

## Fabrication and Surface Characterization of Sodium Alginate–Glycerol–Silver Nanoparticle Composite Films for Wound Dressing Applications

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### ABSTRACT

Sodium alginate composite films may be used as wound dressings, while formulation changes will change the surface and biological responses of the films. In this study, sodium alginate films were prepared as the control sample, and films with reported masses of silver nanoparticles (AgNPs) of 0.0, 1.0, and 2.0 g per 100 g of film were prepared by the solvent casting technique. We investigated the films' morphology and chemical characteristics using FE-SEM and FTIR. Water contact angles were used to assess surface wettability after 3 seconds, and agar diffusion and HaCaT cell examines as preliminary biological screening. The reported contact angles ranged from 20.6° to 50.3°, with the lowest angle for the intermediate AgNP formulation. The response of the films containing AgNPs was not monotonic. Agar examination showed apparent inhibition zones, and they were also observed in silver-free control, so the effect cannot be attributed to the AgNPs alone. The cell viability plot was above the displayed control, but these numbers showed high variability, and the full test details were not provided. This is an initial formulation and a superficial comparison. The films need to be tested separately for mechanical integrity, swelling, wet-state performance, and wound-healing effectiveness before assessing their use as practical dressings.

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## 1. Introduction

Tissue engineering is widely used to address a variety of medical challenges, such as organ transplantation, repairing damaged tissues, and providing alternatives to traditional therapies (Hoang et al., 2025; Socci et al., 2023; Wang et al., 2024). Wounds can be classified by location, injury type, depth, and appearance (Abazari et al., 2022). The overall aim of wound dressings is to support and promote wound healing by generating and maintaining a moist environment (Su et al., 2023). Effective wound-healing approaches have three fundamental characteristics: antibacterial activity, increased cellular proliferation, and maintenance of a local moist environment that supports wound regeneration (Tiwari & Pathak, 2023). Each form of modern dressing product—films, foams, composites, sprays, hydrocolloids, gels, and hydrogels—has a distinct set of features (Hodge et al., 2022; Kus & Ruiz, 2020).

Alginic acid salt is a chemical term for alginates and their derivatives. Still, for broader understanding, we use the alternative term alginates, which is often used instead of the original name (Peng et al., 2025; Sahoo & Biswal, 2021). Phaeophyceae cell walls, which exist as divalent alginic acid salts and form an intercellular gel, are the structural components of alginate (Beuder & Braybrook, 2023). In applications requiring sterilization or protection from external influences, sodium alginate derivatives can be used, such as sodium alginate, a natural anionic polymer. These chemical elements have broad applications, such as wound dressings and food packaging (Gheorghita Puscaselu et al., 2020). Antibacterial wound dressings frequently display some degree of cytotoxicity (Zhu et al., 2024). Elevated

cytotoxicity may hinder healing by delaying wound closure or worsening local inflammation (Wang et al., 2022). Recently, silver nanoparticles (AgNPs) have been considered a promising agent for developing a new class of antimicrobials that could provide a new approach to combating a variety of bacterial diseases (Mubeen et al., 2021). Observations show that strong antibacterial activity, broad-spectrum against pathogenic morphological and metabolic pathogens, is linked to complex bacterial nanoparticle interactions (More et al., 2023). Additionally, their structure and different ways of interacting with bacterial surfaces can provide a suitable yet understudied antibacterial mechanism to build on Li et al. (2021). From a structural perspective, AgNPs have at least one dimension between 1 and 100 nm (Kaabipour & Hemmati, 2021).

