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Comparative Analysis of Dielectric Properties of Polyvinyl Alcohol and Polyethylene

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Abstract. The article presents a new comparative analysis of the dielectric properties of polyvinyl alcohol (PVA) and polyethylene (PE) at different temperatures and their other physical properties. The characteristic peaks were observed in the FTIR spectra of the polymers. The amounts of carbon and oxygen on PVA's surface differed from PE. It was hypothesized that these properties could be affected by the increase in temperature and difference in the chemical structures of the polymers. We investigated the dielectric properties of these polymers between 20 °C and 100 °C. Our results revealed that the dielectric properties of these polymers were not the same. The actual permittivity values of PVA at low temperatures were almost constant for all frequency values and increased at higher temperatures with the decrease in frequency. The same pattern concerning the increase of imaginary permittivity of this polymer was observed at low frequencies. The increase of the real and imaginary permittivity of the PVA accompanied the increase in temperature. The actual permittivity of PE was almost constant with the frequency at different temperatures. However, the imaginary permittivity of this polymer showed an increase at low frequencies. The increase in temperature accompanies the increase of the PE's imaginary permittivity. As expected, the capacitance, like permittivity, changed differently for the polymers. Moreover, an increase in temperature had more effect on the conductivity of PVA than that of PE. The difference in these polymers' dielectric properties could be due to their chemical structures. The results of this article can be used for further applications of PVA and PE in science and engineering.

Keywords: advanced materials, polymers, physical properties, Fourier transform infrared spectroscopy, scanning electron microscopy.

1 Introduction

Dielectric properties are essential characteristics measured in various materials, such as polymers and nanomaterials, according to their interactions with low electromagnetic energy [1, 2].

Unique sets of electrical characteristics depending on electric properties are found in each type of material. These properties are measured for industrial heating applications or laboratory and research projects [3, 4].

The response of the materials to the external oscillatory electrical field is measured by determining their dielectric constant or actual permittivity ϵ' and loss factor or imaginary permittivity ϵ'' versus frequency. The experimental permittivity data are analyzed using the Debye relaxation equation [5–7]. The dielectric constant measures the material's ability to store electromagnetic

energy, whereas the dielectric loss factor is the imaginary component of permittivity. The first parameter is the ratio of the amount of electrical energy stored for the material stored in a vacuum [4].

Compared with their other physical properties, the dielectric properties of polymers must be investigated. Permittivity determines the measure of the resistance produced by applying an electric field in a medium [8]. The loss factor, which is less than the dielectric constant, is connected to various absorption mechanisms of energy dissipation. This first factor is approximately proportional to the attenuation of a propagating wave as it is the energy loss during the wave passing through the material. This energy loss can be converted into heat. Therefore, materials with more loss factors are heated quicker than materials with less energy loss [4].

2 Literature Review

Polymers can be used in electronic devices. For this purpose, conductive polymers, which are required to improve the electrical conductivity of less conductive ones, are used. It is known that materials with high dielectric constants have high dielectric strength, low dielectric loss, a frequency-independent response, and good mechanical properties [9, 10]. Polymers with low dielectric constant values and thermal stability can be used in electronic packaging and similar applications [11, 12].

The electrical properties of pure composites of polyvinyl alcohol (PVA) and polyethylene (PE) as films or blends have been studied previously [13–17].

This investigation aimed to compare the dielectric properties of polyvinyl alcohol (PVA) and polyethylene (PE) at different temperatures. We hypothesized that these polymers with different chemical structures would behave differently to the electrical field at different temperatures. This study was required to perform a further step in an upcoming investigation on the change of the dielectric properties of these polymers with nanomaterials.

To the authors' knowledge, the comparative analysis of the dielectric properties of these polymers at different temperatures and their other physical properties has not yet been performed. The results of this study could be used for the diverse applications of the studied polymers, especially with the increase of the dielectric properties of polymers using additives for the fabrication of electronic devices aimed at energy transfer, energy generation, and storage [18, 19].

