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One-pot fabrication of durable antibacterial cotton fabric coated with silver nanoparticles via banana peel as a binder and stabilizer

Nilesh D. Jadhav
NTVS's G. T. Patil Arts, Commerce and Science College, Nandurbar, India
Vishal V. Lonikar
H.P.T. Arts & R. Y. K. Science College, Nashik, India
Manojkumar M. Jadhao
Institute of Chemical Technology Mumbai Maharashtra Campus Jalna 431213 (M.S.) India
Vinod S. Khairnar
METs Institute of Engineering, Nashik
Babasaheb R. Sankapal
Visvesvaraya National Institute of Technology
Anil N. Kulkarni
kulkarni.may29@gmail.com

NTVS's G. T. Patil Arts, Commerce and Science College, Nandurbar, India

Research Article

Keywords: Chemical solution synthesis, Silver nanoparticles, Functional textiles, Antimicrobial properties

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11210546/v1

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Additional Declarations: No competing interests reported.

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[1]Nilesh D. Jadhav, [2]Vishal V. Lonikar, [3]Manojkumar M. Jadhao, [4]Vinod S. Khairnar
[5]Babasaheb R. Sankapal, [1]Anil N. Kulkarni*

[1]Department of Physics, NTVS's G. T. Patil Arts, Commerce and Science College, Nandurbar-425412 (M.S.) India.

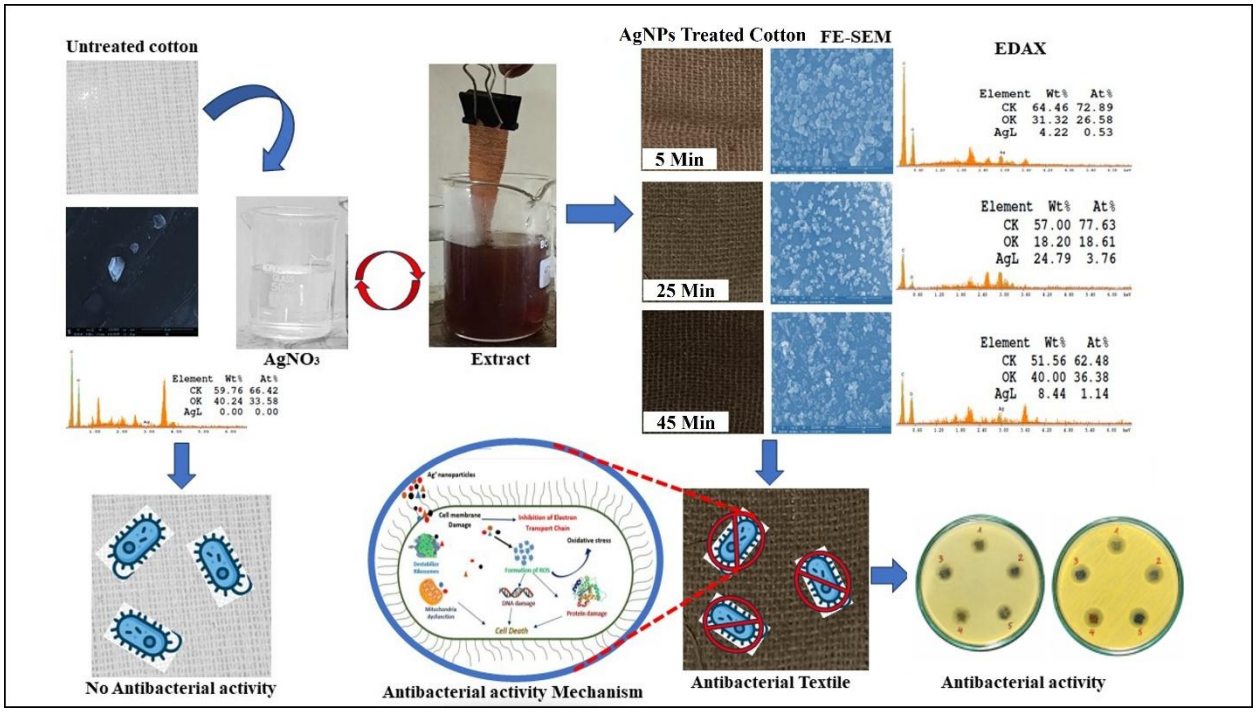
[2]Department of Physics, H.P.T. Arts & R. Y. K. Science College, Nashik-422003 (M.S.) India.

[3]Department of chemistry, Institute of Chemical Technology Mumbai Maharashtra Campus Jalna 431213 (M.S.) India

[4]Department of Physics, METs Institute of Engineering, Nashik -422003 (M.S.) India.

[5]Department of Physics, Visvesvaraya National Institute of Technology, South Ambazari Road, Nagpur-440010 (M.S.) India

Corresponding Author*: kulkarni.may29@gmail.com



Graphical Abstract

Abstract

The development of sustainable antibacterial textiles using plant-derived resources offers a promising strategy for reducing the environmental and health concerns associated with conventional textile functionalization. In this study, a one-pot, in-situ approach was developed for the fabrication of silver nanoparticle (AgNP)-functionalized cotton fabric using banana-peel extract as a natural reducing, stabilizing, and binding agent. The formation and immobilization of AgNPs on cotton fibers were investigated as a function of reaction time (5–45 min) using FE-SEM, EDX, XRD, FTIR, and Raman spectroscopy. FE-SEM revealed a progressive transformation from a relatively clean cellulose surface to finely dispersed Ag-containing nanoparticles at 5 min, followed by increased surface coverage at 25 min and larger, partially aggregated particles at 45 min, demonstrating time-dependent nucleation, growth, and immobilization. EDX confirmed silver incorporation, with Ag contents of 4.22, 24.79, and 8.44 wt% at 5, 25, and 45 min, respectively. XRD confirmed the formation of crystalline metallic Ag^0 while retaining the characteristic crystalline structure of cellulose; the Ag (111) reflection yielded an average crystallite size of 52 nm. FTIR and Raman analyses indicated modification of the cellulose surface and interactions involving cellulose and extract-derived constituents during AgNP formation. The functionalized fabrics exhibited antibacterial activity against both *Staphylococcus aureus* and *Escherichia coli*, with maximum inhibition zones of 9.8 and 12.9 mm, respectively. Overall, the results demonstrate that banana-peel extract enables a simple, green, and efficient route for producing AgNP-coated cotton with promising antibacterial functionality for potential antimicrobial textile applications.

