Gum Acacia/Carbopol-Based Biocomposites Loaded with Silver Nanoparticles as Potential Wound Dressings

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Abstract  
Wounds infected with bacteria are treated using wound dressings loaded with antibiotics. However, the use of antibiotics has resulted in drug resistance. In order to overcome drug resistance common with most of the currently used antibiotics, several researchers have evaluated the potential of metal-based nanoparticles as antimicrobial agents. In this research, smart materials with good antibacterial activity were developed as potential wound dressings from a combination of bio- and synthetic polymers (gum acacia and carbopol, respectively) followed by loading with silver nanoparticles. The biocomposites were pH-sensitive with good water uptake. The hydrogels exhibited a high degree of swelling which increased with increase in pH. Their swelling capability was significant at pH of 7.4 simulating wound exudates. Their physicochemical properties were studied by FTIR, XRD, SEM and AFM. Furthermore, their antibacterial activity was significant against Gram-positive and Gram-negative strains of bacteria used in the study. The significant features of the biocomposites revealed their potential application as smart materials for the treatment of bacteria-infected and high exuding wounds.

Keywords: Gum acacia, Carbopol, Silver nanoparticles, Neem bark extract, Antibacterial activity, Biocomposites.

1. INTRODUCTION  
Bacterial infections are common in damaged skin resulting from wounds [1]. A current study further indicated that a common bacterial pathogen, Pseudomonas aeruginosa partners with a virus to cause chronic wounds [1]. Bacteria infected wounds are treated with wound dressings loaded with antibiotics. However, the currently used conventional antibiotics suffer from serious pharmacological limitations such as drug resistance, poor water solubility and toxicity [2,3]. Due to the aforementioned limitations, several researchers have investigated metal-based nanoparticles as potential antimicrobial agents. Metal-based nanoparticles exhibit good antibacterial activity. The commonly studied nanoparticles are silver, titanium.
dioxide, zinc oxide, gold nanoparticles etc. The unique feature that is responsible for their good antibacterial activity is their large surface area [4]. The antibacterial mechanisms of action of nanoparticles are speculated to be via the toxicity of free metal ion and by oxidative stress as a result of the production of reactive oxygen species on the nanoparticle surfaces [4, 5].

Wound dressings have been developed from biopolymers due to their unique features such as good hydrophilicity, biodegradability, permeability, biocompatibility, non-toxicity, non-immunogenic nature and the ease of surface modification [6,7]. However, their biomedical applications are limited by their poor mechanical properties, uncontrolled water uptake and varied properties that is dependent on the source [8,9]. Biopolymers which have been used in biomedical applications are chitosan, alginate, gum acacia, soy protein isolate, whey protein isolate, starch, cellulose etc. Gum acacia, a biopolymer content is dependent on its source and it is biodegradable with good surface activity [10,11]. Biopolymers are combined with synthetic polymers resulting in enhanced mechanical properties and controlled water uptake [12,13].

Synthetic polymers which have been employed in the development of wound dressings include carbopol etc. Carbopol belongs to the class of carbomers. It is pH-responsive with a high molecular weight composed of 50-60 % of acrylic acid groups. Some researchers prepared biocomposites from a combination of biopolymers and synthetic polymers loaded with silver nanoparticles as potential wound dressings with antibacterial activity. Alginate-based nanocomposites crosslinked with calcium carbonate and D-glucono-δ-lactone followed by loading with silver nanoparticles were effective against E. coli and P. aeruginosa strains of bacteria [14]. Chitosan/poly(vinyl alcohol)-based gels loaded with silver nanoparticles displayed good antibacterial activity and biocompatibility [15]. Chitosan-polyvinyl alcohol-based hydrogel loaded with silver nanoparticles exhibited good antibacterial activity [16]. Polyvinyl alcohol/gum acacia [17,18] and poly(vinyl alcohol)-sodium alginate-carboxymethylcellulose hydrogels loaded with silver nanoparticles exhibited good antibacterial activity [19].

