



Hydrothermal Synthesis of Multifunctional Polyvinyl Alcohol-based Nanocomposites Reinforced with Biosynthesized Silver Nanoparticles: Enhanced Thermal, Dielectric, and Biological Performance

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Abstract

This study focused on the preparation of novel multifunctional polyvinyl alcohol (PVA)-based nanocomposites and the determination of their versatile properties. The nanocomposites contain a blend of PVA and a polystyrene-derived polymer (polymethyl-4-[(4-ethenylphenyl)methoxy]benzoate) (PMST), and biosynthesized silver nanoparticles (AgNPs). The hydrothermal interaction of PVA and PMST resulted in good compatibility and was confirmed by the single glass transition temperature (T_g) value obtained from DSC. The characterization of the nanocomposites produced by incorporating biogenic AgNPs with an average size of 26 nm produced with *Verbascum nudatum var* extract was carried out by SEM-EDX, TEM, XRD, and FTIR. SEM-EDX data confirmed that AgNPs exhibited a good dispersion. The thermal decomposition temperature of PVA, 260 °C, increased to 318 °C with the addition of 7% AgNPs. The same situation was also seen in T_g values. The nanocomposites' determined water contact angle values showed that AgNPs reduced hydrophilicity. The water contact angle value of PVA, which was 53.40°, increased to 74.61° with the addition of AgNPs. It was observed that with the increased AgNP concentration added to the PVA-PMST blend, the alternating current (AC) conductivity increased to 2.61×10^{-6} S/cm, and the frequency-dependent dielectric constant decreased to 2.42. It was observed that the determined antioxidant values of the nanocomposites improved with the addition of AgNPs. In addition, it was determined that the nanocomposites exhibited an effect close to the reference antibiotic with an inhibition diameter of 14 mm against the *E. coli* pathogen at the highest AgNP loading rate. The multifunctional properties of the nanocomposites produced by the hydrothermal method indicate that they can be used in food, electronics, and biomedical fields.

Keywords PVA · Polystyrene · Silver nanoparticle · Antimicrobial effect · Dielectric properties

1 Introduction

Polyvinyl alcohol (PVA) is a biodegradable and water-soluble thermoplastic polymer. It has many applications due to its high mechanical strength, flexibility, biocompatibility,

and non-toxicity. Thanks to its hydrophilic structure, PVA can be easily combined with other materials, forming an ideal matrix for producing nanocomposites [1]. PVA nanocomposites are obtained by combining the PVA matrix with nano-sized materials and improving the mechanical, thermal, barrier, and functional properties of PVA [2]. Nanomaterials commonly used in PVA nanocomposites include metal oxides (Ag, TiO₂, ZnO, Al₂O₃), carbon nanotubes (CNT), graphene, graphene oxide, clay nanoparticles and magnetic nanoparticles (Fe₃O₄) [3]. These materials provide mechanical strength, thermal stability, electrical conductivity, gas barrier, and functional properties to PVA. PVA nanocomposites have improved mechanical strength, thermal stability, and biocompatibility [4]. They also exhibit functional properties such as improved gas and moisture barrier

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properties, antibacterial, electrical conductivity, or magnetic properties [5].

Polystyrene (PS) is a thermoplastic polymer obtained by polymerization of styrene monomer. It is widely used due to its low cost, lightness, and easy processability. General purpose polystyrene (GPPS) has a rugged, brittle, and transparent structure used in electronics, packaging, and toy sectors [6]. Impact-resistant polystyrene (HIPS) is modified with rubber particles and is resistant to impacts; it is common in home appliances, furniture, and packaging sectors. Expanded polystyrene (EPS) is in the form of foam, is lightweight, and is effective in thermal insulation; it is used in the construction and packaging sectors [7]. PS composites produced by adding fillers or reinforcing materials improve polystyrene's mechanical, thermal, and electrical properties [8]. Such composites are widely used in the construction sector as heat and sound insulation panels, food and electronic product protectors in packaging, light and durable parts in automotive, insulation materials in electronic products, and daily consumer products [9].

Green synthesis is a method that focuses on synthesizing materials using environmentally friendly, sustainable, and non-toxic processes [10]. This method minimizes or eliminates harmful substances used in chemical synthesis. Natural resources such as plants, microorganisms, and biomolecules are used as reducing and stabilizing agents in the production of nanoparticles [11]. Biogenic silver nanoparticles (AgNPs) produced in this way are widely used in the medical, environmental, food, and electronic sectors due to their antibacterial, anticancer, antioxidant, and catalytic properties [12]. Plant extracts, microorganisms, and enzymes are reduced and stabilizing agents in green synthesis processes [13].

The combination of PVA and AgNPs offers innovative and effective solutions in many areas. In addition, the high film-forming ability of PVA allows it to be easily integrated with AgNPs. AgNPs are known for their strong antibacterial and antimicrobial properties [14]. In addition, since they have a high surface area, they are quite advantageous in reactivity and effectiveness. Silver nanoparticles provide adequate protection even at low concentrations and have low toxicity. PVA-based nanocomposites containing AgNPs can be used in medical devices, wound dressings, and drug delivery systems thanks to their antibacterial and antimicrobial properties [15]. It is also an effective material in eliminating microorganisms in water treatment systems and extending the shelf life of food packaging [16]. PVA-AgNPs nanocomposites have high mechanical and thermal strength and are also preferred in electronic applications such as sensors and optoelectronic devices. PVA-Ag nanocomposites have a vast potential for use in medical, environmental, and

industrial fields and are essential in developing sustainable and effective materials [17].

The production of polymer nanocomposites by the hydrothermal method has many advantages [18]. This method allows the desired particle size and morphology to be obtained by controlling temperature, pressure, and reaction time [19]. A water-based system provides an environmentally friendly production process and reduces solvent use. In addition, quality products are obtained since high-purity nanomaterial production is possible [20]. Nanocomposites produced by this method have superior mechanical strength, electrical conductivity, thermal stability, and corrosion resistance [21].

This study investigated nanocomposites produced by the hydrothermal method incorporating biogenic AgNPs at different weight ratios into the blend of PVA and a new PS derivative polymer (PMST). PMST is a PS derivative containing an ester group on its side branch. These groups can enter into intermolecular interactions with the hydroxyl groups in the backbone of PVA. Moreover, a polymer blend with PVA-PMST composition is not available in the literature. The number of PVA and PS-based composites in the literature is relatively small. Another novel aspect of the study is that biogenic AgNPs used as fillers were included in such a composite for the first time. These AgNPs were recently produced by green synthesis using *Verbascum nudatum* plant extract and were reported to have antimicrobial and photocatalytic activity [22].

2 Materials and Methods

2.1 Materials and Characterizations

Polyvinyl alcohol (PVA) with a molecular weight between 89,000 and 98,000 and a hydrolysis degree exceeding 99% was obtained from Sigma Aldrich (USA). Methyl-4-hydroxybenzoate and silver nitrate (AgNO_3) were purchased from Merck (USA) and used as received without further purification. The 4-vinylbenzyl chloride (4-VBC) was distilled to remove the inhibitor before use. All solvents employed, such as 1,4-dioxane, dichloromethane (CH_2Cl_2), ethanol, and acetic acid, were of analytical grade.

The surface morphology and the chemical composition were inspected utilizing the Hitachi-S3000H checking Scanning Electron Microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX). FT-IR spectra were obtained in the range of 400–4000 cm^{-1} by the KBr disk method (Nicolet iS5, Thermofisher, USA) to determine the functional groups in the materials. XRD estimations were performed on a Rigaku Desktop Scaled down flex II X-ray powder diffractometer with Cu $\text{K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) as the

vitality source. The diffracted force was recorded between 0–80° at 2θ points. The effect of conductivity, dielectric constant, and dispersion factor of the samples was measured using the Fytronix 9000 Dielectric characterization system in the frequency range of 1 kHz–1 MHz and at room temperature. The contact angle measurements were performed using a FYTRONIX 9000 contact angle analyzer.

2.2 Synthesis of AgNPs

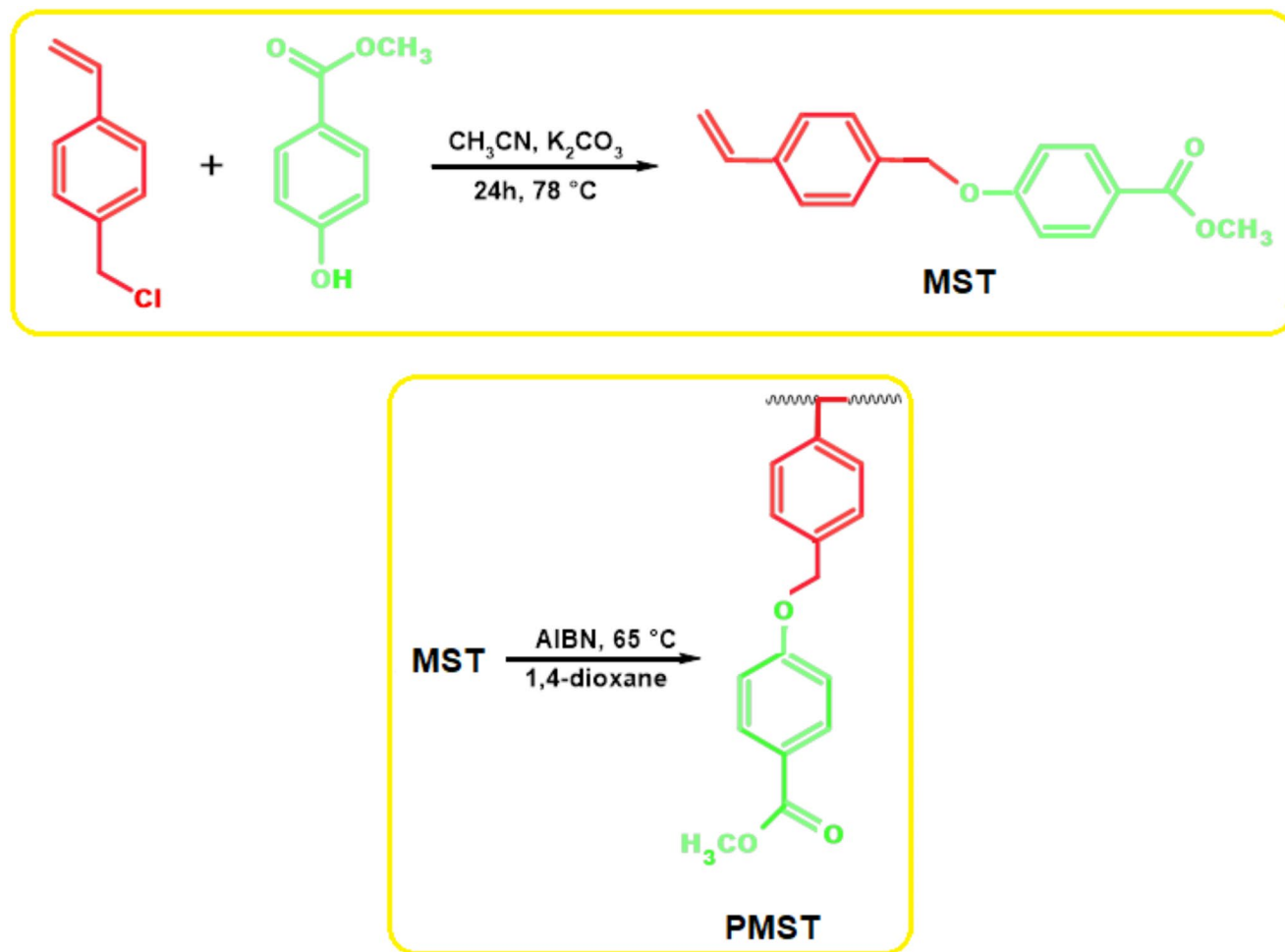
Green synthesis of AgNPs was carried out with *Verbascum nudatum* plant extract (VNE) via the hydrothermal method. First, 40 mL of VNE and 40 mL of 10 mM AgNO₃ solution were stirred in a magnetic stirrer at 60 °C and 800 rpm for 5 h. Then, the mixture, sonicated for 30 min, was taken into a hydrothermal system and incubated at 120 °C for 24 h. At the end of the period, AgNPs formed from the mixture were separated by centrifugation at 8500 rpm for 5 min and washed five times with deionized water. Finally, it was dried in a vacuum oven at 80 °C for one day and characterized.

2.3 Synthesis of PMST

PMST (polymethyl-4-[(4-ethenylphenyl)methoxy]benzoate) was obtained from the radical polymerization of the styrene-based MST monomer (methyl-4-[(4-ethenylphenyl)methoxy]benzoate) synthesized within the scope of the study. The synthesis steps of MST and PMST are presented in Scheme 1.