Keywords: Chemical solution synthesis; Silver nanoparticles; Functional textiles; Antimicrobial properties

1. Introduction

Cotton is one of the most widely used natural textile materials owing to its excellent comfort, breathability, softness, and versatility, making it indispensable in apparel, medical textiles, and household products. Despite these advantages, cotton is inherently vulnerable to microbial adhesion and growth because of its hydrophilic, cellulose-rich structure. Microbial contamination can cause unpleasant odors, deterioration of fabric quality, and hygiene-related concerns, particularly in applications requiring prolonged contact with the human body. Therefore, imparting effective and durable antimicrobial functionality to cotton while preserving its inherent desirable properties has become an important research objective.

Among the various antimicrobial approaches, silver nanoparticles (AgNPs) have attracted considerable attention because of their broad-spectrum activity against a wide range of microorganisms, including bacteria, fungi, and viruses. Incorporation of AgNPs onto cotton fibers can therefore provide an effective route for developing antimicrobial textiles. However, the practical performance of such fabrics depends not only on the antimicrobial activity of AgNPs but also on their uniform distribution, strong attachment, and stability on the fiber surface. Conventional nanoparticle-coating methods often require synthetic reducing, stabilizing, or binding chemicals and multistep processing, which can increase environmental burden and may adversely affect textile properties. These limitations highlight the need for a simpler and more sustainable method for immobilizing AgNPs on cotton.

To address this challenge, plant-derived materials and agricultural wastes have emerged as attractive resources for green nanoparticle synthesis. Among them, banana peel is particularly promising because it is abundant, biodegradable, inexpensive, and rich in bioactive constituents capable of participating in the reduction and stabilization of metal nanoparticles. Thus, banana peel can provide a multifunctional platform for AgNP formation while simultaneously contributing to the utilization of agricultural waste. During nanoparticle synthesis, factors such as reaction temperature, pH, reagent concentration, and reaction time influence the nucleation, growth, and stabilization of AgNPs; controlling these parameters is therefore essential for obtaining suitable nanoparticle characteristics and effective textile functionalization.

Building on this concept, the present study explores banana-peel extract as a multifunctional reducing, stabilizing, and anchoring agent for the in-situ fabrication of AgNP-coated cotton fabric. The approach is designed to combine nanoparticle synthesis and textile functionalization in a simple process, potentially promoting direct interaction and

immobilization of AgNPs on the cotton surface. In this system, the banana-peel-derived constituents not only facilitate the formation and stabilization of AgNPs but also contribute to their attachment to the cellulose fibers. The resulting functionalized cotton is intended to retain the intrinsic advantages of cotton while acquiring enhanced antibacterial functionality.

Accordingly, this study presents a sustainable strategy for developing AgNP-functionalized cotton through the valorization of banana-peel waste. The approach integrates green chemistry, agricultural-waste utilization, and functional textile development into a single material-processing concept. Such antibacterial cotton fabrics have potential relevance to medical textiles, hygiene products, protective clothing, and everyday apparel, where microbial control is an important functional requirement.

2 Materials and methods:

2.1 Materials

Banana peels *(musa spp)* were collected from a local shop in Nandurbar, Maharashtra, India (21.3675° N, 74.2522° E), in December. The plant material was authenticated by Dr. Sandip Marathe, Assistant Professor, Department of Botany, G. T. Patil ACS College, Nandurbar, Maharashtra, India. The collected peels were transported to the laboratory in clean polyethylene bags and processed immediately for extract preparation. The banana peel extract was collected and stored in an air tight container in an environment protected from light and in the proper condition. The collection and use of the plant Extract complied with applicable institutional, local, and national guidelines for scientific research involving plant materials. 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 Preparation of banana peel extract:

Soxhlet extraction is a widely used method for extracting bioactive compounds from plant materials, including *banana peels*. Initially, ripe *banana peels* were collected and meticulously cleaned to remove any visible contaminants. Subsequently, the peels were washed thoroughly to eliminate dirt and residues. Following this, the bananas were carefully peeled to separate the peels from the fruit pulp. Once peeled, the banana peels were spread on a clean surface. There after peels were loaded into a cellulose thimble and placed in the Soxhlet extraction unit. The Soxhlet extraction process involved heating (80 OC for 1 hour)

the solvent to reflux, allowing it to extract bioactive compounds from the banana peels in the thimble. Once extraction was completed, the extract was collected, filtered to remove solid particles to obtain the desired concentration of bioactive compounds. Finally, the banana peel extract was stored in suitable containers in a cool, dark place to maintain stability and prolong shelf life.