The design of hybrid hydrogels loaded with in situ formation of silver nanoparticles was based on the hypothesis that they exhibit high water uptake, rough surfaces with good antibacterial activity. In this study, gum acacia/carbopol-based biocomposites loaded with silver nanoparticles prepared via in situ formation using neem bark extract were prepared. To the best of our knowledge, this is the first report on gum acacia/carbopol biocomposites containing silver nanoparticles. The biocomposites were characterized by Fourier Transform Infrared Spectroscopy (FTIR), Atomic Force Microscopy (AFM), X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) followed by swelling and antibacterial analysis.

2. MATERIAL AND METHODS
2.1. Materials
N,N-methylenebisacrylamide (MBA) and acrylamide (AM), N,N,N,N -Tetramethylethylenediamine (TEMED), neem bark extract and potassium persulfate (KPS) were obtained from Merck Chemicals (South Africa). Gum acacia and silver nitrate were obtained from Total Lab, South Africa. Carbopol® 974P NF was obtained from Lubrizol, USA.

2.1.1. Preparation of the Biocomposites
Gum acacia was dissolved in 1 mL of distilled water and AM was added followed by the addition of MBA solution. The mixture was stirred to obtain a homogenous mixture. Carbopol was then added followed by KPS and TEMED (Table 1). The resultant mixture was stirred at room temperature until a
A homogenous mixture was obtained. The biocomposites were formed at a temperature between 30 and 50 °C. The biocomposites were then soaked in distilled water overnight in order to get rid of the unreacted amine, before drying at ambient temperature for 5 days.

### Table 1. Composition of the hydrogel biocomposites.

<table>
<thead>
<tr>
<th>Biocomposites</th>
<th>AM (g)</th>
<th>MBA (65 mM)</th>
<th>TEMED (86 mM)</th>
<th>KPS (37 mM)</th>
<th>Gum acacia</th>
<th>Carbopol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank</td>
<td>1 g</td>
<td>1 mL</td>
<td>1 mL</td>
<td>1 mL</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ag-1</td>
<td>1 g</td>
<td>1 mL</td>
<td>1 mL</td>
<td>1 mL</td>
<td>0.5 g</td>
<td>0.05 g</td>
</tr>
<tr>
<td>Ag-2</td>
<td>1 g</td>
<td>1 mL</td>
<td>1 mL</td>
<td>1 mL</td>
<td>0.5 g</td>
<td>0.10 g</td>
</tr>
<tr>
<td>Ag-3</td>
<td>1 g</td>
<td>1 mL</td>
<td>1 mL</td>
<td>1 mL</td>
<td>0.5 g</td>
<td>0.15 g</td>
</tr>
</tbody>
</table>

#### 2.1.2. The Loading of the Biocomposites with Silver Nanoparticles

The biocomposites were transferred to 0.005 M solution of silver nitrate and left in the solution overnight. The hydrogels were then wiped with tissue and transferred to neem bark extract and left in the fridge for 2 h resulting in a colour change of the biocomposites to brown confirming the formation of silver nanoparticles.

#### 2.2. Methods

**2.2.1. FTIR**

FTIR analysis was performed in the range of 4000-500 cm⁻¹. It was performed on (Perkin Elmer Spectrum 100 FTIR spectrometer). The sample was placed on the diamond sample surface of the machine. The number of scans used was 32 at a resolution of 4 cm⁻¹.

**2.2.2. XRD**

XRD was performed using (PANalyticalX’Pert PRO), Netherlands. It was performed at (Cu Ka radiation, k 5 0.1546 nm) running at 45 kV and 40 mA. This analysis was performed in order to evaluate the amorphous or crystalline state of the biocomposites and to confirm the loading of the nanoparticles into the biocomposites.

**2.2.3. SEM**

The biocomposites were sputtered with gold nanoparticle before SEM analysis using JEOL-JSM 7500F SEM. It was used to evaluate the surface morphology of the biocomposites.

