

Article

Development and Testing of Zinc Oxide Embedded Sulfonated Poly (Vinyl Alcohol) Nanocomposite Membranes for Fuel Cells

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Abstract: The sol-gel technique was adopted to synthesize the zinc oxide (ZnO) nanoparticles. Nano-sized ZnO particles are embedded in-situ to the poly(vinyl alcohol) (PVA) matrix to form the nanocomposite polymeric membranes. The nanocomposite membranes were fabricated by varying concentration of ZnO nanoparticles of 2.5, 5, and 10 wt.% in the base PVA membrane matrix. The membranes were crosslinked using tetraethyl orthosilicate (TEOS) followed by hydrolysis and co-condensation. Immersion in a 2 molar sulphuric acid (H₂SO₄) bath produced sulfonated membranes. The membranes were characterized using Fourier transform infrared (FTIR) and scanning electron microscopy (SEM). The fabricated nano-composite membranes are being evaluated for proton exchange membrane fuel cell research (PEMFC). The computed test results demonstrate that increasing the concentration of ZnO in the membrane increased the ionic exchange capacity and proton conductivity efficiency of the nano-composite membranes. The incorporation of a quantum quantity of ZnO particles in the membrane improved the presentation in terms of proton conductivity characteristics. Membranes demonstrated excellent proton conductivity (10^{−2} S cm^{−1} range) while consuming less hydrogen gas. The highest measured proton conductivity is observed for 10 wt.% ZnO embedded PVA membrane and the value is 15.321 × 10^{−2} S cm^{−1} for 100% RH. The combination of ZnO and PVA nanocomposite membrane is a novel, next-generation eco-friendly method that is economical and convenient for large-scale commercial production in fuel cell applications.

Keywords: proton exchange fuel cell; Poly(vinyl alcohol); ZnO nanoparticles; nanocomposite

1. Introduction

The consumption of energy for domestic and industrial utility across the globe has been elevated dramatically. It has been estimated that the energy consumption will be raised up to 56% in the year 2040 and the reason behind this rise is modernization factors such as huge quantity of urbanization and uncontrolled population growth. This ends up with an overburden of the energy demand. To address this severe difficulty, alternative energy generation technologies have emerged in recent years. Among the newer technologies that have emerged in recent years, fuel cell (FC) is found to be most promising [1]. FC technology is believed to be as efficient in current generating and it provides clean energy for domestic applications, automobiles and portable power generator tools in the 21st century [2–5]. On a basic level, an FC is an electrochemical power generating instrument

that instantly turns the chemical energy fuel (such as hydrogen, natural gas, methanol, ethanol, etc.) into electric energy with water and heat as byproducts as long as fuel and oxidizing agents are provided [6]. Using liquid fuels such as methanol and ethanol in FCs reduces the need to build entirely new substructures, since it is required when using hydrogen as a fuel source [7]. It is worth quoting that, currently, bioethanol dominates the global biofuel production capacity and can be produced in bulk from biomass feedstocks via a fermentation process [8,9]. Despite global reforms to decrease greenhouse gas (GHG) discharges in several sectors, emissions from the transportation sector, in particular, have increased dramatically in recent years. The share of total carbon dioxide emissions attributed to road transportation in the European Union (EU) increased from 16% in 1990 to 26% in 2018, with road transportation emissions increasing by 24% while net emission decreased by 23% [10]. As a countermeasure, many states have adopted strategies for total zero-emission public vehicle sales goals [11]. Working towards the zero emission target, from the beginning of 2035, the EU has projected a ban on new hydrocarbon fuel origins such as petrol and diesel cars to accelerate the transition [12]. Furthermore, automobile manufacturers in the EU, particularly truck manufacturers, need to reduce emitted CO₂ from new trucks by 30% by 2030 compared to levels in 2019–2020 [13,14]. In this regard, fuel cell technology is regarded as an alternative energy source. This generates clean and environmentally friendly fuel.

The resources employed in synthesizing the polymer electrolyte membranes, also known as PEMs, can be categorized into five different groups, namely, (1) partially-fluorinated polymers, (2) perfluorinated ionomers, (3) non-fluorinated polymeric membranes with aromatic backbones (4) non-fluorinated hydrocarbons, and, (5) acid-base complexes [15–17]. Several inorganic species have been used as fillers in various polymeric membranes developed to use proton exchange membrane fuel cells (PEMFC). Among various approaches applied to blending, incorporating inorganic fillers into polymer matrix, an in situ method and sol-gel synthesis route [18,19], have gained more attention due to their extensive accessibility.

The amalgamation of inorganic particles/fillers in organic polymeric membranes (inorganic-organic hybrid membranes) has exploited a noteworthy arrangement of awareness over the last few years. The reason behind it is that the induced persuasion of the inorganic and organic phases towards proton conductivity and stability of the membrane, apart from this cost effectiveness, possesses better water retention by means of crosslinking and also hindering fuel crossover by enhancing the transport pathway tortuousness. By considering the above points, the authors developed nanocomposite membranes and tested for PEMFC.

Several researchers [20–22] have investigated the tunable characteristics of PVA nanofiber membranes and enhanced their capability to filter gaseous substance and aqueous substances. Most studies, however, have focused on increasing the hydrophilicity of PVA electrospun membranes rather than their lipophilicity. Increasing the lipophilic properties of PVA membranes can aid in the removal of harmful substances from oil or the separation of oil and water [23]. The combination of ZnO with crosslinked sulfonated PVA in the evaluation of fuel cell application is a novel approach and is not reported elsewhere. In the current study, the performance of nano-sized ZnO was evaluated by embedding in the base PVA membrane matrix with varying ZnO nanoparticles concentration and measuring fuel cell performance. The fuel cell tests were carried out on the prepared hybrid membranes. This article will discuss fillers and their effects on proton conductivity, mechanical and thermal properties, and fuel cell performance, resulting in modified nanocomposite membranes.

