MJPS, VOL. (12), NO. (2), 2025

Study The Dielectric Properties and Response of Nanofiber Composite polymer of PVA/Chitosan for different frequencies

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Received 17 Sep. 2025, Accepted 13 Oct. 2025, published 30 Dec. 2025.
DOI: 10.52113/2/12.02.2025/197-206

Abstract: This study investigates the dielectric frequency response and structural e ution of nanofiber composed polymer of polyvinyl alcohol (PVA) with with different concentrations of added chitosan (0, 10, 20, and 30) wt%. The dielectric properties are studies at the range frequency (10-1000) KHz. The measurement of insulation properties is represented by the real and imaginary parts of permittivity (ε′ and ε″), Capacitance (Cs), Impedance (Z), Dielectric loss tangent (tan δ), and alternating current conductivity (σ_ac). To characterize and calculate the diameters of the fabricated nanofibers, scanning electron microscopy (SEM) was used. In this study we found, The average diameters of pure PVA nanofiber was approximately (181) nm. Nanofibers with a 20% concentration exhibited a smaller diameter of approximately (75.7 nm). At a 30% concentration, the material demonstrated the most stable and enhanced electrical performance, including a high and consistent capacitance (~33 pF), a remarkably low dielectric loss (tan δ = 0.0013), and minimal impedance (<50 kΩ). Additionally, AC conductivity decreased as chitosan content increased from 1×10^{-11} S/m in pure PVA to 4.5×10^{-12} S/m at 30% concentration indicating reduced charge mobility due to structural entanglement. These findings highlight the crucial role of chitosan in improving the electrical characteristics of PVA-based composites, making them promising candidates for advanced dielectric applications.

***Keywords*: Chitosan, Dielectric behavior, Electrospinning, Nanofiber Composite, Polyvinyl alcohol.**

1. Introduction

Dielectric polymers represent fundamental segment of modern materials, recognized for their remarkable capacity to block electrical current and their versatile physical attributes. By impeding the passage of electricity, and protective surface treatments. Thanks to their chemical versatility, they these polymers play an essential role across numerous industrial sectors, particularly in electronics, energy storage systems, and protective surface treatments. Thanks to their chemical versatility, these materials perform reliably under changing environmental conditions such as temperature fluctuations, moisture exposure, and mechanical stress. Their strength as electrical insulators lies in their extremely low conductivity, high dielectric strength, and strong resistance to harsh chemical substances including concentrated acids, oxidizing agents, and organic solvents[1, 2]. These properties are rooted in their molecular architecture, which typically features abundant nonpolar segments or stabilized polar groups allowing them to preserve both mechanical stability and electrical efficiency even in demanding environments.[3]. This chemical resilience is particularly valuable in systems exposed to corrosive or high-energy compounds, such as industrial electronics and energy storage devices[4].

Among the most studied dielectric polymers are polyvinyl alcohol (PVA), chitosan (Cs), polyvinyl pyrrolidone (PVP), polyvinyl chloride (PVC), polyethylene oxide (PEO), and nylon. Polymers like polyethylene and polypropylene are widely used in cable insulation and dielectric membranes due to their low dielectric constants and high breakdown strength[5, 6].

Recent advances in nanotechnology have further enhanced these properties by incorporating inorganic fillers, resulting in polymer nanocomposites with improved energy density, thermal stability, and mechanical strength. These innovations have expanded the role of insulating polymers in high- tage systems, capacitors, and flexible electronics [7, 8].

Although dielectric polymers are gaining attention for their efficiency and reliability in energy storage, their relatively low energy density remains a challenge. Recent investigations aim to refine polymer mixtures and nanocomposite architectures to address existing limitations and introduce novel functionalities[9]. With the growing demand for efficient and eco-friendly insulating materials, composite polymer systems have emerged as promising alternatives that combine structural performance with biological compatibility[10]. One such system is the blend of polyvinyl alcohol (PVA) with chitosan, which offers a synergistic combination of flexibility, thermal stability, and electrochemical functionality making it suitable for advanced dielectric applications[11].