**2.2.4. AFM**

The surface morphology of the hydrogel biocomposites was evaluated using Atomic Force Spectroscopy (AFM) Digital Instruments Nanoscope, Veeco, MMAFMLN-AM (Multimode) instrument, USA. The samples were scanned over a length of 5 μm to give a surface area of 25 μm². The experiment was performed at room temperature in a tapping mode using a probe (RTESPAW-300 model). The scan rate was set to 0.50 Hz, the amplitude set point ranged from 1.27 to 1.440 V and probe frequency in the range of 280-310 kHz for all the analysis. The height and phase images were obtained.

**2.2.5. Swelling Analysis**

50 mg of the dry biocomposite was placed in 25 mL of buffer solutions (1.2 or 7.4) at ambient temperature simulating acidic and wound exudates pH, respectively. The water uptake of the biocomposites was evaluated by allowing the biocomposites to swell in selected buffer solutions until an equilibrium swelling was reached over a period of 24 h. They were then removed and blotted gently with blotting paper to remove the overloaded water on the surface and weighed. The swelling ratio at equilibrium (ER) was calculated from equation (1):

\[
Seq = \frac{w_t - w_s}{w_s}
\]
$W_s$ - weight of the biocomposite at equilibrium $W_i$ - weight of the biocomposite before swelling. The swelling ratio, SR of the biocomposites was evaluated by immersing dry biocomposites 50 mg in 25 mL of selected buffer solution (pH 7.4 or 10) at ambient temperature. At an interval of 30 min, the biocomposite was removed from the buffer solutions and blotted gently with blotting paper and weighed. SR was calculated from equation 2:

$$SR = \frac{M_s - M_d}{M_d}$$

3.2.6. In Vitro Antibacterial Analysis

Disc diffusion method was used to determine the antimicrobial activity of each compound. The test was carried out following the procedure recorded by Othman et al. with some minor changes [20]. Each sample (200 mg) was suspended in the corresponding volumes and tested against 12 bacterial strains. Gram positive bacteria include Bacillus cereus (BC) (ATCC10876), B subtilis (BS) (ATCC19659), Enterococcus faecalis (EF) (ATCC13047), Mycobacterium smegmatis (MS) (MC2155), and S aureus (SA) (ATCC25923). Gram negative bacteria: Enterobacter cloacae (ECL) (ATCC13047), Escherichia coli (EC) (ATCC25922), Enterobacter aerogenes, (EA) (ATCC13048) Klebsiella oxytoca (KO) (ATCC8724), K pneumonia (KP) (ATCC13882), Proteus mirabilis (PM) (ATCC7002) and Pseudomonas aeruginosa (PA) (ATCC27853).

3. RESULTS

3.1. FTIR

The blank biocomposite FTIR spectra revealed characteristic peaks at 3267 cm$^{-1}$ for N-H stretch, for C-H stretch at 2955 cm$^{-1}$, for C=O stretch at 1645 cm$^{-1}$, for C-H stretch and at 1538 cm$^{-1}$ (Figure 1a). FTIR spectrum of Ag-2 displayed characteristic peaks at 3343 cm$^{-1}$ for N-H stretch, at 3192 cm$^{-1}$ for aromatic C-H stretch, at 2925 and 2853 cm$^{-1}$ for C-H stretch, at 1645 cm$^{-1}$ for C=O stretch, at 1588 for N-H bending and at 1082 cm$^{-1}$ for C-O-C stretch (Figure 1b). FTIR spectrum of Ag-3 and blank loaded with silver nanoparticles displayed characteristic peaks at 3267 cm$^{-1}$ for N-H stretch, C-H stretch was visible at 2917 cm$^{-1}$, C=O stretch was found at 1658 cm$^{-1}$ and N-H bending was visible at 1594 cm$^{-1}$ (Figure 1c).

![Figure 1a. FTIR spectrum of blank biocomposites.](image)

![Figure 1b. FTIR spectrum of Ag2 biocomposites.](image)
broad peak at 22° and sharp peaks at 29.34 °, 35.76 °, 38.26 °, 39.27 °, 42.93 °, 44.05 °, 47.32 °, 48.44 °, 56.37 ° and 57.34 ° (Figure 2a).

