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Reaction Time Dependent Antimicrobial Functionalization of Textile Fibers with Aloe vera Mediated Silver Nanoparticles

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Abstract

In the present study, silver nanoparticles (AgNPs) were synthesized from the *Aloe vera extract* and immobilized on cotton, polyester, polycotton and silk fibres with a special focus on the effect of reaction time on the surface functionalization and antimicrobial activity. The textiles were treated for 5, 25 and 45 min, and the resulting textiles were systematically characterized using FESEM, EDS, XRD, FTIR and Raman spectroscopy. Progressive changes in the nucleation, surface coverage, aggregation and morphology of the nanoparticles were observed with reaction time by FESEM. Typical apparent particle size at 5 min were 75.75, 60.88, 92.17, and 44.88 nm for cotton, polyester, polycotton and silk respectively, but the apparent particle size at 45 min were smaller on cotton (55.52 nm), polycotton (70.58 nm), and silk (50.00 nm) suggesting re-nucleation and stabilization. The EDS results confirmed the incorporation of Ag on all substrates, with the highest Ag concentration being 25.3 wt. % (4.1 at. %) for polycotton substrates after 45 min. XRD showed that the intrinsic crystalline structures of the textiles were preserved, with the Ag reflections being either weak or not resolved due to the low concentration of Ag and/or highly dispersed nanoscale Ag particles. FTIR and Raman spectral changes were identified and analyzed, which highlighted changes in the functional group of the textile, Ag species and biomolecules from Aloe vera as a function of the reaction time. The antimicrobial testing results showed that *Staphylococcus aureus* and *Escherichia coli* were inhibited at distances of around 18.9–24.5 mm. The maximum response was seen for silk

against *S. aureus* at 25 min (24.3 mm) and cotton against *E. coli* at 45 min (24.5 mm). Overall, the results show that in situ synthesis using *Aloe vera* is a promising approach for the preparation of Ag-functionalized textiles with tunable surface properties and antimicrobial activity.

Keywords: Aloe vera; Silver nanoparticles; Antimicrobial textiles; Reaction time; In situ functionalization.

1. Introduction:

Bacterial infections continue to be a significant health issue, especially in wound management, both in acute and chronic wound care. Damage to the skin barrier allows pathogenic bacteria to penetrate and proliferate, resulting in delayed wound healing, local infections and, if severe, systemic complications [1-4]. This is exacerbated by the rapid spread of antimicrobial resistance (AMR) which has led to loss of efficacy of many of the traditional antibiotics [5,6]. The rise of multi-drug-resistant bacteria, such as clinically significant ESKAPE-resistant species, reinforces the need for new methods to combat them without antimicrobial drugs that are safe, effective and sustainable [7].

In this context, the development of materials with antimicrobial properties using nanoparticles has gained a lot of interest. It is among these methods, plant-mediated green synthesis, that offers a simple and environmentally friendly method to prepare antimicrobial nanoparticles. Naturally occurring bioactive compounds present in plant extracts like phenolics, flavonoids, tannins, terpenoids and saponins can be used as natural reducing, stabilizing and capping agents in the process of nanoparticle production [8-10]. Therefore, the plant-assisted synthesis can also save the use of toxic chemicals and be an economical alternative to the traditional nanoparticles synthesis processes [11,12]. Silver nanoparticles (AgNPs) are considered as one of the most interesting particles due to their broad-spectrum and potent antibacterial properties among the different metal nanoparticles. The antimicrobial properties are shown to manifest through several mechanisms such as disruption of bacterial membrane, interaction with bacterial cellular proteins, production of oxidative stress and disruption of bacterial DNA [13-15]. The great number of modes of action involved in AgNPs makes them a promising candidate for the development of antimicrobial surfaces and reduction of the danger associated with bacterial infection.

Addiction of AgNPs in textiles is one of the most interesting uses of AgNPs. The antimicrobial textile has a direct protection role with regard to microbial contamination and

has a lot to offer in healthcare, wound-care and protective application. Medical textiles are widely used in medical applications because of the characteristics of cotton, which includes softness, breathability, high absorbency, and biocompatibility [16]. But its water-holding capacity can also make it an ideal breeding ground for bacteria. The antimicrobial properties can be obtained by application of plant extract onto textile materials, but such direct application is often restricted due to difficulty of durability and removal in washing or use. However, the immobilization of AgNPs on textile surfaces can result in a more long-lasting antibacterial effect and can also impart other functional properties, like UV protection [17-19].

As a result, interaction between the biogenic AgNPs with various textile substrates has not been well explored with the same synthesis conditions. Cotton, silk, polyester and polycotton are all examples of textile materials with distinct chemical makeup, surface properties, fiber structure and hydrophilic/hydrophobic properties [20]. These variations can affect the reduction of Ag^+ ions, the nucleation and growth of nanoparticles, the distribution on the surface, and the adhesion of the AgNPs. Hence, it is crucial to compare the various textile substrates in a systematic manner to gain insights into the factors that affect the formation and performance of the biogenic AgNP coatings.

Therefore, in the present study, the simple green synthesis of AgNP coated cotton, polyester, polycotton and silk fabrics with the use of *Aloe vera* extract as natural reducing and stabilizing agent is developed. The effect of reaction time on silver deposition was systematically studied and comparative analysis of the morphology, surface distribution and physicochemical characteristics of the silver-nanoparticles coated fabrics were performed. The antibacterial activity was then tested to identify how the textile substrate and the AgNP deposition affects the activity. The objective of this study is to determine the optimum fabric–AgNP combination and to develop a sustainable method for creating durable antimicrobial fabrics that can be used in biomedical, wound-care, healthcare, and protective applications.

2. Materials and methods:

2.1. Materials

Fresh leaves of *Aloe vera (Aloe barbadensis Mill.)* were collected from a cultivated plant maintained in a garden at G. T. Patil ACS College, Nandurbar, Maharashtra, India (21.3675° N, 74.2522° E). The plant material was identified as Aloe vera by Dr. Tanveer Akhtar Khan**,** Plant Taxonomist, Head, Department of Botany, H. J. Thim College of Arts & Science, Jalgaon, Maharashtra, India. A representative voucher specimen was deposited in the

herbarium of Department of Botany, H. J. Thim College of Arts & Science, Jalgaon, Maharashtra, India, under accession/deposition number HJTC/BOT/TAK/HERB-219/2026-27. The leaves were used for the preparation of the aqueous extract employed in the green synthesis and in-situ functionalization of textile fibers with silver nanoparticles. The collection and use of the plant Extract complied with applicable institutional, local, and national guidelines for scientific research involving plant materials. The collected leaves were transported to the laboratory in clean polyethylene bags and processed immediately for extract preparation. Deionized water was used throughout the experimental work for solution preparation, extraction of phytochemicals, washing of the synthesized nanoparticles, and all dilution procedures. $AgNO_3$ was bought and used in analytical grade without further purification.