2. Experimental

2.1. Materials

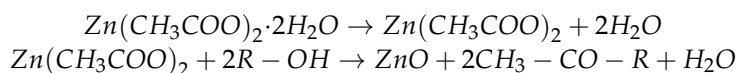
Polyvinyl alcohol (PVA) of viscosity: 54.0–66.0 mPa s^{−1} and Tetraethoxysilane (TEOS, >98%) were supplied by Sigma-Aldrich. Zinc acetate dihydrate (Zn(CH₃COO)₂·2H₂O),

HCL, and ammonia (NH₄OH) were purchased from s.d. Fine Chemicals, India. All the chemicals taken for the experiment were of reagent grade. Two stage distilled water has been used during the course of experiment.

2.2. Synthesis of ZnO NP's by Sol-Gel Method

A 0.6 M Zn(CH₃COO)₂·2H₂O solution was prepared by mixing 13 gm of zinc acetate in methanol and stirring constantly at room temperature to obtain homogeneity. To obtain a transparent sol, the solution was stirred at 600 rpm for 2 h at 80 °C. The pH of the sol was adjusted by adding NH₄OH between 9 and 11. After fine-tuning the pH, the sol was dried out at 100 °C for 2 h. Following this step, the temperature was raised to 200 °C until gelatin formation occurred. The precipitate was curdy white in color, and the sol was filtered off, washed with methanol several times, and finally dried at 250 °C. Once dried, the sol was calcined in a muffle furnace at 500 °C for 4 h. The temperature in the furnace was increased with a ramp rate of 2 °C. The resultant white colored powder was zinc oxide nanoparticles. The obtained product was weighed and found to be 3.75 g.

The desertion of water followed by the respective disintegration of zinc acetate was carried out in the reaction. According to the literature, ZnO crystallization occurs at around 250 °C via the following reaction [24,25]:



2.3. Preparation of Crosslinked Nanocomposite Membranes

PVA (6 g) was made soluble in 95 mL of water by stirring continuously at a temperature of 70 °C until the solution became clear and homogeneous. Known weights of synthesized ZnO nanoparticles (2.5, 5, and 10 wt.% with gravimetric ratio to PVA) were suspended in 5 mL of water, sonicated for 90 min (Make: Aczet, Model: CUB), and then added to the prepared PVA solution. The solution was stirred for approximately 2 h to achieve a homogeneous solution; a light white-colored solution was obtained. In the reaction vessel, 0.5 g of TEOS and 4–5 drops of HCl were added as a catalyst, and the solution was vigorously stirred at 70 °C for 6 h. The resulting mixture was then slowly dropped onto a dry and clean glass surface using a membrane applicator (Elcometer, Model: 3580) to obtain nanocomposite membranes with uniform thickness. The casted membranes were dried in a dust-free environment at room temperature before being peeled off the glass surface and properly stored. Figure 1 depicts a schematic diagram of the nanocomposite membrane.

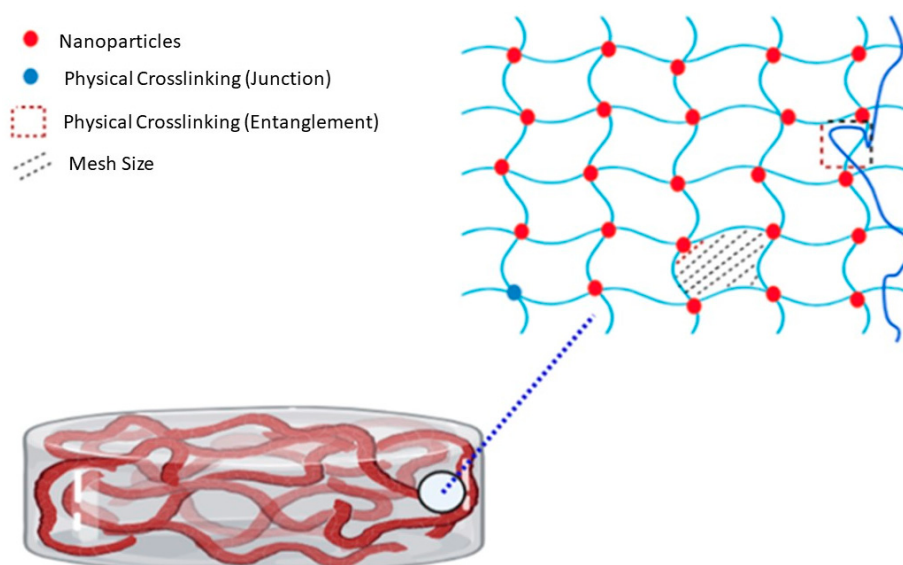


Figure 1. Schematic diagram of nanocomposite polymeric membranes.

2.4. Sulfonation of the Membranes

The prepared membranes were soaked in to the 2 N H₂SO₄ solvent bath overnight. During this period, the ion exchange took place by SO^{−4} exchange onto the surface of the nanocomposite membrane. This facilitated the subsequent ion transfer in proton exchange. The hybrid composite membranes are named as M_1, M_2 and M_3, containing 2.5, 5, and 10 wt.% of ZnO, respectively. Table 1 shown the naming of the nanocomposite membranes with their varying ZnO concentration.

Table 1. Naming of the PVA nanocomposite membranes with varying ZnO concentration.