Chronic and infected wounds are a huge worldwide healthcare problem, and they are a concern for millions of people around the world, causing a burden on healthcare systems. Wound management requires dressings that not only defend the wound from external infection but also help maintain a moist healing environment, absorb excess transudate, and prevent or treat microbial infection. Conventional dressings, such as gauze and plain films, usually do not meet these needs, especially for chronic wounds that often involve bacterial biofilm and antimicrobial resistance. To meet these demands, researchers have begun developing more sophisticated biomaterial-based dressings that combine the benefits of natural polymers with the added power of nanoparticles. One of the most promising methods involves incorporating silver nanoparticles (AgNPs) into biopolymer matrices, where they can exert antimicrobial effects and promote tissue regeneration. Sodium alginate is a polysaccharide commonly derived from brown seaweeds and used as a wound-dressing material because of its biocompatibility and non-toxicity (Joudeh & Linke, 2022). Because of its highly hydrophilic properties, alginate dressings can absorb a significant amount of wound exudate, forming a gel that provides a physiologically moist environment that encourages cell migration and healing. However, pure alginate films lack mechanical and antimicrobial properties, which can be improved by adding plasticizers, cross-linkers, and functional nanofillers (Singh et al., 2022). A low-molecular-weight polyol, glycerol, is generally used to increase the flexibility, ductility, and processability of alginate-based films to avoid brittleness and enhance handling. Sodium alginate–glycerol–silver nanoparticles (AgNPs) is a synergistic formulation that can be used in wound dressing design. Alginate is biodegradable and retains moisture, glycerol provides flexibility, and AgNPs add strong antimicrobial properties. Silver nanoparticles are being applied in wound healing because of their widespread activity against both Gram-positive and Gram-negative bacteria, fungi, and viruses; also, their ability to release silver ions ( $\text{Ag}^+$ ) by oxidation, which disrupt bacterial cell membranes, interfere with thiol-containing proteins, and generate Reactive Oxygen Species (ROS), causing damage to cellular components; minimal mammalian cell toxicity of Ag has also helped in their use in wound healing applications. Importantly, the surface area of AgNPs is much greater than that of bulk silver; thus, more  $\text{Ag}^+$  is released from the surface of AgNPs, resulting in enhanced antimicrobial effectiveness at lower concentrations. AgNPs have also been shown to promote wound healing through re-epithelialization, anti-inflammatory effects, and fibroblast migration. The incorporation of AgNPs in alginate films could also lead to some strengthening of the mechanical properties of the films and provide better antimicrobial properties in addition to their swelling and degradation behavior (Pinto et al., 2026). Sodium alginate–glycerol–silver nanoparticle composite films are usually fabricated by solution casting or solvent evaporation, with AgNPs uniformly dispersed in the polymer matrix and glycerol added as a plasticizer. A cross-linking agent such as calcium chloride can stabilize the film structure and control silver ion release. The composite films resulting from this process have a porous or semi-porous morphology that can absorb exudates without losing structural integrity. Surface characterization techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and energy-dispersive X-ray spectroscopy (EDS) are essential to confirm successful incorporation of AgNPs and composite homogeneity. The suitability of the films as wound dressings is also evaluated by swelling tests, water vapor transmission rate (WVTR), and mechanical testing for tensile strength and elongation at break. Alginate-based wound dressing properties were strongly influenced by the polymer ratio, the nature of the cross-linker, nanoparticle wt%, and plasticizers (Tripathi et al., 2025). For instance, AgNW-coated porous calcium alginate films were found to be non-toxic and were used in a simulated body fluid study; it was shown that water vapor transmission rate, swelling capacity, and fibroblast cell proliferation were enhanced. Similarly, alginate–AgNP composite films have shown good water absorption, high antimicrobial and antibiofilm efficacy against pathogenic bacteria ubiquitous in wounds, and low cytotoxicity against keratinocytes and fibroblasts. These findings support the use of the alginate–glycerol–AgNP composite as a promising material for wound dressings, benefiting from the properties of natural biopolymers and the synergistic enhancement provided by nanomaterials. Although these studies are encouraging, challenges remain in preparing alginate–glycerol–AgNP composite films for wound-dressing applications. First, uniform dispersion of AgNPs throughout the alginate matrix is important to ensure consistent antimicrobial activity and prevent particle agglomeration, which can reduce mechanical properties and cause tissue incompatibility. Second, the release of silver ions into the water should be optimized to balance antimicrobial activity

with the risk of cytotoxicity to mammalian cells or skin irritation from excessive silver-ion release. Third, the long-term stability and biodegradation behavior of the composite films in the wound environment should be well defined to ensure safe and effective performance during the healing period.

As discussed, and supported by studies showing positive clinical outcomes, allogeneic wound dressings are effective primary dressings suitable for medical use on oozing wounds. In medical applications for treating chronic wounds that may be susceptible to infection and risk non-healing, elements such as silver can be used, and antimicrobial substances can be added to dressings used in the treatment of chronic wounds. Silver reduces the dressing and wound microbial bioburden (Crumley, 2022).

Adding glycerol and crosslinking it with calcium chloride synergistically improve the mechanical properties of alginate membranes. Crosslinking had no noticeable effect without glycerol, but became evident in its presence, achieving optimal combinations of strength and elongation. The results show the potential use of these membranes in wound dressing applications.

Pure alginate films are not suitable for such applications because they are water-soluble and brittle, with poor physicochemical and biological properties; however, adding plasticizers and antimicrobial agents can improve these properties. Therefore, in this study, sodium alginate and glycerol were used in fixed quantities to prepare wound films, while the weight percentage of the antibacterial agent silver varied from 0.1 to 0.3 gm. We also investigated the swelling degree, wettability, antibacterial activity, and cell viability of the as-prepared films, alongside the FESEM and FTIR results. Based on the results, one can select a suitable set of parameters for a desired application, such as wound dressing (Kadri et al., 2025).

This presentation introduces the fabrication and surface characterization of sodium alginate–glycerol–silver nanoparticle composite films as a potential material for wound dressing applications. The subsequent sections describe the synthesis methodology, surface characterization techniques used, and the swelling, mechanical, and antimicrobial properties of the wound dressings, along with the analysis and implications of these test results for developing future-generation wound dressings. These properties make this work a compelling opportunity to develop more intelligent, multifunctional wound dressings that overcome the shortcomings of current materials and improve clinical wound treatment (Chousidis, 2024).

## 2. Materials and Method

### 2.1 Materials

Sodium Alginate (medium viscosity and molecular weight) was purchased from China. Glycerol (Gly), a hydrous, purity  $\geq 99.5\%$ , boiling point  $290\text{ }^{\circ}\text{C}$ , purchased from a chemical supplier. Antibacterial agent: silver nanopowder (spherical AgNPs, purity  $99.99\%$ ,  $20\text{ nm}$ ). Deionized water (DW) and phosphate-buffered saline (PBS; pH 7.2) were prepared; 1 M sodium hydroxide (NaOH) was used as received.

