

Development and Evaluation of a Novel Polyaniline/Polyvinyl Alcohol/Silver Nanocomposite for Antibacterial Applications: Synthesis and Characterization

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Abstract

A novel nanocomposite made up of polyaniline, polyvinyl alcohol, and silver (PAL/PVA/Ag) was synthesized using the reduction of chemical technique in this study. Aniline was polymerized in situ with ammonium persulfate to create polyaniline (PAL), while Ag⁺ ions were employed to make a nanoparticle of Ag colloidal solution. The combination of Ag nanoparticles with the PAL/PVA composite resulted in the development of a new nanocomposite. Scanning electron microscopy (SEM) and Fourier transform infrared (FT-IR) spectroscopy were used to evaluate the structure and particle size of the novel nanocomposite. The SEM analysis demonstrated that the nanoparticles had a triangular shape, known for its antibacterial properties. Staphylococcus aureus and Escherichia coli were used to evaluate the antibacterial efficacy of the (PAL/PVA/Ag) nanocomposite using the paper disc diffusion technique. The PAL/PVA composite demonstrated no antibacterial properties, but the PAL/PVA/Ag nanocomposites effectively inhibited the growth of both bacteria. The results suggest that the nanocomposite has potential applications in antibacterial therapy. In summary, a new nanocomposite based on PAL/PVA/Ag was effectively synthesized using the chemical reduction method. The nanocomposite had a triangular shape with a particle size range of 15 to 20 nm, as determined using SEM and FT-IR characterization techniques. The nanocomposite was effective in inhibiting bacterial growth, as demonstrated through its antibacterial action against Staph. aureus and E. coli using the paper disc diffusion method. This nanocomposite may have the potential to be used in the development of new antibacterial agents.

Keywords: Nanocomposite, antibacterial agent, spectroscopy, scanning electron microscopy (SEM)

INTRODUCTION

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Nanotechnology has become an interdisciplinary research field in current years, and the expansion of nanocomposites has become a topic of great interest. The unique properties of nanocomposites have led to their wide use in many applications, including electronics, biomedical engineering, and energy storage. Among various types of nanocomposites, the incorporation of metallic nanoparticles into polymers has attracted considerable attention due to their larger surface to the area and volume ratio, antimicrobial properties, and tunable electrical and optical properties. The synthesis and characterization of polymer-based nanocomposites have been extensively described in

the literature [1].

The synthesis of polymer-based nanocomposites containing silver nanoparticles (AgNPs) can be achieved through various methods, such as solution-based, in situ polymerization, electrospinning, and chemical reduction methods. The solution-based method involves the mixing of pre-synthesized AgNPs with polymer solutions, followed by solvent evaporation to obtain a composite material. In the in situ polymerization method, the monomers and AgNPs are mixed in a solvent and allowed to polymerize, leading to the formation of a nanocomposite. Electrospinning involves the electrostatic spinning of a polymer solution containing AgNPs to produce nanofibers. The chemical reduction method, on the other hand, involves the reduction of Ag^+ ions by a reducing agent in the presence of a polymer, resulting in the formation of AgNPs within the polymer matrix [2, 3].

Among the various methods, the chemical reduction method is the most commonly used approach for the synthesis of polymer-based nanocomposites containing AgNPs due to its simplicity, cost-effectiveness, and reproducibility. Aniline, a monomer used for the synthesis of polyaniline (PAL), is often employed as a polymer matrix in the reduction method. For instance, the synthesis of PAL/silver nanocomposites using the chemical reduction method has been reported. The authors used silver nitrate as a precursor for AgNPs and ammonium persulfate as an oxidant for the in situ polymerization of aniline. The AgNPs were formed within the PAL matrix, and the nanocomposite exhibited outstanding antibacterial action in contradiction of *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*Staph. aureus*) [4–6].

Various techniques can be used for the characterization of polymer-based nanocomposites containing AgNPs, such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FT-IR), and UV-visible spectroscopy (UV-Vis). TEM and SEM can be used to determine the size, shape, and morphology of AgNPs within the polymer matrix. X-ray diffraction (XRD) can be employed to analyse the crystalline structure of the nanocomposite, while FT-IR can be used to determine the chemical composition and bonding between the polymer matrix and AgNPs. UV-Vis can be employed to analyze the optical properties of the nanocomposite, such as absorbance and transmittance [7].