Sl. No.	ZnO (gm)	ZnO (%)	Name
1	0.15	2.5	M_1
2	0.3	5	M_2
3	0.6	10	M_3

2.5. Membrane Characterization

2.5.1. Fourier Transmission Infrared (FTIR) Spectroscopic Studies

FTIR spectra were taken for pristine PVA membrane and ZnO nanoparticle-incorporated PVA membrane. The membranes were scanned to verify that the incorporated ZnO was impregnated in the molecular level using an FTIR spectrometer (Make: Shimadzu Model: IR Affinity-I). The membrane sample was thoroughly mixed with KBr until the mixture was homogeneous, and pellets were formed under the influence of a hydraulic pressure of 450 kg/cm². The prepared pellets were scanned between 400 and 4000 cm^{−1}.

2.5.2. X-ray Diffraction Studies

The powder X-ray diffractometer was used to investigate the solid-state morphology of synthesized ZnO. (Make: Siemens Model: D 5000). The Cu K α source generated X-rays with a wavelength of 1.5406 Å. The angle of diffraction, 2 θ was varied from 0° to 65° to identify ZnO nanoparticles and any changes in the crystal structure and intermolecular distances between the inter-segmental chains. To achieve a good result, the step-size for the 2 θ scan was 0.02°.

2.5.3. Scanning Electron Microscopy (SEM) Studies

SEM images of ZnO NPs were incorporated with PVA membrane and were taken crosslinked with TEOS. Before taking the images, the membranes were sputtered by gold to formulate the membrane becoming conductive and positioned on copper stub. Images were taken by using a scanning electron microscope (SEM) analyzer (Make: JOEL, MODEL: JSM 840A) at high resolution of Mag. 300X 5 kV. The operating voltage applied was 10–15 kV. At this applied voltage, the secondary electrons are generated near the surface of the sample and provide topographic information. The energy-dispersive analysis of X-ray (EDAX) embedded with FESEM at 15 kV was used to examine the surface morphology and chemical composition of the structures to examine the individual structure morphology and comprehend the growth dynamics.

2.5.4. Measurement of Particle Size

The particle size of completely dried ZnO was measured on a Zetasizer with a sample adapter (Model 3000HS, Malvern, UK). Before placing the particles on a cuvette holder, they were dispersed in distilled water and the zeta average diameter of the ZnO particles was measured. To avoid contamination, the sample cuvette was thoroughly washed shortly after the measurement. The average particle size was calculated after measuring the particle size three times.

2.5.5. UV-Visible Analysis

A Shimadzu UV spectrophotometer was employed in the measurement of the interaction of the polymer and nanoparticles to confirm the formation of nanocomposite. The UV-visible spectrum in a quartz cuvette was measured using a UV 1800 UV-Vis spectrophotometer (Japan). Between 200 and 800 nm, the PVA solution and ZnO-embedded PVA samples were examined.

2.5.6. Mechanical Properties

Plain PVA and sulfonated ZnO-loaded PVA membrane were tested for mechanical properties by means of universal testing machine (UTM) (Make: Hounsfield, Model H 25 KS, UK) containing operational load head with capacity of 5 kN; the test method is followed as per the protocol of ASTM D-638. Cross sectional area of the membrane of fixed thickness and width was computed. The strips of membrane were fixed between holders of the measuring device. The measuring length was fixed exactly at 5 cm, while the testing speed was set at 5 mm/min. Tensile strength of the membranes was computed by the (1) [26]:

$$\text{Tensile Strength} = \frac{\text{Max Load}}{\text{Cross Sectional Area}} \quad (1)$$

2.5.7. Ion Exchange Capacity (IEC)

The ion exchange capacity of the prepared membranes was measured using acid-base titration. The extent of crosslinking and the ion exchange capacity (IEC) of the polymer were calculated. The overall number of functional groups in the polymer prior to and after the crosslinking reaction is represented by the IEC value. This gives a clear picture of the extent of crosslinking. In fact, IEC denotes the number of mill equivalents of ions contained in 1 g of dried-up polymer [27]. The ion exchange capacity was calculated using the Formula (2):

$$\text{IEC} = \left(\frac{(B - P) \times 0.1 \times 5}{m} \right) \quad (2)$$

where: The normality of H_2SO_4 is indicated by 0.1, B indicates H_2SO_4 for blank sample neutralization, while P also denotes H_2SO_4 , but for copolymeric membrane neutralization.

-Number 5 indicates the factor corresponding to the ratio of the amount of NaOH consumed to dissolve the polymer to the amount used for titration and

- m is the weight of the polymeric sample in g.

2.5.8. Fuel Cell Measurements

On the anode and cathode sides, the nanocomposite membranes were mounted between Toray carbon sheets charged with platinum (Pt) as catalyst and containing $0.5 \text{ mg Pt cm}^{-2}$ of loading ((10 wt. percent Pt)/Vulcan[®]), Electro Chem SA). The active membrane area measured is 4.8 cm^2 . The PEMFC operates at 50°C with a hydrogen flow rate of 0.15 L/min and a gas pressure of 98.066 kPa on one side and 0.3 L/min of air with a pressure of 98.066 kPa on the other. The relative humidity was kept at 75 percent, 90 percent, and 100 percent throughout the experiment. The values of proton conductivity (s) were calculated using the Formula (3) shown below.

$$\sigma = \frac{l}{R \times A} \quad (3)$$

where s is the proton conductivity (S/cm); l is membrane thickness (the distance between the electrodes) (cm); A is the active membrane area or surface area to conduct the proton across the membrane (cm^2); R is the resistivity shown by the membrane (Ω).

The fuel cell assembly set-up is illustrated in Figure 2.