Therefore, this article presents a new comparative analysis of the dielectric properties of polyvinyl alcohol (PVA) and polyethylene (PE) at different temperatures and their other physical properties. For this purpose, PVA Mw 13,000–23,000, 87–89 % hydrolyzed, and low-density polyethylene (LDPE) with 95 % bio-based content determined according to ASTM tests, both with excellent processability were purchased from Fisher Scientific and Marplex, respectively. Information on the structure of the polymers from their chemical formulas is presented in Figure 1.

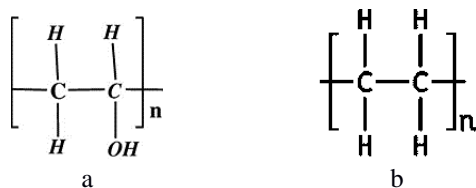


Figure 1 – The difference between chemical structures of PVA (a) and PE (b)

3 Research Methodology

PVA and LDPE were molded using a heating press at 190 °C and 160 °C, respectively. The samples were put between the broadband dielectric spectroscopy (BDS) electrodes for the measurements.

The Fourier transform infrared spectroscopy (FTIR) on the samples was performed with the Thermo Scientific Nicolet 6700 / Smart iTR 64 spectra scans with a resolution of 4.0 cm⁻¹ was performed for each sample.

The scanning electron microscopy (SEM) imaging of samples accompanied by the electron dispersive spectroscopy (EDS) was performed with a HITACHI SU8230 SEM, and the Bruker detector FlatQuad and cold field emission equipped with the Espirit 2.2 software was used for the analysis of samples. Samples were coated with Pt with a nanometric thickness distributed over the samples' surfaces for a few seconds before the SEM imaging to reduce their charge effects.

A Novocontrol Technologies BDS equipped with Detachem software was used to measure samples at different temperatures. The measurements were performed at frequencies between 0.1 and 1.0 · 10⁶ Hz. The calibration was performed before the measurements. The dielectric properties of samples were measured in triplicate and analyzed with the QtiPlot software.

The chemical formula of PVA is [CH₂CH(OH)]_n, and the formula of PE is (C₂H₄)_n (Figure 1).

The difference in their chemical structures is as follows. PVA has an OH⁻ group, whereas PE does not have it. This difference in the chemical formulas of these polymers makes the difference in their molecular structures and properties.

Figure 2 shows the FTIR spectra of PVA and PE.