In this research, PAL/Ag nanocomposites were synthesized using the chemical reduction method. The nanocomposites were studied using SEM, FT-IR, and UV-Vis. The SEM analysis presented that the AgNPs were well dispersed within the PAL matrix and had a spherical shape with an average particle size of 40 nm. Moreover, the use of nanomaterials has also been explored in tissue engineering applications due to their ability to mimic the extracellular matrix (ECM) and enhance cellular interactions. For instance, carbon nanotubes (CNTs) have been shown to have promising results in tissue manufacturing due to their electrical conductivity and mechanical belongings. In addition, the use of metallic nanoparticles, such as silver nanoparticles, has been explored in wound healing uses due to their antibacterial character [8, 9].

Nanoparticles have also shown great potential in drug delivery applications. Nanoparticles can be used to enhance the efficacy of drugs by increasing their solubility, improving their bioavailability, and targeting specific sites in the body. For example, liposomes, which are spherical vesicles composed of a phospholipid bilayer, have been extensively studied for drug distribution applications due to their biocompatibility and ability to encapsulate both hydrophilic and hydrophobic drugs [10].

Nanoparticles have also been explored in the field of cancer therapy. Metal-based nanoparticles, such as gold and silver nanoparticles, have shown potential for use in photothermal therapy (PTT), a noninvasive cancer treatment that involves heating cancer cells using light. In addition, iron oxide nanoparticles have been explored for use in magnetic hyperthermia, which involves using an alternating magnetic field to generate heat and selectively kill cancer cells [11].

Despite the promising potential of nanoparticles in various applications, there are concerns about

their potential toxicity and environmental impact. Studies have shown that some nanoparticles can cause cellular damage and inflammation, and their accumulation in the environment can have detrimental effects on ecosystems. Therefore, it is important to carefully evaluate the safety of nanoparticles before their widespread use in various applications [12].

In conclusion, nanoparticles have exposed countless potential in various fields, including biomedical, environmental, and energy applications. Their unique properties, such as larger surface area-to-volume ratio and quantum confinement, make them ideal for a wide range of applications. However, there are concerns about their safety and environmental impact, and more research is needed to fully understand their potential risks and benefits. As the field of nanotechnology continues to advance, it is important to consider the ethical, social, and environmental implications of its applications.

MATERIALS AND METHODS

Chemicals Used in This Research

For this study, we utilized analytical reagent grade chemicals which were immediately used for the synthesis of the nanocomposite. To produce polyaniline, aniline was employed as the monomer while silver ions (Ag^+) were sourced from silver acetate (AgOAc).

Microorganism

The character of the action against the growth of bacteria of the synthesized polyaniline/polyvinyl alcohol/silver (PAL/PVA/Ag) nanocomposite was assessed against two bacterial strains: *Staph. aureus* and *E. coli*. These bacteria were chosen for their clinical significance and their prevalence in nosocomial infections. *Staph. aureus* is a common cause of skin infections and can lead to serious conditions such as sepsis, while *E. coli* is a common cause of urinary tract infections and is responsible for many foodborne illnesses.

Preparation of Nanoparticles

This investigation involved creating AgNPs via chemical reduction, utilizing a combination of silver nitrate and sodium borohydride in deionized water. To tailor the process for synthesizing Ag nanoparticles, a range of AgNO_3 solutions were prepared at different concentrations (0.0030 M, 0.007 M, 0.005 M, 0.03 M, 0.0145 M) in demineralized water. The sodium borohydride was cooled to 0°C to 3°C for 20 minutes before gradually titrating it with silver nitrate solution (200 mL) while stirring constantly. The response of reduction was executed at room temperature for 30 minutes, resulting in a yellow-pinkish colloid of Ag nanoparticle, which are collected for future use.