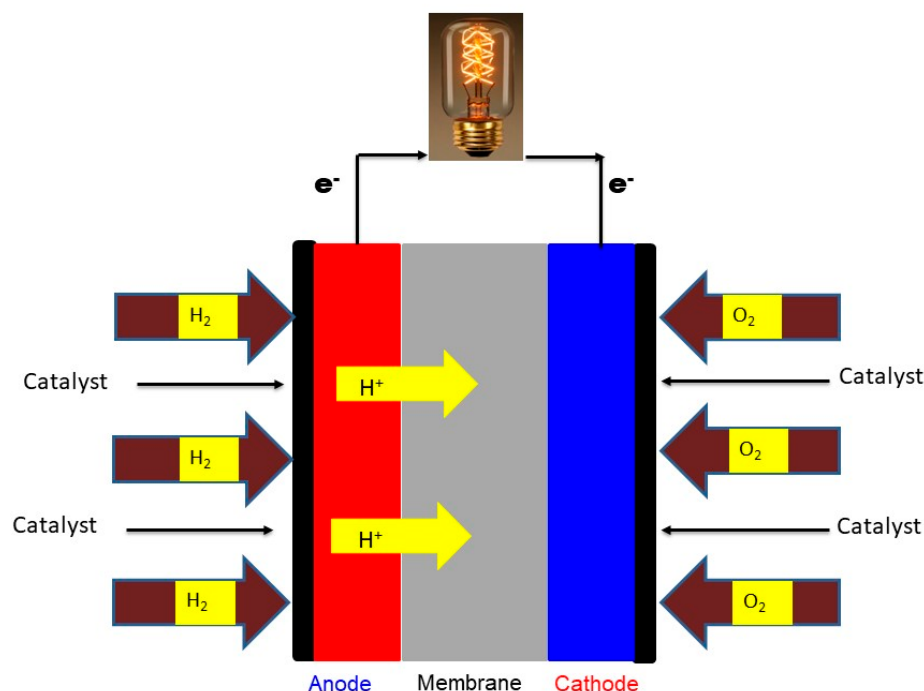
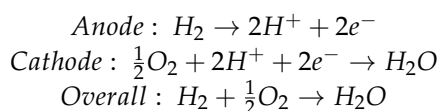


Figure 2. Fuel cell assembly illustration.

The reaction scheme of the fuel cell is given as below. The hydrogen gas was passed through the anode side and at cathode oxygen in the fuel cell, containing acidic electrolyte sandwiched between the cathode and anodic ends, the reaction occurred individually and the overall reaction is shown below,



3. Results and Discussion

3.1. Fourier Transform Infrared Spectroscopy Study

To understand the changes in modified membrane, FTIR analysis was performed. The FTIR spectra of PVA and ZnO-loaded PVA ranged from 4000 cm^{-1} to 400 cm^{-1} . The FTIR curves were shown in the Figure 3. In Figure 3(A), the peak 3400 cm^{-1} corresponds to the stretching of O-H, and the peak at 2937 cm^{-1} represents the asymmetric stretching of CH_2 bonds. The peak shown appeared at 1437 cm^{-1} , 1093 cm^{-1} , and 850 cm^{-1} , represents the stretching of C-C, and C-O groups present in the PVA moiety, respectively [28]. Figure 3(B) shows the ZnO-loaded PVA membrane. The peak appearing at 476 cm^{-1} represents characteristic absorption of metal-oxygen Zn-O stretching vibration band. This will confirm the typical impregnation of the ZnO in the base PVA matrix. The findings are consistent with those reported in the literature [29].

3.2. X-ray Diffraction Studies

An X-ray diffractometer (Make: Siemens, Model: D, 5000 powder) was used to investigate the solid-state morphology of synthesized ZnO. The XRD pattern for synthesized ZnO nanoparticles was shown in Figure 4. The wavelength of $1.5406\text{ \AA}$ X-rays produced by a Cu $\text{K}\alpha$ source was shown. The diffraction angle, 2θ was changed from 0° to 65° to better understand the crystal structure and intermolecular distances between the inter-segmental blocks. The prominent typical peak at $2\theta = 32^\circ$ – 37° represents the ZnO mixed planes (1 0 0) and (1 0 1) [30,31]. The peak intensity of the ZnO diffraction patterns decreased by about $2\theta = 47^\circ$. The Zinc oxide wurtzite structure could be assigned to all visible peaks

(JCPDS Data Card No: 36-1451). Zinc oxide crystallizes into two distinct phases: hexagonal wurtzite and cubic zincblende. At ambient temperatures, the wurtzite structure is the most stable available structure and common. It similarly confirms that the synthesized white powder was free from impurities because no XRD peaks other than zinc oxide peaks are visible [32].

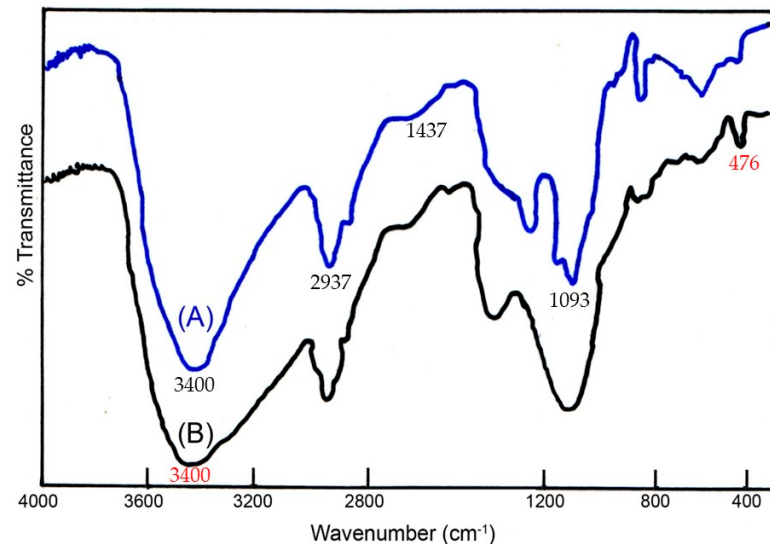


Figure 3. FTIR tracings of (A) Plain PVA and (B) PVA-ZnO membranes.