2.3 In-situ synthesis of silver particles on cotton:

The cotton fabric was first immersed in 0.005 M concentration of $AgNO_3$ solution was prepared at room temperature by mixing 0.016 g of $AgNO_3$ salt in 20 mL DI water and stirred using a magnetic stirrer. 10 mL of the *banana peel* extract was added to 20 mL of $AgNO_3$ solution, stirred and heated at 40- 60°C. After few minutes, the reaction mixture becoming sparkling yellow and finally becoming sparkling brown. This was a visual indicator of the formation of AgNPs. The steps were repeated by varying the time period i.e. 5 min, 25 min and 45 min respectively. Lastly, the functionalized cotton fabric samples were rinsed in cold deionized water and air-dried at room temperature.

2.4 Characterization

The structural analysis of the coated fabric was carried out using X-ray diffractometer (Rigaku miniflex 600), Morphology analysis is carried out using Field Emission Scanning Electron Microscopy (FESEM) (Model: Nova Nano SEM 450). The compositional study of the film was done by energy dispersive analysis by X-ray (EDAX) using (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.

To check the antibacterial activity of test compounds/ substances using the agar well diffusion method, first prepare nutrient agar plates and solidify them in sterile petri dishes. Inoculate the plates with a 24 h old bacterial active suspension matching a 0.5 McFarland standard by evenly spreading it over the agar surface using a sterile glass spreader or cotton swab. Soak cotton cloth disc in test compounds and place on agar plate. Incubate the plates at 37°C for 18-24 hours in an inverted position. After incubation, measure the diameters of the clear zones around the wells.

3. Results and discussion

3.1 X-ray diffractometer studies of AgNPs coated fabrics

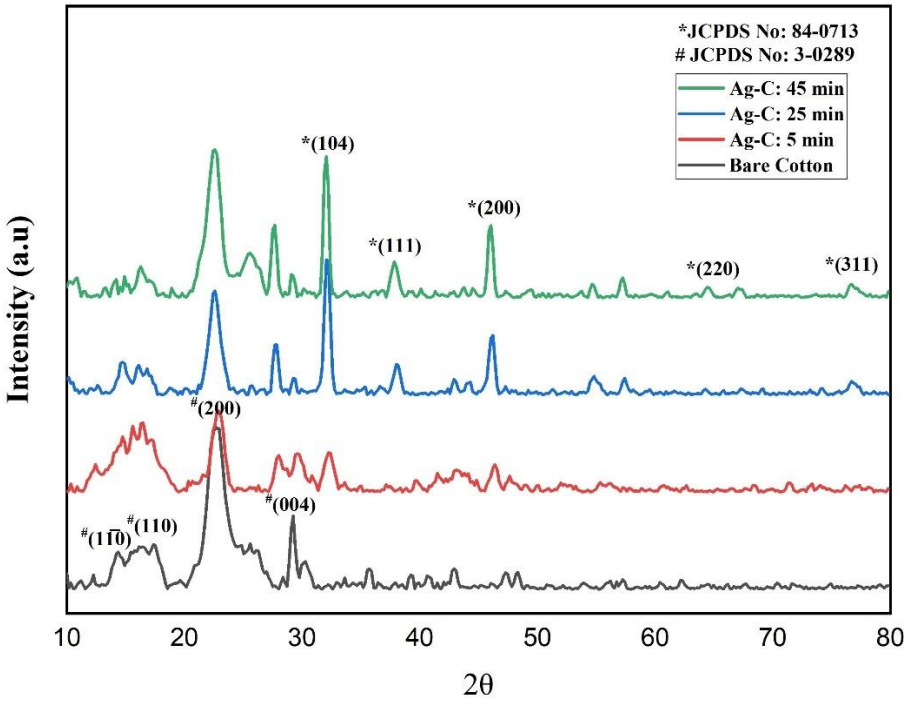


Figure 1 X-ray diffraction (XRD) patterns of bare cotton and silver-coated cotton (Ag-C) fabrics prepared at different reaction times (5, 25, and 45 min).

The crystalline structure of the bare cotton and AgNP-functionalized cotton fabrics was investigated by X-ray diffraction (XRD), as shown in Fig. 1. The XRD pattern of bare cotton exhibits characteristic diffraction peaks associated with the crystalline cellulose structure, particularly at approximately 2θ = 15.0°, 16.5°, 22.6°, and 34.5°, which can be indexed to the characteristic reflections of cellulose I. These characteristic cotton peaks are retained in the AgNP-coated cotton samples prepared at reaction times of 5, 25, and 45 min, indicating that the fundamental crystalline structure of the cellulose substrate is preserved during the in-situ functionalization process.

In addition to the cellulose reflections, the AgNP-functionalized cotton samples exhibit distinct diffraction peaks at approximately 2θ = 38.1°, 44.3°, 64.5°, and 77.5°, which are assigned to the (111), (200), (220), and (311) planes, respectively, of metallic silver (Ag^0). These reflections are consistent with the standard diffraction pattern of crystalline silver (JCPDS No. 84-0713), confirming the formation of crystalline Ag nanoparticles on the cotton substrate. The increasing prominence of these Ag-related reflections with increasing reaction time is consistent with progressive formation and deposition of AgNPs on the cotton fibers, in agreement with the FE-SEM observations.

The presence of relatively broad and weak additional features in the XRD patterns may arise from the amorphous or poorly crystalline organic constituents associated with the banana-peel extract and the cotton substrate. However, these features should not be directly assigned to phytochemicals without complementary spectroscopic evidence. The phytochemicals present in the banana-peel extract are more appropriately considered as reducing and stabilizing/capping agents involved in the formation and stabilization of AgNPs rather than as the origin of the characteristic sharp Ag diffraction peaks.

