# DIELECTRIC PROPERTIES OF PVC NANOCOMPOSITES MODIFIED WITH NANO-QUARTZ $SiO_2$

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PVC/$SiO_2$ nanocomposites containing various amounts of silicon dioxide ($SiO_2$) (1–10 vol%) were prepared via ex-situ mixing and hot pressing, and their dielectric properties were studied. TEM and EDAX analyses confirmed uniform distribution of nanoparticles and a high purity level of the composites. Measurement results indicate that the addition of $SiO_2$ increases the dielectric constant (ε′) and the intensity of interfacial polarization. At low frequencies, dipole and interfacial polarizations dominate, while increasing temperature enhances the mobility of polymer segments and dielectric permittivity. External influences—thermal treatment, gas discharge, and long-term high field/temperature (ETP) exposure—further enhance the dielectric and conductive properties of the composites, demonstrating the material's potential for electrical regulation. The results show that $SiO_2$ effectively improves the dielectric, conductive, and thermal properties of PVC composites, making them promising materials for flexible electronics, insulating coatings, and capacitor applications.

**Keywords:** PVC, nano-quartz $SiO_2$, nanocomposite, specific conductivity, dielectric permittivity**,** electrical conductivity
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## INTRODUCTION

The development of modern electronics, electrical engineering, and sensor technologies requires the creation of new dielectric materials with high performance, stability under external influences, and cost-effectiveness. In this context, polymer composite materials combining an organic matrix with inorganic nanofillers represent a promising area of research.One of the most widely used polymers in electrical insulation technology is polyvinyl chloride (PVC). It possesses several valuable properties, such as chemical resistance, processability, thermoplasticity, and relatively good dielectric characteristics. However, pure PVC has limitations in terms of thermal stability, dielectric parameter stability under high voltages and frequencies, and mechanical strength. These shortcomings can be mitigated by modifying the polymer with dispersed or nanoscale fillers. Silicon dioxide ($SiO_2$), as one of the most accessible and inert oxides, exhibits high dielectric strength, stability over a wide temperature range, and good compatibility with polymer matrices. Incorporating $SiO_2$ into PVC allows significant morphological changes, reduces the degree of crystallinity, enhances dielectric permittivity, reduces losses, and improves thermal stability.

Currently, PVC-based composites containing dispersed or nanosilicate $SiO_2$ in various concentrations are of particular interest. Such materials are considered as a foundation for flexible electronics, insulating coatings, capacitor films, and other applications where a combination of flexibility, stability, and good electrical performance is required.This work focuses on the effect of silicon dioxide content on the dielectric properties of PVC composites. The aim of the study is to analyze the dependence of key dielectric parameters (dielectric permittivity, dielectric loss tangent, and volume resistivity) on $SiO_2$ concentration, as well as to investigate the morphological structure of the resulting materials.To date, a comprehensive and systematic study of the influence of the morphology and distribution of silicon dioxide, as well as the method of its incorporation into the PVC matrix, on the combination of physicochemical, dielectric, mechanical, and thermal properties of PVC/$SiO_2$ composites has not been conducted. A key research direction involves studying the dielectric properties of PVC/$SiO_2$ composites at various AC field frequencies and temperatures. In particular, study [2] evaluated the effect of water absorption on PVC/$SiO_2$ nanocomposites with different filler concentrations (1–7.5 wt.%), obtained via solution casting. It was found that water absorption significantly increases both dielectric permittivity and the dielectric loss tangent, which is important for assessing composite stability under high humidity conditions.