### 2.2 Synthesis of Alginate Dressing Films

Wound dressing films were prepared via the solvent casting method. First, deionized water was mixed with sodium alginate in a glass beaker to prepare a  $2\%$  (w/v) solution for about 15 min using a magnetic stirrer at  $1000\text{ rpm}$ . Then,  $10\%$  glycerol solution was added to the solution with continuous stirring for about 30 min to obtain a homogeneous solution. After that, the antibacterial agent (AgNPs) ( $0.1$ ,  $0.2$ ,  $0.3\text{ gm}$ ) was added to the previous mixture and mixed for 30 min. The solutions were poured into Petri dishes and left to dry for two days. Figure 1 shows the experimental films. Table 1 shows the sodium alginate film compositions and their codes.

**Table 1:** Wound Dressing Films Compositions

| Film Code | Films Compassion                                                         |
|-----------|--------------------------------------------------------------------------|
| S         | ( $2\%$ w/v sodium alginate)                                             |
| SG        | ( $2\%$ w/v sodium alginate) ( $10\%$ glycerol)                          |
| SG1Ag     | ( $2\%$ w/v sodium alginate) ( $10\%$ glycerol) ( $0.1\text{ gm AgNp}$ ) |
| SG2Ag     | ( $2\%$ w/v sodium alginate) ( $10\%$ glycerol) ( $0.2\text{ gm AgNp}$ ) |
| SG3Ag     | ( $2\%$ w/v sodium alginate) ( $10\%$ glycerol) ( $0.3\text{ gm AgNp}$ ) |

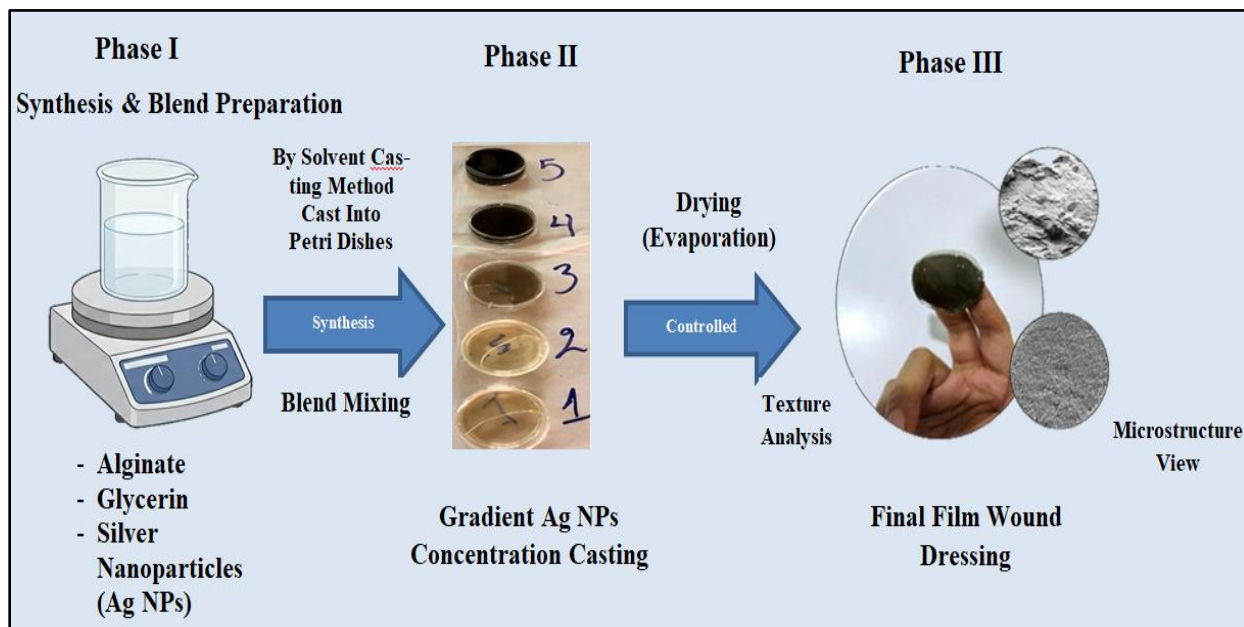


**Figure 1:** Experimental Part (Preparation of the Films)

### 3. Experimental Procedure

#### 3.1 Scanning Electron Microscopy

In our experiments, we used a scanning electron microscope to examine the surface of the prepared films, particularly their morphology. We tested the prepared films at a current of 50 picometers and an acceleration voltage of 15 kilovolts. We used magnifications of 1000x and 2000x for the surface and cross-sectional areas of the film, respectively. The samples were broken and remounted on a gold-plated metal support to prevent external factors such as humidity from affecting them.

#### 3.2 Spectroscopy of Fourier Transform Infrared

For the analytical and observational experiments, a Shimadzu FT-IR 8201 PC spectrometer was used. This spectrometer specializes in infrared spectra and uses Fourier transform infrared (FTIR) technology. These experiments recorded values ranging from 4000 to 300  $\text{cm}^{-1}$  for the transmission spectra of the composite nanofilms, falling within the wavelength range recorded above.

#### 3.3 Wettability Assay

In this section, we used a video optical contact angle measurement system (OCA-15-plus; Data-physics) with specific settings, such as the stationary droplet method, and measured at several points. In our experiment, we used three points on each membrane. We recorded the experiments and results, including changes in the shape of the optical contact angles and their contact with the surface, after pouring 4 microliters of water droplets onto the membrane surfaces.

#### 3.4 Antibacterial Activity

In the antibacterial activity section, two types of bacteria were used: *Pseudomonas aeruginosa* and *Staphylococcus aureus*. The aim was to evaluate the effectiveness and resistance of the prepared membranes to these bacterial species. This was done using a test medium consisting of a  $1.5 \times 10^8$  (w/v) nutrient broth dissolved in water. The evaluation focused on:

- Observing the area of bacterial growth inhibition.
- The resulting membrane was cut into a circular shape before preparing the antibacterial test medium.