The crystallite size of the deposited AgNPs was estimated using the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos\theta}$$

where D is the average crystallite size, K is the shape factor (typically ~0.9), λ is the wavelength of Cu Kα radiation (1.5406 Å), β is the full width at half maximum (FWHM) of the diffraction peak in radians, and θ is the corresponding Bragg angle. Based on the broadening of the Ag (111) reflection, the average crystallite size was estimated to be 52 nm. This value represents the XRD crystallite size, which may differ from the particle size observed by FE-SEM because an individual nanoparticle can consist of one or more crystallites.

Overall, the XRD results confirm the successful formation of Ag^0 nanoparticles on the cotton substrate, while retention of the cellulose diffraction peaks demonstrates that the crystalline framework of cotton remains largely intact after functionalization.

3.2 Morphological and elemental studies of AgNPs coated fabrics

The FE-SEM observations clearly demonstrate the time-dependent nucleation, growth and immobilization of AgNPs on cotton cellulose fibers. In the bare cotton [Fig. 2 (a)], the fibers exhibit the characteristic elongated fibrillar morphology with longitudinal grooves and a comparatively clean/smooth surface, with only a few irregular residues. This morphology is consistent with the absence of externally formed AgNPs and indicates that the cellulose surface is initially available for interaction with silver ions.

The abundant hydroxyl (–OH) groups of cellulose provide potential interaction/coordination sites for Ag^+ ions. Upon introducing the cotton into the silver-containing reaction medium, Ag^+ ions are attracted toward and adsorbed/interact with these oxygen-containing sites on the fibre surface.

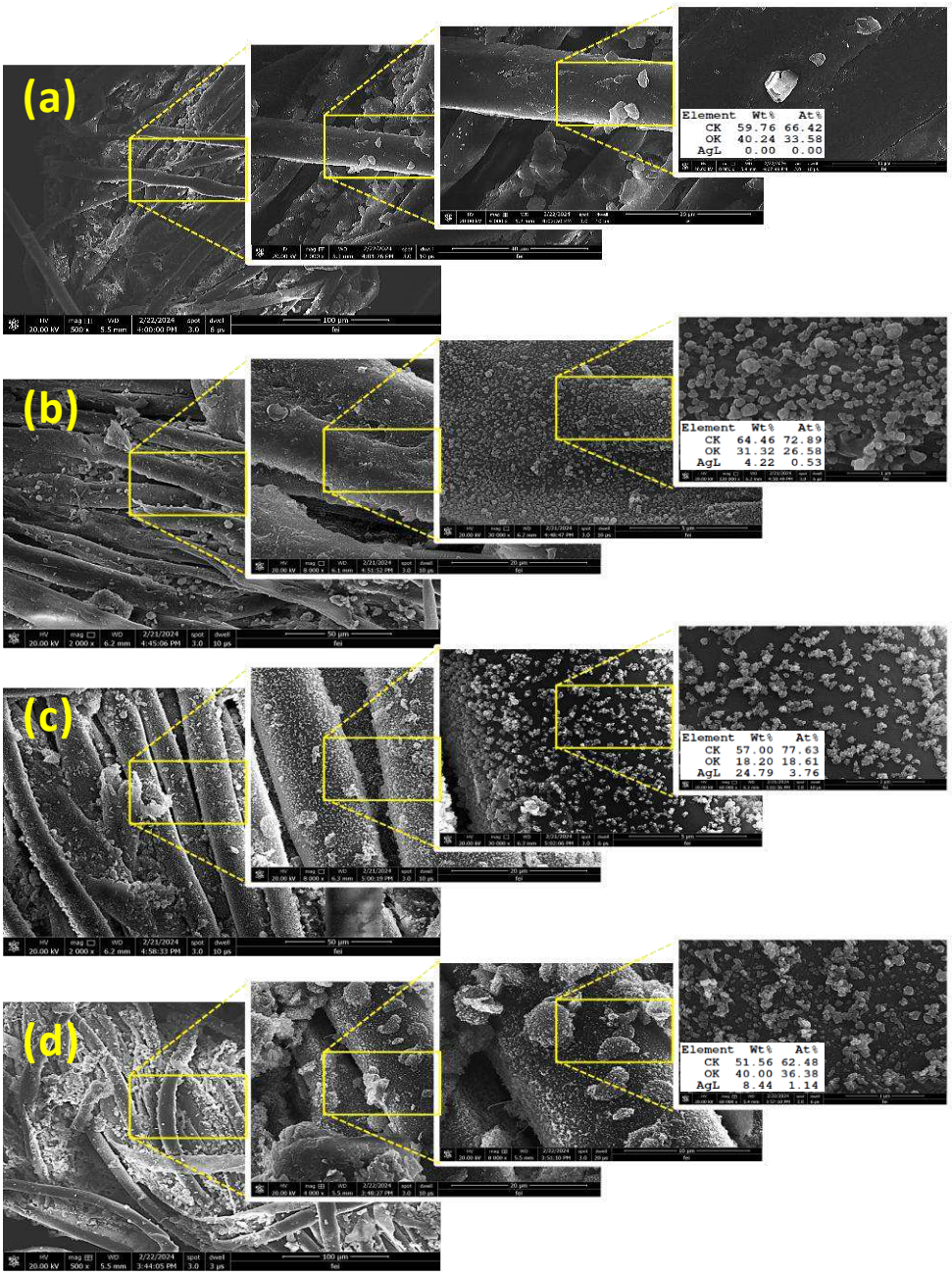


Figure 2 FESEM images of (a)bare cotton and (b), (c) and (d) are in-situ functionalized AgNPs cotton for reaction time 5, 25, and 45 min respectively.