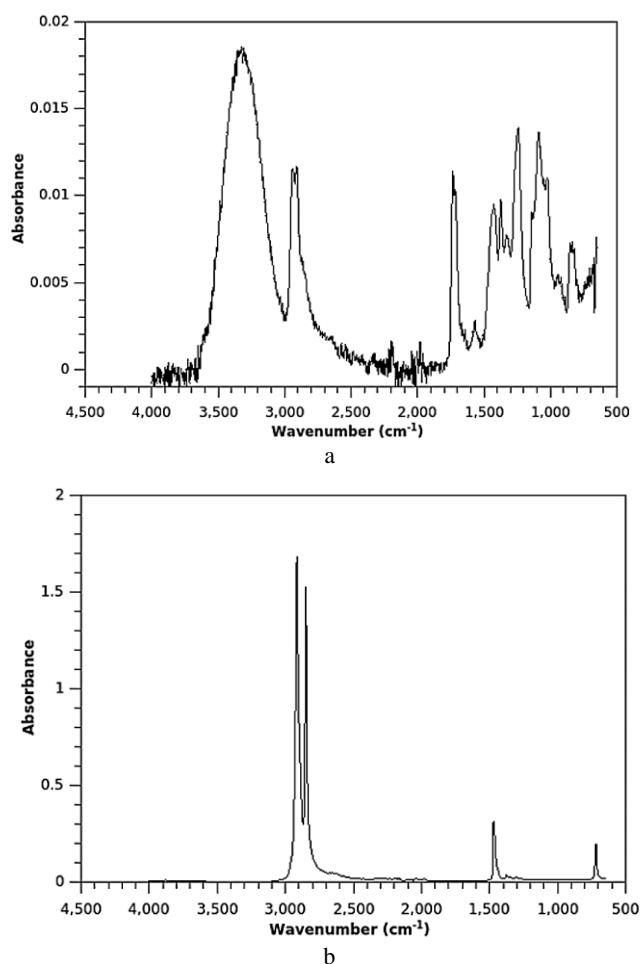


Figure 2 – The FTIR spectra of (a) PVA and (b) PE

The peaks observed in the spectrum of PVA at around 2900 cm⁻¹, 1416 cm⁻¹, 1325 cm⁻¹, 1138 cm⁻¹, 1083 cm⁻¹, 916 cm⁻¹, and 822 cm⁻¹ were attributed to the symmetric stretching of CH₂, CH₂ bending, (δ (OH)), rocking with CH

wagging), stretching of C—O, CH₂ rocking, and C—C stretching, respectively (Figure 2a) [20]. The spectrum peaks for PE at around 2914 cm⁻¹, 2847 cm⁻¹, 1470 cm⁻¹, and 718 cm⁻¹ were attributed to the CH₂ asymmetric stretching, CH₂ symmetric stretching, CH₃ bending, and CH₂ vibration, respectively (Figure 2b) [21].

4 Results

The SEM images of PVA and PE are presented in Figure 3.

The same scale was used for imaging carbon and oxygen atoms on the samples' surfaces.