The steps followed were as follows:

1. A bacterial colony was drawn using a needle and placed in 10 mL of the nutrient broth medium in an Erlenmeyer flask, where it was incubated for 24 hours.

2. The nutrient broth medium containing the bacteria was poured into a Petri dish.
3. The fabricated membranes were cut to approximately 6 mm in diameter, placed on the nutrient broth medium, and incubated for 24 hours at 37°C.

After completing the above steps sequentially, the results were recorded by measuring the area of inhibition (using a digital scale) on the membrane.

### 3.5 MTT Assay

In the MTT phase, HaCaT cells were cultured in 96 wells of a single microplate. We counted the cells using a specialized stain known as trypan blue, and after verification, the count was approximately  $1 \times 10^4$  distributed across the 96 wells. After completing this phase, we proceeded to the remaining steps, which were as follows:

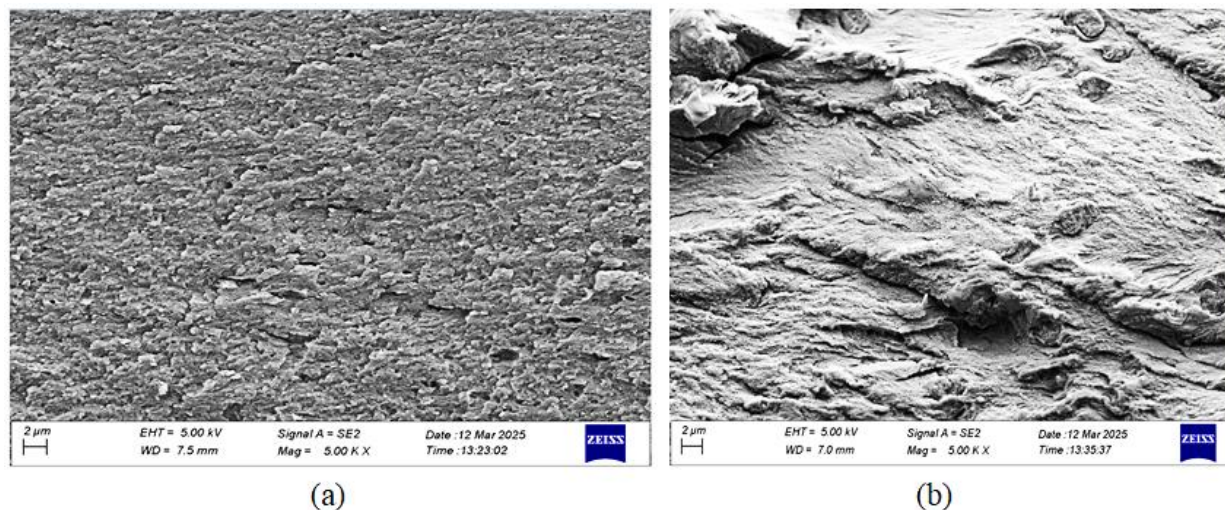
1. The plate was placed in an incubator at 37°C for 24 hours until 60% of the well surface was filled. This technique ensured that a longer incubation time was not required.
2. The cells were treated with different concentrations of the substances. Prepare the dilutions as needed; prepare all dilutions in sterile microtubes.
3. The supernatant was drained from each well using a sampling device. Note that 100  $\mu$ L of each dilution was added to the wells.
4. The casting pattern was drawn, and eight wells were selected for each dilution.
5. After 24 hours, the medium was removed, and 100  $\mu$ L of MTT solution (0.5 mg/mL) was added to the plates in the dark.
6. The plates were incubated for 4 hours. Then, remove the top medium from the wells using a swab, and add 100  $\mu$ L of DMSO to the wells.
7. The plates were shaken for 20 minutes (the container should be covered during this stage to prevent light exposure).
8. Finally, the intensity of the resulting color was measured using a microplate reader (DNM-9602G) at a wavelength of 570 nm.

## 4. Results and Discussions

### 4.1 SEM Results

Figure 2 shows field-electron microscopy images of sodium alginate (SA) films after adding glycerol and AgNPs. The surface of the sodium alginate film (SA) shown in Figure 2(a) was smooth and uniform, devoid of pores or ruptures.

Adding silver nanoparticles did not affect the films' surface morphology; however, the cross-section micrographs in Figure 2 (b-d) showed a significant increase in film roughness. Overall, the SEM images showed that although the AgNP particles aggregated, the lack of serious defects might imply improved physicochemical properties.