2.2. Methods

2.2.1. Preparation of Aloe Vera extract:

Fresh and mature leaves of *Aloe vera* were picked and washed well with running water to remove the dust and impurities on the leaf surface. The outer, thick epidermal layer (leaf skin) was stripped carefully so that the inner, translucent gel composed of parenchyma could be seen. The gel was separated, cut into small pieces and air-dried to achieve the constant dry mass. The dried Aloe vera material was then ground to a fine powder and placed in a Soxhlet extraction thimble. The extraction was carried out with Soxhlet method for 1 hour at 80 °C with an appropriate extraction solvent. The extract was then filtered to ensure the removal of any solid matter to give a clear liquid extract. The filtrate was collected and stored in an air tight container in an environment protected from light and in the proper condition to reduce the oxidation of the bioactive components and the effect of photochemical degradation until it was used for the synthesis of Ag nanoparticles.

2.2.2. Green synthesis of AgNPs on different fabrics:

Firstly, 0.020 g of $AgNO_3$ salt was dissolved in 20 mL DI water at room temperature with magnetic stirrer and prepared $AgNO_3$ solution was used for cotton fabric. 5 mL of Aloe vera extract was mixed with 20 mL of $AgNO_3$ solution and the mixture was stirred and heated to 50 – 60 ℃. The reaction mixture started to sparkle brown after some minutes. This was a visual indicator of the formation of AgNPs. The steps were repeated by varying the time period. Finally, the functionalized fabric samples were washed in cold deionized water and then air dried at room temperature. Repeat the same procedure for polyester, polycotton and silk.

3. Characterization

The structural analysis of the coated fabric has been taken by using X-ray diffractometer (Rigaku miniflex 600) and Morphology analysis is done by using Field Emission Scanning Electron Microscopy (FESEM) (Model: Nova Nano SEM 450). The energy dispersive analysis by X-ray (EDAX) method has been used to carry out the compositional study of the film by (Ametek EDS). FT-IR (Shimadzu IR affinity) was used to perform the surface functional groups. The following measuring conditions were used: Wavenumber range: 4000-350 cm-1; Resolution: 0.5 cm-1. The samples were tested for the antibacterial activity by standard agar-disc diffusion method. The species of gram-positive bacteria (*S. aureus*) and gram-negative bacteria (*Escherichia coli*) which are pathogenic to human were used as the test specimen. A pure culture of given pathogen was sub-cultured in nutrient broth and the strain was uniformly spread on sterilized petri plates. The plates were incubated at 37^0C overnight and the zones of inhibition were observed.

4. Results and discussion

4.1. *X-ray diffractometer studies of AgNPs coated fabrics*

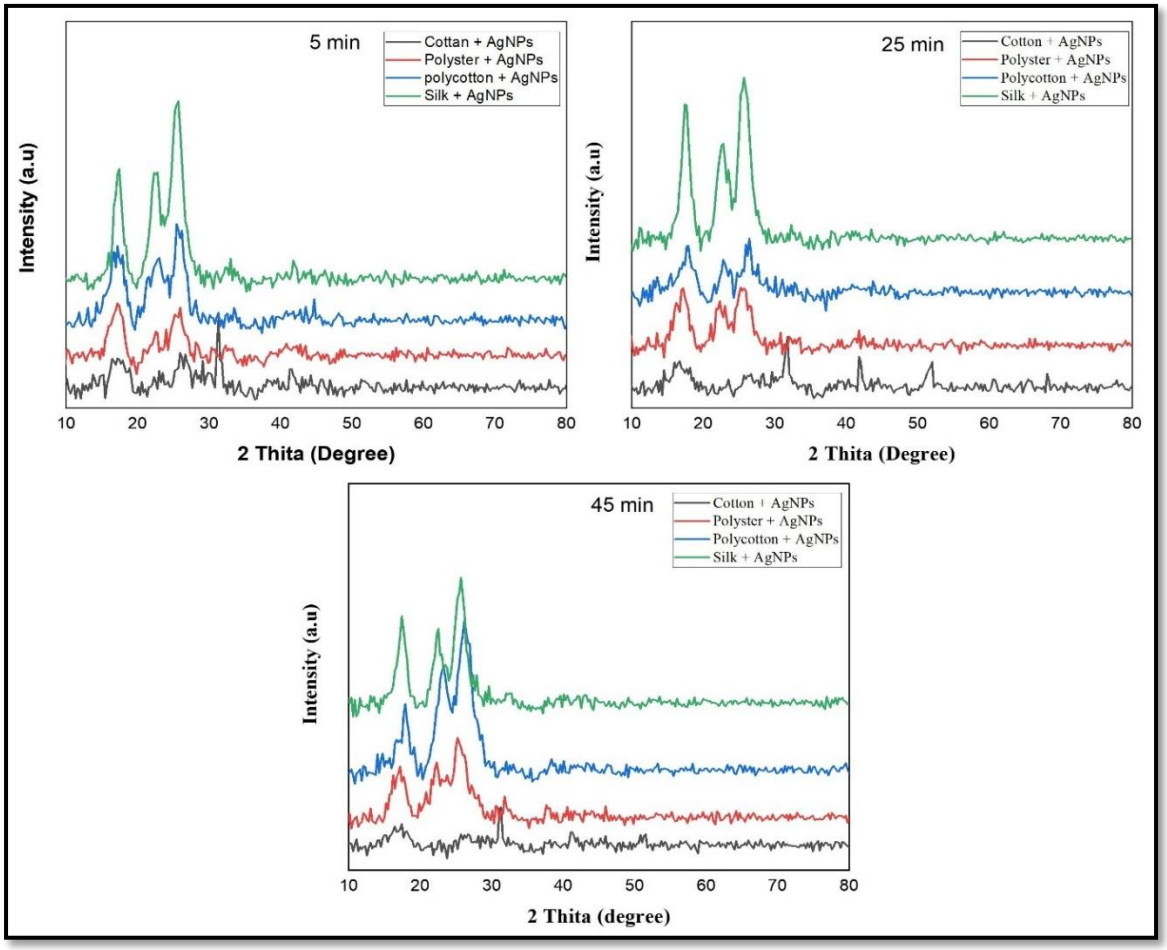


Figure 1. XRD spectra of Aloe vera-mediated AgNP-functionalized cotton, polyester, polycotton, and silk fabrics at (a) 5, (b) 25, and (c) 45 min, showing characteristic textile peaks.