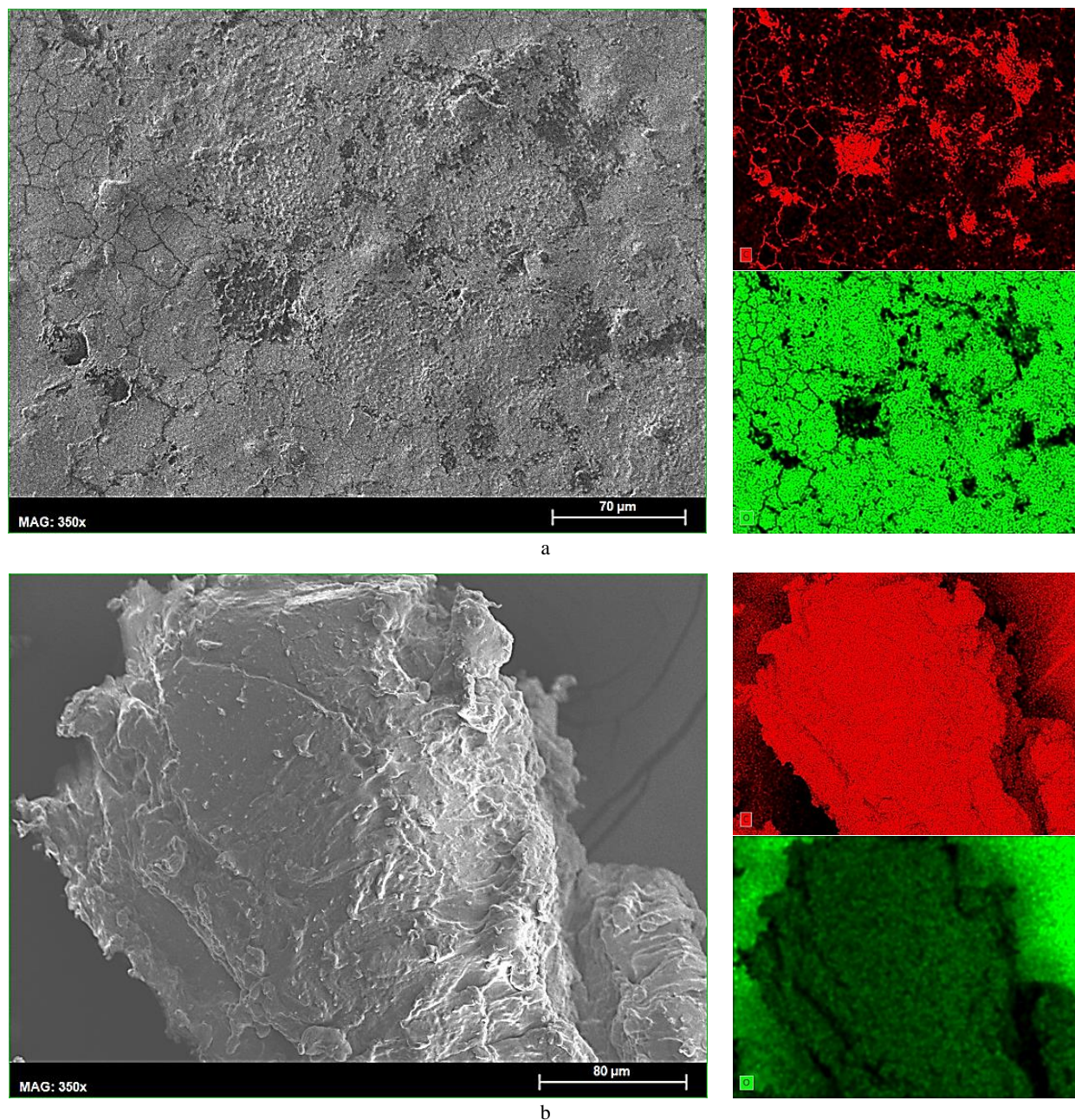


Figure 3 – The SEM images of (a) PVA and (b) PE

The samples' carbon and oxygen atoms were visualized in gray, red, and green. The continuous distribution of these atoms was observed in the SEM images.

The Pt coating of the samples improved the resolution of SEM images, which revealed the expediency of their nanometric coating.

The SEM images showed the homogeneous carbon and oxygen atoms distribution on the samples' surfaces. Moreover, as expected, more oxygen atoms were distributed over PVA than PE.

The EDS spectra of PVA and PE are shown in Figure 4.