2.4 Synthesis of PVA-PMST Blend and Nanocomposites

PVA and PMST were blended using the hydrothermal method. 1 g of PVA and 10 mL of distilled water were added to a beaker and stirred for two hours at room temperature; then 1 g of water-dispersed PMST was added and stirred at 1000 rpm for three hours. Then, the mixture was sonicated for 30 min, transferred to a Teflon container, and treated in the hydrothermal system at 120 °C for 12 h. The resulting blend was separated, washed with pure water, and dried in a vacuum oven for 48 h. A series of PVA-PMST/



Scheme 1 The synthesis procedure of the MST monomer and PMST homopolymer

Ag nanocomposites with different AgNP concentrations were synthesized using the hydrothermal method. For this purpose, 1 g each of PVA was added to three beakers and dissolved in 10 mL of distilled water at room temperature for two hours with stirring. Then, 1 g of PMST dispersed in water was added to each beaker and stirred at 1000 rpm for three hours. AgNPs sonicated for half an hour in another beaker were added to the existing mixtures in three different weight ratios (3%, 5%, and 7%) and stirred continuously at 1200 rpm at room temperature for about two hours. The mixtures were then sonicated for half an hour to ensure homogeneity. At the end of the time, the mix in each beaker was transferred separately into three different Teflon containers and transported to the hydrothermal system. The hydrothermal process continued at 120 °C for 12 h. The resulting product was dried in a vacuum oven for 48 h. The production stages of the nanocomposites are shown in Scheme 2.

2.5 Determination of Antioxidant and Antimicrobial Activity

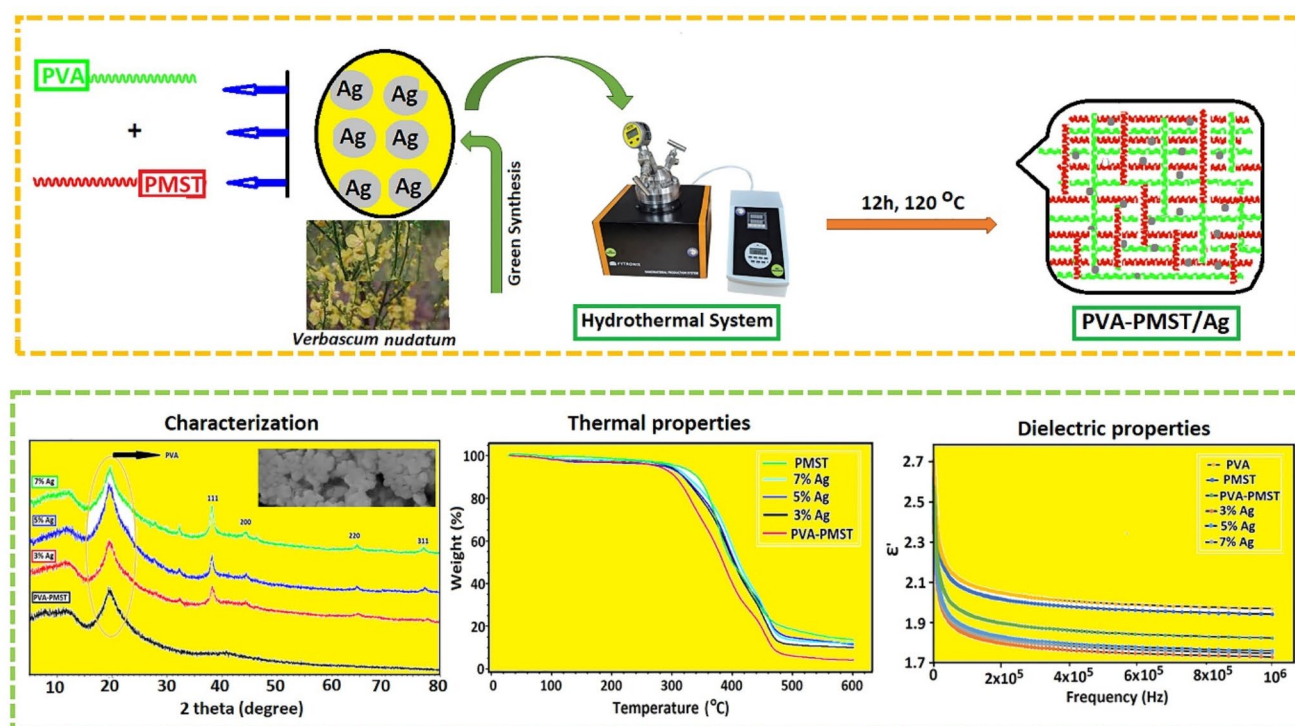
The total antioxidant capacity values of the samples were determined using spectrophotometric commercial kits (Rell Assay, Turkey) and torolox as a standard [21, 22]. The obtained data were expressed as torolox-equivalent (mmol Torolox-Equivalent/L). The disk diffusion method was used to determine antimicrobial activities [22]. Microorganism strains were cultured on Mueller-Hinton Agar in sterile Petri

dishes. 10 μ L of each sample was applied to empty disks and incubated at 37 °C for 24 h. After incubation, inhibition zone diameters were measured. Penicillin (5 IU) served as the reference antibiotic.

3 Result and Discussion

3.1 Characterization of the PMST

The FTIR spectrum of PMST is presented in Fig. 1A. The FTIR spectrum contains characteristic peaks originating from aromatic rings, ester groups, and aliphatic chains in the PMST structure. C=C stretching vibrations originating from aromatic rings were observed at 1600 cm^{-1} . The sharp peak observed at 1718 cm^{-1} belongs to the stretching vibration bands of ester carbonyl. Aromatic C-H stretching vibrations become apparent at 3103 cm^{-1} , while C-H stretching vibrations in aliphatic chains occur at 2925 cm^{-1} . In addition, vibrations originating from the interaction between aromatic rings and aliphatic chains form complex peaks around 1000–1200 cm^{-1} . These spectral features play an important role in defining the chemical structure and functional groups of PMST. The ^1H -NMR spectrum seen in Fig. 1B represents the protons present in the structure of PMST. As marked in the figure, the signals belonging to aromatic ring protons were observed between 6.5 and 8.0 ppm. CH_2 and CH protons in the main chain appeared as a



Scheme 2 The synthesis steps of the PVA-PMST/Ag nanocomposites

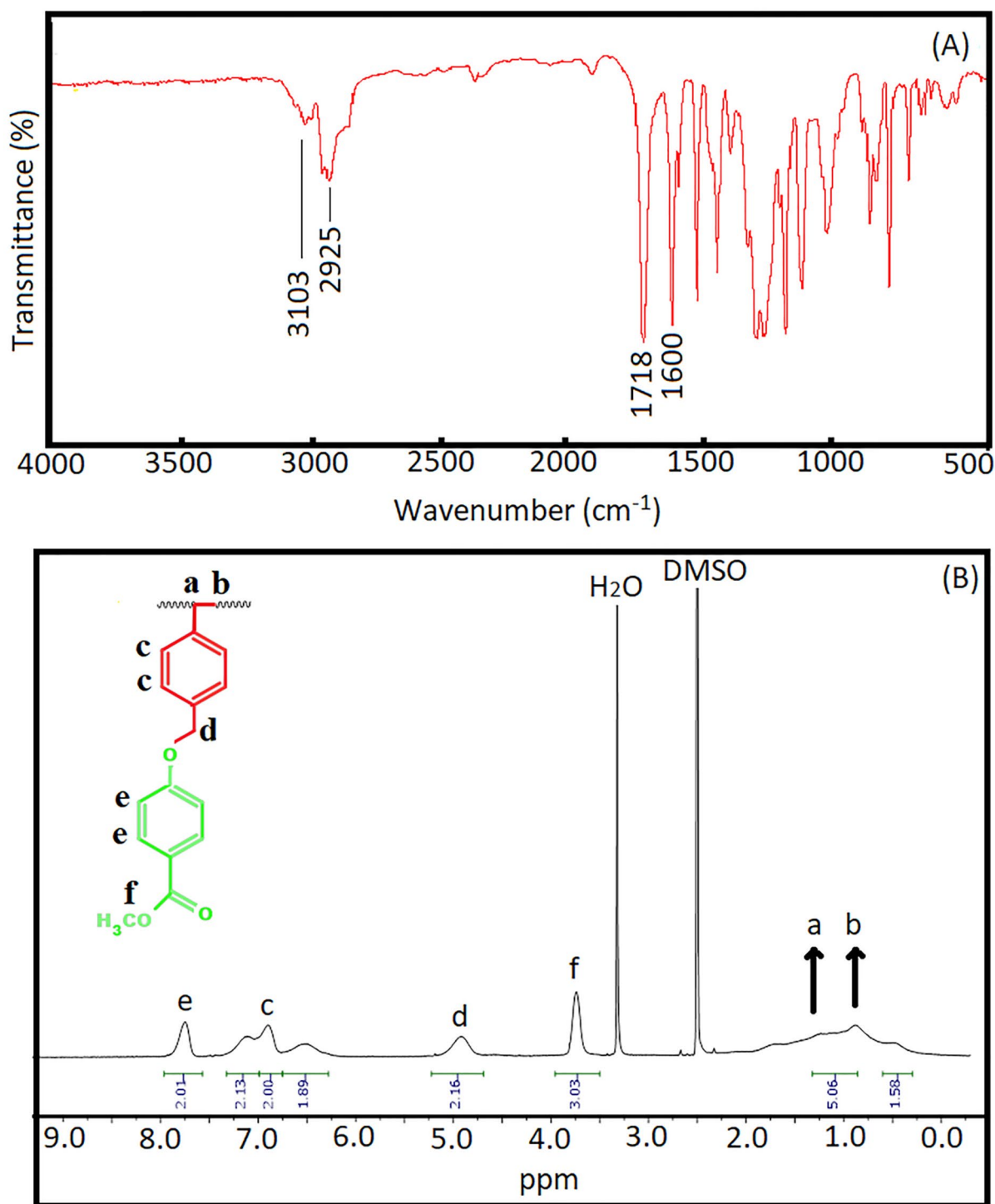


Fig. 1 FTIR spectrum (A), ^1H -NMR spectrum (B) of PMST

broad peak at 0.7–1.1 ppm. CH_3 protons in the ester groups appeared at 3.8 ppm, and OCH_2 protons at 4.8 ppm. Both spectroscopic data strongly support the molecular structure of PMST.

3.2 Characterization of the AgNPs

The characterization of AgNPs was carried out in a multifaceted manner. The peak observed at 417 nm in the UV-vis spectrum in Fig. 2A is characteristic of AgNPs [22]. The FTIR spectrum in Fig. 2B shows the functional groups of phytochemicals that play a protective role in the green synthesis process. The broad peak observed at 3383 cm^{-1} may belong to flavonoids, phenolics, or proteins carrying hydroxyl (OH), amine ($-\text{NH}_2$), or amide ($-\text{NHC}=\text{O}$)

functional groups. Other peaks supporting these structures are amide carbonyl stretching vibrations at 1653 cm^{-1} and aromatic $\text{C}=\text{C}$ vibrations at 1558 cm^{-1} . Peaks related to aliphatic CH and CH_2 structures appeared at 2922 cm^{-1} and 1106 cm^{-1} .

The SEM image of AgNPs is presented in Fig. 2C. These images show detailed information about the nanoparticles' structure, size, and properties. This information can be related to the morphology, size, surface properties, interactions between particles, and the success of the synthesis process. In the presented SEM image, it is seen that the AgNPs have a regular spherical shape. The average size of AgNPs was determined to be 23 nm. EDX analysis (Fig. 2F) confirmed the high purity of the nanoparticles by detecting only the Ag element. Combined with SEM, EDX provides