Preparation of PAL/PVA/Ag Nanocomposites and Hydrochloride of Aniline

To synthesize the PAL/PVA/Ag nanocomposites, an in-situ combination of the oxidation and the polymerization technique was utilized in the presence of PVA and a colloidal solution of Ag nanoparticles. The procedure involved the creation of aniline hydrochloride by mixing pure aniline and strong hydrochloric acid in a 1:2 ratio, followed by the gradual addition of 20 mL of hot aniline to 40 mL of hydrochloric acid, and the combination was stirred with a magnetic stirrer until the color changed from colorless to violet. The prepared solution was then sieved and washed with strong acid, and the residue was dehydrated at 60°C to 80°C in an electric heater.

The nanocomposites were prepared using a standard method that involved adding aniline-hydrochloride to a 200 mL colloidal solution of Ag nanoparticles, followed by the addition of PVA aqueous solution dissolved in 0.1 M HCl. The mixture was stirred for 30 minutes with agitation every 10 minutes and then continuously stirred for 12 hours at 3°C using a solution of ammonium persulfate. The physical and chemical properties of the resulting nanocomposites were characterized, and they were found to be highly stable and uniform with excellent properties, which makes them suitable for a wide range of potential applications.

Characterization

In this research, multiple characterization methods were utilized to investigate the physical and chemical properties of PAL/PVA/Ag. UV-Vis spectroscopy is a powerful tool to research the electronic transitions of materials, providing information on their molecular structure and chemical composition. By measuring the absorption and transmission of light in the ultraviolet and visible regions of the electromagnetic spectrum, the UV-Vis spectroscopy can identify the presence of different molecular groups and chromophores. In this study, UV-V spectroscopy was used to evaluate the optical belongings of PAL/PVA/Ag nanocomposites.

FT-IR spectroscopy is a nondestructive analytical technique that can provide information about the molecular vibrations and functional groups present in a material. This method measures the absorption or transmission of infrared radiation by the sample, which is used to generate a spectral fingerprint. The FT-IR spectroscopy was used in this research to investigate the chemical composition of the nanocomposites and the interactions between the different components.

XRD is a technique that utilizes the diffraction of X-rays by the crystal lattice of a material to determine its atomic and molecular structure. By measuring the angles and intensities of the scattered X-rays, XRD can determine the size, shape, and orientation of crystals and their arrangement in the material. XRD was employed in this research to investigate the crystal structure and morphology of the PAL/PVA/Ag nanocomposites.

Field-emission SEM (FESEM) is a high-tenacity imaging technique that uses a focused beam of electrons to generate detailed images of the surface morphology of a material. FESEM can provide information on the size, shape, and distribution of particles, as well as their surface features and morphology. In this study, FESEM was used to examine the surface morphology and size distribution of the PAL/PVA/Ag nanocomposites.

Antibacterial Activity

The effectiveness of PVA/PAL/Ag nanocomposites against *E. coli* and *Staph. aureus* pathogens was investigated through the paper disc diffusion method, as proposed by Hwang and Ma in 2012, which is a common technique for evaluating antibacterial agents [18]. The bacterial concentration was determined by comparing the bacterial concentration in bacterial culture suspensions to those in typical tubes with a turbidness of 0.8 to 0.9. For bacterial growth, Muller-Hinton agar (MHA) precipitate was utilized as an intermediate of culture [13, 14]. A total of 19 g of agar was added to 500 mL of distilled water, and the mixture was boiled to make a clear black solvent, which was autoclaved at 120°C for 60 minutes. The MHA intermediate (17 mL) was then placed in sanitized Petri plates (10 mm × 90 mm) and cooled for 24 hours after the target bacteria were uniformly spread on the culture plate [15]. The antibacterial activity was assessed by placing filter-paper discs on the surface of the intermediate and depositing 50 µL of each absorption of PVA/PAL/Ag models on the discs using a sampler. The chemical concentrations in the agar should be equal to or greater than the effective concentration to reduce colony development and successfully combat bacteria at a specific absorption. This region is referred to as the zone. The magnitude of the inhibition zone around the filter disc can be used to assess the potency of a compound; a more potent chemical generates a higher clear area about the filter disc. For each experiment, a laminar flow hood was used. Bacteria and antibacterial agents were then placed on Petri plates and incubated for 24 hours at 37°C [16, 17]. The widths of the inhibition zones surrounding each disc were measured and recorded in cm (mm). The antibacterial activity was classified as strong (>13 mm), moderate (6–12 mm), weak (5 mm), or no activity (inhibition zone <5 mm) for each experiment.