The structural properties of the cotton, polyester, polycotton and silk fabrics functionalized with Ag using Aloe vera at 5, 25 and 45 min was analyzed using X-ray diffraction (XRD) analysis. Figure 1 shows the diffraction pattern that are obtained are mainly dominated by the intrinsic crystalline structure of the textile substrates; the major diffraction peaks are found in the range 15–30° 2θ. Metallic silver (Ag) crystallizes with a face-centered cubic (fcc) crystal structure and typical diffraction angle reflections at 38.1°, 44.3°, 64.4°, and 77.5° corresponding to the (111), (200), (220), and (311) planes respectively, as per the JCPDS/PDF No. 04-0783.

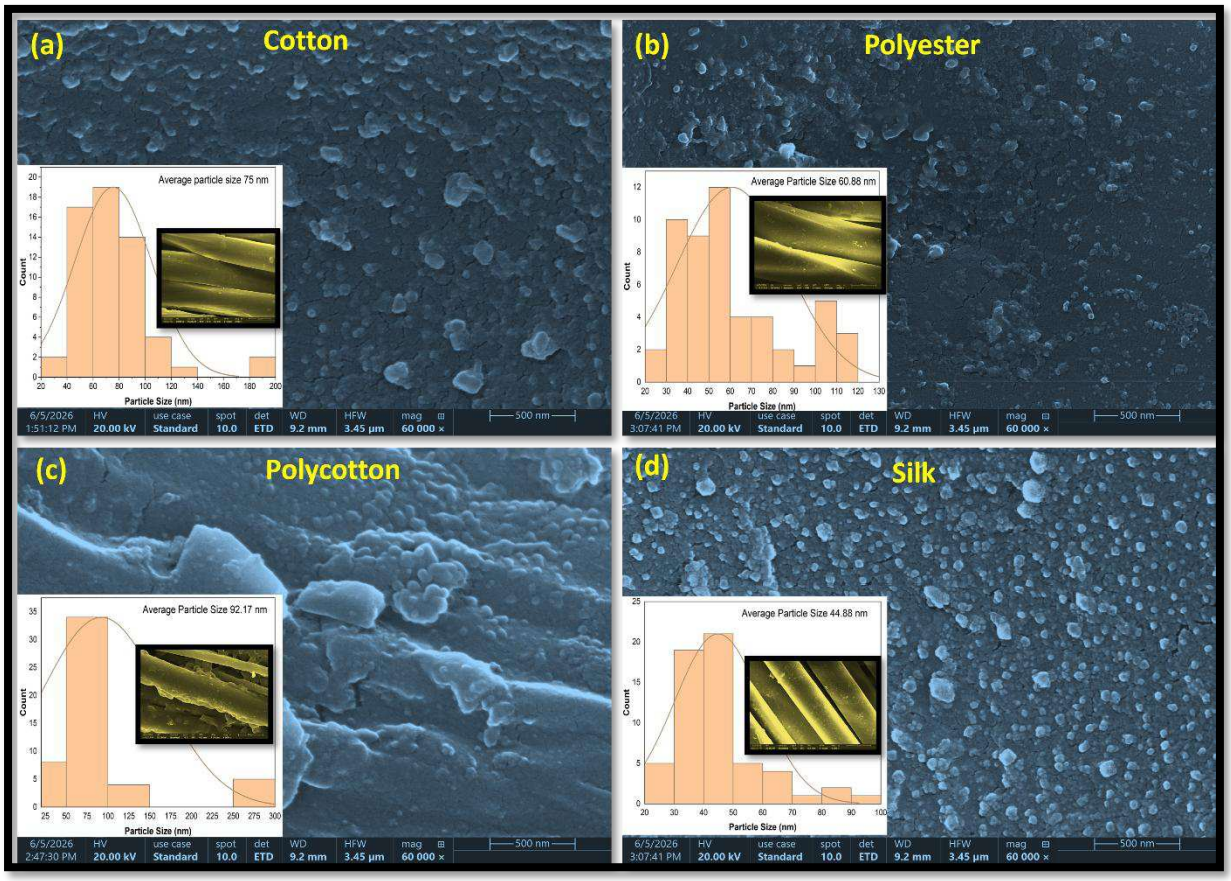
In the diffraction profiles of the 5-min treatment, the characteristic reflections of the different matrices, namely textile matrices, are predominant while the distinct reflections related to Ag are not clearly resolved. Cotton containing samples show the typical crystalline pattern of cellulose, polyester and silk samples show the pattern characteristic of their substrate. At this point, the lack of well-defined Ag peaks may be due to the limited quantity of newly formed silver, the dispersion of the nanoparticles over the surface of the fiber and the relatively high diffraction contribution of the textile matrix. These factors can make it difficult to detect the weak reflections from surface-deposited nanoparticles.