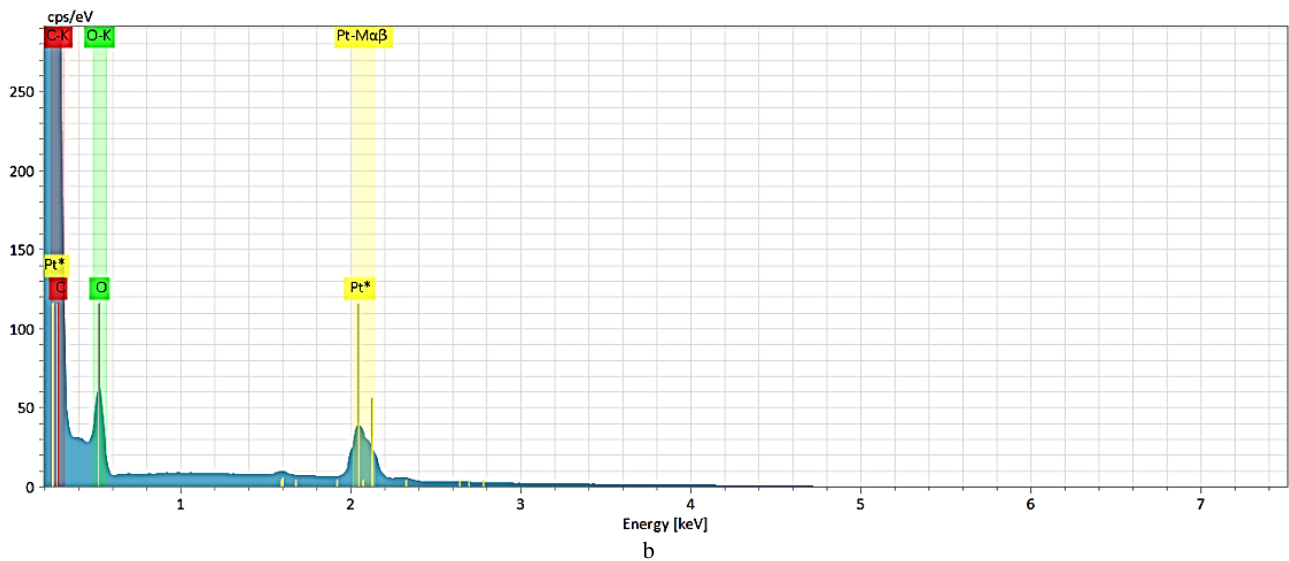
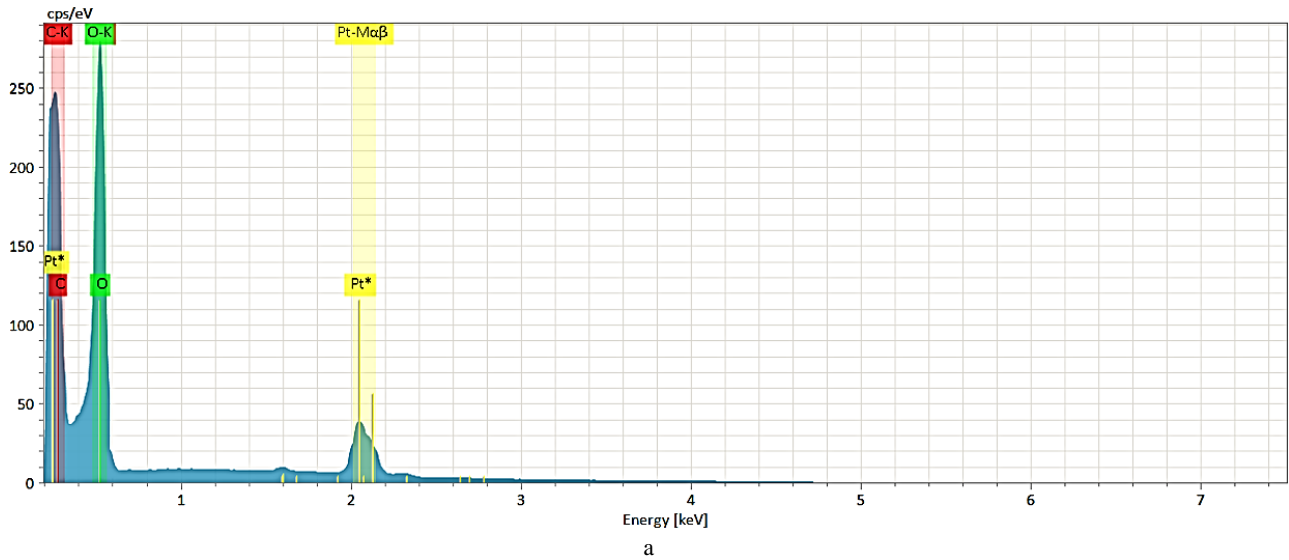