PVA is a synthetic, water-soluble polymer rich in hydroxyl groups, allowing the formation of flexible and uniform films[12]. Chitosan, a natural polymer derived from chitin, provides antimicrobial properties and reactive amino groups that enhance interfacial interactions[13].

Studies have shown that incorporating nanoparticles such as Al_2O_3 and V_2O_5 into PVA–Cs blends significantly improves their electrical, thermal, and mechanical properties, enhancing charge transport and structural stability under operational stress [14, 15].

This study aims to design and investigate electroactive nanofiber composites based on PVA and chitosan blends with varying chitosan ratios, to explore their dielectric behavior across the frequency range of 10–1000 kHz. Beyond analyzing relaxation dynamics and interfacial polarization, the research seeks to understand how biopolymer integration affects charge transport pathways and molecular mobility within the polymer matrix By bridging experimental dielectric analysis with sustainable material design, this work aspires to redefine the role of biodegradable polymers in next-generation electronic applications, offering a green alternative to conventional synthetic dielectrics.

2. Experimental

Preparation of Nanofiber composite polymer of (PVA-Cs), by using polyvinyl alcohol (PVA) has a linear formula [-CH2CHOH-]n (obtained from SHIJIAZHUANG TUYA TECHNOLOGY CO.) was dissolved in distilled water (DIW), using a magnetic stirrer for 3 hours (500 rpm) at 80°C to obtain a homogeneous solution with a concentration of 10 wt% [16]. chitosan has a molecular structure (C56H103N9O39), (obtained from SHIJIAZHUANG TUYA TECHNOLOGY CO.) was dissolved in glacial acetic acid for 2 hours (500 rpm) at 30°C using a magnetic stirrer to achieve a homogeneous solution with a concentration of 3 wt% and PH equal to 3 [17]. The two solutions are mixed together by taking ume (10, 20, and 30) v/v% by adding Cs to PVA and stirring them for 24 hours (500 rpm)[17].

After mixing various umes of PVA and chitosan solutions, a part of the solution 10 ml from each of concentration was used by syringe (23G), an electrospinning device (manufactured by Nanolab Instruments Co. Ltd.) The electrospinning device is a versatile technique for producing nanofibers with uniform morphology and controlled diameter. It is widely used in biomedical and electronic applications. This method relies on applying a high- tage electric field between the needle tip and the collector surface, which draws the polymer solution into fine nanofibers [18]. During the experiment, operational parameters such as tage, needle-to-collector distance, and flow rate were carefully adjusted to ensure the formation of uniform fibers in terms of diameter and distribution. Aluminum foil sheets were placed on the collector facing the needle tip to facilitate the deposition and collection of the formed nanofibers during the electrospinning process[16, 19].

The needle tip and the collector were connected to a high- tage power supply (20 kV), maintaining a tip-to-collector distance of 10 cm to facilitate the formation of nanofibers[19]. The experimental section can be represented by a flowchart as shown below (1).

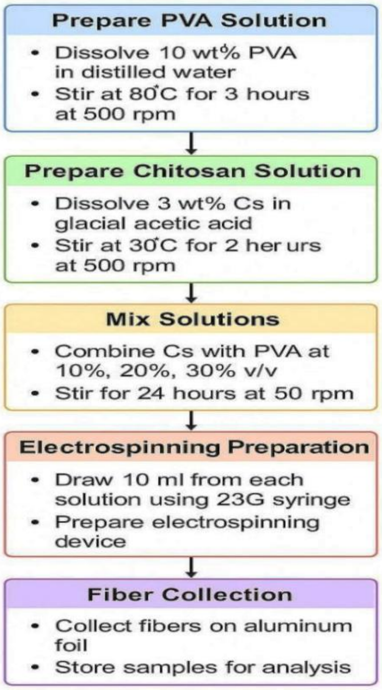

Fig (1): Process diagram of Experimental Procedure for PVA–Cs Nanofiber Preparation.