**Figure 1c.** FTIR spectra of Ag3 and blank biocomposites loaded with Ag nanoparticles.

The XRD diffractogram of Ag1-3 loaded with silver nanoparticles also revealed a combination of a broad peak at 22° and sharp peaks (Figure 2b-d). The sharp peaks on Ag1 and Ag2 were visible at 29.34 °, 38.52 °, 42.92 °, 44.17 °, 47.92 °, 48.44 °, and 57.36°. However, Ag3 displayed two distinct broad peaks at 22 and 44.04° resulting from a high degree of crosslinking of the polymers (Figure 2d).

**Figure 2a.** XRD diffractograms of blank biocomposites.

**Figure 2b.** XRD diffractograms of Ag1 biocomposite.

**Figure 2c.** XRD diffractogram of Ag2.

**Figure 2d.** XRD diffractogram of Ag3.
3.3. SEM
The blank SEM image was characterized by irregular morphology with a rough surface (Figure 3a). The morphology of biocomposite Ag1 was similar to the blank (Figure 3b). However, there were pores which were significant when compared to the blank biocomposite. The morphology of Ag2 was a combination of a smooth and rough surface (Figure 3c). The degree of roughness of the Ag2 was enhanced resulting from the higher degree of crosslinking of the polymer when compared to Ag1 and Ag2. The morphology of Ag3 displayed a rough surface with irregular morphology (Figure 3d).

![Figure 3. SEM images (a) Blank biocomposites (b) Ag1 (c) Ag2 and (d) Ag3.](image)

3.4. AFM
The topography variations on the surface of the biocomposite was studied. (Figure 4a-d). The AFM images of the biocomposites revealed a high degree of roughness in Ag3 when compared to the blank. However, Ag2 biocomposite revealed a combination of a smooth and rough surfaces which similar to the SEM image. The WSxM software analysis of the biocomposites is shown in (Table 2) [21].

![Figure 4. AFM images (a) Blank biocomposites (b) Ag1 (c) Ag2 (d) Ag3.](image)

<table>
<thead>
<tr>
<th></th>
<th>Ag1</th>
<th>Ag2</th>
<th>Ag3</th>
<th>Blank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness average</td>
<td>46.3524</td>
<td>49.6151</td>
<td>51.4176</td>
<td>44.9736</td>
</tr>
<tr>
<td>Root mean square</td>
<td>55.3259</td>
<td>59.2844</td>
<td>60.5385</td>
<td>54.6139</td>
</tr>
<tr>
<td>Surface skewness</td>
<td>-1.2509</td>
<td>-1.2496</td>
<td>-1.1874</td>
<td>-1.3264</td>
</tr>
<tr>
<td>Surface kurtosis</td>
<td>2.6697</td>
<td>2.7172</td>
<td>2.5414</td>
<td>3.0136</td>
</tr>
<tr>
<td>Average height</td>
<td>152.4043</td>
<td>150.5566</td>
<td>143.7547</td>
<td>151.2625</td>
</tr>
</tbody>
</table>

3.5. Swelling Property
Ag1-3 exhibited high swelling capability at pH 7.4 when compared to pH 1.2. The enhanced swelling capability of Ag1-3 is attributed to the hydrophilic nature of gum acacia and carbopol (Figure 5a & 5b). The swelling capability of the biocomposites at acidic pH was low suggesting that they are pH-sensitive.

![Figure 5. Swelling ratio vs time.](image)
Figure 5a. Swelling capacity of the biocomposites at pH 1.2.

Figure 5b. Swelling capacity of the biocomposites at pH 7.4.

The water uptake kinetics of the hydrogel biocomposites were evaluated using equation 3.

\[ M_t / M_e = K t^n \]  \hspace{1cm} (3)

Where \( M_t \) and \( M_e \) are the masses of the hydrogel biocomposites at time \( t \) and equilibrium, respectively. \( K \) is the diffusion constant of water into the hydrogel biocomposite matrices and \( n \) is the diffusion exponent.

Table 3. Diffusion coefficient (D), diffusion exponent (n) and diffusion constant (K) of the biocomposites at pH 1.2 and 7.4.