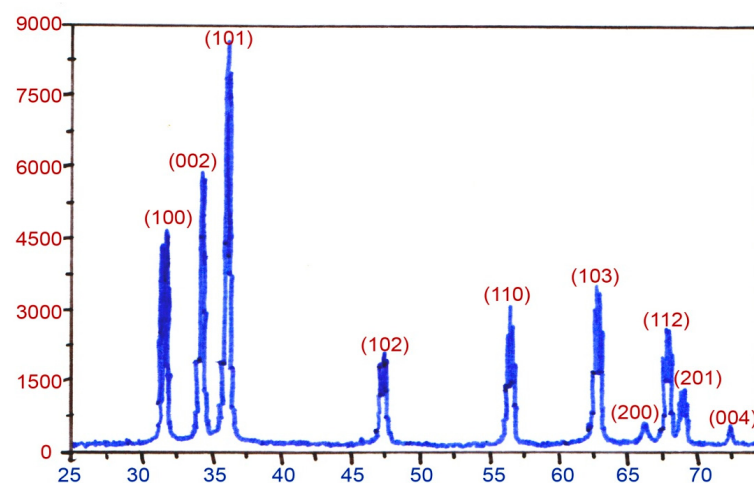


Figure 4. X-RD patterns of ZnO Nanoparticles.

3.3. Scanning Electron Microscopy (SEM) Studies

To understand the surface morphology of the pristine and modified membrane and to confirm the nanoparticles, SEM analysis was carried out. SEM micrographs of the pristine and nanocomposite PVA are shown in the Figure 5. SEM images of sulfonated crosslinked plain PVA and sulfonated ZnO nanocomposite membranes were taken. The films were nonconductive in nature; hence, gold sputtering (thickness of 15 nm) was performed on the samples. Figure 5A shows the pristine PVA membrane, it is observed uniform and Figure 5B depicts a hybrid membrane of PVA-ZnO nanoparticles, and it was discovered that the ZnO nanoparticles were dispersed across the membrane segments [33,34].

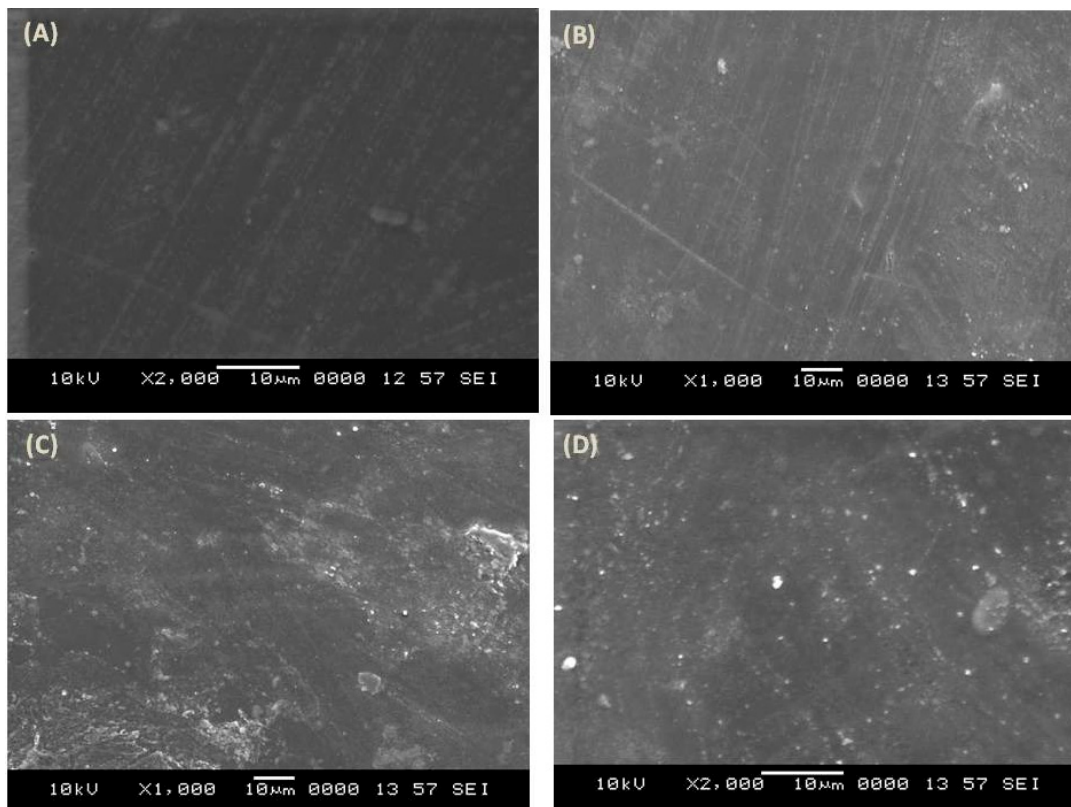


Figure 5. SEM images of (A) Plain PVA, (B) PVA-ZnO-2.5%, (C) PVA-ZnO-5 and (D) PVA-ZnO-7.5% membranes.

Figure 6 depicts the SEM image of ZnO NPs. The SEM image clearly shows that the synthesized ZnO is on the nanoscale and uniform in size. The SEM image revealed that the majority of the nanoparticles are spherical and nearly uniform in shape.