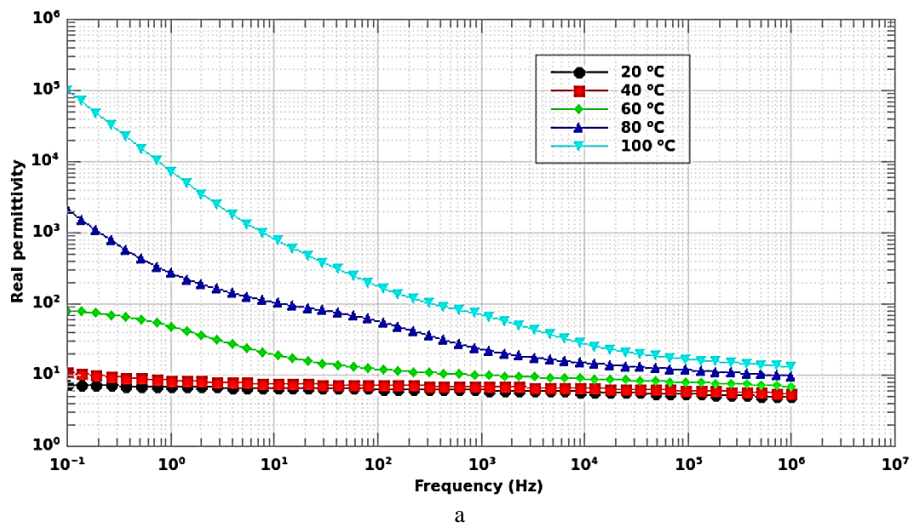
Figure 4 – The EDS spectra of (a) PVA and (b) PE

The peaks of Pt in the EDS spectra were attributed to the Pt used for the coating of samples. The samples C and O in Figure 2 are represented in grey, red, and green colors, respectively.

The surface of PE was oxidized as the oxygen peak was observed in the EDS spectrum of this polymer. The

amount of oxygen in PVA was more than that of PE, whereas the amount of carbon in PE was more than that of PVA.

Figure 5 shows the real and imaginary parts of the relative permittivity of PVA at different temperatures.



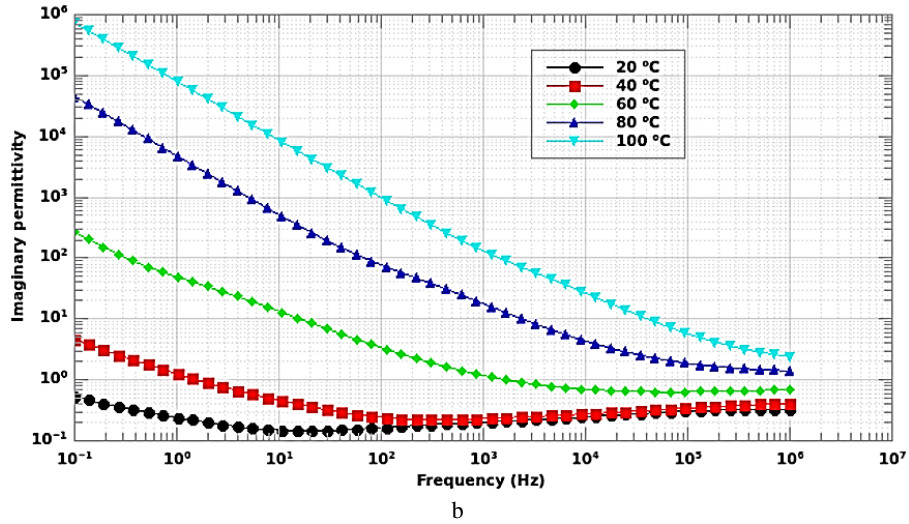


Figure 5 – The real (a) and imaginary (b) parts of the relative permittivity of PVA at different temperatures

The real permittivity values of PVA at 20 °C and 40 °C were almost constant for all frequency values, and they increased at higher temperatures with the decrease of frequency. The same pattern concerning the increase of imaginary permittivity of this polymer was observed at

low frequencies for all the temperatures. The increase in temperature caused more increase in the real and imaginary permittivity of the polymer.

Figure 6 shows the real and imaginary parts of the relative permittivity of PE at different temperatures.