After 5 min [Fig. 2 (b)], numerous fine particulate deposits become visible over the cellulose fibrils, particularly in the higher-magnification images. This morphological change can be attributed to the initial surface-assisted reduction of Ag^{+} to Ag^{0}, followed by the formation of small Ag^{0} nuclei. Thus, the appearance of finely distributed particles at 5 min provides morphological evidence for the beginning of heterogeneous nucleation directly on the cotton surface rather than the untreated fibrillar morphology observed in Fig. 2 (a).

At 25 min [Fig. 2 (c)], the density of particulate deposits and the extent of surface coverage are visibly increased. The nanoparticles appear distributed along the cellulose fibrils, with localized clusters also becoming evident. This observation can be correlated with continued reduction of Ag^{+}, generation of additional Ag^{0} atoms and growth of the initially formed nuclei. Once Ag^{0} nuclei are established, newly reduced Ag^{0} species preferentially deposit on these nuclei, resulting in progressive nanoparticle growth and increased AgNP coverage of the cotton surface. The FE-SEM morphology therefore suggests that 25 min represents a more advanced stage of nucleation and nanoparticle growth than the 5 min treatment.

For the 45 min sample [Fig. 2 (d)], a substantial amount of particulate material is observed on the cotton fibers. Compared with the finer deposits at shorter reaction time, the particles appear relatively larger and more aggregated, particularly in the magnified regions. This morphology can be explained by continued Ag^{+} reduction, nanoparticle growth and increased particle–particle interaction during prolonged reaction. As the available cellulose surface becomes progressively occupied, neighboring AgNPs can come into close proximity and form aggregates. Hence, the morphology at 45 min indicates that the process has progressed from primary nucleation toward significant nanoparticle growth and aggregation.

The progressive morphological transformation observed by FE-SEM—from a comparatively clean cellulose surface to increasingly decorated and partially aggregated surfaces—supports a sequential mechanism involving Ag^{+} interaction with cellulose, reduction to Ag^{0}, heterogeneous nucleation, nanoparticle growth, and eventual immobilization/agglomeration on the cotton fibers. The specific identification of these deposits as metallic AgNPs is further substantiated by the corresponding XRD and Raman spectroscopic results.

The elemental composition of the AgNP-functionalized cotton fabrics was investigated by EDX analysis. The untreated cellulose substrate is expected to be dominated by carbon and oxygen, whereas the appearance of Ag in all treated samples provides direct elemental evidence for silver incorporation on the cotton surface. At 5 min, the EDX spectrum shows 4.22 wt% Ag (0.53 at%), indicating the initial formation and deposition of silver species. A substantial increase in Ag content is observed after 25 min, reaching 24.79 wt% (3.76 at%), which is consistent with enhanced Ag^{+} reduction, Ag^{0} nucleation, nanoparticle growth, and increased surface coverage observed in the corresponding FE-SEM images.

After 45 min, Ag remains clearly detectable at 8.44 wt% (1.14 at%), although its measured concentration is lower than that obtained at 25 min. This reduction should be interpreted cautiously because EDX provides localized semi-quantitative elemental analysis and is strongly influenced by the selected analysis area, particle distribution, agglomeration, and contribution from the underlying cellulose substrate. The substantial oxygen contribution at 45 min also indicates greater sampling of the cellulose-rich region. Overall, the EDX results confirm the presence of silver on the cotton fibers and, together with the FE-SEM observations, support the time-dependent formation, growth, and immobilization of Ag-containing nanoparticles on the cellulose surface. The chemical state and crystalline nature of the deposited silver should be established using complementary XRD and Raman analyses.

3.3 Spectroscopical (FTIR) studies of AgNPs coated fabrics

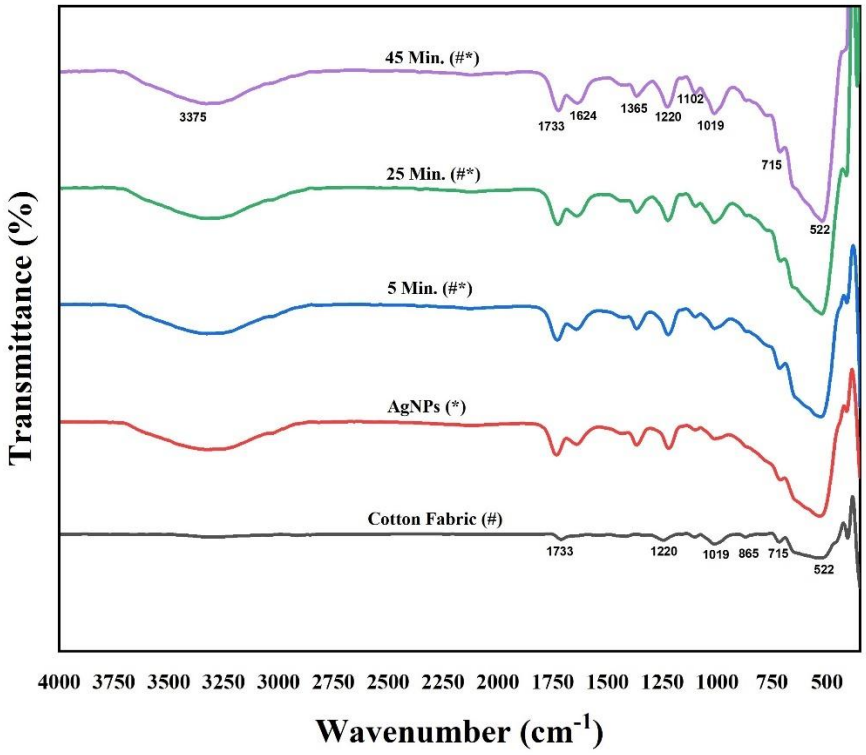


Figure 3 FTIR spectra of banana peel extract-mediated AgNP-functionalized cotton fabrics at (a) 5, (b) 25, and (c) 45 min, showing characteristic textile vibrations and reaction-time-dependent spectral changes associated with AgNP immobilization and surface interactions