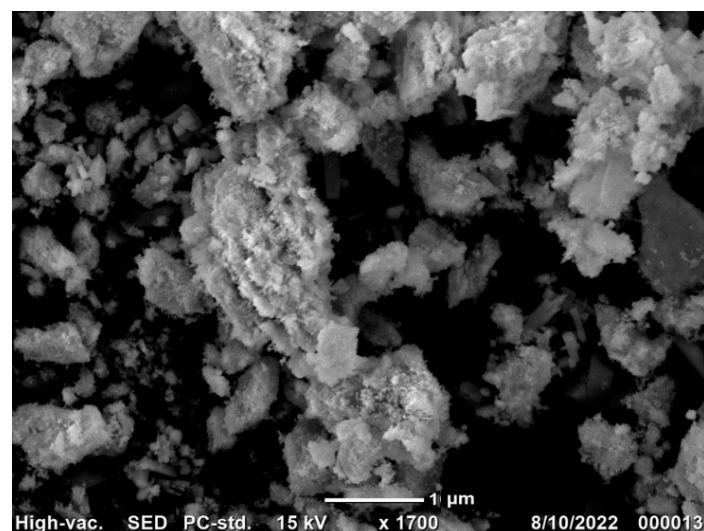


Figure 6. SEM images of ZnO nanoparticles.

3.4. Composition

Figure 7 depicts the EDAX profile of ZnO NPs structures grown under optimized substrate temperature and solution quantity. The obtained atomic percentage ratio of Zn and O is about 0.6, indicating that the as-deposited ZnO NPs structures have an oxygen-rich

chemical composition. The structures, however, do not show any element other than Zn and O, revealing the chemical purity of as-deposited structures. As a result, the as-deposited ZnO NPs structures are pure ZnO in composition, but they are oxygen-rich in nature. The purity of the synthesized ZnO NPs was demonstrated by XRD studies and confirmed by composition analysis.

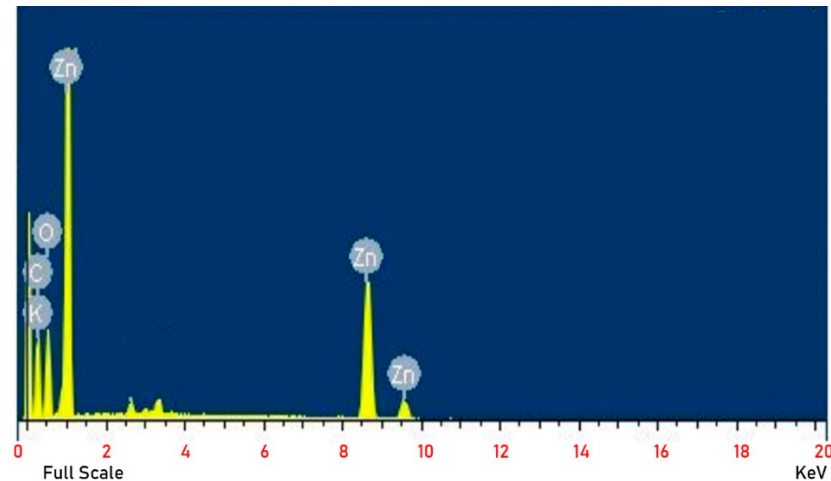


Figure 7. EDAX profile of ZnO nanoparticles.

3.5. Particle Size and Distribution Analysis

The Particle Size Distribution (PSD) analysis calculates and reports on the size and range of ZnO particles. The particle size distribution histogram is shown in Figure 8. The ZnO particles ranged in size from 55 to 90 nm. The average particle size was calculated to be 80 nm.

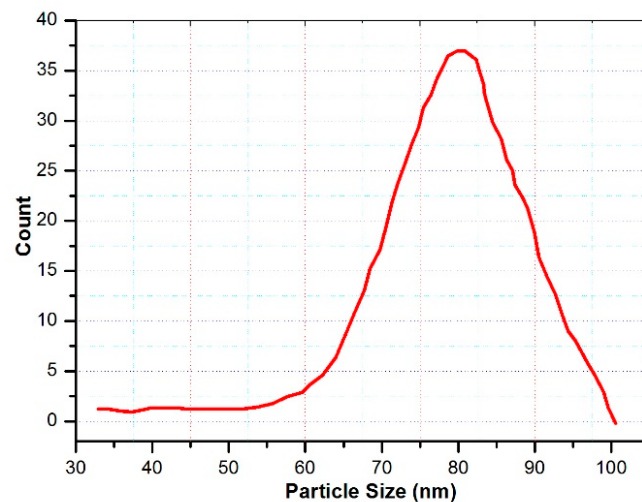


Figure 8. Histogram of the particle size distribution of ZnO nanoparticles.

3.6. UV–Visible Analysis

Because of surface plasmon resonance, the absorbance pattern of nanoparticles differs from that of their bulk counterpart, and the synthesis of nanoparticles is confirmed by UV–visible analysis. The UV–visible absorption spectrum of ZnO-NPs is depicted in Figure 9. The band changes are caused by zinc oxide nanoparticles exciting surface plasmon vibrations. The absorbance peak was located at 380 nm, indicating that zinc nitrate hexahydrate was reduced into ZnO-NPs [35–37].