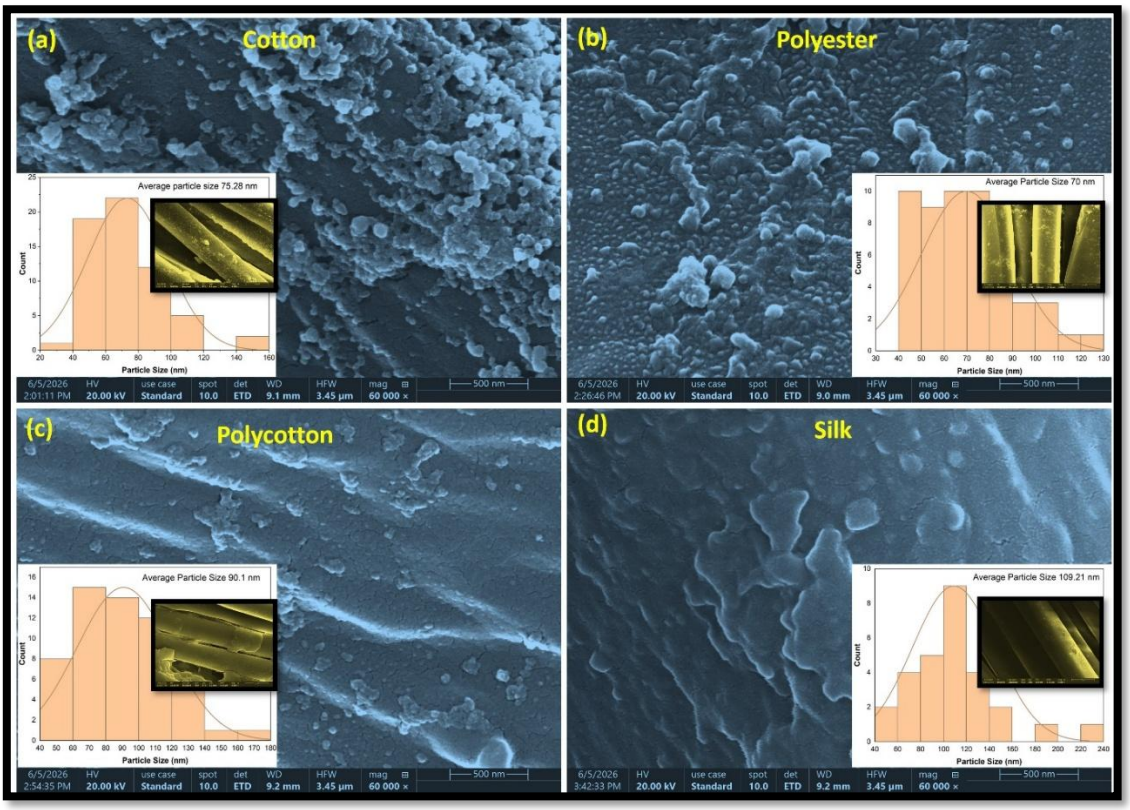
After 25 min, more features appear in the high angle region, which appears to indicate a progressive development of the inorganic phase during the reaction. The anticipated Ag reflections at ~38.1°, 44.3°, 64.4° and 77.5° are however not sufficiently resolved to allow for unequivocal identification based on the diffractograms shown. Thus, these weak features cannot be attributed to the metallic Ag, unless there is quantitative analysis of the raw XRD data. Despite this, the evolution observed is consistent with the progressive nucleating and growth of Ag nanoparticles on the textile surfaces by the reduction of Ag^{+} ions assisted by the phytochemicals.

The reflection intensity due to textile is dominant and further features appear at high 2θ. (After 45 min.) The lack of sharp Ag reflections suggests that the silver phase is in a relatively small concentration and/or highly dispersed, with nanoscopic crystallites. The characteristic substrate reflections remaining after in-situ functionalization further confirms that the basic crystalline structure of the textile fibers is preserved during the process of in-situ functionalization.

In general, the XRD results confirm that in-situ functionalization of the textile substrates with Aloe vera does not significantly affect the crystalline structure of the textile substrate and that an increase in the reaction time led to progressive incorporation of the nanoscale silver phase. The XRD analysis was carried out along with FESEM, EDS, FTIR, and Raman analysis, which supports the formation and immobilization of Ag nanoparticles on various textile fibers. The preservation of the structure of the substrate and the incorporation of Ag on its surface is beneficial for the production of durable antimicrobial textiles that retain all the properties of the fibers.

4.2 Morphological and elemental studies of AgNPs coated fabrics





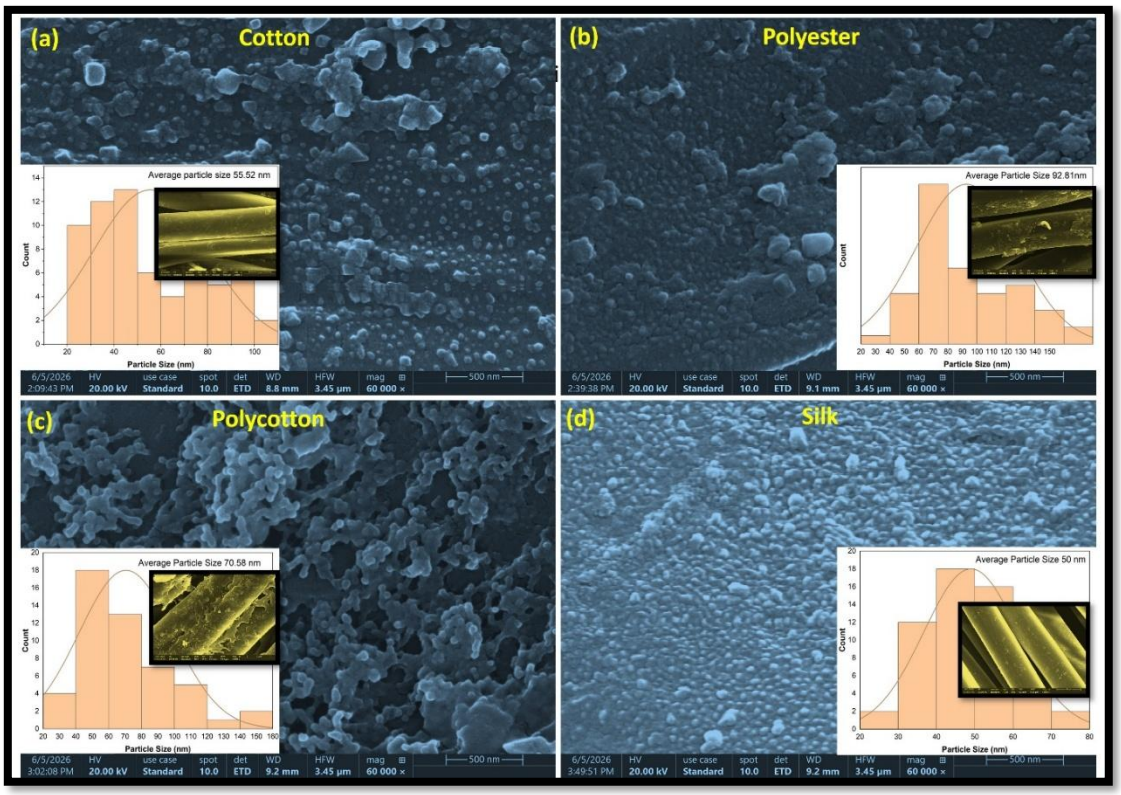


Figure 2. *FE-SEM micrographs (60,000×, 20 kV, scale bar 500 nm) of Aloe vera-mediated Ag nanostructures deposited on (a) cotton, (b) polyester, (c) polycotton, and (d) silk fabrics after 5, 25, and 45 min of reaction. Insets show the corresponding low-magnification fiber images and particle size distribution histograms with average particle size.*