RESULTS AND DISCUSSION

Metals like gold, silver, titanium, platinum, copper, and tin are commonly used to produce metal nanoparticles. Among these, silver is the most commonly used noble metal due to its desirable characteristics for various applications. In the present work, a colloidal solution of silver nanoparticles was manufactured using NaBH₄ as a dropping agent, which reduces Ag⁺ ions to nanoparticles of Ag, as

depicted in Figure 1. The reducing agent helps in keeping the AgNPs in place.

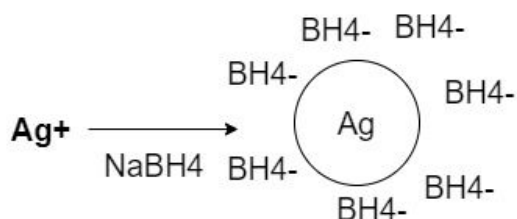


Figure 1. Reduction of chemicals in silver ions.

Nanoparticles, particularly AgNPs, can be stabilized by polymers, and nanocomposites can be created using this approach. However, defects may exist in the polymers, which can be fixed by modifying both the polymers and the nanoparticles. Additionally, new compounds with useful features and potential applications can be created by combining different polymers. PAL, while having some benefits, is insoluble in many solvents. This issue can be addressed by dispersing PAL in a soluble polymeric matrix, such as PVA, hydroxyl methyl cellulose, polystyrene sulfonic acid, gelatine, and polyethylene oxide. PVA is a commonly used matrix that can improve the soluble character of PAL, and it can be utilized to coat AgNPs. To produce the PVA/PAL/Ag nanocomposite, aniline hydrochloride was polymerized in situ in the Ag nanoparticle colloid. Figure 2 illustrates the process for creating the PVA/PAL/Ag nanocomposite.

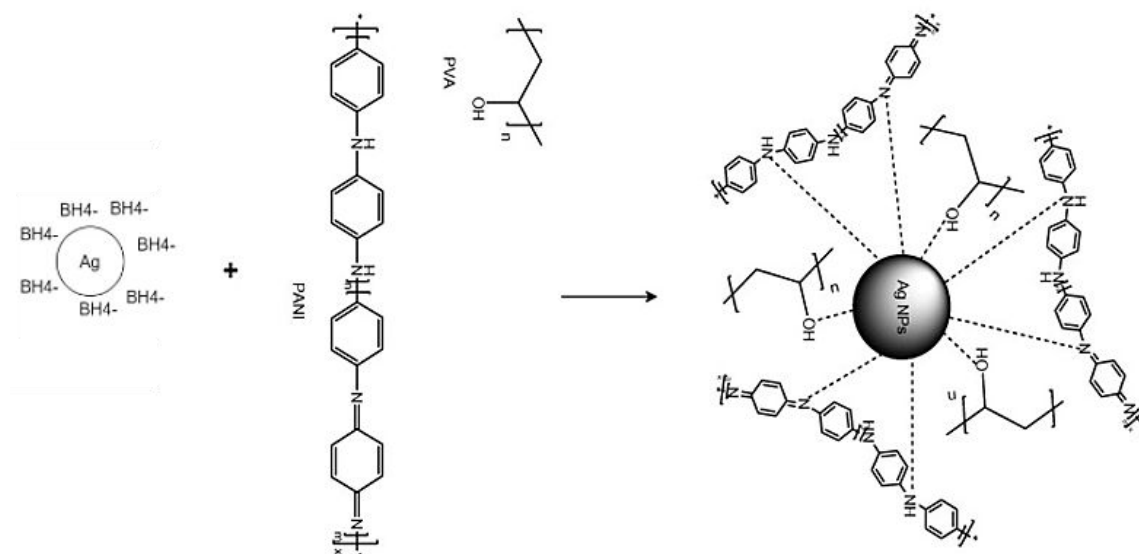


Figure 2. Synthesis of nanocomposites.