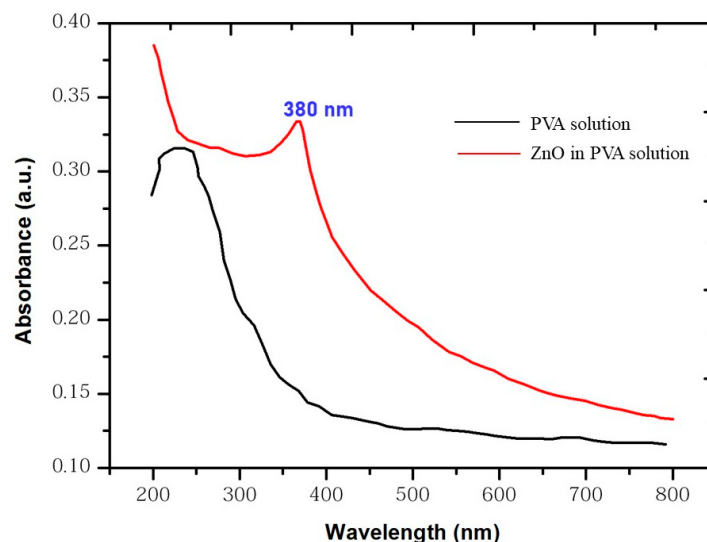


Figure 9. UV-visible spectrum of plain PVA solution and ZnO NPs embedded PVA solution.

3.7. Mechanical Properties

The primary goal of this research is to evaluate the mechanical stability of the prepared membranes because mechanical stability is one of the most important parameters to consider when performing a fuel cell analysis. Figure 10 depicts the mechanical strength of the membrane (pristine PVA, M_1, M_2, and M_3) in terms of tensile strength. As compared to the membranes tested for the tensile strength, M_3 performed the highest tensile strength value, i.e., $11.44 \pm 5\%$ MPa. While at the other side, the tensile strength of M-2 is found to be less than M_3, but the plain PVA membrane performed the slightest tensile strength with the value $4.93 \pm 5\%$ MPa. The obtained data reveal that with the incorporation of ZnO nanoparticles onto the PVA matrix, mechanical properties of PVA membranes are enhanced. The mechanical properties of the membranes were as follows: $M_3 > M_2 > M_1 > \text{plain PVA membrane}$. The enhanced tensile strength of ZnO-incorporated PVA is the result of pleasing physicochemical interactions between ZnO NPs and PVA matrix [38,39].

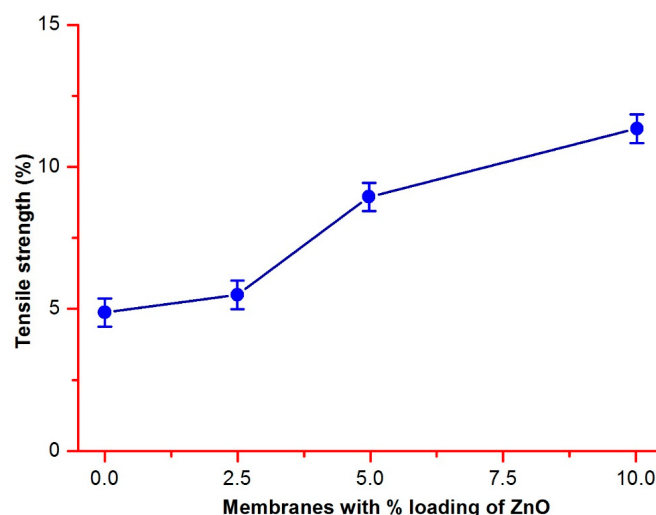


Figure 10. Mechanical Strength of the various prepared membranes.

3.8. IEC Results

Figure 11 depicts the results of testing the ion exchange capacity of plain PVA and crosslinked PVA membranes. Using IEC measurements, the amount of residual hydroxyl groups in the membrane before and after crosslinking was calculated. For IEC, the un-

crosslinked PVA membrane yielded 3.143 meq/g, while the crosslinked PVA membrane yielded 0.612 meq/g [39]. The IEC is similar to the sum of free hydroxyl groups present, and its value decreases after PVA crosslinking with TEOS. The results show that approximately 72 percent of the hydroxyl groups in the uncrosslinked PVA matrix were involved in the crosslinking with TEOS. Despite the presence of a few immobile hydroxyl groups, they cause ion diffusion across the crosslinked membrane.

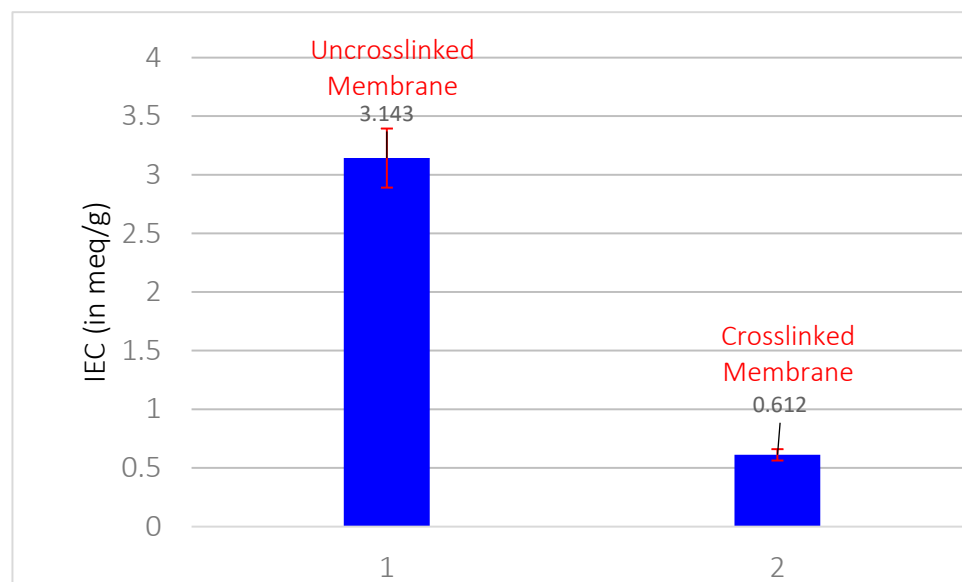


Figure 11. Ion exchange capacity of the plain and crosslinked membranes.