3. Results and Discussion

The Scanning Electron Microscope (SEM) provides high-resolution imaging of the surface morphology of nanofibers, enabling precise measurement of fiber diameter and surface features. This technique is used to analyze fiber distribution, shape uniformity, and detect morphological defects such as bead formation or fiber agglomeration. SEM is considered an essential tool for characterizing nanomaterials[20] . A comprehensive SEM amination was performed to assess the surface morphology and fiber diameter distribution of electrospinning nanofiber membranes composed of polyvinyl alcohol (PVA) and varying concentrations of chitosan. Micrographs revealed well-formed fibers with distinct morphological features and diameter variations influenced by the sample composition. The pure PVA membrane exhibited an average fiber diameter of approximately 181 nm. Upon blending with chitosan, notable changes in fiber dimensions were observed.

At (10 wt%) chitosan content, the nanofibers displayed a significantly increased average diameter of (352 nm), with the thickest individual fiber reaching (400 nm). This increase in diameter can be attributed to the rise in solution viscosity and surface tension caused by the addition of chitosan, which hinders full jet elongation during electrospinning and results in thicker fibers. Moreover, the limited electrostatic conductivity at this concentration may reduce jet stability, leading to irregular fiber formation[21, 22]. In contrast, the (20 wt%) sample produced the finest and most uniform fibers, with an average diameter of (74.7 nm) and the thinnest fiber recorded at (58.2 nm). This behavior suggests that intermediate chitosan concentrations create an optimal balance between viscosity and conductivity, enhancing jet stability and molecular alignment during fiber formation. The improved miscibility between PVA and chitosan at this ratio may also facilitate better chain entanglement and stretching, resulting in thinner, more consistent fibers[23].

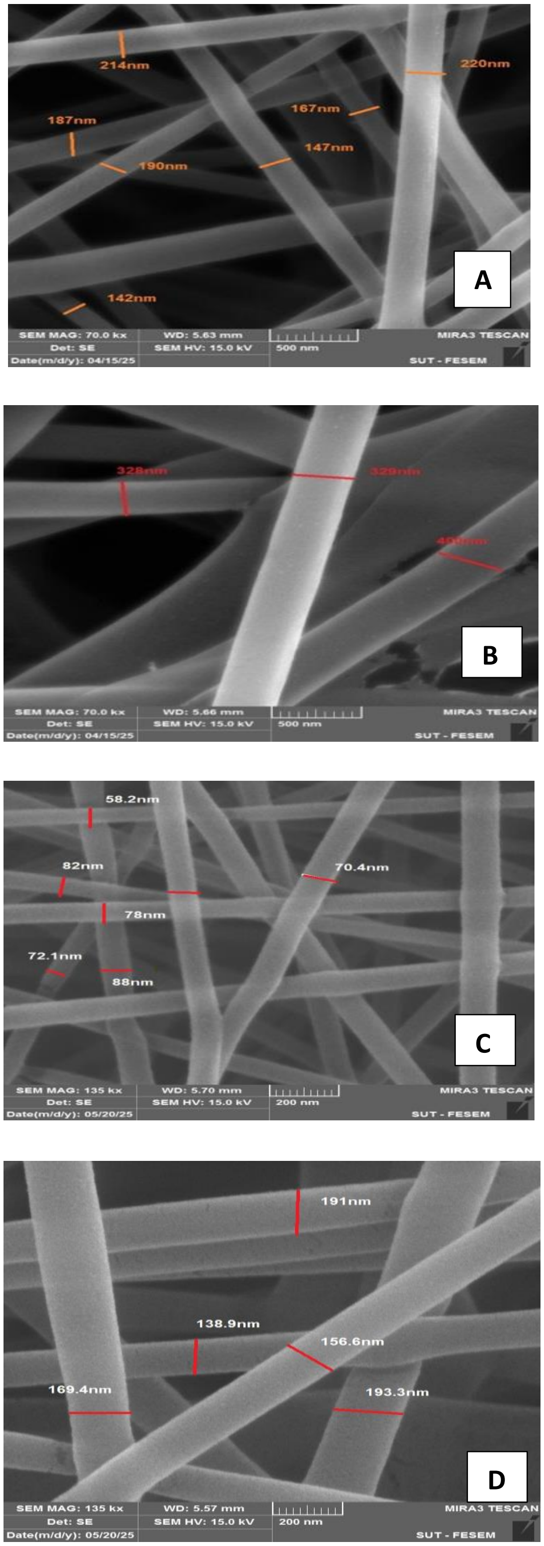

Fig (2): image SEM for nanofiber PVA-Cs, A: 0% , B : 10 %,C : 20 %, D: 30 %.