<table>
<thead>
<tr>
<th>pH</th>
<th>Biocomposites</th>
<th>n</th>
<th>( R^2 )</th>
<th>K</th>
<th>D</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4</td>
<td>Blank</td>
<td>0.44</td>
<td>0.99</td>
<td>0.51</td>
<td>0.28</td>
<td>0.99</td>
</tr>
<tr>
<td>7.4</td>
<td>Ag-1</td>
<td>0.44</td>
<td>0.99</td>
<td>0.79</td>
<td>0.39</td>
<td>0.99</td>
</tr>
<tr>
<td>7.4</td>
<td>Ag-2</td>
<td>0.42</td>
<td>0.99</td>
<td>0.28</td>
<td>0.41</td>
<td>0.99</td>
</tr>
<tr>
<td>7.4</td>
<td>Ag-3</td>
<td>0.50</td>
<td>0.99</td>
<td>0.73</td>
<td>0.45</td>
<td>0.99</td>
</tr>
<tr>
<td>1.2</td>
<td>Blank</td>
<td>0.51</td>
<td>0.99</td>
<td>0.89</td>
<td>0.41</td>
<td>0.98</td>
</tr>
<tr>
<td>1.2</td>
<td>Ag-1</td>
<td>0.43</td>
<td>0.99</td>
<td>0.75</td>
<td>0.28</td>
<td>0.99</td>
</tr>
<tr>
<td>1.2</td>
<td>Ag-2</td>
<td>0.34</td>
<td>0.94</td>
<td>0.12</td>
<td>0.28</td>
<td>0.94</td>
</tr>
<tr>
<td>1.2</td>
<td>Ag-3</td>
<td>0.40</td>
<td>0.99</td>
<td>0.69</td>
<td>0.24</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The \( n = 0.5 \) indicates case 1, which is a perfect Fickian process whereby the rate of network relaxation is faster than the rate of diffusion. When \( n = 1.0 \), it indicates a non-Fickian diffusion whereby water transport is controlled and the rate of diffusion is faster than the network relaxation. When \( 0.5 < n < 1.0 \), it indicates that the rate of penetrant mobility and segmental relaxation are comparable [22]. The slope of the graph of ln (\( M_t / M_e \)) versus ln \( t \) for 60% swelling ratio determined the diffusion exponent, \( n \) of the biocomposites. The diffusion exponent values were found to be in a range of 0.34-0.51 indicating a combination of pseudo-Fickian and Fickian diffusion with a coefficient of determination of 0.99 indicating good linearity (Table 3). At pH 1.2, the \( n \) value of the blank biocomposite was 0.51 suggesting Fickian diffusion and the \( n \) values of Ag1, Ag2, Ag3 were 0.43, 0.34 and 0.40, respectively indicating pseudo-Fickian diffusion. At pH 7.4, the \( n \) values of blank, Ag1, Ag2 were 0.44, 0.44, 0.42 respectively indicating pseudo-Fickian diffusion and Ag3 was 0.5 suggesting Fickian diffusion. The hydrogels diffusion coefficients were also calculated using equation 4.

\[ S = 4 \left( \dfrac{D}{r^2 \pi t} \right)^{1/2} \]  \hspace{1cm} (4)

where \( D \), \( r \), \( S \), and \( t \) represent the diffusion coefficient, radius, fractional swelling of the hydrogels and time, respectively. To investigate the diffusion coefficient, \( D \) of the biocomposites, a graph of \( S \) versus \( t^{1/2} \) were drawn and the diffusion coefficients were obtained from the slopes of these graphs. The diffusion coefficient was found to be between 0.24-0.45 respectively (Table 3). The coefficient of determination was in a range of 0.98-0.99 indicating good linearity.