From the perspective of optical properties, adding $SiO_2$ affects the bandgap of PVC. Study [3] showed that increasing $SiO_2$ concentration reduces the optical bandgap from 4.36 to 3.39 eV, related to changes in the electronic structure of the matrix, which can be used to tune optical transparency and light absorption.Thermal and mechanical properties of PVC/$SiO_2$ composites also change with the addition of nanofillers. According to review [4], modified nano-$SiO_2$ enhances thermal stability, increases decomposition temperature and tensile strength, and can improve interfacial interaction through chemical or plasma treatment of nanoparticles. Various synthesis methods—sol-gel, in-situ polymerization, mechanical mixing—affect nanoparticle distribution in the polymer matrix and consequently the final properties of the material.Study [5] demonstrated the possibility of using recycled PVC in combination with wood flour and nano-$SiO_2$ for environmentally friendly packaging materials. Results showed that nano-$SiO_2$ content up to 3 wt.% improves mechanical properties (strength, modulus), while higher concentrations reduce these properties, likely due to nanoparticle aggregation and decreased interfacial adhesion.Review [1] emphasizes the importance of clay and silicate fillers (including $SiO_2$) for enhancing PVC properties, especially in fire resistance, biomedical applications, and water treatment. Modification of PVC using various forms of $SiO_2$ and processing methods leads to significant morphological changes, directly linked to aggregation, adhesion, and uniform nanoparticle distribution in the polymer matrix.

Thus, a comprehensive literature analysis concludes the high effectiveness of $SiO_2$ as a functional nanofiller for PVC. Despite significant progress, challenges remain in ensuring property stability during long-term use, minimizing nanoparticle aggregation, and improving reproducibility and scalability of the materials.

## EXPERIMENTAL SECTION

Polyvinyl chloride—a polar dielectric (Dema Import and Export Co. Ltd., China), with dielectric permittivity 3.0–4.5 and volume resistivity $10^{13}$–$10^{16}$ Ω·cm—was used. It is a thermoplastic polymer with a density of 1.38–1.41 g/cm³ in its rigid form and molecular weight ranging from 40,000 to 150,000 g/mol. The polymer structure is based on the repeating unit $–CH_2–CHCl–$ (62.5 g/mol).

$SiO_2$ nanoparticles with a particle size of 20–25 nm (Sigma-Aldrich, USA), density 1.96 g/cm³, molecular weight 60 g/mol, were used as filler. Particle shapes and sizes were determined from TEM images (Fig. 1). TEM analysis was performed using a JEM-1400 microscope (JEOL, Japan) at 80–120 kV.

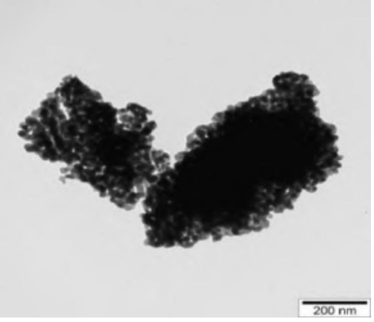

*Fig. 1.* TEM analysis of $SiO_2$.

The PVC was dissolved in hydrotetrafluoroethane at 50 °C. $SiO_2$ nanoparticles were added and stirred for 7 hours with a magnetic stirrer. The solution was thermally treated for 7 hours and then vacuum dried to remove free solvents. After one day in a vacuum oven, PVC+$SiO_2$ composites were obtained with various filler concentrations (1, 3, 5, 7, 10 vol%). Disc-shaped samples were prepared by hot pressing at 110 °C and 15 MPa for 2 minutes. Nanocomposite films had a thickness of 70–100 μm. EDAX analysis was performed using SEM (JEOL JSM-7600F, USA) to determine elemental composition. To measure dielectric properties, composite surfaces were coated with silver foil to form capacitors. Dielectric measurements were carried out by the Precision LCR Meter 1920 (IET Labs. Inc., USA) over the frequency range of 20 Hz – 1 MHz and at temperatures between 18 °C – 70 °C. In such a case, applied voltage was 0.5 V. Electric capacity C and dissipation factor (the loss tangent) D were recorded by means of this device at different frequencies f. Dielectric permittivity was calculated using:

$$\varepsilon = \frac{Cd}{\varepsilon_0 \ S} \tag{1}$$

where C is the capacitance, $\varepsilon_0 = 8{,}85\cdot10^{-12}$ $м^{-3}\cdot кг^{-1}\cdot с^{4}\cdot А^{2}$ ,S is the area, and d is the sample thickness. Real permittivity (ε′) and conductivity were calculated using:

$$\varepsilon' = \frac{\varepsilon}{\sqrt{1+D^2}} \tag{2}$$

$$D = \frac{\varepsilon''}{\varepsilon'} \tag{3}$$

$$\sigma = 2\pi f \varepsilon'' \varepsilon_0 \tag{4}$$

## RESULTS AND DISCUSSION

Figure 2 presents the energy-dispersive X-ray spectroscopy (EDS) analysis of the PVC-based composite material modified with nanoscale silicon dioxide ($SiO_2$).

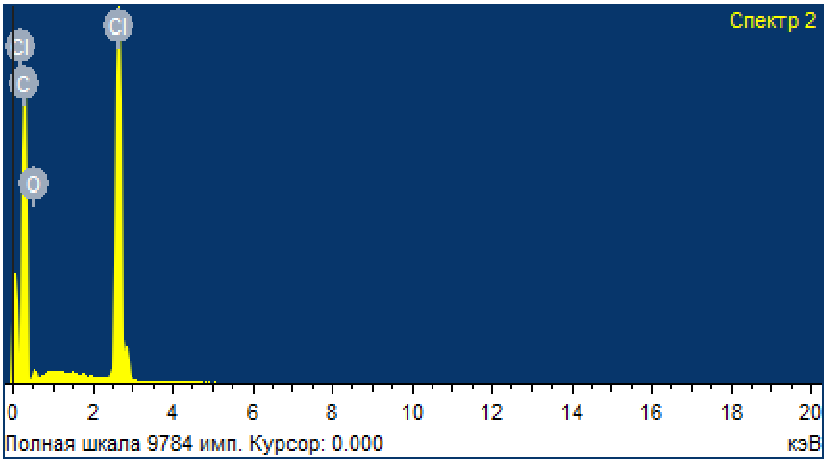

*Fig.2* Analysis of the structure by X-ray dispersion energy spectroscopy (EDAX) X images. of the PVX+5%$SiO_2$ nanocomposite.

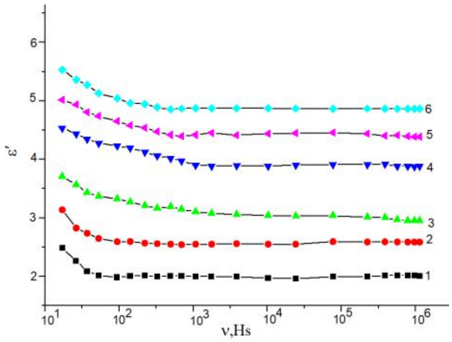

*Fig. 3.* Dependence of the real part of the dielectric permittivity (ε′) of PVC-based composites with varying silicon dioxide content on the frequency of the alternating electric field.

The spectrum clearly shows signals corresponding to three elements: carbon (C), oxygen (O), and silicon (Si). The presence of carbon corresponds to the organic PVC polymer matrix, whose main component is vinyl chloride. The detection of oxygen and silicon confirms the incorporation of nanosilica dispersed within the polymer structure. The absence of extraneous elements in the spectrum indicates the high purity of the composite and the reliability of the modification process. The obtained data are consistent with the declared material composition and confirm the formation of a polymer–inorganic composite based on PVC and $SiO_2$.

The graph illustrates the frequency-dependent behavior of the real part of the dielectric permittivity (ε′) for PVC-based composites with different $SiO_2$ contents. All samples exhibit typical dispersion behavior: ε′ decreases with increasing frequency, which is attributed to the limited mobility of dipoles and their inability to follow a high-frequency electric field. Simultaneously, an increase in $SiO_2$ content leads to an overall enhancement of ε′ values, which can be explained by the contribution of the polarizability of the silica nanoparticles and the increase in interfacial polarization (Maxwell–Wagner effect).