In situ treatment of the cotton, polyester, polycotton and silk textiles for 5, 25 and 45 min with Aloe vera was studied using FESEM and EDS analysis to examine the surface morphology, particle distribution and elemental incorporation of Ag. The aggregate results indicate that the formation of Ag-containing nanostructures was achieved on all types of textile materials and the morphology of the nanostructures and their Ag enrichment were strongly dependent on the reaction time as well as fiber chemistry. Previously, the in-situ formation of AgNPs on textiles has been linked to effective deposition and antibacterial property by Aloe vera.

In figure 2, At 5 min, FESEM showed fairly discrete and rare deposits, corresponding to an early stage of Ag^+ reduction, nucleation and attachment. The mean apparent particle sizes (MPS) were 75.75 nm, 60.88 nm, 92.17 nm, and 44.88 nm for cotton, polyester, polycotton, and silk, respectively. Silk had the smallest particle size (MPS) of 44.88 nm, followed by polyester with 60.88 nm, polycotton with 92.17 nm, and cotton with 75.75 nm. Although the extent of surface coverage was small, the nanoscale deposits formed in just 24 hours, as a result of this short reaction time, show the rapid reducing and stabilizing action of the biomolecules extracted from the Aloe vera. The Ag contents for cotton, polyester, polycotton and silk were simultaneously confirmed as 2.4, 1.5, 2.7 and 1.8 wt.%, respectively, by EDS. Thus, the order of Ag deposition at the early stages was as follows: polycotton > cotton > silk > polyester.

The surface coverage increased with the reaction time of 25 min, while the surface roughness increased, especially for cotton and polyester, suggesting the continued nucleation and particle growth. The mean apparent particle sizes were 75.28 nm (cotton), 70.00 nm (polyester), 90.10 nm (polycotton), and 109.21 nm (silk). The significant rise in the number of silk particles is attributed to the growth and coalescence in the region, but the large FESEM features should be considered as apparent dimensions, as fused particles or continuous deposits may not represent individual nanoparticles. The highest increase was observed in EDS for cotton (11.2 wt.%) as compared with polyester (1.8 wt.%), polycotton (2.8 wt.%) and silk (0.8 wt.%). The increased Ag accumulated on cotton is in keeping with the increased availability of cellulose hydroxyl groups that can interact with Ag^+ and promote the formation of nanoparticles.

At 45 min, there was a fair amount of particulate coverage on all substrates. The mean apparent sizes were reduced to 55.52 nm cotton, 82.81 nm polyester, 70.58 nm polycotton and 50.00 nm silk. Reduction observed for cotton and silk indicates that it was secondary nucleation and stabilization and not free growth that was encouraged by the prolonged treatment. As for

the material characteristics, polyester held relatively large aggregates, while polycotton features a very coarse and interwoven particulate layer.

The best results were observed for polycotton as the Ag content increased from 2.8 wt.% at 25 min to 25.3 wt.% at 45 min, with a corresponding increase from 0.4 to 4.1 at.%. Cotton increased slightly to 12.1 wt.%, and polyester and silk increased to 3.6 and 1.5 wt.%, respectively. The Ag enrichment in the polycotton after 45 min is found to be extremely high, and also consistent with its FESEM morphology which suggests that there is an extensive storage of Ag, their growth and merging on the heterogeneous surface of cellulose/polyester.

In general, the results from the combined FESEM and EDS support the dynamic mechanism of adsorption of Ag^{+} followed by partial reduction by *Aloe vera* to form nuclei of Ag^{0} and growth of the particles followed by coalescence and surface immobilization. The results also indicate that the particle size does not necessarily correspond to the direct loading of Ag; FESEM is a surface morphology map and EDS is an elemental composition map. Accordingly, EDS is not a quantitative measure of the silver loading, but should be regarded as a semi-quantitative. Despite this, both Ag and progressive morphological changes were detected, indicating effective surface functionalization of all four textiles.

4.3 Spectroscopical (FTIR) studies of AgNPs coated fabrics

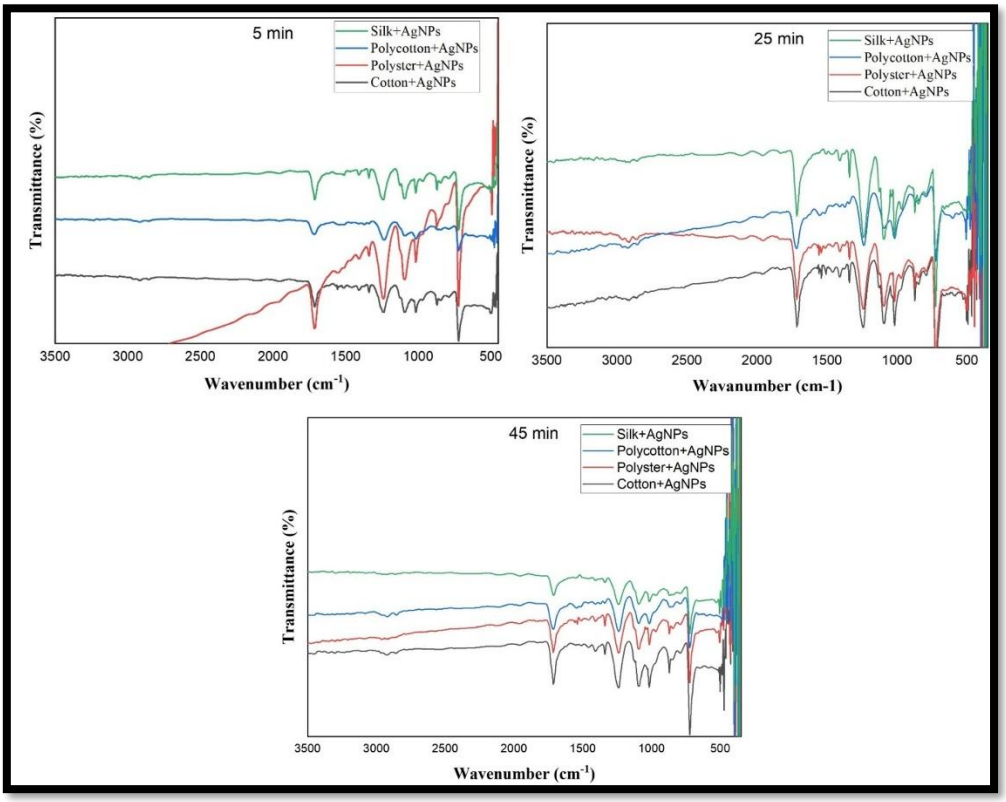


Figure 3. FTIR spectra of Aloe vera-mediated AgNP-functionalized cotton, polyester, polycotton, and silk fabrics at (a) 5, (b) 25, and (c) 45 min, showing characteristic textile vibrations and reaction-time-dependent spectral changes associated with AgNP immobilization and surface interactions.