The (30 wt%) composite demonstrated a relatively stable morphology, yielding fibers with an average diameter of (169.8 nm), indicative of improved regularity and consistency. At this higher concentration, the system may reach a saturation point where excess chitosan increases viscosity beyond optimal levels, slightly reducing jet elongation but maintaining fiber uniformity due to enhanced intermolecular interactions and reduced bead formation[24].

These findings highlight the influence of chitosan concentration on fiber formation, suggesting that intermediate compositions (around 20 wt%) may enhance uniformity and structural integrity in electrospinning nanofiber systems, as shown in Table (1) and Figure (2). SEM images were captured at different magnifications to assess both the general fiber distribution and fine surface morphology. A scale bar of 500 nm was used to visualize overall alignment, while 200 nm provided higher-resolution details for accurate diameter measurement.

Table 1: The SEM analysis for different concentrations of PVA- Cs.

No. of symbol	PVA-Cs (wt%)	Average Diameter (nm)
P0	0	181
P1	10	352
P2	20	75.7
P3	30	169.8

3.1. Dielectric Characterization of Nanofiber Samples

Using an LCR meter type (Hioki IM3536) The LCR meter is an electronic instrument used to measure the fundamental electrical properties of materials, including inductance (L), capacitance (C), and resistance (R). This device is essential for analyzing the dielectric behavior of polymers across various frequency ranges, It helps in understanding relaxation dynamics, interfacial polarization, and insulation efficiency, making it suitable for characterizing materials in energy storage and electronic applications [25]. The electrical conductivity (σac) can be determined using the following equation [26, 27]:

$$\sigma ac = \varepsilon 0 \,.\, \omega \,.\, \acute{\varepsilon} \,.\, \tan\delta \qquad (1)$$

Where: ε0 // Permittivity of free space, ω// Angular frequency, έ // The real part of the dielectric constant.

To explore how the studied samples respond to alternating electric fields, a series of graphical plots were developed. These visualizations show how changes in frequency affect several electrical and dielectric characteristics, such as the ability to store charge, resistance to current flow, energy loss during polarization, and the overall insulating behavior of the material. By analyzing these trends, the study offers deeper insight into how the material polarizes, dissipates energy, and conducts under varying conditions, helping to clarify its performance within the nanostructured polymer system.

Figure (3) illustrates the relationship between capacitance (Cs) and frequency (F) for four different material samples (0, 10, 20, and 30) %. From figure the concentration (0%) exhibits a noticeable decline in capacitance, starting at approximately 15.5 pF at low frequencies and decreasing to around 14.5 pF at the frequency (1000) KHz. This downward trend indicates that pure PVA is sensitive to frequency changes, gradually losing its ability to store electrical charge as frequency increases. The concentration (10%) shows improved performance, with capacitance values around 17.5 pF that remain relatively stable across the frequency range, with only a slight drop of about 0.5 pF . This suggests that the addition of chitosan enhances the material’s structural integrity and reduces its susceptibility to frequency-induced variations.

Sample P2 showed further improvement, maintaining a stable capacitance of around 20 pF across all frequency ranges. This consistency reflects a better-integrated polymer network and a stronger ability to retain charge under varying electrical conditions. On the other hand, Sample P3 recorded the highest and most stable capacitance, remaining at approximately 33 pF regardless of frequency. This behavior indicates the formation of a dense and cohesive polymer matrix with excellent insulating properties and minimal sensitivity to frequency changes [28, 29]. The results clearly show that increasing the chitosan content in PVA leads to a progressive enhancement in both capacitance and frequency stability. The higher the chitosan concentration, the greater the material’s ability to store electrical charge and resist frequency-induced fluctuations. Sample P3, exhibits the most favorable electrical behavior, making it a promising candidate for applications requiring high and stable dielectric performance. These findings highlight the structural and functional role of chitosan in reinforcing the polymer matrix and optimizing its electrical characteristics [30]. The real part of the dielectric constant (έ) was illustrated in figure (4).