The FTIR analysis (Figure 3) provides further evidence for the in-situ functionalization of cotton fabric with silver nanoparticles (AgNPs) and offers insight into the changes occurring in the chemical environment of the cellulose substrate during the coating

process. The spectrum of pristine cotton exhibits characteristic vibrational features of cellulose, particularly the broad O–H stretching band at approximately 3375 cm^{-1}, together with characteristic C–O and C–O–C vibrations in the fingerprint region. The abundance of hydroxyl groups in cellulose provides potential interaction sites for Ag^{+} ions during the functionalization process. Following 5 min of treatment, changes in the O–H- and C–O-associated bands suggest modification of the local chemical environment of the cellulose surface, which is consistent with the interaction and surface localization of silver species. With increasing reaction time to 25 min, further changes in the cellulose-related vibrational bands are observed, indicating progressive modification of the surface during silver deposition.

At 45 min, more pronounced spectral changes are observed, with characteristic bands appearing at approximately 3375, 1733, 1624, 1365, 1220, 1102, 1019, 715, and 522 cm^{-1}. The persistence of the major cellulose-associated bands indicates that the fundamental cellulose structure of the cotton substrate is retained during the functionalization process. However, the changes in band position, intensity, and profile indicate alterations in the surface chemical environment associated with silver deposition. These observations are consistent with the FE-SEM results, which demonstrate progressive deposition of particulate material on the cotton fibers with increasing reaction time.

Based on the combined FTIR and morphological observations, a plausible mechanism for the in-situ formation of AgNPs involves the interaction of Ag^{+} ions with hydroxyl-rich cellulose and phytochemical constituents derived from banana peel extract, followed by reduction of Ag^{+} to metallic Ag^{0}, nucleation, nanoparticle growth, and subsequent immobilization on the cellulose fibrils. With prolonged reaction time, continued nucleation and particle growth may promote interparticle interactions and aggregation, consistent with the aggregated morphology observed in the FE-SEM images. The formation and presence of silver nanoparticles are supported by the complementary XRD, Raman, and EDX analyses.

3.4 Raman studies of AgNPs coated fabrics

Raman spectroscopy was used to investigate the molecular and structural changes associated with the in-situ deposition of silver nanoparticles (AgNPs) on cotton fabric. The Raman spectra of bare cotton, AgNPs, and AgNP-coated cotton fabrics prepared at reaction times of 5, 25, and 45 min are presented in Fig. 4. The spectra exhibit distinct vibrational features in the 200–2000 cm^{-1} range, and systematic changes in peak intensity and spectral

profile are observed following AgNP functionalization.

The Raman spectrum of bare cotton exhibits characteristic bands associated with the cellulose molecular structure. The observed features at approximately 290, 450, 520, 680, 850, 1050, 1120, 1380, 1460, 1580, 1630, and 1730 cm^{-1} are associated with different skeletal and functional-group vibrations of cellulose and surface-associated molecular species. In particular, the bands in the 1000–1200 cm^{-1} region are primarily related to C–C, C–O and C–O–C stretching vibrations of the cellulose backbone, whereas bands around 1380–1460 cm^{-1} can be associated with CH/CH_2 deformation and cellulose skeletal vibrations. The feature near ~1630 cm^{-1} can contain contributions from O–H/H–O–H bending and surface-associated species.

After AgNP functionalization, substantial changes in the Raman response are observed. The spectrum of Ag-C: 5 min shows a pronounced increase in the intensity of several cellulose-associated bands compared with bare cotton. This modification indicates that the chemical environment of the cellulose surface is altered during the initial stage of the coating process. At this stage, Ag^+ ions can interact with hydroxyl-rich cellulose surfaces, while reducing phytochemicals from the banana-peel extract participate in the conversion of Ag^+ into metallic Ag^0.

With increasing reaction time to 25 min, the Raman bands become more pronounced and better resolved, particularly around ~450, ~1050, ~1120, ~1380, ~1460, ~1580 and ~1630 cm^{-1}. The progressive enhancement of these features indicates increasing modification of the cotton surface and is consistent with enhanced deposition of silver species. The change in Raman intensity may arise from two simultaneous effects: (i) modification of the local chemical environment of cellulose and surface-bound organic molecules, and (ii) enhancement of Raman scattering from molecules located in close proximity to AgNP surfaces. The latter effect is particularly relevant because Ag nanoparticles can provide localized electromagnetic enhancement and therefore increase the Raman response of surface-associated molecules.

The Ag-C: 45 min sample exhibits the most pronounced Raman response among the cotton-based samples. Strong features are observed around 290, 450, 520, 680, 850, 1050, 1120, 1380, 1460, 1580, 1630 and 1730 cm^{-1}, with particularly prominent bands near 1580 and 1630 cm^{-1}. The increased intensity and spectral complexity at prolonged reaction time indicate substantial modification of the cotton surface. This behavior is consistent with progressive AgNP formation, increased surface coverage and stronger interaction between

AgNPs, cellulose and extract-derived molecules. The Raman results therefore correlate well with the FE-SEM observations, where increasing particulate deposition and eventual aggregation are observed with increasing reaction time.