At low frequencies ($10^1$–$10^2$ Hz), the differences in ε′ between samples with varying $SiO_2$ content are most pronounced, whereas at high frequencies, ε′ values tend to converge. Specifically, at low frequencies (up to $10^3$ Hz), the increase in dielectric permittivity is mainly due to interfacial (Maxwell–Wagner) and dipolar polarization contributions. These processes require sufficient time for charge redistribution and dipole orientation, making them most effective at low frequencies.

As the frequency of the applied electric field rises above $10^4$–$10^5$ Hz, the polarizable units cannot respond rapidly enough to the changing field. This results in reduced polarization efficiency and, consequently, stabilization of ε′ at a lower level [6]. At low frequencies (10–$10^3$ Hz), dipoles and charges within the material can respond to the slowly varying field. As the frequency increases ($10^4$ Hz and above), molecules, dipoles, and phase boundaries fail to follow the field, leading to a diminished contribution of polarization. Interfacial polarization effectively “switches off” at high frequencies due to its slow response, leaving primarily electronic and partial dipolar polarization, which are almost frequency-independent.

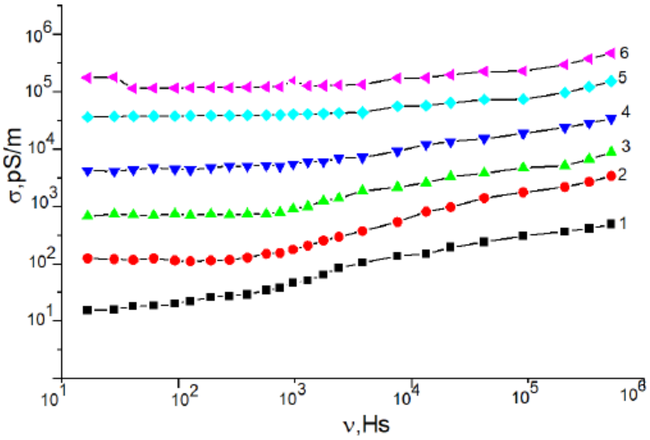

*Fig.4.* Frequency dependence of the specific conductivity of PVC +$SiO_2$ composites with varying contents of nanoscale silicon dioxide ($SiO_2$).

Figure 4 presents the frequency-dependent behavior of the specific conductivity (σ) of PVC composites containing different amounts of nanoscale $SiO_2$. All samples exhibit a characteristic increase in σ with increasing frequency, which is associated with the enhancement of alternating current conduction mechanisms, particularly interfacial and boundary conduction.Increasing the $SiO_2$ content leads to higher σ values across all frequencies. This effect can be attributed to the increased number of free charges and the formation of localized conductive pathways at the PVC/SiO₂ interfaces, the enhancement of interfacial polarization, and charge transport processes, as well as changes in the composite morphology and particle packing density. At low frequencies, conductivity is relatively low, indicating the dominance of charge displacement processes of capacitive nature. At higher frequencies, σ increases, reflecting the activation of dynamic conduction processes and charge migration within the material.Thus, the incorporation of nanoscale $SiO_2$ into PVC contributes to an increase in the composite's specific conductivity, an important factor when designing materials with tailored electrical properties. Controlling the filler content allows tuning both the conductivity and, consequently, the dielectric characteristics of the material[6,7]. The study of the temperature dependence of dielectric permittivity and specific conductivity in PVC/$SiO_2$ composites provides insights into the mechanisms of polarization and conduction, allows the estimation of activation energies for charge transport, and helps define temperature ranges for stable material performance. These findings aid in optimizing the composition and structure of the composites to enhance their dielectric and electrical properties, which is crucial for practical applications in electrical insulation and other functional materials.