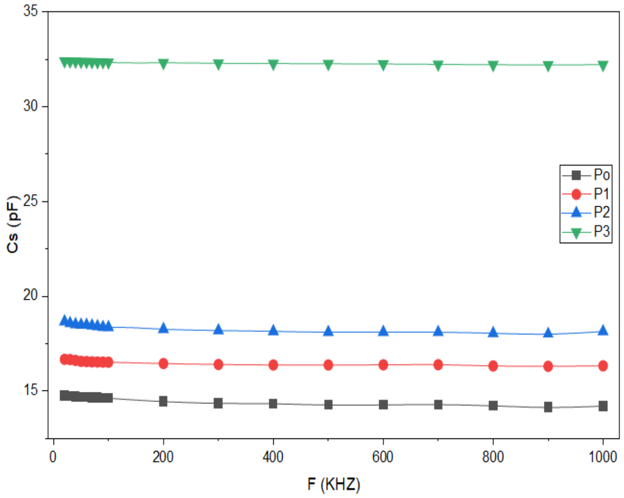

Fig (3): Show the relation between capacitance (Cs) and frequency (F) for the Nanofiber composite polymer of PVA-Cs

The results showed that for pure polyvinyl alcohol (PVA) exhibited the highest έ values equal to (0.78 to 0.80) and semi stable with increasing the frequency, indicating a strong ability to store electrical energy due to the high polarity of pure PVA. we see that All samples with different concentrations showed relatively stable έ values across the frequency range, suggesting minimal frequency-dependent dispersion and indicating structural stability within the studied range [31]. When added chitosan to the PVA polymer, its effect on the behavior of dielectric response έ where its decreases with increasing chitosan content [32]. The imaginary part of the dielectric constant (ε") for all nanofiber samples are illustrated in figure (5), for the concentration (PVA pure (0%)), was begins with high ε" values at low frequencies and continues to increase gradually until around 600 kHz, after which it slightly decreases at higher frequencies. This indicates strong polarization capability in the mid-frequency range before the material's response diminishes due to the rapid oscillation of the electric field.

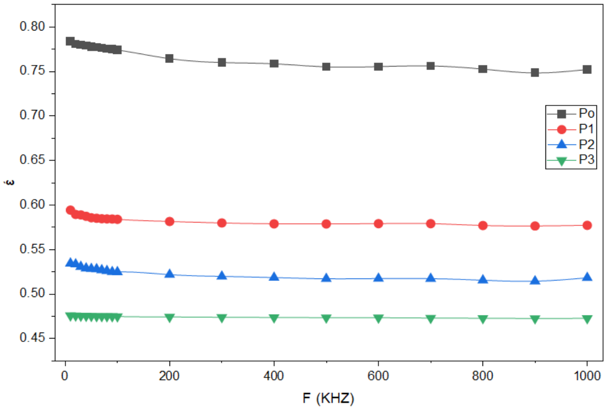

Fig (4): the relationship between real part of the dielectric constant (ε′) and frequency (F) for the Nanofiber composite polymer of PVA-Cs

The concentration (10%), follows a similar trend but with lower ε" values than PVA pure, increasing up to approximately 500 kHz before declining, suggesting that chitosan reduces chain mobility and thus the dielectric response. the concentration (20%), starts with relatively low ε" values, increases slightly until around 400 kHz, then stabilizes or decreases gradually, indicating further suppression of polarization due to increased hydrogen bonding. But at the concentration (30%), exhibits the lowest ε" values across all frequencies, with a limited increase up to about 300 kHz followed by a decline, reflecting a pronounced reduction in dielectric activity [33]. Increasing chitosan content leads to lower ε" values and an earlier onset of decline, confirming that the structural interactions within the polymer matrix play a critical role in determining its dielectric behavior with frequency [29, 34].

