wavelength of 650 nm is reached. On the other hand, Figure 3(b) depicts a roughly 13% increase in transmittance between 415 and 475 nm, after which the transmittance curve stays mostly steady. However, Figure 3(c) indicates a nearly 5% decrease for the early wavelength region (400 to 520 nm), before reaching a constant transmittance level. Therefore, it reveals that the PVA nanofibrous mats created from using the highest solution concentration has the most consistent transmittance throughout a wide wavelength range (520 nm to almost 800 nm) when compared to the other two cases from less concentrated PVA.

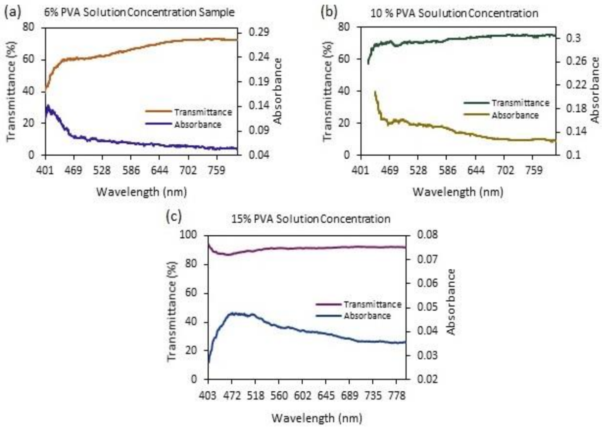


Figure 3. Transmittance and absorption curves for the three types of fabricated mats

In addition to that, the patterns in transmittance that have been seen for the fabricated electrospun membranes at various PVA solution concentrations offer important new information on the optical characteristics of electrospun membranes and their possible uses. Longer wavelengths exhibit an increase in transmittance, which points to these mats' advantageous optical behavior in the visible spectrum. The molecular configuration of the polymer chains, the degree of crystallinity, and the existence of defects in the membrane structure are some of the aspects that might be responsible for this phenomenon. Furthermore, the uniformity of transmittance within wavelength ranges suggests the possibility of consistent optical performance throughout a broad spectrum, especially in mats with greater PVA concentrations. These outcomes emphasize the significance of PVA solution concentration in adjusting the optical properties of electrospun PVA membranes for particular applications, while also furthering our understanding of the optical properties of these nanofibrous mats. Additionally, according to earlier studies (Bouzidi *et al*., 2020; Mahendia *et al*., 2011), pure PVA film has a constant high transmittance over the 400–800 nm spectral region, with average values of 90% and around 93%, respectively. It may be inferred from these results that mats with increased PVA concentrations have almost constant transmittance levels in this wavelength range. Our investigation also supports their findings only for the mats created from high solution concertation. But our results are clearly demonstrating a significant impact on this constant transmittance level as PVA concentration is decreased.

Finally, we can say that these electrospun mats have applications beyond their inherent optical qualities in the future. Further the outcome of this study might be helpful for the researchers to assess whether to further alter or enhance the optical properties of the already reported PVA and PVA/composite nanofibrous membranes or to fabricate new ones with better performance.

## 3.3 Refractive index analysis

The refractive index of the generated PVA mats from alternative concentrations are evaluated using the

Fresnel equations, which determine the relationship between incoming light and its transmission and reflection at a two-media interface. The transmittance and reflectance values are calculated using equations (1) and (2).

$$T = \frac{4n}{n + 1} \qquad (1)$$

$$R = \frac{n - 1}{n + 1} \qquad (2)$$

To analyze the refractive index of produced PVA mats, the experimentally obtained transmittances and reflectances are analyzed, together with calculated transmittance and reflectance values. For this purpose, an objective function is defined such that it assessed the difference between the estimated and observed values. Furthermore, refractive index values are computed and adjusted repeatedly utilizing optimization approaches to reduce errors or mismatches in the calculated results and effectively fitting the model to the experimental data. For every pair of transmittance and reflectance measurements, this iterative method is repeated. In this way, we assessed the variation in the refractive index to explore the optical characteristics of PVA mats. All the computational assessment in this work is based on Python software, which provides efficient and adaptable data processing and optimization capabilities. Figure 4 shows the plots of wavelength verses estimated refractive index for the three fabricated nanofibrous mats made from PVA of different concentrations.

Refractive index values of the three PVA nanofibrous mats made at different solution concentrations, specifically, 6%, 10%, and 15%, show significant differences. A visual inspection of Figures 4(a), 4(b), and 4(c) clearly reveals a dispersion in the refractive index values from 1.57 to 1.48, 1.62 to 1.49, and 1.308 to 1.335 for the three respective cases of PVA mat. The refractive index dispersion seen in Figures 4(a) and 4(b) is 0.09 and 0.13, respectively. On the other hand, the mats produced with the highest tested PVA content shows the lowest variation in refractive index of 0.027 in the spectral range of 400–700 nm. Interestingly, the fiber mat made with the 10% PVA solution shows a greater dispersion than the other two fabricated membranes. A dispersion of 0.09 in the refractive index of PVA film is also reported in (Bouzidi *et al*., 2020).

The size of the nanofibers inside the mats is one of the possible causes of the observed variances in the refractive indexes of the three different samples of PVA mats. Another way of saying it is that the solution concentration variations during the electrospinning process are going to affect the nanofiber size distribution and morphology that eventually control the optical properties of the final mats. Furthermore, different packing densities and fiber diameters often cause changes in light absorption and scattering, which in turn lead to refractive index fluctuations.

Finally, this part's results summarize how the refractive index values are the most sensitive parameters of the PVA electrospun mats or membranes affected by solution concentration and by the nanofiber composition. It can be inferred that future research will be more about the development of a fabrication process for achieving the required quality of the fiber mat through process optimization.

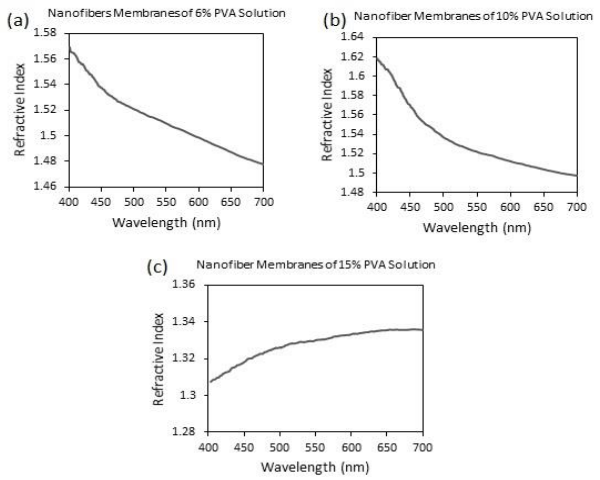


Figure 4. Dispersion in the refractive index for each fabricated PVA mat

Additionally, exploring the possibility of new methods or additives might broaden the role of these electrospun PVA membranes in the optics industry.

## 4. Conclusions

The current work was aimed at establishing the transmittance spectra of PVA thin mats produced by electrospinning using three different solution concentrations. The results demonstrated that the mats performed differently, especially in the region of visible wavelengths; the lower the solution concentration for making the mats was, the more pronounced was this effect. Similarly, the refractive index of PVA mats was computed and analyzed in detail in order to get a better understanding of the optical properties of the mats. The described results allow us to better understand the optical properties of PVA-based materials and give us the opportunity to explore their potential in different types of applications.

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