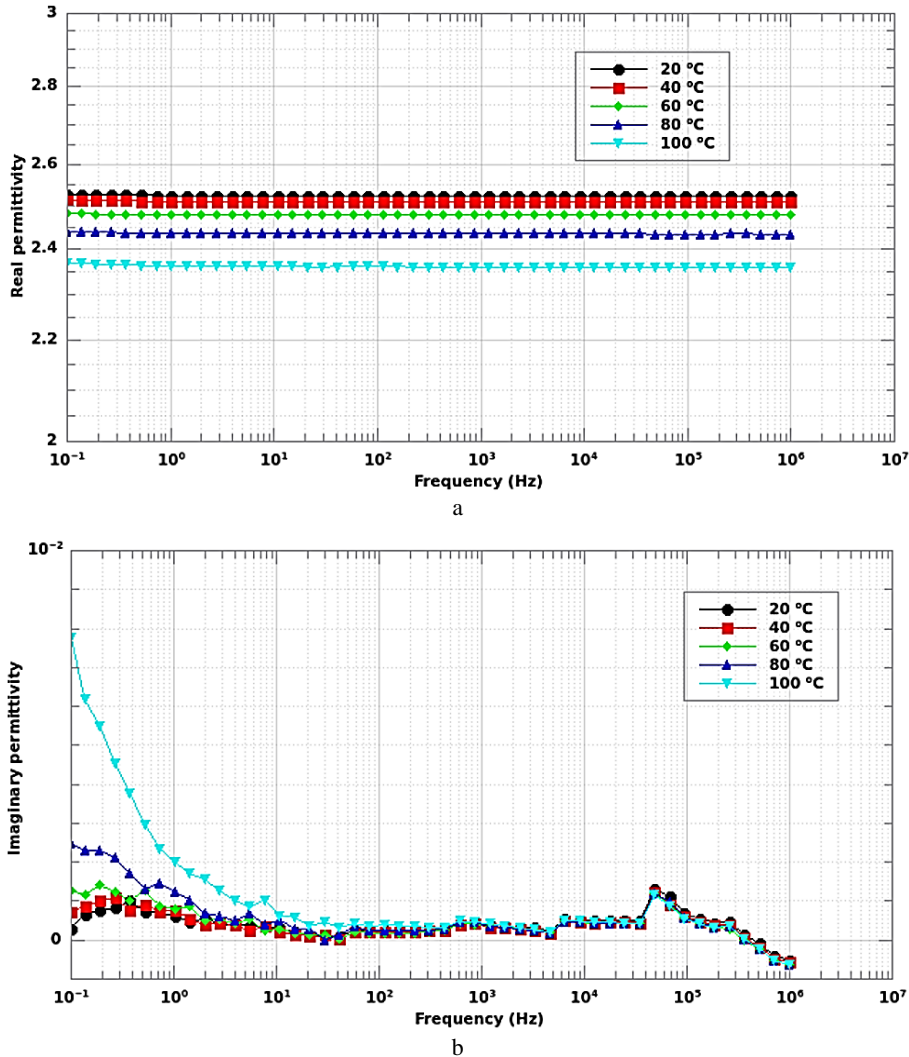


Figure 6 – The real (a) and imaginary (b) parts of the relative permittivity of PE at different temperatures

The real permittivity of PE did not change with the frequency at different temperatures. However, the imaginary permittivity of this polymer showed some fluctuations attributed to the equipment noise at high-frequency values and showed an increase at low frequencies. The increase in temperature caused more increase in the imaginary permittivity of the polymer.

The comparison of Figures 5 and 6 revealed that the increase in temperature increased the permittivity of PVA. In contrast, it did not affect the real permittivity of PE and had a negligible effect on the increase of the imaginary permittivity of this second polymer. The decrease of permittivity observed in these figures can be due to the reduction of the space charge polarization effect.

5 Discussion

The results obtained in this study showed that, as expected, PVA and PE had different patterns for changing their dielectric properties at each frequency and temperature, which could be due to the difference in their chemical structures.

As shown in Figure 1, PVA has an OH group, whereas PE does not. This can impact the difference in the dielectric properties of these polymers. The different distribution of oxygen atoms on the surface of PVA compared to PE, as shown in the SEM images of samples in Figure 2, could explain that the presence of oxygen atoms impacts the difference in the dielectric properties of samples. Recently, the permittivity of PVA and PEG without and with nanomaterials has been investigated [22].