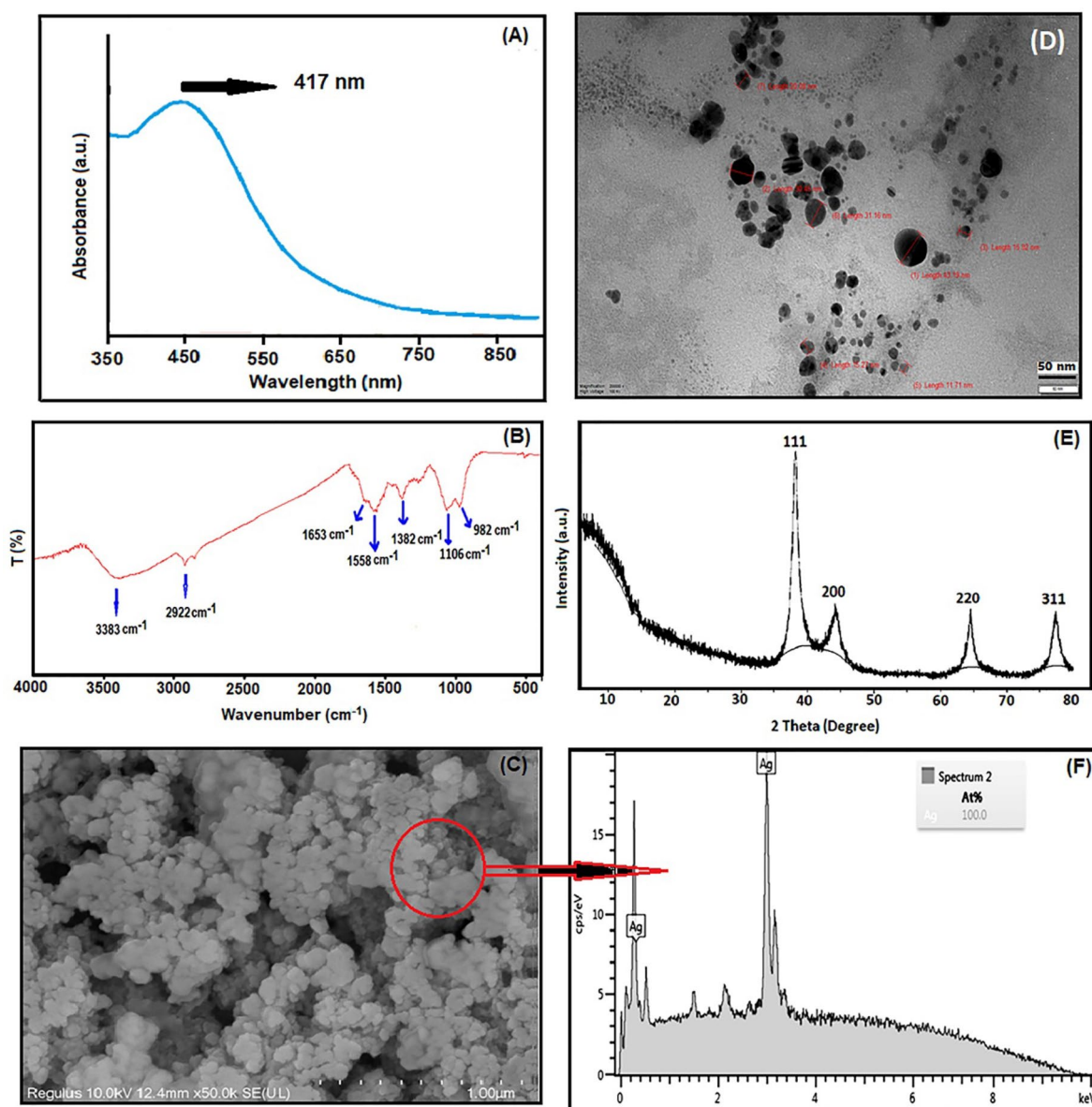


Fig. 2 UV-vis (A), FTIR (B), SEM image (C), TEM image (D), XRD pattern (E), and EDX analysis (F) of the AgNPs

valuable insights into the chemical composition and purity, which is crucial for applications in biomedicine, catalysis, and electronics.

The TEM image shown in Fig. 2D confirms the spherical structure of AgNPs and shows that their average size is 24 nm. It is observed in the TEM images that AgNPs do not tend to aggregate. This may be due to the phytochemicals responsible for the reduction during the green synthesis process [23]. These phytochemicals act as a stabilizer or capping agent on the surface of the nanoparticles. In this way, they can prevent aggregation by reducing the attractive forces that may occur between the particles [24]. In the XRD pattern of AgNPs presented in Fig. 2E, prominent peaks belonging to the FCC crystal structure are generally observed. These peaks correspond to the planar lattices of $2\theta=38.1^\circ$ (111), $2\theta=44.3^\circ$ (200), $2\theta=64.4^\circ$ (220), and $2\theta=77.5^\circ$ (311), respectively. The 111 plane stands out as the most potent and intense reflection and represents the main feature of the FCC structure of AgNPs. The other planes, 200, 220, and 311, appear as lower-intensity reflections. The width of the peaks is related to the nanoparticle size, and the average crystallite size calculated by the Scherrer Equation is 23 nm, which is quite close to the value obtained in TEM and SEM. These peaks observed in the XRD pattern of AgNPs coincide with the JCPDS No: 04-0783 data, which is attributed to the FCC structure of pure crystalline Ag [22].

3.3 Characterization of the PVA-PMST/Ag Nanocomposites

An essential method for understanding the structural and crystalline properties of the material is XRD analysis of the nanocomposites. The XRD patterns obtained in the range $2\theta=0-80^\circ$ are shown in Fig. 3A. The peak observed at 19.5° of PVA-PMST is related to the semi-crystalline structure of PVA supported by intramolecular and intermolecular hydrogen bonds [25]. The.

The characteristic peaks of AgNPs at $2\theta=38.19^\circ$, 44.15° , 64.73° , and 77.39° and the corresponding lattice planes 111, 200, 220, and 311 were detected in the XRD patterns of the nanocomposites. The presence of these peaks confirms the presence and distribution of AgNPs in the PVA-PMST blend. In addition, the intensity of the characteristic peaks belonging to AgNPs exhibits a smooth change depending on their concentrations. The chemical reactions and environmental factors that occur during the preparation of nanocomposites can also be monitored using XRD. This information is crucial to determine the performance and areas of application of nanocomposites.

The FTIR spectrum of pure PVA (Fig. 3B) shows a peak at 3422 cm^{-1} for OH stretching vibration bands. A peak at 1718 cm^{-1} is due to the carbonyl of acetate groups from

PVA hydrolysis residue. Stretching of aliphatic CH_2 groups in the PVA main chain was observed at 2940 cm^{-1} and 1560 cm^{-1} . Peaks at 1144 cm^{-1} are due to stretching vibrations of C-O groups. There are slight shifts in some peaks in the FTIR spectrum of PVA-PMST. Ester and OH stretching vibration bands are shifted. These shifts may be due to hydrogen bonding and dipole-dipole interactions between polar functional structures. FTIR spectra of PVA-PMST/Ag nanocomposites showed changes due to the interaction of AgNPs with functional groups of polymer blend [26]. The peak at 3422 cm^{-1} is due to OH stretching vibration, and the peaks at 1715 cm^{-1} are due to ester stretching bands. The peaks at 3014 and 2924 cm^{-1} are attributed to ArC-H and aliphatic C-H stretching vibration bands.

3.4 SEM-EDX Analysis

SEM images of the materials are shown in Fig. 4. SEM analyses allow for a detailed examination of the material surface and provide important information. PVA does not have a smooth surface and contains large amounts of voids. The surface of PMST consists of spheres. It has been reported that similar spheres can be formed in the SEM images of pure PS [27]. In the SEM image of the PVA-PMST blend, it is seen that the PMST spheres fill the pores of the PVA. However, the surface is quite rough. However, it was observed that AgNPs were homogeneously distributed in PVA-PMST and there was no major agglomeration problem in the SEM image of the nanocomposite containing 3% AgNPs. In addition, the roughness on the surface was partially reduced. The surface of the composite containing 5% AgNPs became smooth due to its homogeneous distribution. The gaps left by PMST spheres on the composite surface containing 7% AgNPs were filled by AgNPs, and the surface became smooth. The fact that AgNPs functioned very well as a filler material on the surface may be due to the interaction of the capping phytochemicals in the green synthesis process with the PVA-PMST blend. Similar results were previously observed in polymer nanocomposites containing green biosynthesized nanoparticles [28, 29, 30]. EDX data of the materials support the elemental composition in their molecular structures. Using EDX, the chemical composition of the material and the distribution of elements on the surface can be determined. This information plays a critical role in optimizing the performance of nanocomposites and improving manufacturing processes. Valuable data supporting the homogeneous distribution is the presence of Ag among the elements defined in the selected regions in the EDX analysis of the nanocomposites.

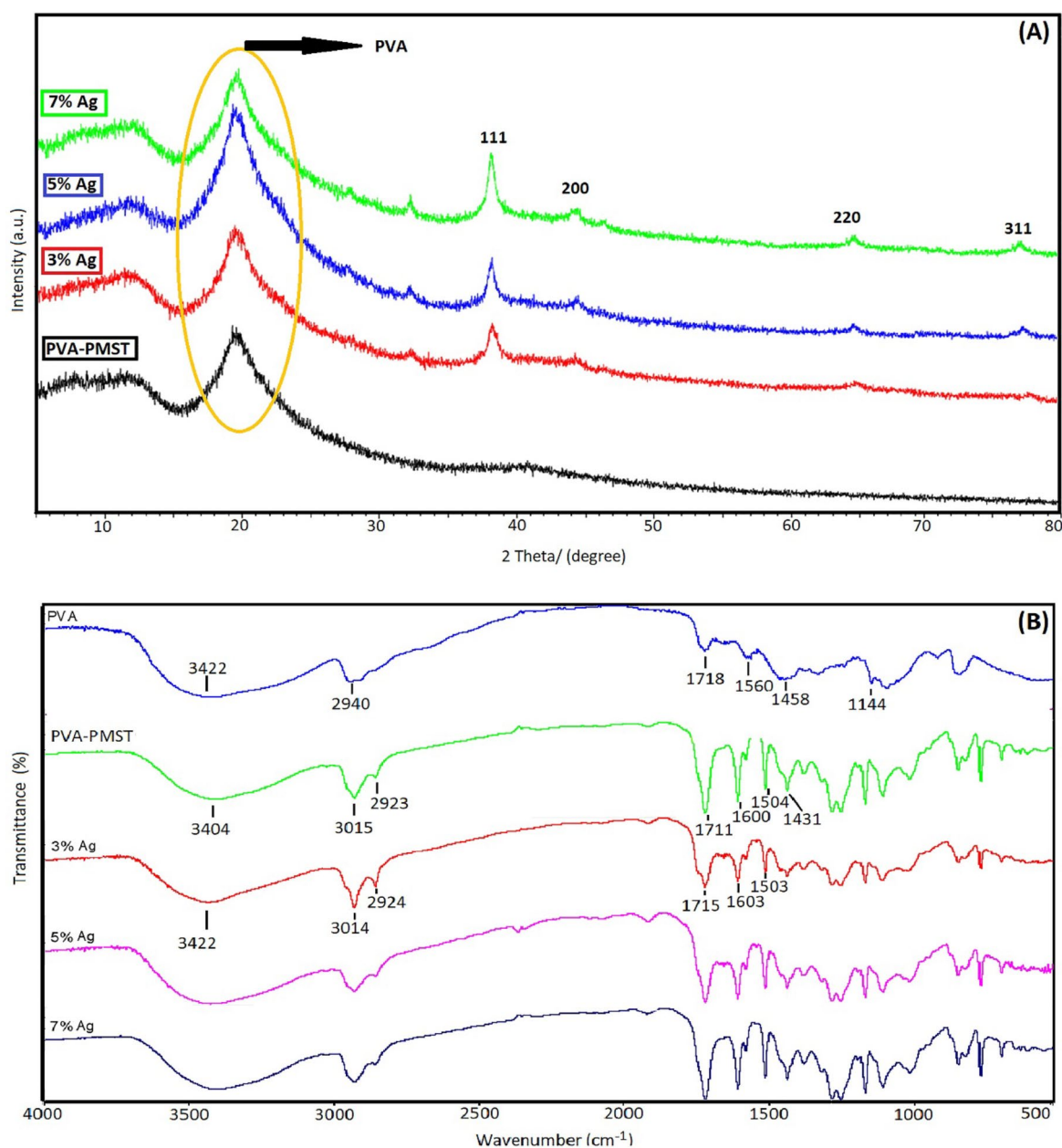
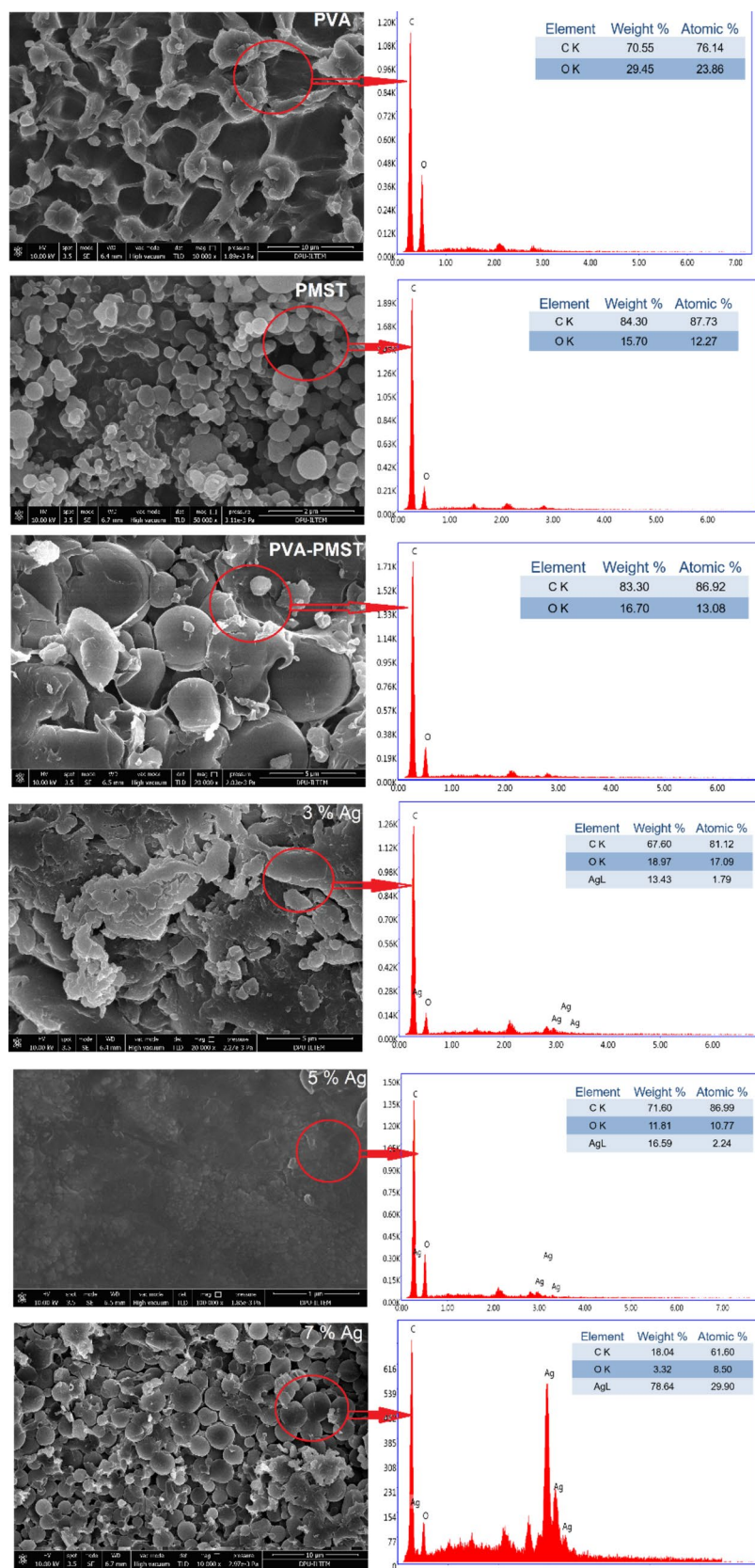