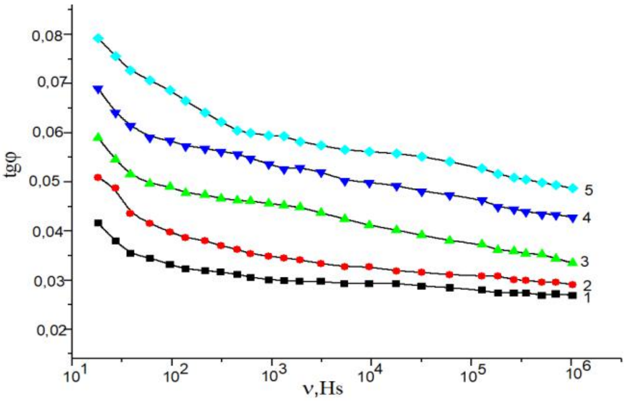

*Fig. 5.* Frequency dependence of the loss tangent (tan δ) for PVC/$SiO_2$ composites: 1 – pure PVC, 2 – PVC+1 % $SiO_2$, 3 PVC+3 % $SiO_2$, 4 PVC+5 % $SiO_2$, 5 PVC+ 7 % $SiO_2$.

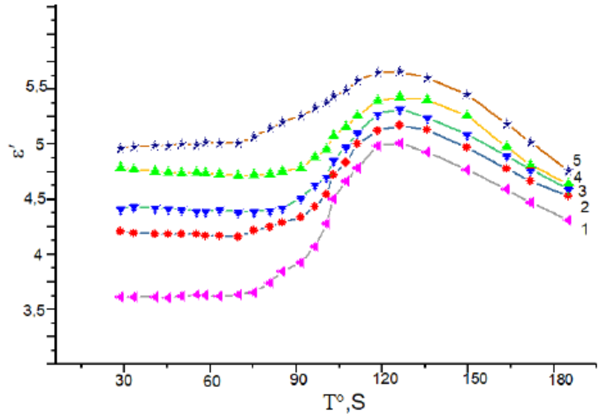

*Fig. 6.* Temperature dependence of the real part of the dielectric permittivity (ε′) for composites with different filler concentrations**.** 1 – pure PVC, 2 – PVC+1 % $SiO_2$, 3 PVC+3 % $SiO_2$, 4 PVC+5 % $SiO_2$, 5 PVC+ 7 % $SiO_2$.

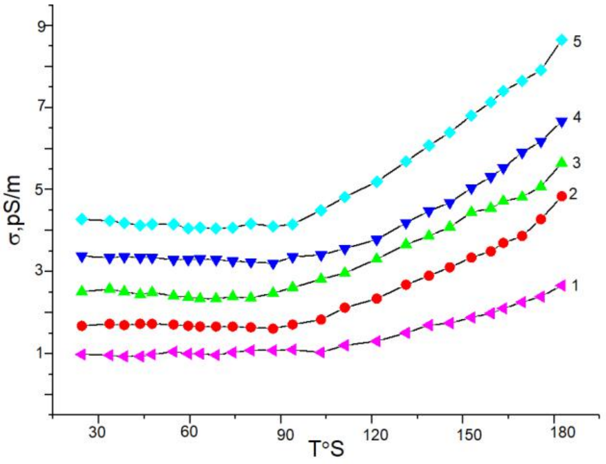

*Fig. 7.* Temperature dependence of electrical conductivity for PVC composites with varying $SiO_2$ content (1 – PVC, 2 – PVC + 3 % $SiO_2$, 3 – PVC + 5 % $SiO_2$, 4 – PVC + 7 % $SiO_2$, 5 – PVC + 10 % $SiO_2$.

Figure 5 shows the variation of the loss tangent (tan δ) as a function of the alternating field frequency for PVC/$SiO_2$ composites. It is evident that tan δ decreases with increasing frequency for all composites, which can be explained by the attenuation of dispersion processes. The lowest tan δ is observed for curve 1 (black), corresponding to pure PVC. This indicates that the incorporation of nanoscale $SiO_2$ leads to strong interactions with the polymer chains (e.g., hydrogen bonding or physical hindrance), which:reduces dipole mobility,decreases energy losses, resulting in a minimum tan δ, and enhances electret behavior and dielectric stability[8].As the $SiO_2$ content increases (3–7 %), tan δ rises:nanoparticles tend to aggregate, forming local stress zones within the matrix,chain mobility increases and the number of defects grows, leading to enhanced polarization relaxations, and consequently, tan δ increases, indicating greater energy losses.