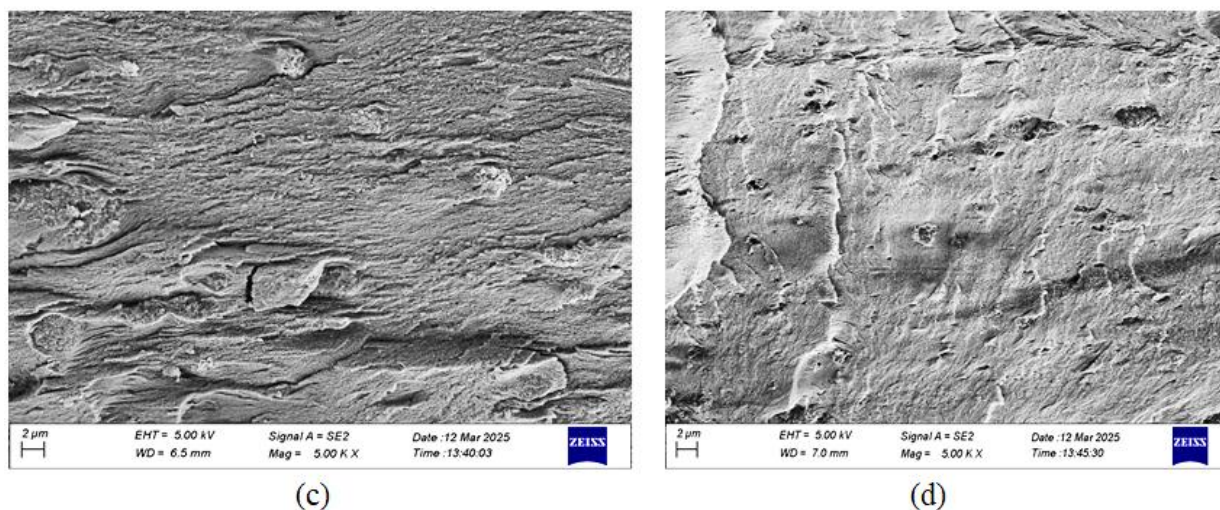


**Figure 2:** FESEM Images of Films, a: SG, b: SG1Ag, c: SG2Ag and d: SG3Ag)

The results confirmed that the films are compatible with SA and were satisfactorily distributed throughout the particle matrix, despite the increase in film roughness mediated by the AgNPs. A strong collision between particles and SA may be suggested by the regularity of AgNPs dispersion. The film's roughness increased with AgNP concentration, allowing observation of AgNP agglomeration.

#### 4.2 FTIR

Figure 3 shows the spectra of the wound dressing film. In every spectrum in the image, the O-H and C-H bonds at  $3285\text{ cm}^{-1}$  and  $2931\text{ cm}^{-1}$  are visible. The COO-group includes the peaks at  $1644\text{ cm}^{-1}$  and  $1414\text{ cm}^{-1}$ . The C-O-C stretching vibrations are indicated by peaks at  $1108\text{ cm}^{-1}$  and  $1031\text{ cm}^{-1}$ . The coupling of C-O, C-C, and C-O-H vibrations in the carbohydrate region ( $1031\text{--}850\text{ cm}^{-1}$ ) gives rise to the peak near  $1027\text{ cm}^{-1}$ . The  $850$  and  $994\text{ cm}^{-1}$  peaks are typical of polysaccharide structures. Therefore, FTIR revealed alkane, carboxyl, hydroxyl, and amine groups, which may be responsible for capping silver ions to form silver nanoparticles. Van der Waals interactions may occur between alginate and AgNPs. Through electrostatic attraction, anionic alginate may absorb silver nanoparticles.

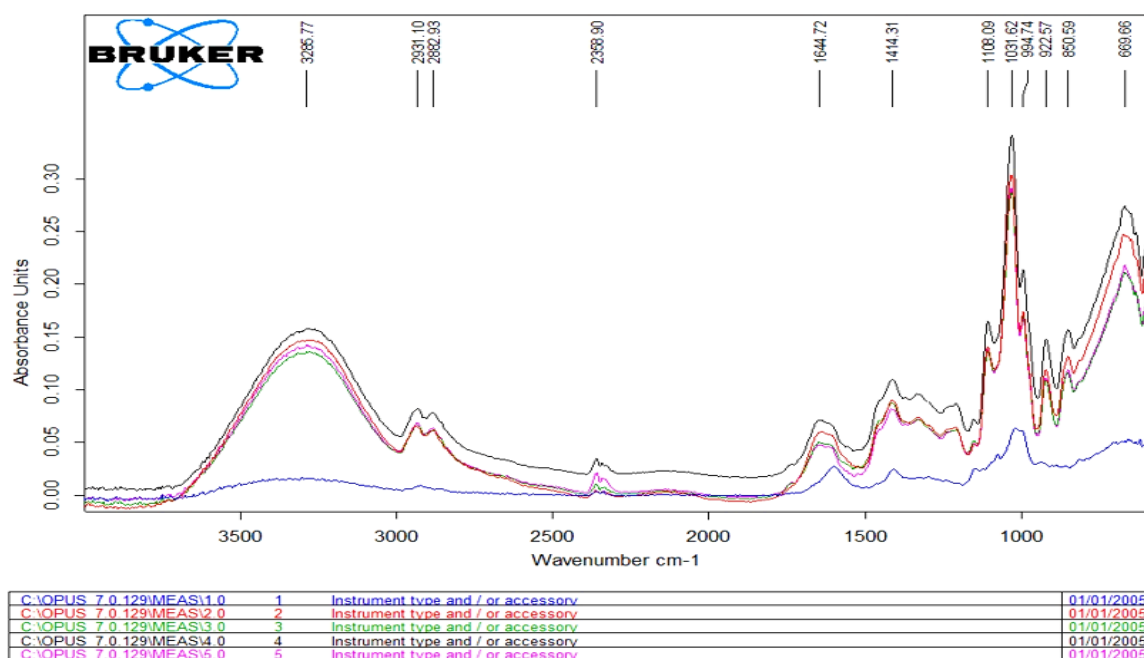


**Figure 3:** FTIR of Wound Dressing Films: 1: S, 2: SG, 3: SG1Ag, 4: SG2Ag, 3: SG3Ag

### 4.3 Wettability Assay

Wettability is one of the basic surface properties that control the efficiency of wound dressings, especially those based on sodium alginate, due to its direct effect on absorbing secretions, adhering the dressing to the wound, and the interaction of cells with the surface. Wettability influences cells' ability to attach properly to the films. We assessed film hydrophilicity using the water contact angle. Table 2, along with Figures 4 and 5, illustrates the contact angle of as-prepared films. After 3 seconds, we show images of water droplets on film surfaces and the measured contact angles for films with and without AgNPs.