3.6. In Vitro Antibacterial Analysis

The biocomposites were effective against gram-positive and gram-negative bacteria (Table 4). Ag3 biocomposites exhibited enhanced antibacterial activity against Bacillus cereus, Enterobacter cloacae and


Pseudomonas aeruginosa. The biocomposites were also effective against K pneumonia, Mycobacterium smegmatis and Pseudomonas aeruginosa when compared to the neem bark extract. However, the biocomposites were not effective against Klebsiella oxytoca and Proteus mirabilis revealing the selective antibacterial activity of the biocomposites against some strains of bacteria. Ag2 was effective against Proteus mirabilis when compared to Ag1 and Ag3.

<table>
<thead>
<tr>
<th>Biocomposites</th>
<th>EA</th>
<th>EF</th>
<th>SA</th>
<th>BS</th>
<th>EC</th>
<th>BC</th>
<th>ECL</th>
<th>KO</th>
<th>PA</th>
<th>KP</th>
<th>MS</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
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<td>9</td>
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<td>7</td>
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<td>~</td>
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<td>9</td>
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<td>~</td>
</tr>
<tr>
<td>Ag-2</td>
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<td>9</td>
<td>7</td>
<td>7</td>
<td>9</td>
<td>10</td>
<td>9</td>
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<tr>
<td>Ag-3</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>~</td>
<td>12</td>
<td>8</td>
<td>9</td>
<td>~</td>
</tr>
<tr>
<td>Neem bark extract</td>
<td>9</td>
<td>9</td>
<td>~</td>
<td>8</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>8</td>
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</tbody>
</table>

### 4. DISCUSSION

Gum acacia/carbopol-based biocomposites were prepared by free-radical polymerization and loaded with silver nanoparticles. Neem bark extract was used as a reducing agent and this approach was employed in order to enhance the antibacterial efficacy of the biocomposites. Some researchers used neem extract as a reducing agent [23, 24]. Neem leaf extract was used as a capping and reducing agent. The nanoparticles prepared were effective against gram-positive and gram-negative bacteria [23, 25, 26]. Natural extracts are eco-friendly, cost-effective and useful for the preparation of silver nanoparticles [27-30]. The formation of the nanoparticles was performed in situ in the prepared biocomposites. The biocomposites serve as a potential reservoir for the sustained release of silver ions to promote wound healing. The in situ formation of the nanoparticles in the biocomposites was due to the reduction of Ag+ silver to Ag0 by the reducing agent, NaBH4 [31, 32]. This method promotes the formation of monodispersed silver nanoparticles within the matrices of the biocomposites [33, 34]. The biocomposites were prepared by free-radical polymerization in which the hydroxyl group on the gum acacia was useful for crosslinking with the functional groups on the carbopol. Free radical polymerization is the most commonly used cross-linking technique. It offers several advantages such as it is very reactive resulting in high density of cross-linking density, it is appropriate for different functional groups and it occurs under mild conditions [35, 36].

The FTIR spectra of the biocomposites revealed characteristic peaks of C-O-C stretch confirming the successful crosslinking of gum acacia in the hydrogel matrix [37, 38]. The signal for the carbonyl group was significant at 1658 and 1645 cm⁻¹ in the biocomposites due to carbopol crosslinked in the hydrogel matrix [38, 39]. The FTIR further revealed the non-interaction of the loaded nanoparticles with the biocomposites network indicating the stability of the nanoparticles in the biocomposites. Biocomposites are good drug delivery systems and they have been employed for the delivery of silver nanoparticles [40-42]. Biocomposites exhibit some unique features making them useful systems for drug delivery such as they can be tailored for sustained and controlled drug release mechanism, exhibit high drug loading capacity, they are biocompatible and non-toxic [43-45].

The XRD diffractograms of the biocomposites loaded with silver nanoparticles displayed a combination of broad and sharp peaks confirming the successful loading of silver nanoparticles in the biocomposites. The broad peaks are due to the amorphous nature of the biocomposites resulting from the
crosslinking of the polymers. The sharp peaks are due to the Ag\textsuperscript{0} with face-centred cubic crystal structure nanoparticles in the biocomposites [46-48].