Fig. 3 XRD pattern (A) and FTIR spectrum (B) of the materials

3.5 TGA and DSC Analysis

The TGA method allows an understanding of the thermal stability and decomposition behavior of a material by measuring its weight loss with temperature or time. Thermograms showing the thermal stability of materials are shown in Fig. 5. The PMST thermogram shows that the first mass loss temperature (T_{id}) is 342 °C. The temperature at 50% mass loss is 410 °C. The residue at 600 °C (where degradation ends) is 8%. According to the previously reported thermal behavior characteristic of PVA, it was reported that the first mass loss begins at 160 °C with the removal of surface

water, and the central degradation occurs at 260 °C [31]. It was determined that the degradation of PVA-PMST happened in a single step, and the first mass loss occurred at 298 °C. The amount of waste formed at 600 °C was 5%. The addition of AgNPs to the PVA-PMST blend increased the thermal stability. This increase was parallel to the rise in the amount of AgNPs in the blend. AgNPs, thanks to their high thermal conductivity, effectively distribute heat within the composite, balancing temperature gradients and preventing local heating. This feature prevents the thermal degradation of PVA-PMST, increasing its thermal stability. At the same time, AgNPs are resistant to oxidation as they

Fig. 4 SEM-EDX analysis of the nanocomposites

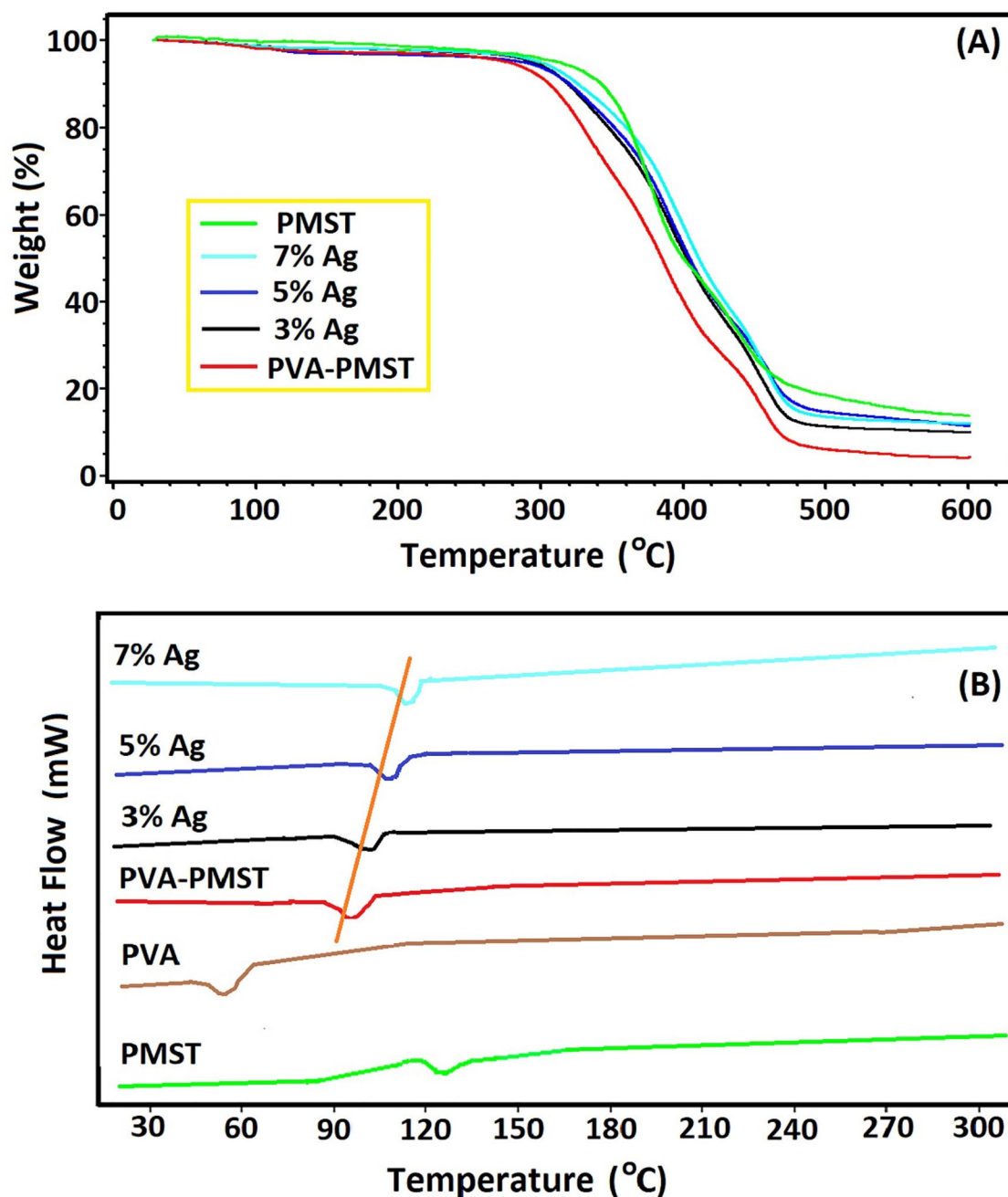


Fig. 5 TGA (A), DSC (B) thermograms of materials

are a chemically inert metal. This slows down the rate of chemical degradation within the composite, acts as a barrier to volatile products, and extends the life of the material [28, 29]. The thermal stability of PVA-PMST increased by about 20 °C at the highest AgNP loading rate (7%). As a result, the thermal stability of PVA was enhanced by the combination of PMST and AgNPs. Improving thermal stability ensures the material's longevity, durability, and functionality. This

directly affects the reliability and performance of many products used in engineering applications and everyday life.

DSC curves showing the T_g values of the materials are shown in Fig. 5B. According to the thermogram, the T_g values of PVA and PMST are 58 and 131 °C. The T_g value of PVA-PMST is between the T_g values of both polymers and is 93 °C. In addition, determining a single T_g value indicates successful blending [32]. The T_g of the nanocomposites increased with AgNP loading and became 99 °C for

3% AgNP and 117 °C for 7% AgNP. This result indicates that AgNPs effectively limit the mobility of polymer chains. Information on the thermal characteristics of the materials is shown in Table 1. AgNPs enter into physical or chemical interactions with polymer chains, limiting the free movement of the chains and creating a situation that requires more energy. As a result, the presence of AgNPs increases thermal stability and mechanical strength while allowing the polymer to remain functional at higher temperatures. Therefore, adding silver nanoparticles acts as a mechanism to improve the T_g value of polymers [33]. The softening temperature of nanocomposites is of critical importance in terms of the physicochemical properties of the material. This temperature determines the resistance of the nanocomposite to external effects, long-term usage performance, and operating conditions.

3.6 Surface Properties of the Nanocomposites

The contact angles of the nanocomposites with water are presented in Fig. 6. The water contact angle is formed by a liquid when it comes into contact with a solid surface. It is measured to evaluate the wettability properties of the surface. This measurement determines whether the surface is hydrophilic or hydrophobic and obtains information about the surface energy. The determined contact angle of PVA is 53.49°, reflecting its surface's hydrophilic character [34]. The contact angle value of PMST, determined as 80.31°, may have occurred due to the hydrophobic $-\text{CH}_2-\text{CH}-$ groups in the main chain. Since the reported contact water angle of pure PS is 90° [34]. Blending PVA with PMST caused the contact angle to increase, i.e., the surface became less hydrophilic. The same trend continued with the addition of AgNPs. The contact angle of the composite incorporating %3 AgNPs was 65.21°, while those incorporating %5 and 7% AgNPs were 69.45° and 74.61°. AgNPs create nanoscale roughness on the surface and increase the contact angle by preventing water droplets from spreading entirely on the surface. In addition, AgNPs can build a structure with low surface energy on the surface, which makes it difficult for water to adhere to the surface. Thus, water droplets

take a more spherical form, and the contact angle increases. These properties make the surface hydrophobic and provide water repellency [35, 36].

The surface free energy (SFE) value of all samples was determined using a Fytronix 9000 Contact angle analyzer based on the ASTM D4790 standard test method. This method uses water (W) as a polar solvent and diiodomethane (DIM) as a nonpolar solvent. DIM angle measurement values of the materials are shown in Fig. 7. Surface free energy values were calculated using software belonging to the relevant standard and are presented in Table 2. The surface free energy of a material expresses the energy stored on the surface due to the bonds between the atoms or molecules forming the surface per unit area. This energy is used to understand the interactions between the surface and other substances (e.g., liquids or gases). It is a fundamental parameter that determines the chemical and physical properties of the surface. While the surface free energy of PVA was 56.69 mN/m, this value decreased significantly as a result of both blending with PMST and AgNPs loading and became 46.94 mN/m. The decrease in the surface free energy with the increase in the contact angle is relatively consistent. Because the surface free energy affects a liquid's spreading or contraction behavior on a material. Surfaces with high surface energy show hydrophilic behavior, and liquids spread easily on these surfaces. Surfaces with low surface energy have hydrophobic properties, and liquids maintain droplet formation on the surface. Nanocomposites with low surface free energy make it difficult for foreign substances, such as dirt and water, to adhere to the surface due to their superhydrophobic surface. As a result, the surface free energy of nanocomposites is a key factor determining the physical and chemical properties of the material. This parameter is critical for optimizing the material's performance in wettability, adhesion, surface modification, and industrial applications.

3.7 Impedances Properties

Figure 8A presents the graph obtained for the impedance (Z) measurements of the materials in the frequency range between 1 kHz and 1 MHz. The graph shows that impedance values decrease consistently with increasing frequency across all adding levels, reaching their minimum at high frequencies. The increase in doping levels reduces the initial impedance values and increases the conductivity. While the initial impedance is $4.6 \times 10^6 \Omega$ for 3% AgNP doping, this value decreases to $3.7 \times 10^6 \Omega$ for 7% doping. With the increase in the AgNP concentration in PVA-PMST, the impedance and energy losses decrease while the conductivity value increases. In addition, the high impedance behavior at low frequencies and the low impedance behavior at

Table 1 Some thermal properties of PVA, PMST, PVA-PMST, and nanocomposites

Sample	T_g (°C)	$^aT_{id}/^{\circ}\text{C}$	$T_{d\%50}/^{\circ}\text{C}$	Residue (%)
PVA	58	260	303	4
PMST	131	342	410	8
PVA-PMST	93	298	394	5
3% Ag	99	306	398	6
5% Ag	108	311	402	6
7% Ag	117	318	405	7

$^aT_{id}$: initial decomposition temperature; T_g : Glass transition temperature; $T_{d\%50}$: The temperature at 50% mass loss