To study the chemical functionalities and surface interactions involved in the in-situ immobilization of Ag nanoparticles (AgNPs) on cotton, polyester, polycotton and silk fabrics at reaction times of 5, 25 and 45 min, FTIR spectroscopy was used (Figure 3). The spectral features were the same as those previously identified in the spectra of the unreacted textile substrates, and the intensity, position and profile of the bands varied as a function of reaction time, signifying a progressive surface modification.

The wide absorption in the ~3200–3500 cm^{-1} region is primarily due to the O–H stretching vibrations related to hydroxyl groups, water molecules in solution and phytochemical components of the Aloe vera plant. The bands at ~2900 cm^{-1} are mainly aliphatic C–H stretching. Vibrations related to the substrate can be seen in the ~1800–1500 cm^{-1} region, such as the stretching of the C=O bonds of various esters, a typical feature of polyester, in the region of ~1700–1750 cm^{-1}, and C=C/C=O, adsorbed water, and amide-related vibrations, especially in silk, are found in the ~1600–1650 cm^{-1} region. The fingerprint region (1500–1000 cm^{-1}) includes the contributions of C–O, C–C, C–N, and other skeletal vibrations of the textile matrices.

For all textile substrates, a set of characteristic bands is still clearly visible at 5 min, showing that the initial functionalization of the Ag does not significantly change the chemical structure of the textile substrates. Several bands show intensity and profile changes at 25 min, indicating more interaction between the Ag species, textile functional groups and Aloe vera derived phytochemicals. After 45 min, additional spectral changes are noticed and the main substrate peaks can still be identified, indicating the maintenance of the basic chemical structure in the substrate after long functionalization. Spectral variations observed indicate that hydroxyl, carbonyl, phenolic and other oxygen-containing phytochemicals are involved with the reduction and stabilization of the Ag species and that the functional groups on the textile surfaces offer suitable attachment sites for the Ag nanoparticles. The spectral changes are viewed as evidence of interaction between the Ag and surface/phytochemical and not a direct FTIR peak of Ag, as there is little in the way of characteristic FTIR absorption in the mid-infrared region in Ag.

In conclusion, FTIR confirms that the reaction-time dependent surface modification of the textiles was possible, but no changes were observed in the intrinsic chemical structure of the textiles during the processing with Aloe vera, suggesting the proposed mechanism of Ag + adsorption, reduction, nucleation, stabilization and immobilization.

4.4 Raman studies of AgNPs coated fabrics

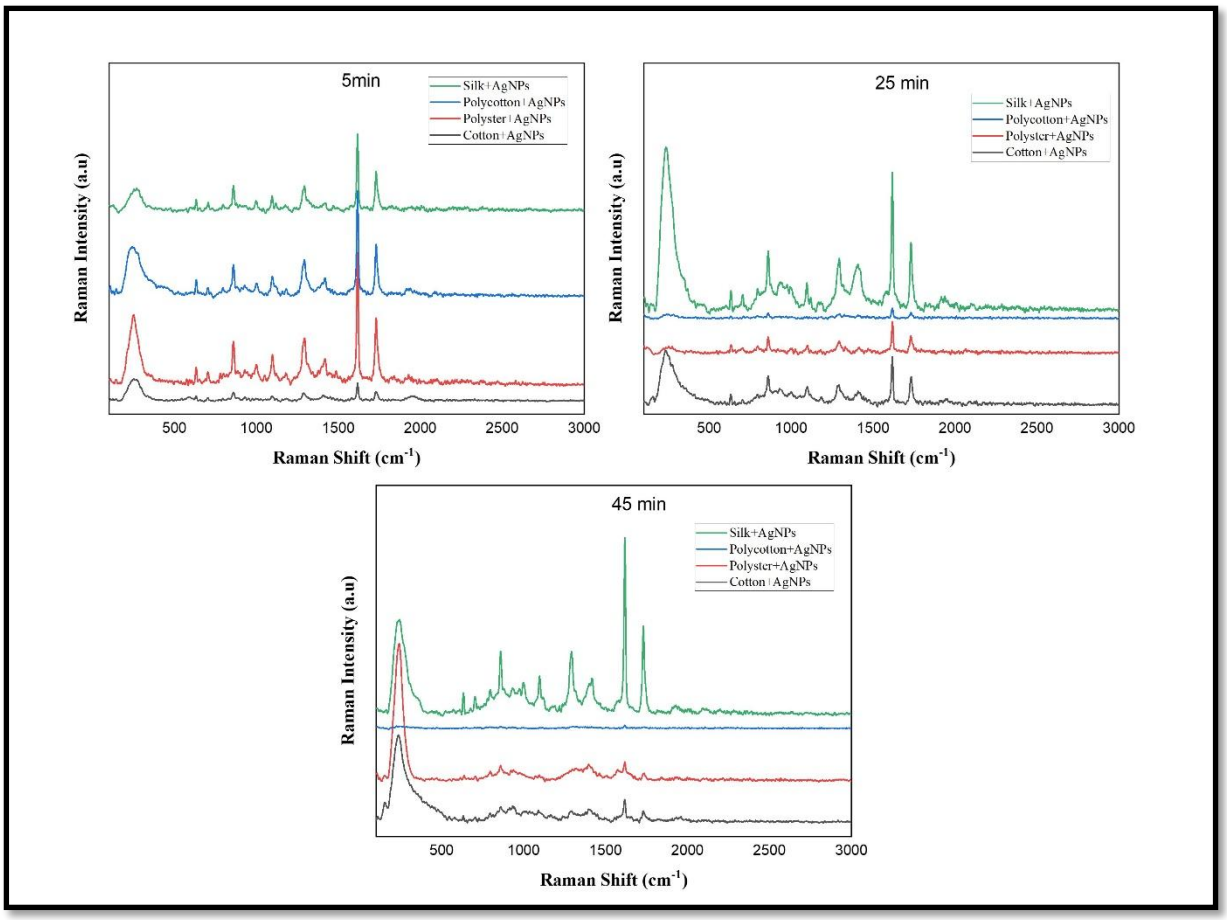


Figure 4. Raman spectra of Aloe vera-mediated AgNP-functionalized cotton, polyester, polycotton, and silk fabrics at 5, 25, and 45 min, showing characteristic textile vibrations and reaction-time-dependent spectral changes associated with AgNP immobilization and surface interactions.