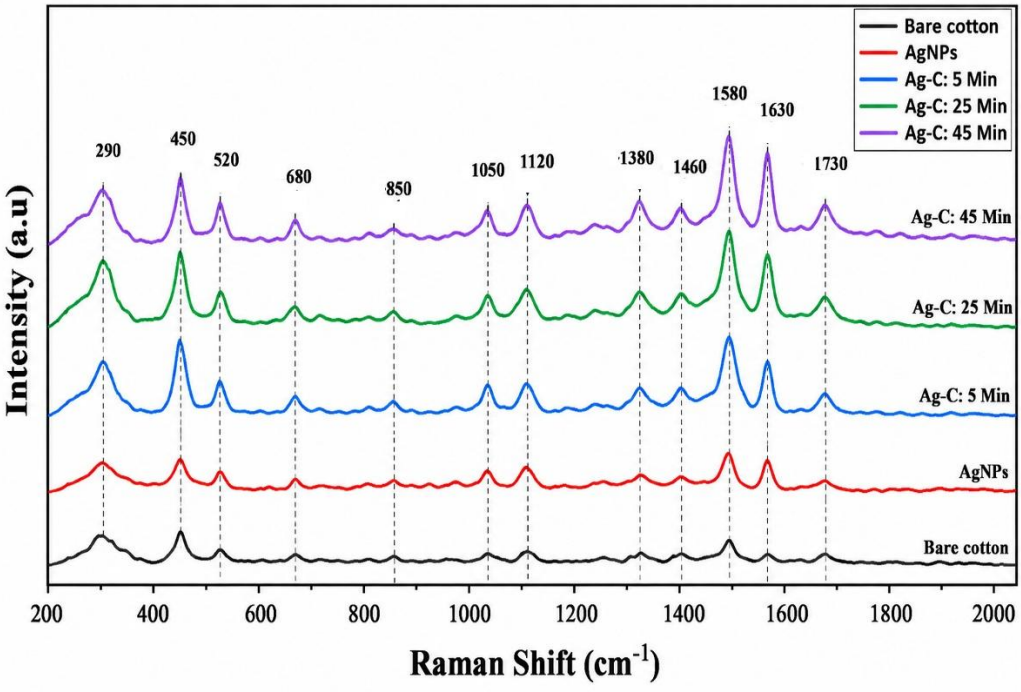


Figure 4 Raman spectra of banana peel extract-mediated AgNP-functionalized cotton fabrics at 5, 25, and 45 min, showing characteristic textile Peaks and reaction-time-dependent spectral changes associated with AgNP immobilization and surface interactions.

3.5 Antimicrobial activity of functionalized fabrics

The antibacterial activity of the AgNP-functionalized cotton fabrics was evaluated against the Gram-positive bacterium *Staphylococcus aureus* and the Gram-negative bacterium *Escherichia coli* using the zone-of-inhibition assay. The corresponding results are presented in Fig. 5. The antibacterial response was assessed for cotton samples prepared at different reaction times, namely 5, 15, 25, 35, and 45 min. The measured zones of inhibition demonstrate that the AgNP-functionalized cotton samples possess antibacterial activity against both bacterial strains, although the magnitude of inhibition varies with reaction time and bacterial species.

For S. aureus, the zone of inhibition increased from 8.4 mm at 5 min to 8.6 mm at 15 min and 9.3 mm at 25 min. A decrease to 8.1 mm was observed at 35 min, followed by the highest value of 9.8 mm at 45 min. Thus, the overall response against *S. aureus* shows a moderate increase with prolonged reaction time, although the trend is not strictly monotonic.

The relatively larger inhibition zone at 45 min suggests that prolonged reaction facilitates greater deposition and/or availability of AgNPs on the cotton fibers, thereby increasing the antibacterial efficacy of the functionalized fabric.

In comparison, the antibacterial response against *E. coli* was more pronounced for most of the investigated samples. The inhibition zone increased markedly from 7.4 mm at 5 min to 11.1 mm at 15 min, followed by a decrease to 9.4 mm at 25 min. The maximum inhibition zone of 12.9 mm was obtained for the 35-min sample, while a slightly lower value of 11.4 mm was observed at 45 min. The larger inhibition zones obtained against *E. coli* at 15, 35, and 45 min indicate a comparatively stronger antibacterial response of the AgNP-coated cotton toward this bacterial strain under the experimental conditions employed.