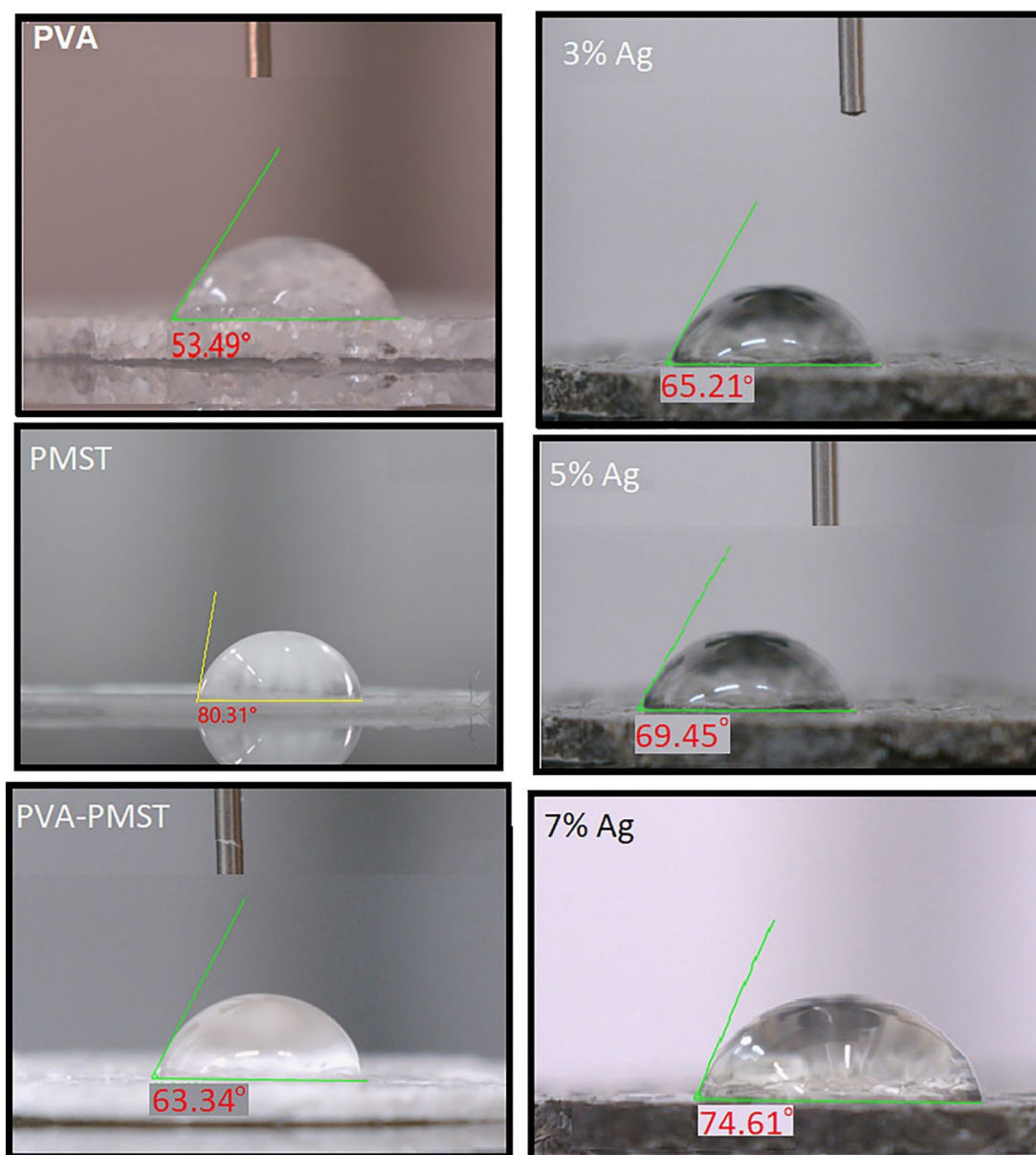


Fig. 6 Water contact angle values of the materials

high frequencies indicate the existence of different transport mechanisms within the material at these frequency ranges. These findings highlight the potential of the material for use in electronic applications. The impedance behavior observed at different frequency ranges indicates two primary transport mechanisms in the material. At low frequencies, ionic or dipole polarization dominates, while conduction mechanisms involving free charge carriers dominate at high frequencies. The high impedance at low frequencies indicates limited charge carrier mobility, where dipole polarization plays an important role. Increasing the doping levels of AgNPs reduces the polarization resistance, allowing greater freedom of charge carrier movement.

Figure 8B presents the prepared materials' series resistance (R_s)-frequency graph. The R_s value, measured using an AC signal, is a crucial equivalent circuit parameter influencing the electrical performance of devices [28, 29, 33]. The real part of impedance represents series resistance (R_s) and corresponds to the real part of AC conductivity. As shown in Fig. 7B, R_s decreases with increasing frequency. At 1 kHz, R_s values of the composites vary significantly with different dopants, indicating that Ag, PMST, and PVA-PMST influence the electrical conductivity of the PVA polymer. The following relation defines the AC conductivity of the nanocomposites [37]:

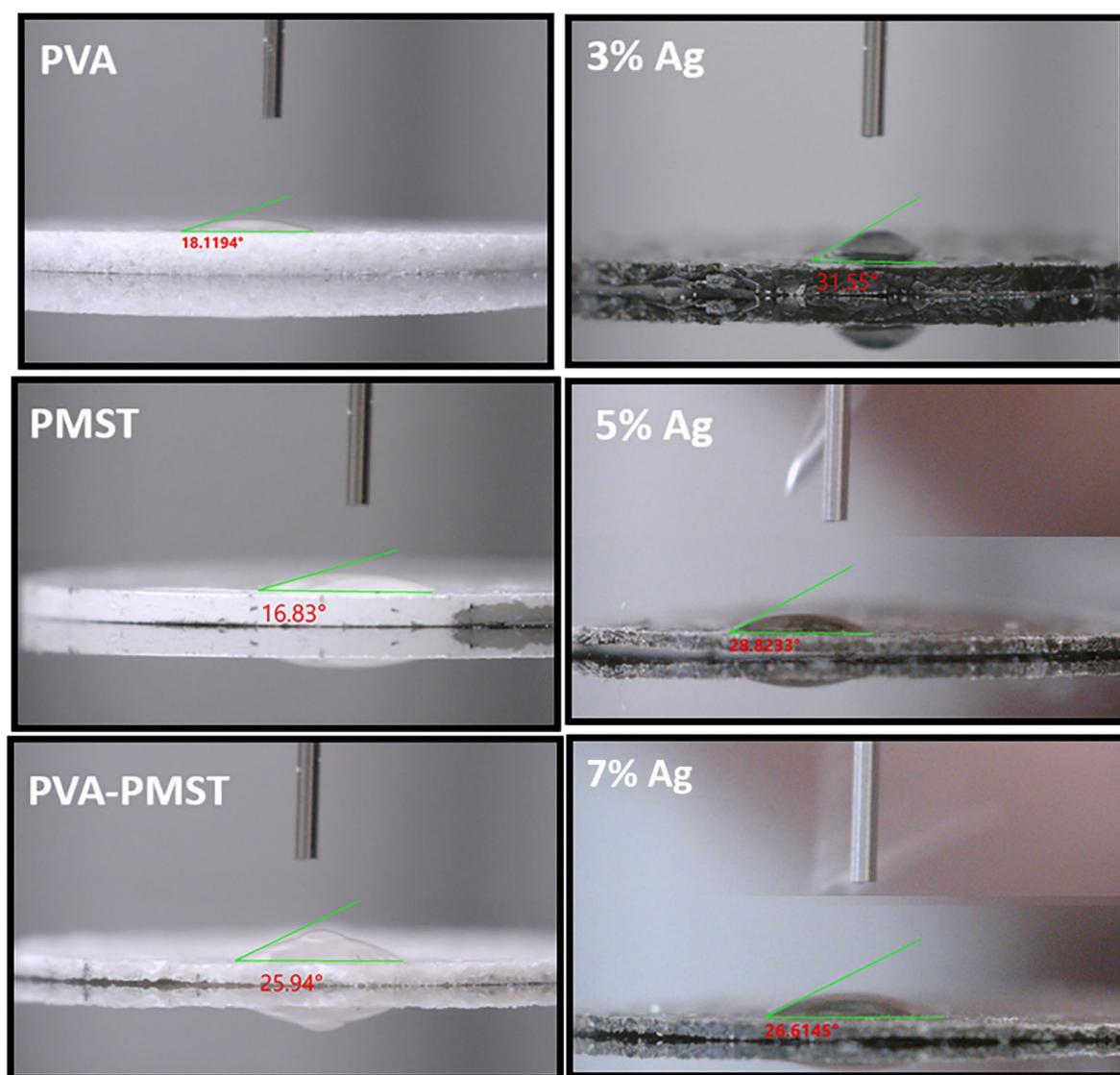


Fig. 7 DIM contact angle values of the materials

Table 2 Contact angle and surface free energy value of the materials

Sample	$W_{\text{angle}}(^{\circ})$	$\text{DIM}_{\text{angle}}(^{\circ})$	SFE (mN/m)
PVA	53.49	18.11	56.59
PMST	80.31	16.83	48.85
PVA-PMST	63.34	25.94	50.65
3% Ag	65.21	31.55	48.34
5% Ag	69.45	28.82	47.65
7% Ag	74.61	26.61	46.94

$$\sigma = \sigma_{dc} + B\omega^n \quad (1)$$

Where σ_{dc} is the DC conductivity, B is a constant and ω the angular frequency, and n is a component determining the AC conductivity mechanism of the nanocomposites. n values for the composites were obtained from the slope of $\log \sigma$ vs. $\log \omega$ plots and were found to be about 1. This indicates that the nanocomposites exhibited only alternating electrical

conductivity (AC). The nanocomposites do not have a DC (direct) current electrical conductivity, i.e. they are the insulating materials. The change in Rs values is due to dielectric polarization. The polarization losses of the material may be more significant at low frequencies. As frequency increases, the Rs value decreases due to reduced resistive losses. At higher frequencies, inductive effects and reactance dominate, minimizing resistance-related losses. The incorporation of AgNPs into the PVA-PMST blend further reduces the Rs value. This is attributed to the high electrical conductivity of AgNPs and the influence of their nanoparticle size within the material. Additionally, the homogeneous distribution of AgNPs in the matrix likely enhances electrical conduction efficiency by providing a more effective conductive path.

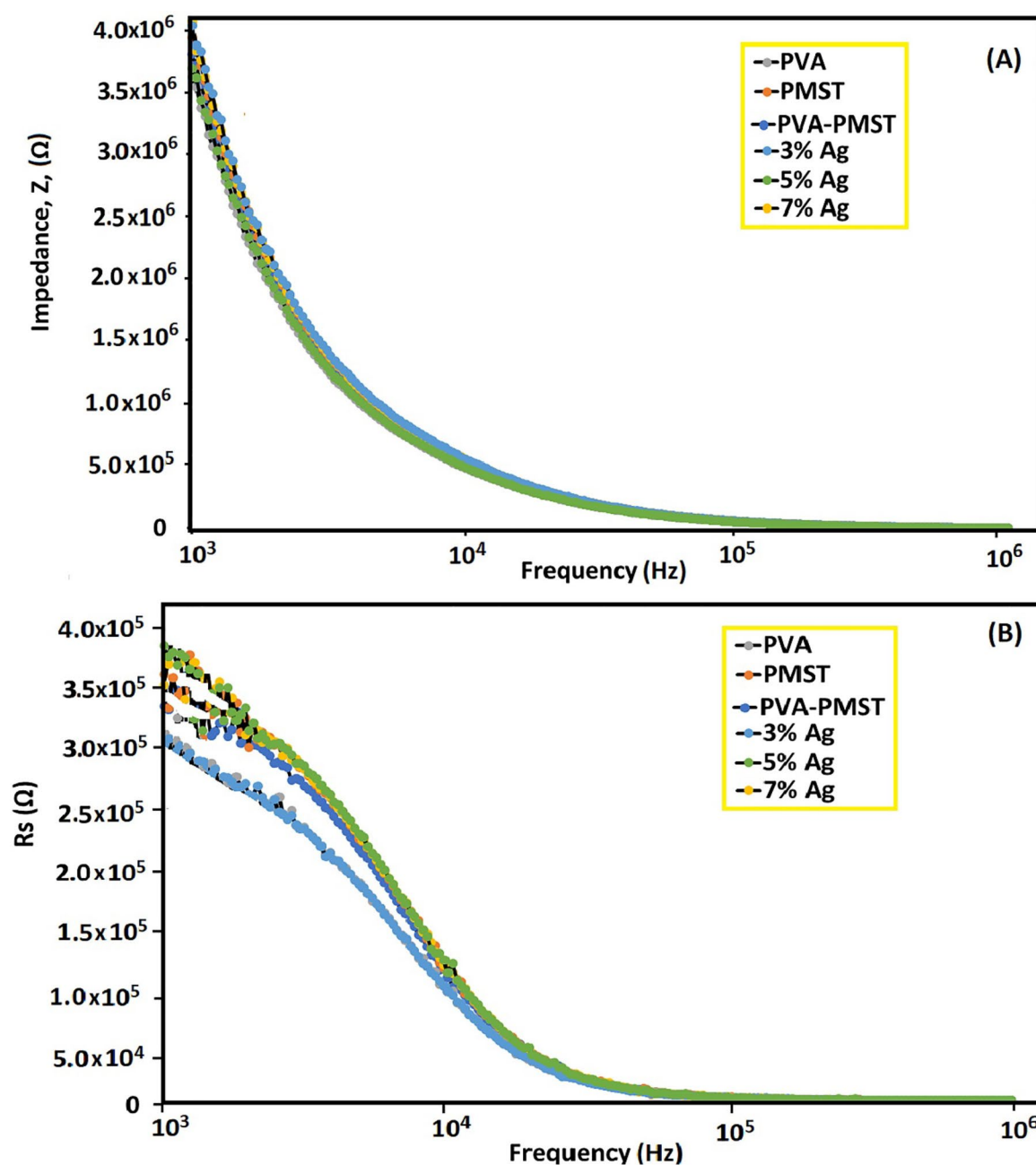


Fig. 8 Real part impedance-frequency (A) and series resistance-frequency (B) graphs in log scale of the materials

3.8 Dielectric Analysis

The dielectric properties of a material describe how it behaves under an electric field and how it stores or conducts electric charges. Dielectric properties play an essential role in the characterization of insulating materials. The dielectric constant is a critical parameter for various electronic nanocomposites, especially capacitors. It determines how effectively a material can store electric charges under an electric field and directly increases the capacitance of the

capacitor. Materials with high dielectric constants allow for high capacitance values at smaller sizes, which is crucial for the miniaturization of modern electronic nanocomposites.