The SEM images of the blank biocomposite and Ag\textsubscript{1} was irregular with a rough surface morphology (Figure 3a). However, the significant pores on Ag\textsubscript{1} when compared to the blank biocomposite is attributed to the crosslinking of gum acacia with carbopol. The morphology of Ag\textsubscript{2} was a combination of a smooth and rough surface (Figure 3c). The degree of roughness of the Ag\textsubscript{3} was enhanced resulting from the higher degree of crosslinking of the polymer when compared to Ag\textsubscript{1} and Ag\textsubscript{2}. The SEM images revealed the presence of cavities suitable for high water uptake suggesting their capability to exhibit high swelling with enhanced permeability [38, 49]. Furthermore, the AFM images confirmed the rough surface of the biocomposites (Figure 4a-d). Their rough surface is attributed to their degree of crosslinking [50,51]. The rough surfaces of the biocomposites are suitable for accelerating cell adhesion, proliferation, and skin regeneration and these features have been reported to be important in wound dressings that can accelerate wound healing by some researchers [52,53]. The rough surfaces display a high surface area and they are excellent platform for cells that induce fibroblast adhesion [52-54]. Furthermore, the nature of surface of the biocomposites also promote their good adhesiveness making them potential materials for topical application at the wound surface [54]. The presence of cavities in the dressing materials also promote the permeation of atmospheric oxygen to the wound which is useful for accelerated wound healing [55-57].

The water uptake of the biocomposites reveals their capability to absorb wound exudate and maintain a moist environment at the wound bed. The blank hydrogel swelling capability at pH 7.4 was low when compared to Ag\textsubscript{1}-3. The aforementioned finding indicates that the presence of gum acacia and carbopol in the biocomposite play an important role in the swelling capability of the biocomposites. Carbopol and gum acacia contain hydrophilic functional groups that contribute to the swelling capacity of the biocomposites [58]. However, the blank hydrogel exhibited high swelling capability at pH 1.2 when compared to pH 7.4 revealing the pH sensitivity of the biocomposites [17]. The mechanism of water uptake into the biocomposites revealed that the diffusion exponent values were in a range of 0.34-0.51 indicating a combination of pseudo-Fickian and Fickian diffusion. The high water uptake of the biocomposites reveal their exudate drainage ability which is relative to their ability to absorb body fluids, transform cell nutrients, and provide a moist environment suitable for accelerated wound healing. Furthermore, the capability of the biocomposites to absorb exudates also protect the wound from microbial invasion which is usually responsible for chronic wound infections and also prevent wound drying thereby alleviating pains [55, 59].

The biocomposites antibacterial activity against Bacillus cereus, Enterobacter cloaceae and P. aeruginosa was significant for Ag\textsubscript{3} when compared to other biocomposites suggesting that the degree of crosslinking of the biocomposites influenced their selective antibacterial activity against selected strains of bacteria. The three aforementioned strains of bacteria have been reported to be responsible for infection in wounds [60,61]. Co-infection of P. aeruginosa and S. aureus can result in worse patient outcomes when compared to a single infection [62]. The biocomposites were also effective against K pneumonia, Mycobacterium smegmatis and Pseudomonas aeruginosa when compared to the neem bark extract. However, the biocomposites were not effective against Klebsiella oxytoca and Proteus mirabilis revealing the selective antibacterial activity.
positive and Gram-negative strain of bacteria.

5. CONCLUSION
The biocomposites exhibited high water uptake at pH 7.4 when compared to pH 1.2. The highly crosslinked biocomposite, Ag3 exhibited a high degree of swelling when compared to other biocomposites.

The FTIR spectra revealed characteristic peaks confirming the successful crosslinking of gum acacia in the biocomposites. Their SEM images was a combination of irregular morphologies with rough surface and cavities which was influenced by the degree of crosslinking. The XRD diffractograms of the biocomposites displayed crystalline peaks of silver nanoparticles confirming the successful incorporation of the nanoparticles in situ. The antibacterial activity of the biocomposites was significant and selective against gram-positive and gram-negative strains of bacteria. The unique features of the biocomposites such as high water uptake, rough surfaces with cavities and good antibacterial activity suggest that they are potential wound dressings for accelerated wound healing.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

REFERENCES