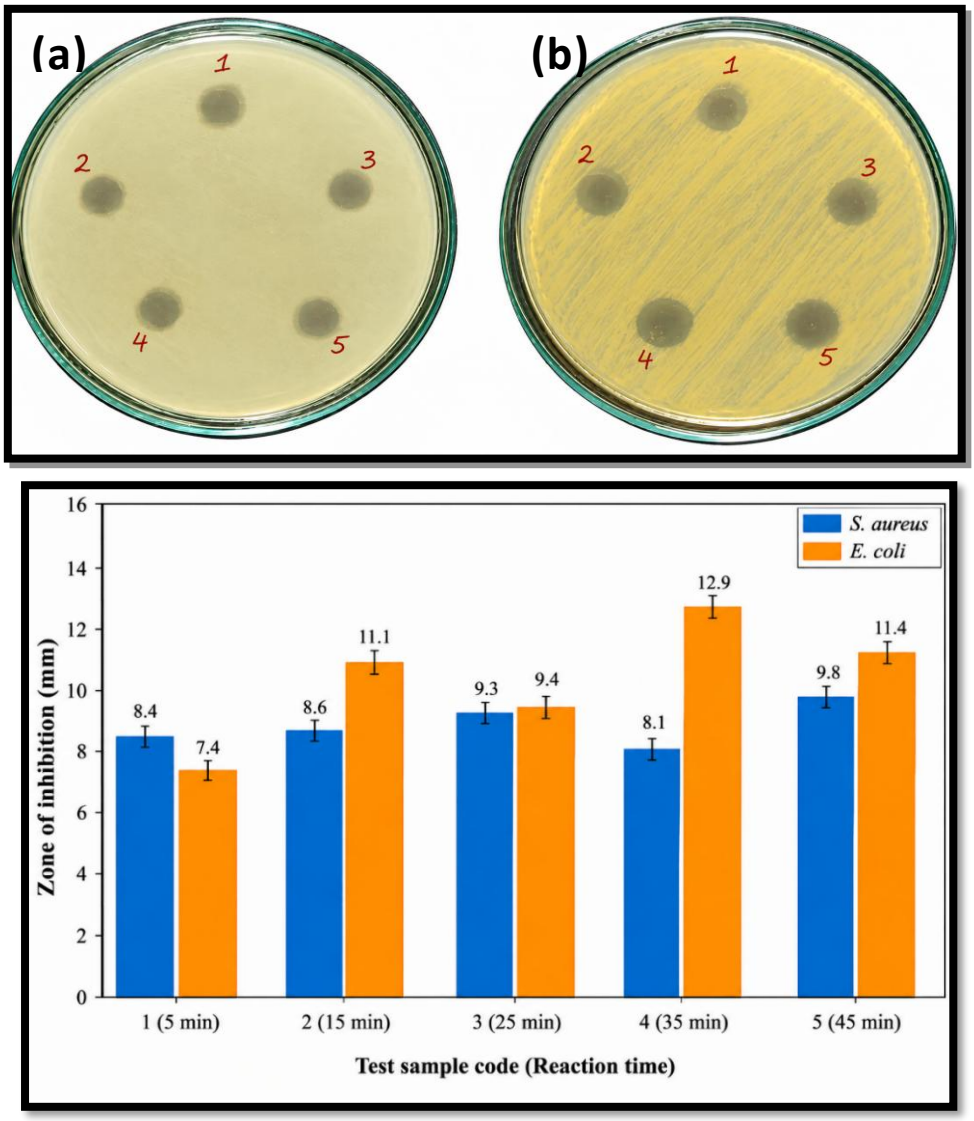


Figure 5. Antibacterial activity of banana peel extract-mediated AgNP-functionalized cotton fabrics against (a) Staphylococcus aureus and (b) Escherichia coli

Overall, the AgNP-functionalized cotton fabrics exhibited measurable antibacterial activity against both *S. aureus* and *E. coli*, confirming the successful development of an antibacterial textile surface. The inhibition zones varied with reaction time, demonstrating that the antibacterial performance is strongly influenced by the conditions of AgNP formation and deposition. The maximum inhibition zones of 9.8 mm against *S. aureus* and 12.9 mm against *E. coli* were obtained for the 45- and 35-min samples, respectively. The comparatively higher activity against *E. coli* for most reaction times may arise from differences in bacterial cell-envelope structure and interaction with surface-deposited AgNPs. The observed antibacterial activity is attributed to the combined effects of direct AgNP–cell interaction, Ag^{+} ion release, membrane disruption, interference with cellular proteins, and oxidative stress. The reaction-time-dependent variation further suggests that nanoparticle distribution, surface accessibility, and aggregation are important factors governing antibacterial performance. These findings, together with the FE-SEM, FTIR, Raman, XRD and EDX results, demonstrate the potential of green-synthesized AgNP-functionalized cotton as an antibacterial textile material.

4. Conclusion and Future Directions

In conclusion, the present study demonstrates a simple and sustainable one-pot, in-situ strategy for the fabrication of AgNP-functionalized cotton fabric using banana-peel extract as a multifunctional reducing, stabilizing, and anchoring medium. FE-SEM revealed a clear time-dependent evolution from initial nanoparticle nucleation to increased surface coverage and, at prolonged reaction times, particle growth and aggregation. EDX confirmed silver incorporation, with the highest measured Ag content of 24.79 wt% at 25 min, while XRD verified the formation of crystalline metallic Ag^{0} with an average crystallite size of 22 nm, without significant disruption of the cellulose crystalline framework. FTIR and Raman analyses further supported modification of the cellulose surface and interactions involving extract-derived constituents during AgNP formation and immobilization. Importantly, the functionalized fabrics exhibited antibacterial activity against both *S. aureus* and *E. coli*, with maximum inhibition zones of 9.8 and 12.9 mm, respectively, demonstrating effective antimicrobial functionality.

Future studies should focus on establishing durability through standardized washing, abrasion, and repeated-use tests, together with Ag^{+}/AgNP release analysis and quantitative antibacterial assays. Optimization of extract concentration, silver precursor concentration, pH,

temperature, and reaction time could further control nanoparticle size, loading, and aggregation. Evaluation of cytocompatibility, long-term stability, and scale-up feasibility will also be essential for translating this green approach toward practical medical, hygiene, and antimicrobial textile applications.

5. Acknowledgements

NDJ and ANK are thankful to Management and Principal NTVS's G. T. Patil Arts, Commerce and Science College, Nandurbar for support and encouragement. NDJ is thankful to Government of Maharashtra for SARTHI Fellowship. NDJ and ANK are thankful to Dr. Sandip Marathe, Department of Botany, NTVS's G. T. Patil Arts, Commerce and Science College, Nandurbar for identify and authenticate the plant. The authors are thankful to all individuals and institutions who directly or indirectly contributed to the successful completion of this work.

6. Statements and Declarations

Data Availability Statement

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

Funding Declaration

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

Conflicts of interest

This study did not involve human participants, human tissue, or animal subjects and did not require specific ethics approval.

"**Ethics, Consent to Participate, and Consent to Publish declarations:** Not applicable."

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