The complex dielectric function for the nanocomposites is expressed by the following relation

$$\epsilon^* = \epsilon' + \epsilon'' \quad (2)$$

Where ϵ' is the real part of the dielectric constant, ϵ'' is the imaginary part of the dielectric constant. To analyze the

dielectric properties of the nanocomposites, the complex dielectric function is measured as a function of frequency.

Figure 9A presents the dielectric constant (ϵ')-frequency plots of the materials, measured at room temperature within the 1 kHz to 1 MHz range. The ϵ' values at 1 kHz for PVA, PMST, and PVA-PMST are 2.70, 2.49, and 2.58, respectively, indicating that the dielectric constant varies with different dopants. The addition of dopants to the PVA polymer alters its electrical polarization. This effect is attributed to the polar hydroxyl and ester groups in the polymer, which influence the rearrangement of electric charges and the alignment of dipole moments within the material. This determines the material's response to an electric field and is the fundamental physical source of the dielectric constant. The dielectric constant of polymers changes with frequency depending on the polarization processes that occur within the material when an electric field is applied. The main reason for this change is that different polarization mechanisms within the material respond to varying speeds according to the frequency of the electric field. At low frequencies, the charge carriers and dipoles within the material quickly adapt to the direction of the field, and therefore, the dielectric constant is generally high [37]. However, as the frequency increases, it becomes difficult for the polarization mechanisms to keep up with the change in the electric field [38]. First, slower mechanisms, such as dipole polarization, lose effectiveness and decrease the dielectric constant. Only faster processes, such as ionic and electronic polarization,

become effective at higher frequencies. Electronic polarization becomes effective when the frequency is very high and the dielectric constant reaches a constant value. In addition, the deactivation of polarization types that cannot adapt to the frequency of the electric field is the main reason for the decrease in the dielectric constant with frequency [39].

Figure 9B illustrates the dielectric loss factor variation with frequency. The dielectric loss factor quantifies the energy lost or converted into heat when a material is subjected to an electric field. As observed in the graph, the dielectric loss decreases with increasing frequency. This decline suggests a reduction in energy dissipation, likely due to the inability of dipoles to reorient quickly at higher frequencies. The reason for these decreases is that the polarization mechanisms in the material cannot adapt to high-frequency field changes. While slow mechanisms such as dipole and ionic polarization interact effectively with the electric field at low frequencies, these mechanisms become inactive as the frequency increases. As a result, the energy loss decreases. In addition, at higher frequencies, only processes such as electronic polarization, which can respond quickly, become active, and these mechanisms cause lower losses [40]. This loss is usually caused by the delay of polarization processes occurring within the material and electrical conductivity. The loss factor is essential to determine the efficiency of the material, especially in high-frequency applications and during energy transmission. A high loss factor means more loss in energy storage or transmission

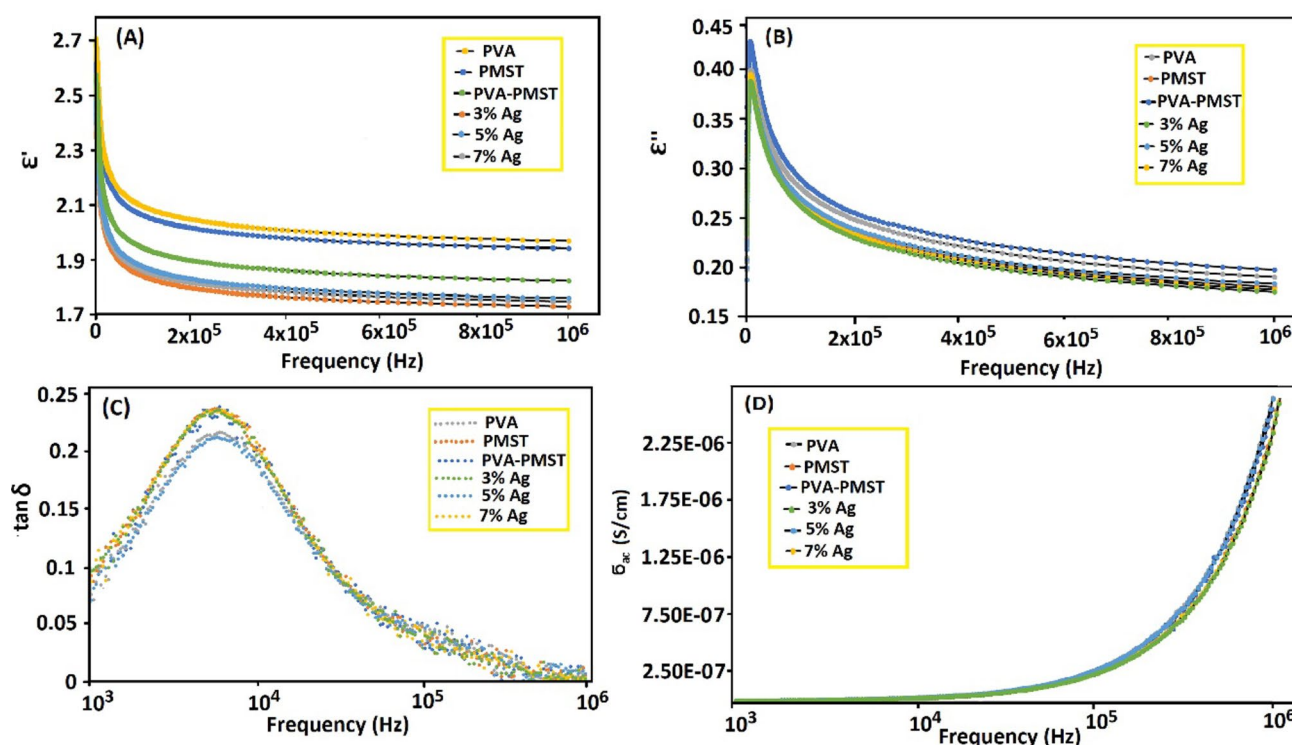


Fig. 9 Graphs of the variation of dielectric constant (A), dielectric loss factor (B), $\tan \delta$ (C), and AC constant (D) of the materials with frequency

processes, which can negatively affect the performance of devices. A low loss factor indicates low energy losses; the material is a good insulator. This property is critical in many technological applications, such as capacitors, antennas, and insulating materials.

The dielectric constants of the nanocomposites loaded with 3%, 5%, and 7% AgNPs at 1 kHz were recorded as 2.52, 2.46, and 2.42, respectively. These values indicate a decrease in dielectric constants with increasing AgNP loading compared to the PVA-PMST blend. Similar trends have been reported previously [40]. The change in the dielectric constant of the nanocomposites is due to the change in dielectric polarization with the incorporation of dopants in the polymer matrix. The incorporation of AgNPs into PVA polymer causes charge accumulation on their surfaces due to their free electrons under an electric field, and this charge accumulation reduces the effectiveness of the dipole polarization formed inside the dielectric material [41]. In addition, AgNPs in nanocomposites can disrupt the homogeneous distribution of the material's electric field and weaken processes such as interface polarization. In addition, metal nanoparticles generally cause the dielectric constant to decrease more rapidly with frequency because nanoparticles make it difficult for the polarization to adapt to electric field changes. When these factors combine, a decrease in the dielectric constant of the nanocomposite is observed [42].

The graph showing the loss tangent or dielectric dissipation factor ($\tan\delta$) values of the materials is presented in Fig. 9C. $\tan\delta$ is an important parameter when evaluating the dielectric properties of a material. This term is usually called dielectric loss angle tangent and describes the electrical energy losses. The loss tangent values of all materials were relatively low at low frequencies. Still, a significant increase in the loss tangent was observed as the frequency increased, especially with the AgNPs loading [43]. The low $\tan\delta$ indicates that the material has low energy loss and is an efficient dielectric. Due to the high electrical conductivity of AgNPs, the loss tangent decreases by increasing the free electron density in the nanocomposite [44]. In addition, AgNPs minimize polarization losses by stabilizing the dipole movements under the electric field and reducing the losses due to ion movements. The interfaces between the PVA-PMST blend and AgNPs provide more effective electrical energy storage and prevent energy losses due to irregularities [45].

Figure 9D shows the frequency dependence of AC electrical conductivities of materials. AC conductivity value is a critical parameter for understanding the electrical behavior of the material, energy losses, and application areas. This value expresses how the material carries electrical charges under an alternating electric field and behaves in energy storage or loss processes [46]. As seen in Fig. 8D,

the conductivity values of all materials increase with frequency. This increase is due to the direct dependence of the electrical behavior of a material on the rate of change of the electric field. When an electric field is applied, the charge carriers (electrons or ions) in the material move under the influence of the field. This movement is slower and limited at low frequencies, but as the frequency increases, the charge carriers change direction more frequently and move faster. This means more charge transfer and increased conductivity [47]. The highest frequency AC conductivity values for PVA, PMST, and PVA-PMST were determined as 2.48×10^{-6} S/cm, 2.31×10^{-6} S/cm, and 2.37×10^{-6} S/cm, respectively. The AC conductivity of the nanocomposites increased with AgNP doping. Specifically, the nanocomposite containing 3% AgNPs had an AC conductivity of 2.39×10^{-6} S/cm, while the composite with 7% AgNPs showed a higher conductivity of 2.61×10^{-6} S/cm. This increase is attributed to the enhanced charge transport facilitated by AgNPs incorporation. It is seen that the nanoparticles improve the AC electrical properties of PVA polymer [48]. When Fig. 8D was analyzed by Eq. 1. The logs vs. $\log\omega$ plots exhibited a linear behavior. This suggests that nanocomposites exhibited an AC electrical conductivity mechanism. The charge carries a jump between the polymer chains in the AC electrical conductivity mechanism. Also, AgNPs significantly impact the conductivity of the electric field due to their high free electron density. AgNPs increase the free electron movement in the nanocomposite in the applied electric field and create paths (conductive networks) where electric charges can quickly move [49]. This provides a faster response to the frequency of an alternating electric field and increases AC conductivity.

3.9 Antioxidant and Antimicrobial Effect

The graph showing the antioxidant values of the materials is shown in Fig. 9A. Antioxidants can neutralize free radicals. Free radicals can damage biological macromolecules such as DNA, proteins, and lipids by creating oxidative stress in cells. Antioxidant properties protect cell health by preventing this damage. Since the properties of PVA were tried to be improved in the presented study, statistical comparisons were made according to PVA. When the TAC data were examined, it was determined that the AgNPs TAC level (0.69 ± 0.4 mmolTrolox-Equivalent/L) was higher than PVA (0.52 ± 0.4 mmolTrolox-Equivalent/L) and the PMST TAC level (0.41 ± 0.2 mmolTrolox-Equivalent/L) was lower than PVA, which was statistically significant ($p=0.000$). The high antioxidant value of AgNPs has been reported in many previous studies [13, 22]. The antioxidant effects of AgNPs may vary depending on their size, shape, surface properties, and synthesis method. AgNPs can reduce

oxidative stress by neutralizing free radicals. AgNPs produced with plant extracts by green synthesis methods especially may show more potent antioxidant properties [50, 51]. Antioxidant levels of PVA and PMST are low. The antioxidant effect of PVA-PMST is lower than PVA but higher than PMST. However, there was an increase in the antioxidant effect of nanocomposites produced with the addition of AgNPs. Especially the antioxidant value of the composite containing 3% AgNPs was recorded as 0.58 mmol Equivalent Torolox/L. This increase may result from the synergistic effect of AgNPs dispersed in a polymer blend [21, 28].

The graph showing the antimicrobial effects of the materials against three different pathogens is shown in Fig. 10B, and the pictures of the zones formed are shown in Fig. 10C. While AgNPs were seen to be highly effective against *S. aureus* bacteria, PVA was seen to exhibit antifungal effects against *C. albicans*. PMST was found to have moderate effectiveness against all three pathogens and formed zones with an average diameter of 10 mm on the disk. PVA-PMST was seen to be particularly effective against *E. coli*, and the diameter of the zone in which it formed was 13 mm. With the addition of AgNPs to PVA-PMST, the activity against *E. coli*, in particular, increased. The diameter of the zone formed by the composite containing 7% AgNPs against this pathogen was 14 mm. This value is quite close to the effect of the reference antibiotic (15 mm zone diameter). Undoubtedly, the impact of AgNPs is excellent in forming this activity because there are many reports in the literature that AgNPs show antibacterial effects with very different mechanisms [11, 14, 15, 16, 28, 49].