**Table 2:** Contact Angle of Wound Dressing Films

| Code  | Contact angle |
|-------|---------------|
| S     | 50.3°         |
| SG    | 25.9°         |
| SG1Ag | 27.7°         |
| SG2Ag | 20.6°         |
| SG3Ag | 28.           |

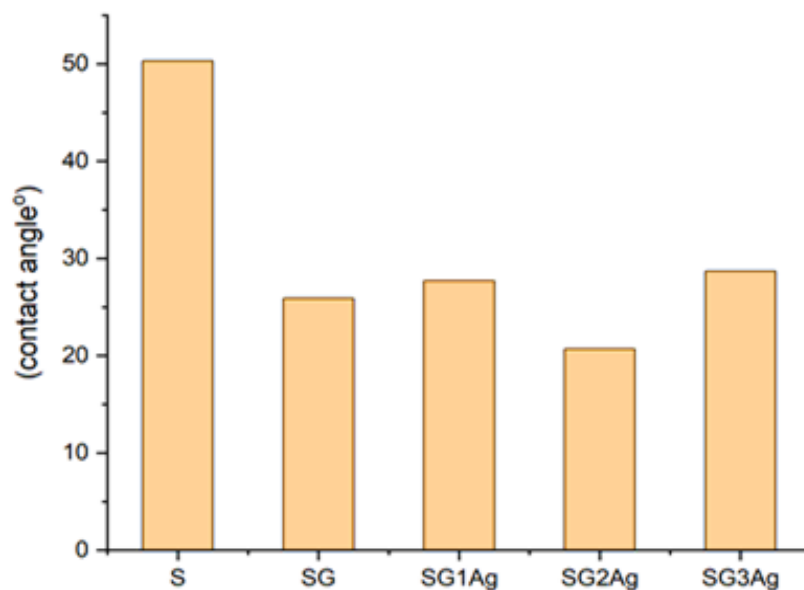
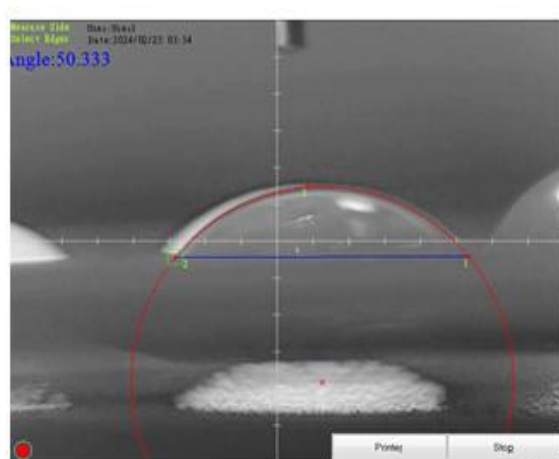
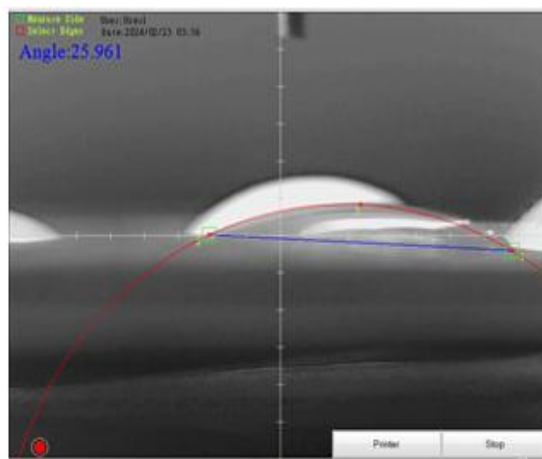


**Figure 4:** Wettability of Wound Dressing Films



(a)



(b)