Figure 4 shows Raman spectra of functionalized cotton, polyester, polycotton, and silk fabrics with different reaction times—5, 25, and 45 min—showed both the characteristic peaks of cotton or polyester and changes in the Raman intensity and spectrum. Such variations suggest the progressive modification of the fibers' surfaces and the interactions with the functional groups of the fibers and biomolecules of the *Aloe vera*.

The spectra are characteristic of those associated with cellulose, with both spectra showing the major bands in the fingerprint region (around ~900–1100 and ~1370–1460 cm^{-1}) that are associated with the cellulose. Progressive changes in intensity with reaction time indicate progressive modification of the cellulose surface during nucleation and deposition of AgNPs. Cellulosic hydroxyl groups may act as adsorption sites to trap the Ag+ and stabilize the molecules derived from plants to allow the process of heterogeneous nucleation. The spectra of the polyester are essentially the same as the spectra of PET, but the intensities of the vibration features change as a result of the changes that have occurred in the outer surface of the polymer following AgNP deposition. In the case of polyester, the lack of easily accessible polar groups would be expected to give rise to a different interaction with the Ag^{+} and phytochemicals, in keeping with the different FE-SEM morphology.

The silk spectra show prominent protein-related bands, particularly near ~1085, ~1230–1265, and ~1660–1670 cm^{-1}. These are characteristic vibrations of Amide III and Amide I modes of fibroin. Raman studies reported by the authors suggest the bands in the region of 1230 cm^{-1} and 1666 cm^{-1} are typical of silk fibroin β-sheet structures. The strong spectral response of the silk, especially at 25 min and 45 min, indicates a significant interaction between the FPS and the deposited AgNP-associated molecular environment.

One of the more important characteristics of the present spectra is the change of bands in the ~1080–1100 and ~1590–1620 cm^{-1} regions. The same Raman/SERS characteristics have been reported for Aloe vera-mediated AgNP systems, in which bands at 1082 and 1594 were observed due to molecules of the Aloe vera reacting with the Ag nanostructures to increase the Raman scattering from the molecules. Therefore, the features observed in the present textile samples could be a result of a mixture of molecules, surface molecules of AgNPs and textile vibrations. This interpretation is in line with the already known effect of Ag nanostructures on the enhancement of the Raman scattering signal by means of localized electromagnetic fields.

The effect of reaction time is especially pronounced in the spectra for 25 min where silk has a strong and complex Raman response while the response for polycotton is comparatively weak. These differences should not be attributed to the differences in AgNP loading only, as the Raman intensity depends on many factors, including the distribution of the AgNPs, the distance between the AgNPs, the orientation of the molecules, the position of sampling and the formation of hot spots. After 45 min, the silk shows strong vibration signatures, cotton, polyester and polycotton show altered, but distinctly wider spectral profiles. The changes are in line with the FE-SEM observation that showed that significant differences

in particle size, aggregation and surface coverage of the particles occurred with the use of reaction time.

In summary the Raman results are consistent with a time dependent mechanism that includes the adsorption of Ag^{+}, followed by phytochemical reduction of Ag^{+}, nucleation of Ag^{0}, growth/coalescence of nanoparticles, and stabilization by the functional groups on the fiber/extract. In situ formation of AgNPs on textiles using Aloe Vera as a reducing and stabilizing medium enhances its use of previously reported cotton systems with AgNP deposition and antibacterial properties. Importantly, it should be emphasized that Raman spectroscopy cannot completely identify specific Aloe vera phytochemicals and cannot confirm certain types of Ag–functional group bonds. However, the progressive changes in the spectra, combined with the FE-SEM results, offer strong evidence for progressive surface functionalization and immobilization of AgNPs on the different textile fibers, which is important for their potential future antimicrobial activity.

4.5 Antimicrobial activity of functionalized fabrics

The Ag-functionalized *aloe vera* treated fabrics showed significant antibacterial activity against *S. aureus* and *E. coli* with inhibition zone in most of the cases were in the range of 18.9-24.5 mm. The antibacterial response was different depending on the type of textile and reaction time. *S. aureus* exhibited the maximum inhibition zone with the silk (25 min – 24.3 mm), while the polycotton exhibited good activity at 45 min (23.4 mm). The maximum inhibition zone was achieved in *E. coli* for cotton after 45 min (24.5 mm). At 45 min, the mean inhibition zones had grown to approximately 22.3 mm for S. aureus and 22.5 mm for *E. coli* which suggested that the overall antimicrobial response improved with prolonged reaction.

Such increased activity after 45 min is scientifically explained by the fact that the AgNP nucleation and surface coverage are increased, AgNPs immobilized on textile fibres and extensive reduction of Ag^{+} ions. These observations are in line with the FESEM results; the fibers were decorated with a significant number of particles after the extended reaction time. The antibacterial effect of AgNP decorated fabrics is generally linked with the release of Ag+ from the decorated fabric, the interaction with components of the bacterial membrane, the alteration of the permeability of the bacterial membrane, the disruption of the bacterial protein and enzymes and the generation of the oxidative stress in the bacterial cells, ultimately resulting in the inhibition of bacterial growth.

The various differences in the textile substrates are due to differences in their surface chemistry, surface morphology, availability of functional groups, loading of Ag, distribution of

nanoparticles, and interactions between Ag and fibers. It has been noted that the activity of cotton in the presence of *E. coli* is relatively higher at 45 min and this is ascribed to its highly decorated surface and desirable cellulose-Ag interactions. In contrast, the high activity of silk against *S. aureus* at 25 min could be due to favorable distribution and accessibility of Ag species on the surface of silk at that stage.