The graph showing the antimicrobial effects of the materials against three different pathogens is shown in Fig. 9B, and the pictures of the zones formed are shown in Fig. 9C. While AgNPs were seen to be highly effective against *S. aureus* bacteria, PVA was seen to exhibit antifungal effects against *C. albicans*. PMST was found to have moderate effectiveness against all three pathogens and formed zones with an average diameter of 10 mm on the disk. PVA-PMST was seen to be particularly effective against *E. coli*, and the diameter of the zone in which it formed was 13 mm. When these data were compared with PVA data, it was determined that the antimicrobial activity of MS, PMST, and PVA-PMST were close to PVA, and there was no difference at a statistical level ($p=0<0.05$). It was determined that the inhibition zone of AgNPs and the antibiotic used as a positive control (penicillin, 5 IU) against the *S. aureus* strain was statistically ($p=0.000$) higher than PVA. However, it can be said that adding AgNPs to the structure of PVA-PMST used as a blend increases the antimicrobial activity, especially against *E. coli* and *S. aureus* strains, statistically ($p<0.05$). With the addition of AgNPs to PVA-PMST, the activity against *E. coli*, in particular, increased. The diameter of the zone

formed by the composite containing 7% AgNPs against this pathogen was 14 mm. This value is quite close to the effect of the reference antibiotic (15 mm zone diameter). These data show that antimicrobial activity increases when AgNPs are added to the blend structure. The main reason may be related to the easier release of AgNPs into the environment where microorganisms are present when they interact with the blend. Numerous studies indicate that AgNPs can have antibacterial effects through different mechanisms [11, 14, 15, 16, 28, 49]. These mechanisms may vary depending on factors such as the environment in which AgNPs are present with microorganisms, solvent, and particle size. In particular, as the nanoparticle particle size (mainly 10–20 nm and below) decreases, it can be more easily transferred into the cell and affect molecules within it. As the AgNP particle size increases, their interactions with the cell membrane can play a role in the formation of antimicrobial activity. The particle sizes used in the presented study have a size distribution that can enter the cell and show its effect from outside. For this reason, the antimicrobial effect may have occurred by the two mechanisms expressed (intrinsic and extrinsic pathways). It has also been discussed in the literature that AgNPs can exhibit antimicrobial activity by affecting microbes intracellularly and/or extracellularly [52, 53]. AgNPs bind to the cell membrane, change the membrane's permeability, and cause imbalances in the internal structure of the bacteria, which leads to the leakage of intracellular materials. AgNPs are also effective by producing reactive oxygen species. Reactive oxygen species cause oxidative stress in the cell, leading to irreversible damage to essential molecules such as DNA, proteins, and lipids. This causes the cell to lose its function and die [52]. Another effective mechanism is that AgNPs bind to bacterial DNA, preventing the copying and processing of genetic material. This binding stops the cell from multiplying and prevents the spread of bacteria. In addition, these nanoparticles disrupt the structure of bacterial enzymes, disrupt metabolic processes, and stop energy production [53].

4 Conclusions

Biosynthesized AgNPs were added to a new polystyrene derivative PMST and PVA blend by hydrothermal means at different concentrations. It was observed that the concentration of AgNPs greatly affected the thermal, dielectric, and biological properties of the PVA-PMST matrix. The addition of AgNPs caused an increase in the thermal stability and Tg values of both pure PVA and PVA-PMST. The addition of 7% AgNPs caused an increase in the thermal stability of PVA by 58 °C and in the Tg value by 59 °C. The water contact angles determined for the AgNPs embedded

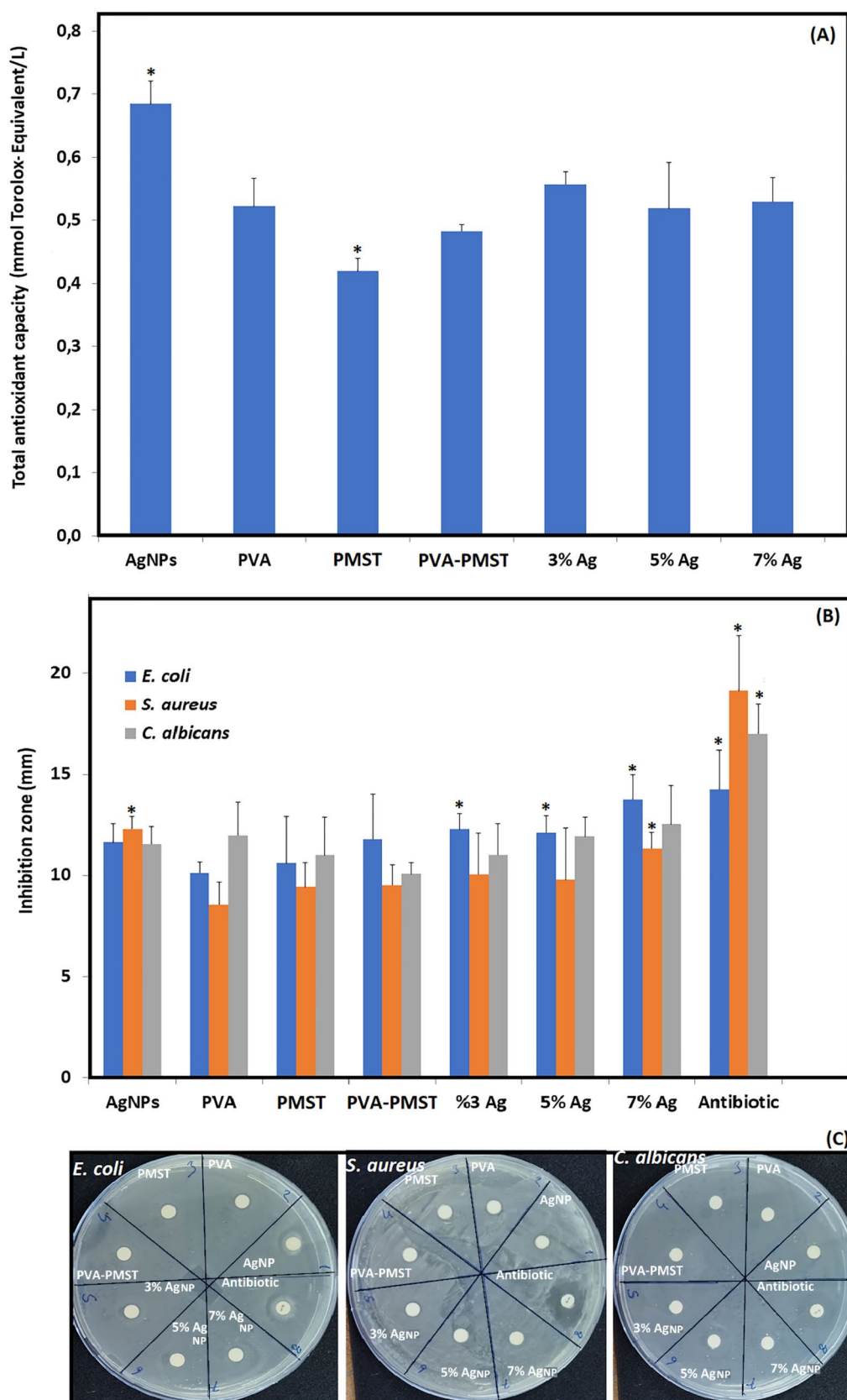


Fig. 10 The antioxidant (A), antimicrobial (B), and inhibition zone (C) of the materials. Data are expressed as “mean ± standard deviation” ($n \geq 3$). *It represents the group that shows a statistically significant difference according to PVA data

PVA-PMST blend showed that the surface had a hydrophobic tendency. An increase in AC conductivity and a gradual decrease in the dielectric constant were observed with the rise in the dispersed AgNP concentration in the PVA-PMST blend. It was observed that the antioxidant properties of the PVA-PMST/Ag nanocomposites improved. The nanocomposite with the highest AgNP loading rate was as effective as the reference antibiotic on the *E. coli* pathogen with a 14 mm inhibition zone. The results indicate that PVA biopolymer has improved thermal, dielectric, and biological properties thanks to the combination of synthetic PMST and biogenic AgNP. Therefore, the produced PVA-based materials can offer alternative material options in the food, packaging, and biomedical fields. Future studies should focus on testing the performance of these nanocomposites in food packaging and biomedical applications through prototype studies. In this way, it will be possible to expand the application areas of the obtained results and evaluate the commercial potential of the material.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare no competing interests.

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References

1. N.S. Diab, H.M. Ragab, R.A. Aziz et al., Synthesis and characterization of PVA/PEO-MWCNT/TiO₂ nanocomposites: enhancements in structural, optical, and antibacterial properties. *J. Inorg. Organomet. Polym.* (2024). <https://doi.org/10.1007/s10904-024-03471-z>
2. M. Aslam, M.A. Kalyar, Z.A. Raza, Polyvinyl alcohol: a review of research status and use of polyvinyl alcohol based nanocomposites. *Polym. Eng. Sci.* **58**(12), 2119–2132 (2018). <https://doi.org/10.1002/pen.24855>
3. M. Teodorescu, M. Bercea, S. Morariu, Biomaterials of poly(vinyl alcohol) and natural polymers. *Polym. Rev.* **58**(2), 247–287 (2018). <https://doi.org/10.1080/15583724.2017.1403928>
4. G. Sobhiga, H.J. Maria, M. Mozetič, S. Thomas, A review on green materials: exploring the potential of poly(vinyl alcohol) (PVA) and nanocellulose composites. *Int. J. Biol. Macromol.* **283**, 1, 137176 (2024). <https://doi.org/10.1016/j.jbiomac.2024.137176>
5. Z. Rahimi-Ahar, L. Rahimi Ahar, Thermal, optical, mechanical, dielectric, and electrical properties of nanocomposites. *Eur. Polym. J.* **218**, 113337 (2024). <https://doi.org/10.1016/j.eurpolymj.2024.113337>
6. A. Gaidhani, L. Tribe, Charpentier polystyrene carbon composite foam with enhanced insulation and fire retardancy for a sustainable future: critical review. *J. Cell. Plast.* **59**(5–6), 419–453 (2023). <https://doi.org/10.1177/0021955X231215753>
7. B. Gayretli, R. Shanthar, T.T. Öpöz, C. Abeykoon, Mechanical properties of LDPE and PS polymer matrix composites reinforced with GNP and CF—a critical review. *Int. J. Lightweight Mater. Manuf.* **7**, 4, 572–596 (2024). <https://doi.org/10.1016/j.ijlmm.2024.03.005>
8. O.A. Moskaluk, A.V. Belashov, Y.M. Beltukov, E.M. Ivan'kova, E.N. Popova, I.V. Semenova, V.Y. Yelokhovskiy, V.E. Yudin, Polystyrene-Based nanocomposites with different fillers: fabrication and mechanical properties. *Polym.* **12**, 2457 (2020). <https://doi.org/10.3390/polym12112457>
9. K. Bulanda, M. Oleksy, R. Oliwa, Hybrid Polymer Composites Based on Polystyrene (PS) Used in the Melted and Extruded Manufacturing Technology. *Polym.* **14**, 5000, (2022). <https://doi.org/10.3390/polym14225000>
10. S. Srikar, D. Giri, D. Pal, P. Mishra, S. Upadhyay, Green synthesis of silver nanoparticles: a review. *Green. Sustain. Chem.* **6**, 34–56 (2016). <https://doi.org/10.4236/gsc.2016.61004>
11. M. Rafique, I. Sadaf, M.S. Rafique, M.B. Tahir, A review on green synthesis of silver nanoparticles and their applications. *Artif. Cells Nanomed. Biotechnol.* **45**(7), 1272–1291 (2016). <https://doi.org/10.1080/21691401.2016.1241792>
12. M. Fahim, A. Shahzaib, N. Nishat, A. Jahan, T.A. Bhat, A. Inam, Green synthesis of silver nanoparticles: a comprehensive review of methods, influencing factors, and applications. *JCIS Open.* **16**, 100125 (2024). <https://doi.org/10.1016/j.jciso.2024.100125>
13. Ö. Hazman, G. Khamidov, M.A. Yilmaz, M.F. Bozkurt, M. Kargioğlu, M. Savrik, D. Tukhtaev, I. Erol, Green synthesis of ag nanoparticles from *Verbascum insulare* Boiss. And heldr.: evaluation of antimicrobial, anticancer, antioxidant properties And photocatalytic degradation of MB. *J. Photochem. Photobiol A: Chem.* **453**, 115601 (2024). <https://doi.org/10.1016/j.jphotochem.2024.115601>
14. A.G. El-Shamy, W. Attia, K.M. Abd El-Kader, The optical and mechanical properties of PVA-Ag nanocomposite films. *J. Alloys Compd.* **590**, 309–312 (2014). <https://doi.org/10.1016/j.jallcom.2013.11.203>
15. A.G. El-Shamy, A.A. Maati, W. Attia, K.M. Abd El-Kader, Promising method for preparation the PVA/Ag nanocomposite and ag