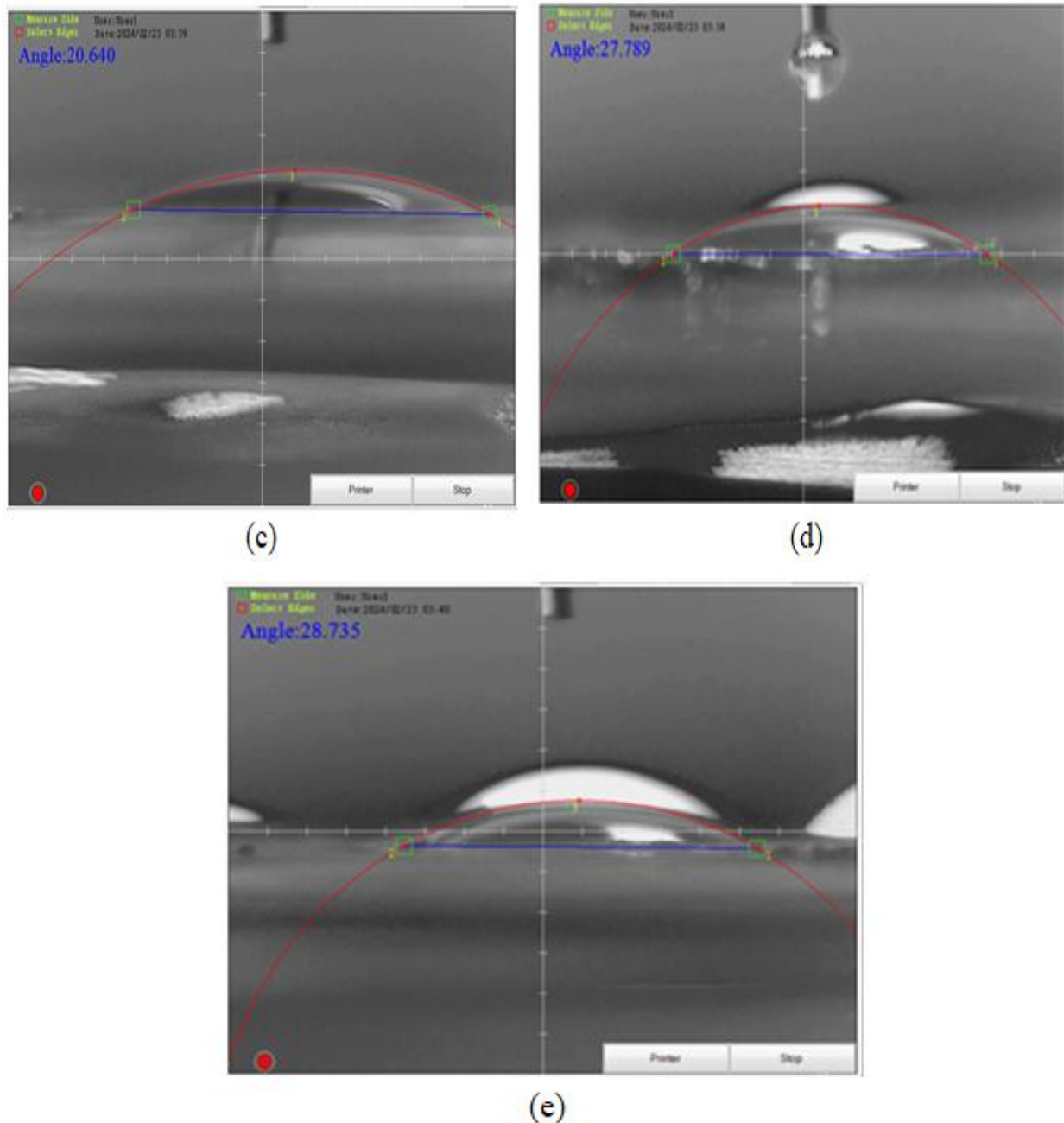


**Figure 5:** Wettability Results of Wound Dressing Films: a: S, b: SG, c: SG1Ag, d: SG2Ag, and e: SG3Ag.

#### 4.4 Antibacterial Activity

Silver nanoparticles inhibited the Gram-positive bacterium *S. aureus* more effectively than the Gram-negative bacterium *Pseudomonas aeruginosa*, as shown in Figures 6 and 7, respectively. Gram-negative bacteria have a small lipopolysaccharide structure on the outside of the membrane, which makes their barrier more effective than that of Gram-positive bacteria. Meanwhile, silver nanoparticles attach more easily to Gram-positive bacteria because of their peptidoglycan structure. AgNPs act at the membrane level because they can pass through the outer membrane and accumulate in the inner membrane, where their adherence destabilizes and damages it, increases membrane permeability, causes cellular contents to leak out, and ultimately kills the cell. Silver-alginate films showed a substantial inhibitory effect against both Gram-positive and Gram-negative bacteria by forming a clear zone on the agar medium containing these bacteria.

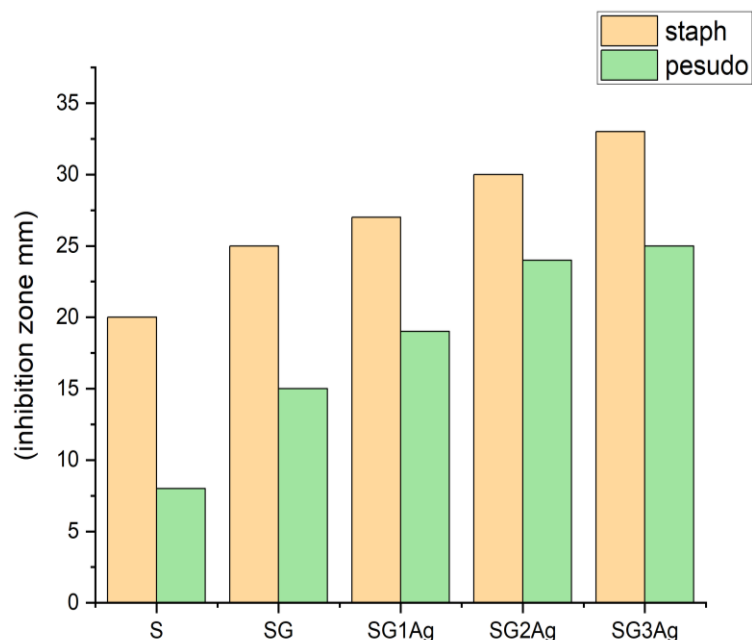


**Figure 6:** Antibacterial Activity Assay of Wound Dressing Films.



**Figure 7:** Antibacterial Activity Inhibition Zone of Wound Dressing Films

#### 4.5 Cell Viability

In this section, we monitored cell viability using the biocompatibility analysis technique for the wound dressing membranes proposed in our study. The cell-efficacy experimental phase tested the viability of normal human keratinocytes. One characteristic of successful cell adhesion for wound dressings is adhesion. As shown in Figure 8, our experiments demonstrate that the cells adhered completely, showing that both membranes are biocompatible systems suitable for skin tissue engineering. Studies show that adhesion plays a crucial role in dressing success, as evidenced by the mechanical interactions between the dressing and its extracellular substrate. This success is observed through tissue growth and maintenance after applying the wound dressings.