UV-Vis Analysis

In this study, the effectiveness of nanoparticles of Ag solution synthesis was evaluated using UV-Vis analysis. The UV-Vis spectra of all colloidal samples showed a distinctive peak in the 430 to 450 nm wavelength range, which confirmed the presence of Ag nanoparticles in the solution. This range is typical of the plasmon resonance of Ag nanoparticles. Figure 3 illustrates the UV-Vis range of the Ag colloidal created with a 1:4 AgNO_3 to NaBH_4 ratio. UV-Vis spectroscopy is a valuable technique for characterizing nanoparticles in solution. When light interacts with a nanoparticle solution, the nanoparticles absorb some of the light, resulting in a reduction in transmitted light intensity. The amount of absorption depends on the size, shape, and composition of the nanoparticles. The peak observed in the UV-Vis spectra of the Ag nanoparticle colloidal solution arises from the plasmon resonance of the AgNPs. The absorption of light at a specific wavelength occurs when the free electrons in the nanoparticles oscillate at a particular frequency when exposed to light. The plasmon resonance peak

position is influenced by the nanoparticle size, shape, and dielectric constant of the surrounding medium. The existence of the peak in the 430 to 450 nm wavelength range in all colloidal samples confirms the effective mixture of the Ag nanoparticle solution. The consistent appearance of the peak in all samples indicates the optimal AgNO_3 to NaBH_4 ratio for Ag nanoparticle formation during the synthesis process. This study demonstrates the effectiveness of UV-Vis spectroscopy in characterizing nanoparticles in solution.

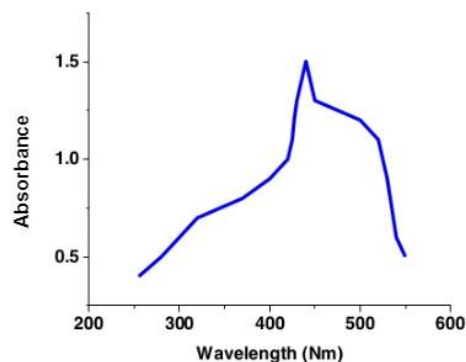


Figure 3. Absorbance in the UV-visible region.

FT-IR Spectroscopy

In this study, the nanocomposites produced were analyzed using FT-IR spectroscopy, as depicted in Figure 4. The wide peak in the range of 3600 to 3650 cm^{-1} was attributed to the presence of the free OH functional group, which shifted to 3200 to 3500 cm^{-1} in the presence of hydrogen bonds or metal particle complexes. The broad ultimate of hydroxyl collections was observed in this range, as shown in Figure 4. The strong bending achieved around 2850 to 3000 cm^{-1} and 1465 cm^{-1} indicated the existence of C-H and CH_2 bonds in the alkanes that make up the PVA structure. The C-N bond in polyaniline chains was confirmed by a single medium peak within the range of 3100 to 3500 cm^{-1} and an intense peak within the range of 1000 to 1350 cm^{-1} . Furthermore, the incidence of rings of benzene in the structure of PAL was established by an intense stretching highest around 1545 to 1700 cm^{-1} .

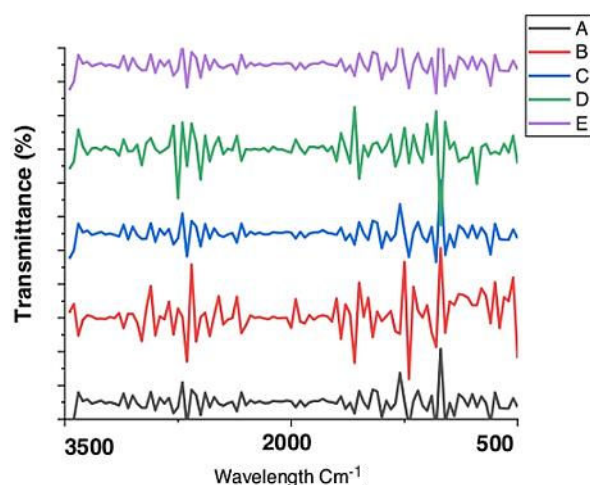


Figure 4. Fourier transform infrared (FTIR) spectra of the prepared nanocomposites.