- nano-rods. *J. Alloys Compd.* **744**, 701–711 (2018). <https://doi.org/10.1016/j.jallcom.2018.02.026>
16. R.K. Das, M. Das, Study of silver nanoparticle/polyvinyl alcohol nanocomposite. *Int. J. Plast. Technol.* **23**, 101–109 (2019). <https://doi.org/10.1007/s12588-019-09229-4>
 17. P.K. Khanna, N. Singh, S. Charan, V.V.V.S. Subbarao, R. Gokhale, U.P. Mulik, Synthesis and characterization of Ag/PVA nanocomposite by chemical reduction method. *Mater. Chem. Phys.* **93**, 1117–121 (2005). <https://doi.org/10.1016/j.matchemphys.2005.02.029>
 18. X. Gong, N.D. Jadhav, V.V. Lonikar, A.N. Kulkarni, H. Zhang, B.R. Sankapal, J. Ren, B.B. Xu, H.M. Pathan, Y. Ma, Z. Lin, E. Witherspoon, An overview of green synthesized silver nanoparticles towards bioactive antibacterial, antimicrobial and antifungal applications. *Adv. Colloid Interface Sci.* **323**, 103053 (2024). <https://doi.org/10.1016/j.cis.2023.103053>
 19. T. Chang, Z. Li, G.Y. Yun, H. Jia, Yang, Enhanced photocatalytic activity of ZnO/CuO nanocomposites synthesized by hydrothermal method. *Nano-Micro Lett.* **5**, 163–168 (2013). <https://doi.org/10.1007/BF03353746>
 20. G. Khamidov, Ö. Hazman, I. Erol, Thermal and biological properties of novel sodium carboxymethylcellulose-PPFMA nanocomposites containing biosynthesized Ag-ZnO hybrid filler. *Int. J. Biol. Macromol.* **257**, 128447 (2024). <https://doi.org/10.1016/j.ijbiomac.2023.1>
 21. Ö. Hazman, G. Khamidov, M.A. Yilmaz, M.F. Bozkurt, M. Kargioğlu, D. Tukhtaev, I. Erol, Environmentally friendly silver nanoparticles synthesized from *Verbascum nudatum* Var. Extract and evaluation of its versatile biological properties and dye degradation activity. *Environ. Sci. Pollut. Res.* **31**, 33482–33494 (2024). <https://doi.org/10.1007/s11356-024-33424-5>
 22. C. Vanlalveni, S. Lallianrawna, A. Biswas, M. Selvaraj, B. Changmai, S.L. Rokhum, Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: a review of recent literature. *RSC Adv.* **11**(5), 2804–2837 (2021). <https://doi.org/10.1039/d0ra09941d>
 23. J.R. Koduru, S.K. Kailasa, J.R. Bhamore, K.-H. Kim, T. Dutta, K. Vellingiri, Phytochemical-assisted synthetic approaches for silver nanoparticles antimicrobial applications: a review. *Adv. Colloid Interface Sci.* **256**, 326–339 (2018). <https://doi.org/10.1016/j.cis.2018.03.001>
 24. S.B. Aziz, R.T. Abdulwahid, M.A. Rasheed, O.G. Abdullah, H.M. Ahmed, Polymer blending as a novel approach for tuning the SPR peaks of silver nanoparticles. *Polym.* **9**, 486 (2017). <https://doi.org/10.3390/polym9100486>
 25. I. Erol, Ö. Hazman, M. Özkan, I. Uygur, G. Khamidov, H. Gerengi, Synthesis of novel PVA-PFPAMA nanocomposites by the hydrothermal method: evaluation of thermal, antimicrobial, and anticarcinogenic properties. *Prog. Org. Coat.* **185**, 107889 (2023). <https://doi.org/10.1016/j.porgcoat.2023.107889>
 26. İ. Erol, G. Khamidov, E. Efe, S. Yurdakal, L. Palmisano, Hydrothermal synthesis of bare TiO₂ nanowires and polystyrene (PS)-TiO₂ nanowires used for selective photocatalytic oxidation of 3-pyridinemethanol in water and PS photodegradation in solid state. *Res. Chem. Intermed.* **50**, 4641–4671 (2024). <https://doi.org/10.1007/s11164-024-05391-6>
 27. I. Erol, Ö. Hazman, G. Khamidov, M. Savrik, Improved physical, thermal, and biological properties of green synthesized Ag-containing nanocomposites of a novel chitosan-based blend. *J. Mol. Liq.* **392**(1), 123506 (2023). <https://doi.org/10.1016/j.molliq.2023.123506>
 28. I. Erol, T. Mutlu, Ö. Hazman, G. Khamidov, Investigation of antimicrobial, antioxidant, and anticancer properties of novel chitosan-based nanocomposite materials reinforced with biosynthesized Ag nanoparticles. *J. Mol. Liq.* **420**, 126855 (2025). <https://doi.org/10.1016/j.molliq.2025.126855>
 29. G. Khamidov, Ö. Hazman, M.N. Hasanovich, I. Erol, Evaluation of thermal, antimicrobial, antioxidant, anticancer, and wound healing properties of GO-Ag containing nanocomposites based on CS- PPFOEMA blend. *J. Drug Deliv. Technol.* **91**, 105258 (2024). <https://doi.org/10.1016/j.jddst.2023.105258>
 30. W. Zhao, Y. Yamamoto, S. Tagawa, Radiation effects on the thermal degradation of poly(vinyl chloride) and poly(vinyl alcohol). *Polym. Sci. Polym. Chem.* **36**, 3089–3095 (1998).
 31. I.M. Kalogeras, W. Brostow, Glass transition temperatures in binary polymer blends. *J. Polym. Sci. B: Polym. Phys.* **47**, 80–95 (2009). <https://doi.org/10.1002/polb.21616>
 32. R.A.A. Khan, A. Zulfqar, M. Mateen, M. Hussain, R.T. Rasool, G.A. Ashraf, G. Xianlong, Improvement of the glass transition temperature in novel molybdenum carbide doped polyaniline nanocomposites. *Ceram. Int.* **49**, 26322–26330 (2023). <https://doi.org/10.1016/j.ceramint.2023.05.158>
 33. H. Wu, D. Xiao, J. Lu, T. Li, C. Jiao, S. Li, P. Lu, Z. Zhang, Preparation and properties of biocomposite films based on Poly(vinyl alcohol) Incorporated with eggshell powder as a biological filler. *J. Polym. Environ.* **28**, 2020–2028 (2020). <https://doi.org/10.1007/s10924-020-01747-2>
 34. E. Lock, S. Walton, R. Fernsler, *Preparation of ultra thin polystyrene, polypropylene and polyethylene films on si substrate using spin coating technology*; NRL/MR/6750-08-9092 (Naval Research Laboratory, Washington, DC, USA, 2008)
 35. M. Xu, N. Lu, D. Qi, H. Xu, Y. Wang, S. Shi, Li, Chi, Fabrication of superhydrophobic polymer films with hierarchical silver microbowl array structures. *J. Colloid Interface Sci.* **360**(1), 300–304 (2011). <https://doi.org/10.1016/j.jcis.2011.04.048>
 36. Z. Li, L. Liu, H. Zheng, F. Meng, F. Wang, Superhydrophobic, corrosion resistance, and antibacterial coating with delayed release of Ag ions. *Compos. Commun.* **31**, 101134 (2022). <https://doi.org/10.1016/j.coco.2022.101134>
 37. M.G.B. Ashiq, Structural, dielectric and magnetic properties of multi-walled carbon nanotubes decorated BiFeO₃ nanocomposites for technological applications. *Solid State Sci.* **160**, 107800 (2025). <https://doi.org/10.1016/j.solidstatesciences.2024.107800>
 38. M. Kashif, M. Khalid, A.D. Chandio, M.G. Ashiq, M. Younas, T. Alshahrani, Z. Uddin, Structural, electrical, and magnetic properties of (x)Cu_{0.05}Co_{0.95}Fe₂O₄/(1-x)La_{0.15}Bi_{0.85}FeO₃ nanocomposites for technological applications. *J. Mater. Sci. Mater. Electron.* **35**(8), 555 (2024). <https://doi.org/10.1007/s10854-024-12210-6>
 39. H.K. Koduru, L. Marino, V. Janardhanam, N. Scaramuzza, Influence of thin layer of silver nanoparticles on optical and dielectric properties of poly(vinyl alcohol) composite films. *Surf. Interfaces.* **5**, 47–54 (2016). <https://doi.org/10.1016/j.surfin.2016.09.008>
 40. S. Mahendia, A.K. Tomar, S. Kumar, Electrical conductivity and dielectric spectroscopic studies of PVA–Ag nanocomposite films. *J. Alloys Compd.* **508**(2), 406–411 (2010). <https://doi.org/10.1016/j.jallcom.2010.08.075>
 41. V.E. Ogbonna, O. Popoola, P. Popoola, Effect of titanium dioxide nanoparticles on the dielectric, thermal, and corrosion resistance properties of polyimide (PI) nanocomposites. *Int. J. Polym. Anal. Charact.* **29**, 533–546 (2024). <https://doi.org/10.1080/1023666X.2024.2394225>
 42. I. Erol, G. Khamidov, Ö. Hazman, C. Çifci, Hydrothermal synthesis of novel chitosan-styrene-based nanocomposites containing TiO₂ nanowires: investigation of thermal, dielectric and biological properties. *Mater. Today Commun.* **41**, 110726 (2024). <https://doi.org/10.1016/j.mtcomm.2024.110726>
 43. J. Dai, S. Meng, C. Yang, W. Lü, X. Chen, Y. Yin, F. Liang, Effect of nano silver modification on the dielectric properties of Ag@TiO₂/PVDF composites. *J. Wuhan Univ. Technol. -Mat. Sci. Edit.* **36**, 303–310 (2021). <https://doi.org/10.1007/s11595-021-2410-1>

44. I. Erol, A. Tataroğlu, H. Artun, G. Khamidov, A. Dere, F. Yakuphanoglu, Dielectric properties of chitosan-based ZnO nanocomposites for high-frequency electronic devices. *Polym. Bull.* (2024). <https://doi.org/10.1007/s00289-024-05581-7>
45. A.S. Zeraati, M. Arjmand, U. Sundararaj, Silver nanowire/MnO₂ nanowire hybrid polymer nanocomposites: materials with high dielectric permittivity and low dielectric loss. *ACS Appl. Mater. Interfaces*. **9**(16), 14328–14336 (2017). <https://doi.org/10.1021/acsami.6b14948>
46. J. Lu, K.-S. Moon, C.P. Wong, Silver/polymer nanocomposite as a high-k polymer matrix for dielectric composites with improved dielectric performance. *J. Mater. Chem.* **18**(40), 4821 (2008). <https://doi.org/10.1039/b807566b>
47. H. Verma, A. Lal, P.K. Singh, M.B. Pandey, R. Dabrowski, R. Dhar, Silver nanoparticles induced enhanced stability, dielectric anisotropy, and electro-optical parameters of a nematic liquid crystalline material 4-(trans-4-n-hexylcyclohexyl) isothiocyanatobenzene. *J. Mol. Liq.* **400**, 124503 (2024). <https://doi.org/10.1016/j.molliq.2024.124503>
48. P.L. Reddy, K. Deshmukh, K. Chidambaram, M.M.N. Ali, K.K. Sadasivuni, Y.R. Kumar, R. Lakshmipathy, S.K.K. Pasha, Dielectric properties of Polyvinyl alcohol (PVA) nanocomposites filled with green synthesized zinc sulphide (ZnS) nanoparticles. *J. Mater. Sci: Mater. Electron.* **30**, 4676–4687 (2019). <https://doi.org/10.1007/s10854-019-00761-y>
49. G. Sahu, M. Das, M. Yadav, B.P. Sahoo, J. Tripathy, Dielectric relaxation behavior of silver nanoparticles and graphene oxide embedded Poly(vinyl alcohol) Nanocomposite Film: An Effect of Ionic Liquid and Temperature. *Polym.* **12**, 374 (2020). <https://doi.org/10.3390/polym12020374>
50. R.W. Pero, H. Lund, T. Leanderson, Antioxidant metabolism induced by Quinic acid. Increased urinary excretion of Tryptophan and nicotinamide. *Phytother Res.* **23**, 335–346 (2009). <https://doi.org/10.1002/ptr.2628>
51. P.D.S.M. Fernando, D.O. Ko, M.J. Piao, K.A. Kang, H.M.U.L. Herath, J.W. Hyun, Protective effect of Luteolin against oxidative stress-mediated cell injury via enhancing antioxidant systems. *Mol. Med. Rep.* **30**(1), 121 (2024). <https://doi.org/10.3892/mmr.2024.13244>
52. S. Anees Ahmad, S. Sachi Das, A. Khatoon, M. Tahir Ansari, M. Afzal, A. Kumar, Nayak, Bactericidal activity of silver nanoparticles: a mechanistic review. *Mater. Sci. Energy Technol.* **3**, 756–769 (2020). <https://doi.org/10.1016/j.mset.2020.09.002>
53. G.M. Shayo, E. Elimbinzi, G.N. Shao, Preparation methods, applications, toxicity and mechanisms of silver nanoparticles as bactericidal agent and superiority of green synthesis method. *Heliyon*. **10**, e36539 (2024). <https://doi.org/10.1016/j.heliyon.2024.e36539>

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