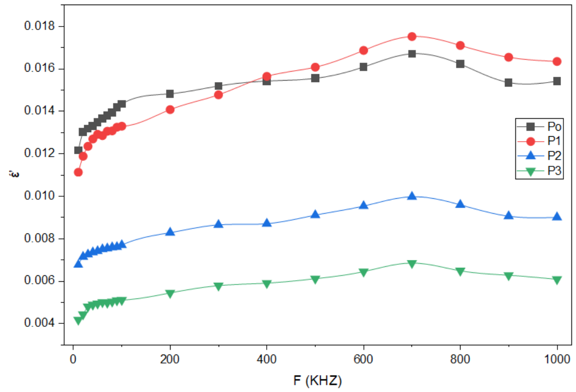

Fig (5): The relationship between imaginary part of the dielectric constant (ε″) and frequency (F) for the Nanofiber composite polymer of PVA-Cs.

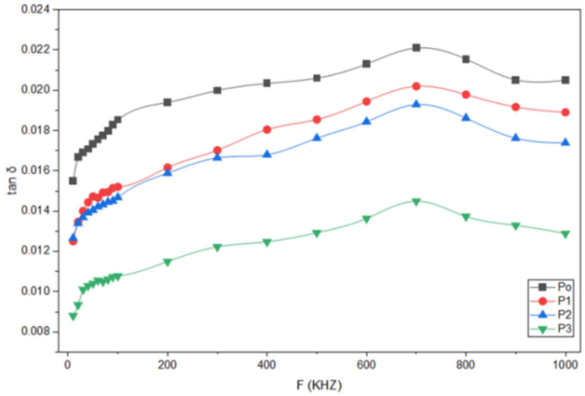

Fig (6): The relationship between energy loss (tan δ) and frequency (F) for the Nanofiber composite polymer of PVA-Cs

The loss Tangent (tan δ) as differing frequencies was illustrated in figure (6). The pure PVA nanofiber (0%), exhibited the highest tan δ values across the entire frequency range, starting at (0.021) and gradually decreasing to approximately (0.015). This reflects greater energy dissipation due to the unrestricted motion of polymer chains, indicating relatively weaker dielectric performance. We see that when added chitosan to the polymer PVA the behavior of tan δ was nearly stable with increasing the frequency, But its decreases with increasing the concentration to be at the range from (0.009 to 0.0013) due to the reduced response time of dipolar polarization in polymeric materials, thereby enhancing insulation efficiency at higher frequencies [28, 33].

Figure (7) shows a gradual decrease in the impedance (Z) for all samples as the frequency increases, which is a typical behavior of polymeric materials with insulating properties. As the frequency rises, the material’s ability to resist current diminishes due to the reduced effect of internal polarization. For PVA pure, begins with a high impedance of approximately 1200 kΩ at low frequencies and gradually decreases to below 100 kΩ at higher frequencies. At the concentration (10%), shows a lower initial impedance of around 1000 kΩ, decreasing to about 80 kΩ, suggesting that the addition of chitosan slightly enhances electrical conductivity. In concentration (20%), the impedance starts at approximately 800 kΩ and drops to around 60 kΩ, reflecting a stronger effect of chitosan in improving conductivity due to increased ionic content or a more favorable internal structure. For the concentration (30%), records the lowest initial impedance among the samples, around 600 kΩ, and falls to below 50 kΩ at high frequencies, indicating that higher chitosan content leads to a clear improvement in electrical properties. Based on this behavior, it can be concluded that increasing the concentration of chitosan within the PVA matrix results in a significant reduction in electrical impedance across all frequencies, highlighting the effective role of chitosan in enhancing the electrical conductivity of the composite polymer and making it promising for applications requiring improved electrochemical properties, such as nanofiber membranes or biosensors [35].