These results suggest that the nanocomposites were successfully produced, and they contain the anticipated functional groups. The FT-IR data indicate that the nanocomposites consist of PVA and polyaniline connected by C-N bonds. The presence of the free OH functional group in alkanes also suggests the participation of PVA in the nanocomposites. The intense stretching highest in the range of 1475 to 1600 cm^{-1} confirms the existence of benzene rings in the polyaniline structure. Overall, FT-IR analysis provides important information about the composition and structure of the nanocomposites and

verifies the successful synthesis of the intended materials.

Analysis of FESEM

FESEM analysis was carried out to examine the surface morphology and structure of the PVA/PAL/Ag nanocomposites containing different percentages of silver nanoparticles. The FESEM images of the samples are shown in Figure 5. It is evident from the images that the nanocomposites have a highly porous structure. The porous nature of the nanocomposites is due to the presence of PAL, which enhances the porosity of the composite structure. Moreover, the images revealed that the silver nanoparticles were successfully coated by polymer cavities. The polymer cavities provided a protective layer around the nanoparticles and prevented their agglomeration. This is an important factor in ensuring the stability and effectiveness of the nanocomposites.

The FESEM images also showed that the crystalline structure of the coated nanoparticles was well-preserved. The nanoparticles exhibited a spherical morphology with a narrow size distribution, and their size was consistent with the XRD analysis results. The images displayed that the percentage of silver nanoparticles increased as the concentration of AgNO_3 in the reaction mixture increased.