3.9. Fuel Cell Measurements

The prepared sulfonated ZnO-loaded PVA membranes, i.e., M_1, M_2 and M_3 were measured for fuel cell by employing hydrogen and oxygen gases. Proton conductivity curves are plotted and shown in Figure 12. The results after measuring the proton conductivity show that the nanocomposite membranes performed better as compared to its pristine membrane. The M_1 membrane showed $3.581 \times 10^{-2} \text{ S cm}^{-1}$ for 75% RH to $4.10 \times 10^{-2} \text{ S cm}^{-1}$. Whereas, M_2 showed 6.315 to $13.333 \times 10^{-2} \text{ S cm}^{-1}$ for 75% to 100% RH. M_3 showed the $8.143 \times 10^{-2} \text{ S cm}^{-1}$, $11.845 \times 10^{-2} \text{ S cm}^{-1}$ and $15.321 \times 10^{-2} \text{ S cm}^{-1}$ for 75%, 85% and 100% RH conditions, respectively. The results obtained say that the increase in humidity level and % incorporation of ZnO enhanced the conductivity of proton. As the % loading of the nanosized ZnO increased the proton conductivity of the membrane increased, and as a result the power generation maximized. The increased proton conductivity is attributed to the incorporation of the little amount of ZnO onto the PVA polymeric membrane. The reason behind this is the increased surface area due to the incorporation of nanosized ZnO in the PVA matrix, which resulted in the absorption of a greater number of H_2 and O_2 gas molecules at the anode and cathodic side of the surface of the membrane, resulting in the increased proton conductive activity.

Van der Waals force of attraction at the molecular level in the case of physisorption and residual chemical bonding in chemisorption are the primary causes of gas adsorption to a solid. In general, physisorption is assumed to occur due to van der Waals force of attraction, resulting in multilayer adsorption. The minimum energy principle states that molecular adsorption within the smallest energy range is always preferred, and molecular adsorption of the next energy level is possible. Adsorption can occur at any solid surface that can rapidly reach saturation without requiring any activation energy, and different gases can be adsorbed, though the content of the adsorbed gas varies greatly. This could explain the improved gas adsorption and proton conductivity of the membrane.

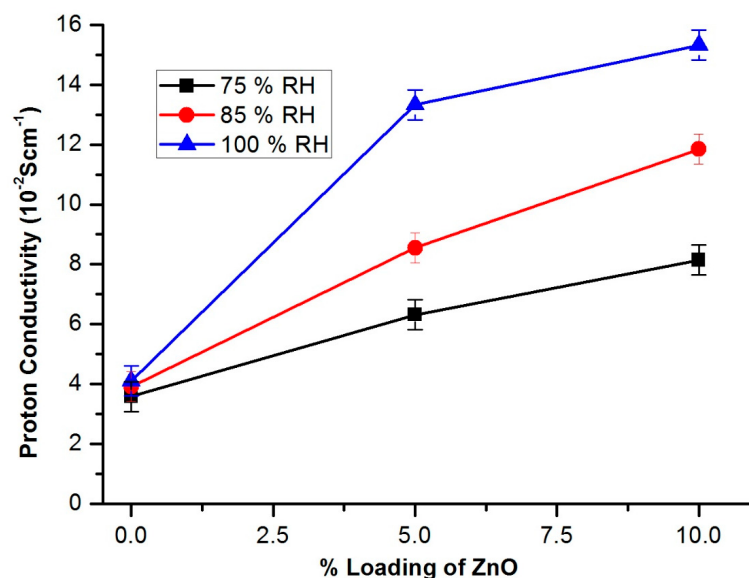


Figure 12. Proton conductivity curves for the various ZnO NP loaded membranes.

4. Conclusions

In this study, we investigated ZnO-filled PVA nanocomposite membranes and tested them for fuel cell measurement. This study's set of nanocomposite membranes had not previously been reported in the literature for fuel cell measurement. The prepared mixed matrix nanocomposite membranes studies demonstrated a factor of 2.5 to 10 effectiveness in fuel cell applications; even a small amount of ZnO can have a significant impact. The particle size analysis showed that the average ZnO particle size was 80 nm. The UV-Visible spectrophotometric study showed that the perfect nanocomposite has been formed between ZnO and PVA. FTIR study confirmed the incorporation of synthesized ZnO was embedded in the polymer matrix, and XRD study showed the typical nature of ZnO. SEM images revealed the surface morphology of the prepared films. The ion exchange capacity for the crosslinked membrane showed that 0.612 meq/g is less than the uncrosslinked membrane confirming that the crosslinking was successful. The mechanical properties of the ZnO-embedded nanocomposite membrane shown especially at 10 wt.% ZnO-embedded PVA matrix showed the highest tensile strength. The fuel cell measurement for the prepared membranes reached $15.321 \times 10^{-2} \text{ S cm}^{-1}$ at 100% RH. It was discovered that the prepared membranes were best suited for the fuel cell.

Author Contributions: Conceptualization, A.A.O. and M.B.P.; methodology, S.B.R. and S.N.M.; software, A.K.; validation, A.Y.P., M.K.A. and J.P.S.; formal analysis, A.M.A. and A.K.; investigation, A.A.O.; resources, M.B.P.; data curation, A.K.; writing—original draft preparation, A.A.O. and M.B.P. All authors have read and agreed to the published version of the manuscript.

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