Previous results showed that PEG's real and imaginary permittivity decreased with the increase in frequency [23].

The current research showed that the real permittivity of PE did not change with the increase in frequency. The comparison of the results of this novel study with those of the previous analysis has shown the difference in the dielectric behavior of these polymers. A study on the dielectric properties of PVA prepared by repeated freezing and controlled thawing was performed between $-50\text{ }^{\circ}\text{C}$ and $-10\text{ }^{\circ}\text{C}$.

This study also showed a broad secondary relaxation process associated with the polymer's local mobility related to the terminal OH polar groups. Moreover, this study showed a constant increase in polymer conductivity at these temperatures [24].

The results on the dielectric properties of this polymer showed the same pattern at $40\text{ }^{\circ}\text{C}$, $60\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ at all frequencies for the permittivity change and a similar pattern at $20\text{ }^{\circ}\text{C}$ for the conductivity at all frequencies. This revealed that the temperature could affect the pattern of the dielectric properties change of the polymer.

Another study was carried out on the dielectric properties of low-density polyethylene before and after UV irradiation and heat treatment [25]. This study showed that the relative permittivity of the treated samples had smaller values than the untreated ones, which was attributed to lower polarization in the treated samples. The authors have indicated the relative permittivity at the low-frequency range, which could be due to the decrease of the polymer polarization, a phenomenon that would be more effective in the heated specimen than in the cooled one.

Other polymers, nanomaterials, and composites have been investigated for their physicochemical [26–29] and biological properties [30, 31]. The dielectric properties of these materials could be investigated in further analysis.

The rapid decrease in the dielectric constant at a low-frequency range in some polymers, such as PVA, may be attributed to the tendency of dipoles to orient themselves in the direction of the applied electric field. However, the dipoles will hardly be able to orient themselves in the direction of the applied field in the high-frequency range. Therefore, the dielectric constant value would decrease at high frequencies [32].

The investigation of the crosslinking effect of PVA on its dielectric properties would be required to provide comparable results. More investigations would be required to determine the crowding caused by the mass density increase due to the entanglement and crosslinking of the polymer and biomolecules [33, 34].

The technique for order of preference by similarity to ideal solution (TOPSIS) is a multi-criteria decision analysis method used to predict and optimize materials and devices [35, 36]. This technique has been widely used in sciences and engineering [37, 38]. It can be used to optimize the properties of PVA and PE.

More investigations would be required to correlate the chemical structure of these polymers with their dielectric properties at different temperatures.

6 Conclusions

This article presented the results of a comparative study of the dielectric properties of PVA and PE and their other physical properties. The same procedure for the molding of the samples was performed.

The results showed that the characteristic peaks of the polymers were observed in their FTIR spectra. Different amounts of carbon and oxygen were observed on the surface of PVA and PE. Moreover, these polymers had different dielectric properties. The real permittivity of PVA was almost constant for all frequency values at low temperatures; they increased at higher temperatures with the decrease in frequency. The increase of imaginary permittivity of this polymer showed the same pattern at low frequencies. The increase of the real and imaginary permittivity of the PVA was observed with the increase in temperature.

The real permittivity of PE did not change significantly with the frequency at different temperatures. However, at low frequencies, the imaginary permittivity of this polymer increased. The increase of the imaginary permittivity of the PE was observed with the increase in temperature. The temperature increase had more effect on the conductivity of PVA than that of PE.

The decrease of the real and imaginary permittivity of PVA and that of the imaginary permittivity of PE can be due to the reduction of the space charge polarization effect in these polymers. The observed results of the dielectric properties of these polymers were attributed to the difference in their chemical structures.

The results can be applied to designing and preparing materials using PVA and PE, improving their dielectric properties for energy transfer, generation, and storage devices.

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