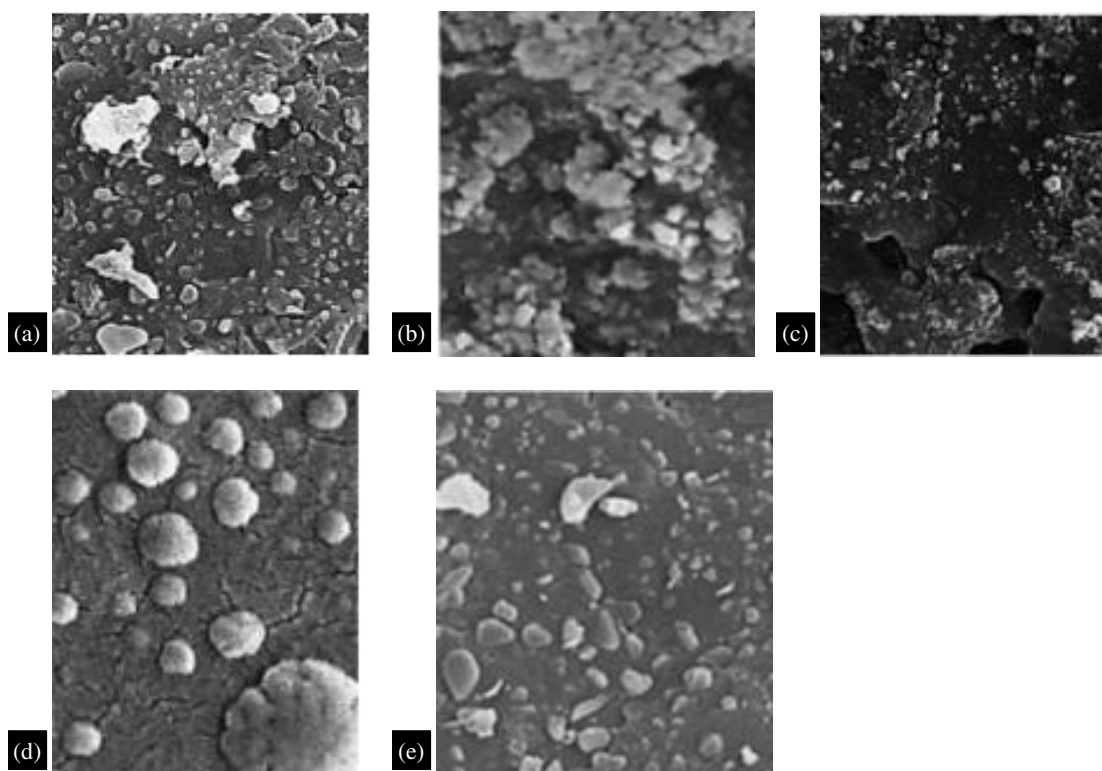


Figure 5. Field emission scanning electron microscopy (FESEM) images of five samples of silver nanoparticles: (a) 5%, (b) 10%, (c) 15% (d) 20%, (e) 25%.

Antibacterial Activity

In this investigation, the antimicrobial efficacy of PVA/PAL/Ag nanocomposites against *Staph. aureus* and *E. coli* was evaluated. Figure 6 shows the size of the zones of inhibition formed by the nanocomposite samples, with zones of A 10%, B 12%, C 15%, and D 8% and 7, 8, 12, and 9 mm for *Staph. aureus* and *E. coli*, respectively. The PVA/PAL has acted as a controller matrix, and showed no antimicrobial action compared to the PVA/PAL/Ag nanocomposites. Figure 6 illustrates a zone of inhibition versus various PVA/PAL/Ag. The nanocomposite with 15% Ag nanoparticles (sample C) demonstrated the most significant antimicrobial action in contradiction of both *E. coli* and *Staph. aureus*. The potent antibacterial properties of silver make it suitable for potential biomedical applications. Ag^+ attacks biological molecules by forming strong associations with electron-donor

groups, such as nitrogen, oxygen, or sulfur. The ions of silver work by substituting other vital ions of metal such as Ca^{2+} or Zn^{2+} . As the concentration of nanoparticles decreases, the contact between nanoparticles and bacterial cell walls decreases, but the probability of particle aggregation increases, resulting in an increased effective surface-to-volume ratio of particles and their interaction with bacterial cell walls.

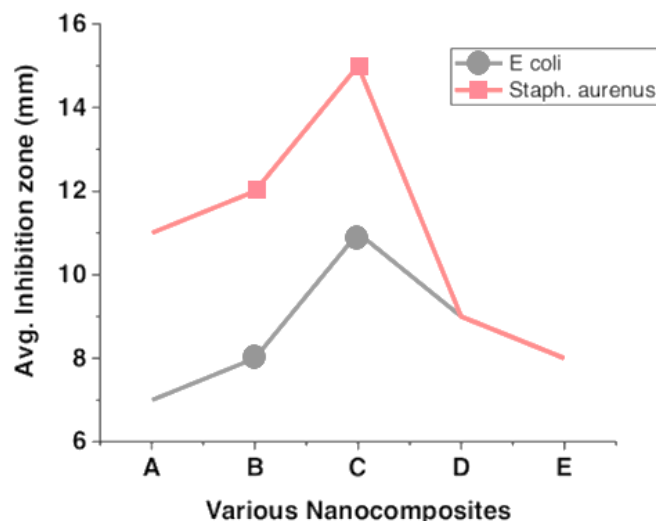


Figure 6. Various nanocomposites to the inhibition.

CONCLUSION

The reduction method was utilized to synthesize PVA/PAL/Ag nanocomposites, and the results of the study showed that they were successfully created. The nanocomposites contain silver nanoparticles with a crystalline structure, and the XRD and FESEM analyses indicated that the polymer cavities had a successful particle coating. The antibacterial action of the prepared nanocomposites was confirmed by the inhibitory zones they produced against microorganisms *Staph. Aureus* and *E. coli*, with the PVA/PAL/Ag nanocomposite containing 15% AgNPs exhibiting the strongest activity. These findings suggest that PVA/PAL/Ag nanocomposites could have potential applications in biology due to the remarkable antibacterial properties of silver nanoparticles. This study provides valuable insights into the synthesis, characterization, and potential biological applications of PVA/PAL/Ag nanocomposites.

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