Generally, it can be concluded that the antimicrobial performance is dependent on substrate and microorganism and not just on the reaction time. However, 45 min was the top average antibacterial response, which makes it an ideal reaction time for wide spread functionalization of textiles.

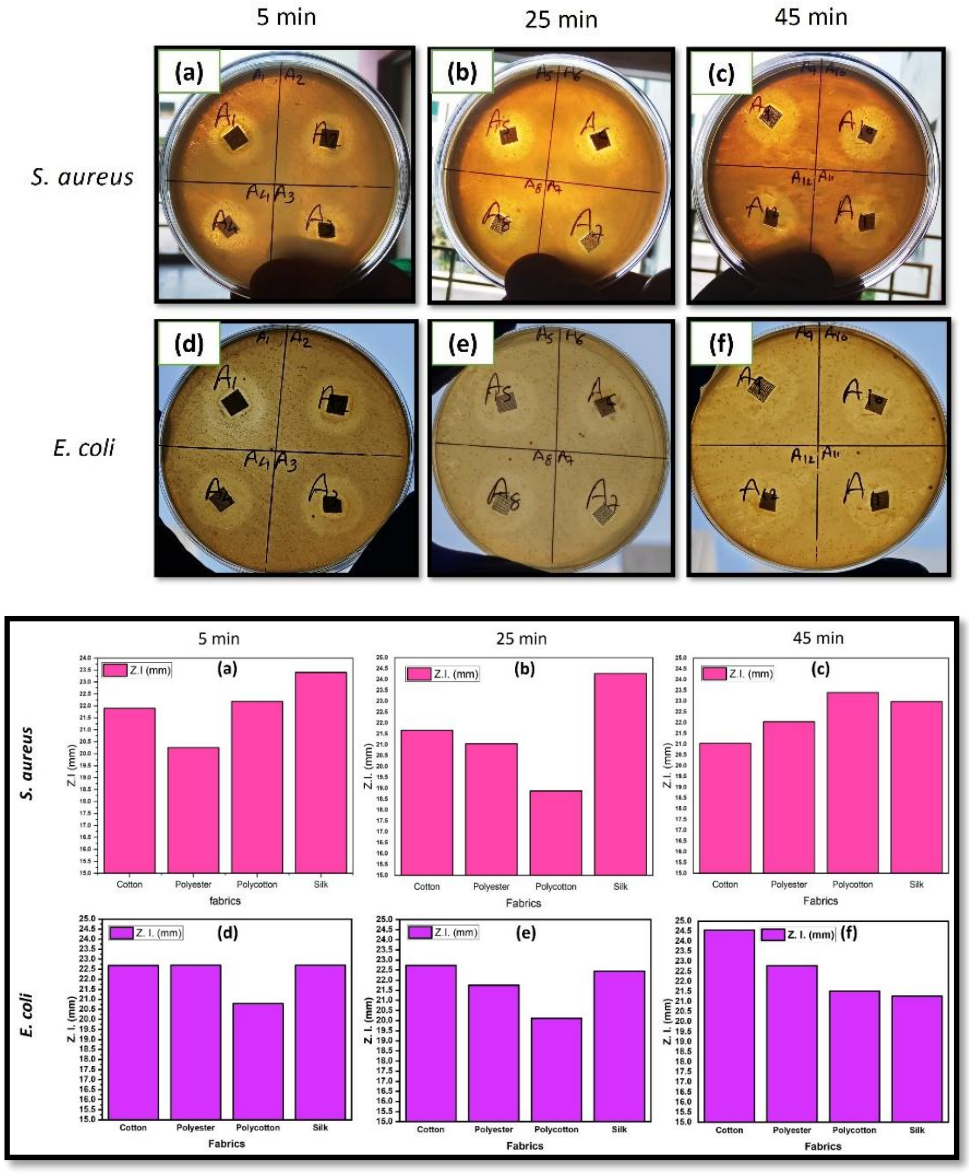


Figure 5. Antibacterial activity of Aloe vera-mediated AgNP-functionalized cotton, polyester, polycotton, and silk fabrics against (a–c) Staphylococcus aureus and (d–f) Escherichia coli after 5, 25, and 45 min of in-situ treatment, expressed as inhibition-zone diameter (mm).

5. Conclusions

A simple Aloe vera extract-mediated method was developed for the in-situ growth and immobilization of silver nanoparticles on cotton, polyester, polycotton, and silk within 5–45 min. Reaction time influenced nanoparticle distribution, surface coverage, and morphology, while EDS confirmed silver incorporation on all four textile types. XRD revealed presence of the silver phase with the diffraction peaks of silver. FTIR and Raman data showed that there were no significant changes in the characteristic features of the textile fibers, but that changes took place in the surface of the fibers depending on the reaction time. It is proposed that Ag^{+} adsorption, reduction by the extract, nucleation, growth and then stabilization or aggregation take place. The antibacterial inhibition zones of the tested compounds varied from 18.9 to 24.5 mm against the different tested bacteria and this depended on the type of textile and the species of bacteria. In conclusion, the present study has been an interesting approach to generate in-situ synthesized silver functionalized textile incorporating tunable surface characteristics and antimicrobial activity which is considered as a fast method.

6. Acknowledgements

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7. Declarations

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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The authors received no external funding for the research, authorship, and/or publication of this article.

Clinical Trial Registration

Not applicable. This study did not involve a clinical trial.

Ethics, Consent to Participate, and Consent to Publish declarations:

The *Aloe vera* leaves used in this study were collected from a cultivated plant maintained in the college garden at NTVS's Gajmal Tulsiram Patil ACS College, Nandurbar, Maharashtra, India. The plant material was not collected from a wild population. The plant was botanically identified by Dr. Tanveer Akhtar Khan**,** Plant Taxonomist, Head, Department of Botany, H. J. Thim College of Arts & Science, Jalgaon, Maharashtra, India, and a representative voucher specimen was deposited at Department of Botany, H. J. Thim College of Arts & Science, Jalgaon, Maharashtra, India. under accession number HJTC/BOT/TAK/HERB-219/2026-27. The authenticated plant material was used for the preparation of the aqueous extract employed in the green synthesis and in-situ functionalization of textile fibres with silver nanoparticles. No human participants or animals were involved in this study.

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