Figure 6 illustrates the temperature dependence of the real part of the dielectric permittivity (ε′) for PVC composites with varying filler concentrations. It is observed that ε′ increases with rising temperature, reaching a maximum in the range of 100–130 °C, followed by a decline. This behavior can be associated with increased mobility of dipoles and polymer chain segments, as well as relaxation processes near the glass transition temperature (Tg).With increasing filler content, ε′ values rise, indicating enhanced polarization effects in the system. Below Tg, the polymer is in a rigid (glassy) state, where dipolar groups and chain segments are immobilized, limiting orientational mobility. As a result, polarization is weak, and ε′ is low [9]. As the temperature approaches Tg, the polymer transitions to a highly elastic (rubbery) state: macromolecular segments gain mobility, and dipolar groups are able to orient under the applied electric field. Consequently, orientational polarization increases, leading to a rise in dielectric permittivity ε′. After reaching the maximum (usually slightly above Tg), polarization begins to decrease because excessive thermal energy disrupts dipole orientation, dielectric losses (ε″) increase, and some polarizations cannot keep pace with the alternating field.

The increase in electrical conductivity with temperature indicates a thermally activated conduction mechanism in the studied composites. In the temperature range of 100–130 °C, a more pronounced rise in σ is observed, which can be attributed to the enhanced segmental mobility of the polymer matrix during the transition through the glass transition temperature (Tg). Higher conductivity values with increasing filler content suggest the formation of additional charge transport pathways and enhanced interfacial interactions between the components.

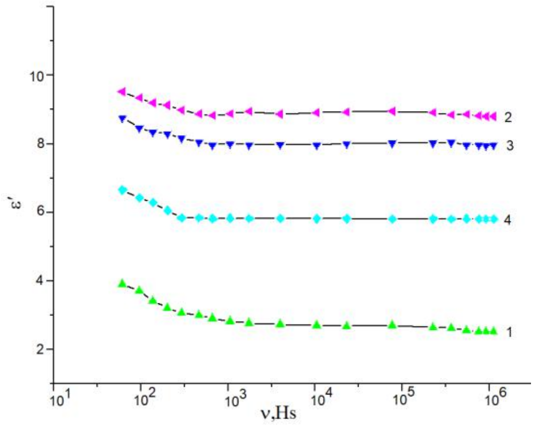

*Fig. 8.* Frequency dependence of the real part of the dielectric permittivity (ε′) for the PVC + 5 % $SiO_2$ composite under various treatments: 1 – without external influence, 2 – after thermal treatment (T = 373 K, t = 3 h), 3 – after gas discharge (7 kV, 1 h, two-sided), 4 – after ETP (T = 373 K, E = $10^7$ V/m, t = 3 h).

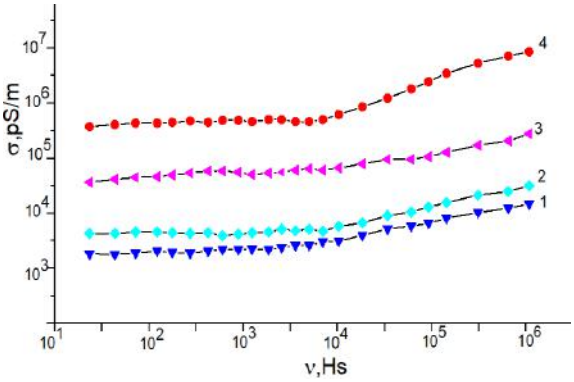

*Fig. 9.* Frequency dependence of electrical conductivity of the PVC + 5 % $SiO_2$ composite before and after various treatments: 1 – without external influence, 2 – after thermal treatment (T = 373 K, t = 3 h), 3 – after gas discharge (7 kV, 1 h, two-sided), 4 – after ETP (T = 373 K, E = $10^7$ V/m, t = 3 h).