From figure (8), The AC conductivity (σac) profiles of the studied for deferent concentrations (0, 10, 20, 30)% revealed a consistent upward trend with increasing frequency a typical response observed in semi-conductive polymer systems. This enhancement is primarily attributed to the hopping conduction mechanism, where charge carriers gain sufficient energy to overcome localized barriers within the polymer matrix. At the highest studied frequency of 1000 KHz, Nanofiber polymer for PVA pure recorded the highest value of alternating current conductivity, reaching (1.0 ×10-^{11} S/m), indicating a strong ability to transport charge carriers in the absence of structural additives. For the concentration 10%, a slight decrease in conductivity was observed, registering (9.0×10^{-12} S/m) at the same frequency, suggesting the initial influence of molecular interactions on charge mobility.

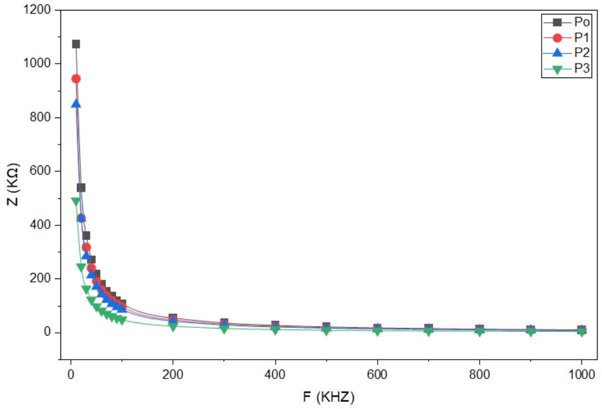

Fig (7): The relationship between the impedance (Z) and frequency (F) for the Nanofiber composite polymer of PVA-Cs

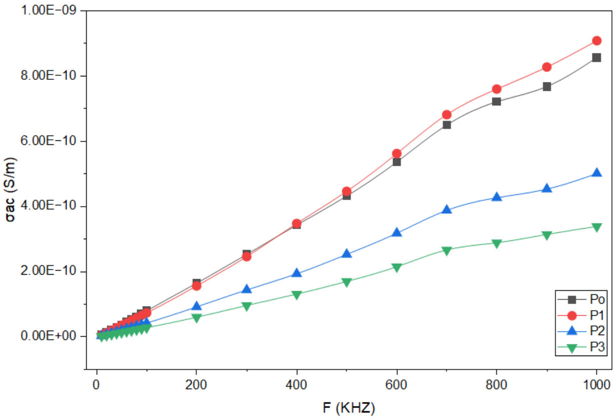

Fig (8): The relationship between AC conductivity (σ ac) and frequency (F) for the Nanofiber composite polymer of PVA-Cs

The concentration (20%), showed a further reduction in conductivity, reaching (6.5×10^{-12} S/m) at 1000 KHz, reflecting increased polymer chain entanglement and reduced electrical transport efficiency. Finally, the concentration (30%), exhibited the lowest conductivity value of (4.5×10^{-12} S/m), despite reaching the maximum studied frequency of 1000 KHz, confirming the significant impact of dense structural composition on limiting electrical response[36, 37].

The results demonstrate that alternating current conductivity increases with frequency across all samples; however, this increase is clearly influenced by the material composition. As the chitosan content within the PVA matrix rises, conductivity decreases due to enhanced structural entanglement, which restricts charge carrier movement. Therefore, controlling the chitosan ratio is a key factor in tuning the electrical properties of composite materials for targeted applications in electronics, insulation, or sensing technologies[28].

4. Conclusion

The pure PVA had an average nanofiber diameter of 181 nm. The best average diameter nanofibers were for the concentration (10%) of added chitosan and equal to (75.7) nm. For Pure PVA, consistently showed the highest ε′ values (0.78–0.80) and elevated ε″ and tan δ readings, indicating strong polarizability and significant energy dissipation due to unrestricted chain mobility. The values of ε′ and ε″ were decreases with increase the concentration of chitosan for all frequencies. The AC conductivity (σac) was increased with increasing the frequency for all concentrations. And its decreased with higher chitosan content, from (1.0×10^{-11} S/m) in PVA (pure) to (4.5×10^{-12} S/m) in the concentration (30%) for nanofiber composite polymer.

Acknowledgment
We would like to express my sincere gratitude to Al-Muthanna University – College of Science – Department of Physics – Postgraduate Laboratory for their generous support and the research facilities provided throughout this work**.**

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