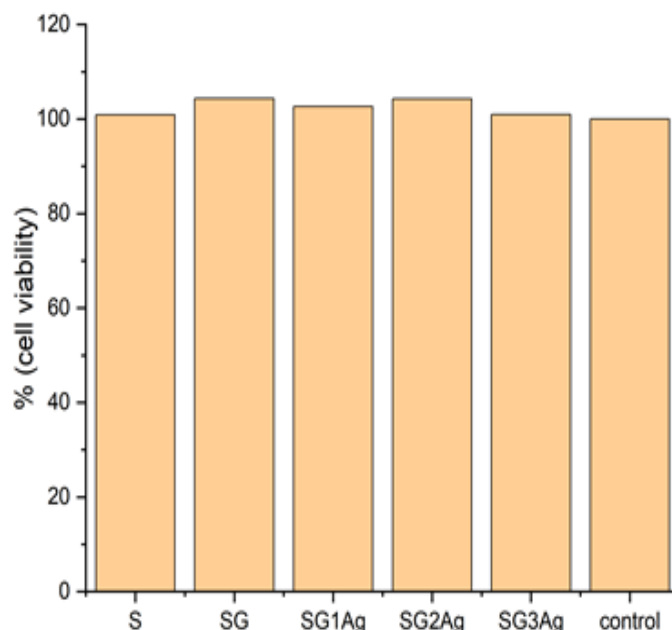


**Figure 8:** Cell Viability Assay of Wound Dressing Films.

## 5. Discussion

This biomaterial system is a potential multifunctional platform for wound-dressing applications, as shown by the fabrication and surface characterization of the SA–Gly–AgNP composite films. The sodium alginate, glycerol, and silver nanoparticle system is especially appealing because each component provides a distinct function. Sodium alginate forms a biocompatible, hydrophilic polymeric matrix that interacts with wound exudate; glycerol acts as a plasticizer to increase flexibility and reduce brittleness; and silver nanoparticles provide antimicrobial activity. This composite product can thus meet several requirements for successful wound dressing, such as moisture management, flexibility, surface function, and protection against microorganisms. A comparatively smooth, flat surface indicates good diffusion of elements in the alginate matrix. Conversely, visible masses or irregularities can indicate insufficient nanoparticle dispersion or incompatibility between components. At suitable AgNP levels, the nanoparticles can disperse throughout the polymer network, providing a larger active surface for interacting with microorganisms. However, high nanoparticle loading can lead to aggregation, which can create surface heterogeneity and make the film more non-uniform. Therefore, surface characterization is useful for selecting a suitable composition for biomedical applications. Physical and surface properties of alginate film are expected to change with the incorporation of glycerol. Dried films of pure sodium alginate can be quite hard and brittle. Glycerol can disrupt the polymer chains and make them more mobile, creating a more flexible and pliable product. This property is important in wound dressings because the dressing should fit the non-uniform surfaces of wounds without breaking during application or removal. Meanwhile, too much glycerol can also make it very soft and hydrophilic, which can impact water resistance and stability. Thus, an optimum glycerol concentration is needed to achieve flexible yet stable structures. The composite films were further modified by including silver nanoparticles, yielding silver nanoparticle composite films. Silver nanoparticle composite films are created by combining silver nanoparticles with the composite films, further altering their surface characteristics.

## 6. Conclusion

The SA–Gly–AgNP composite films fabricated in this study indicate that this multifunctional biomaterial system is promising for wound-dressing applications. Glycerol also contributes to film flexibility, and incorporating glycerol into the sodium alginate matrix reduced the brittleness of dried polysaccharide films; silver nanoparticles also showed important antimicrobial activity. Together, these factors generate a composite material with complementary physicochemical and surface properties. The collaboration and distribution of individual components in the polymer matrix appear to be key factors affecting the morphology, wettability, chemical properties, and overall stability of the

films. A relatively uniform distribution of nanoparticles is necessary to ensure consistent surface functionality and antimicrobial activity. The results also emphasize the need to control AgNP concentration, as high levels can lead to aggregation and negatively affect film homogeneity and mechanical properties. The composite is hydrophilic and has plasticizing properties due to glycerol, enabling it to maintain a moist wound environment while remaining flexible enough to apply. Silver nanoparticles can improve microbial protection. Therefore, the SA–Gly–AgNP composite appears to be a promising approach to combine structural, moisture-management, and antimicrobial properties in a single wound-dressing material. However, wound-dressing development must be optimized beyond surface characteristics. Special consideration should be given to ensuring the right level of antimicrobial activity and cell safety. Research concluded that Sodium alginate–glycerol–silver nanoparticle composite films are a highly promising material for producing a flexible, hydrophilic, antimicrobial wound dressing. They can be further optimized in composition and processing conditions, then rigorously tested and evaluated biologically and for performance, which would further enhance their use in advanced wound care systems.

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