The frequency dependence of the real dielectric permittivity (ε′) shows that at low frequencies, polarization mechanisms such as interfacial/Maxwell–Wagner polarization and segmental/orientational polarization are fully active, resulting in higher ε′ values. As frequency increases, these mechanisms cannot respond to the rapidly changing field, causing ε′ to decrease—this is characteristic dielectric dispersion.Comparatively, thermal treatment (2) leads to a slight increase in ε′, likely due to enhanced segmental mobility and free volume in the matrix, as well as structural changes at the filler–matrix interface, which strengthen interfacial polarization. Gas discharge (3) may induce a more pronounced increase in ε′, as local defects, charge-trapping centers, and surface/subsurface interface imperfections generated by the discharge enhance interfacial polarization and spatial charge accumulation. Long-term exposure to ETP (4) under high field and temperature produces the largest increase; here, chain scission, oxidation, formation of conductive pathways, and strong space-charge polarization may contribute[10]

In conclusion, these treatments create additional polarization channels and charge accumulation regions in the material, leading to increased ε′ at low frequencies. At higher frequencies, dielectric dispersion dominates, and ε′ values of all samples converge. The observed decrease in ε′ with increasing frequency can be explained by the inability of dipoles and interfacial charges to follow the period of the applied field [11]. Specifically, after thermal treatment, enhanced segmental mobility and free volume promote greater orientational polarization; after gas discharge, surface/internal defects and trapped charges increase interfacial polarization; after ETP (3 h, high E, T), chain scission, oxidation, space-charge accumulation, and formation of conductive pathways result in the largest ε′ enhancement.

The graph illustrates the change in electrical conductivity (σ) of the PVC + 5 % $SiO_2$ composite as a function of alternating current (AC) frequency under different external conditions. All samples show an increase in conductivity with rising frequency, which corresponds to the activation of AC conduction mechanisms, including interfacial and space-charge transport.

Thermal treatment (2) results in a slight increase in σ, likely due to enhanced segmental mobility of the polymer chains and slight structural changes at the filler–matrix interface, which improve charge transport. Gas discharge (3) produces a more pronounced increase in conductivity, as it generates local defects, charge-trapping centers, and surface/subsurface interface irregularities that facilitate interfacial polarization and space-charge accumulation[12]. Long-term exposure to ETP (4) leads to the highest conductivity, where effects such as chain scission, oxidation, formation of conductive paths, and strong space-charge polarization collectively enhance charge mobility.

These observations indicate that external treatments create additional conduction pathways and increase the efficiency of charge transport in the composite. At higher frequencies, the conductivity reflects the combined influence of filler–matrix morphology, defect formation, and induced polarization mechanisms[13].

## CONCLUSION

The conducted study demonstrated that the dielectric and conductive properties of PVC + $SiO_2$ composites depend on both temperature and field frequency. As the temperature increases, segmental mobility and dipolar polarization are enhanced, leading to an increase in ε′; however, at higher temperatures, relaxation losses become dominant. An increase in frequency results in a decrease in ε′ and σ, which can be attributed to the limited response of interfacial polarization. External treatments, particularly the ETP process, significantly enhance the conductivity of the composites, demonstrating their potential for electrical regulation.

Moreover, the PVC + 5 % $SiO_2$ composite exhibits high sensitivity of conductivity and dielectric properties to external influences. Specifically, ETP treatment ($T = 373$ K, $E = 10^7$ V/m, $t = 3$ h) sharply increases conductivity, which is explained by the formation of space-charge regions at interface zones and partial reorganization of the polymer chain structure. Thus, ETP application can be proposed as an effective method for controlling the electrical properties of polymer–oxide composites

The scientific novelty of this work lies in the systematic demonstration of how the dielectric properties of PVC/$SiO_2$ nanocomposites depend on composition, frequency, and external effects. The results show that $SiO_2$ effectively improves the dielectric, conductive, and thermal characteristics of PVC composites, making these materials promising for flexible electronics, insulation coatings, and capacitor applications.

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