TRENDS IN SCIENCES 2026; 23(11): 13182
https://doi.org/10.48048/tis.2026.13182 RESEARCH ARTICLE

Green *In-situ* Synthesis of AgNPs and Myristic Acid Coating for Antibacterial and Hydrophobic Functionalization of Naturally Dyed Cotton Fabrics

Mohammad Alauhdin[1], Rohana Adnan[2], Adhi Dwi Hatmanto[3] and Indriana Kartini[3,4,*]

[1]*Department of Chemistry Universitas Negeri Semarang, Kampus Sekaran Gunungpati, Semarang 50229, Indonesia*
[2]*School of Chemical Sciences, Universiti Sains Malaysia, USM Pulau Pinang 11800, Malaysia*
[3]*Department of Chemistry, FMIPA, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia*
[4]*Indonesia Natural Dyes Institute (INDI), The UNESCO Chair on Research and Education of Local Natural Dyes, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia*

([*]Corresponding author's e-mail: indriana@ugm.ac.id)

Received: 28 December 2025, Revised: 22 February 2026, Accepted: 1 March 2026, Published: 30 May 2026

Abstract

Green synthesis of silver nanoparticles (AgNPs) has drawn increasing attention for antibacterial surface applications. However, integrating additional functionalities, such as hydrophobicity, may affect antibacterial performance. In this study, AgNPs were synthesized *in situ* on cotton substrates using bamboo leaf extract as an eco-friendly reducing agent, followed by hydrophobic surface modification with naturally derived organic acids. The AgNPs coating and surface modification of the cotton were confirmed by SEM-EDX, XPS, and FTIR spectroscopy. The prepared AgNP-coated cotton exhibited effective antibacterial activity against both *Streptococcus aureus* and *Escherichia coli*, with inhibition zones ranging from 12.0 to 13.5 mm. While hydrophobic treatment significantly increased water contact angles up to 148°, indicating enhanced surface repellency. Notably, a reduction in antibacterial performance was observed after hydrophobic modification, suggesting a functional trade-off associated with altered surface accessibility and ion diffusion. These results highlight an important design consideration for multifunctional antibacterial surfaces prepared *via* green synthesis routes, emphasizing the need to balance antibacterial efficacy and surface engineering strategies.

Keywords: Cotton, Hydrophobic surface, Antibacterial, Natural dye, Green process

Introduction

Cotton is the most widely used natural fiber because of its comfort, breathability, water absorbency, and biodegradability [1,2]. However, cotton's large surface area and high affinity for water and other liquids make it a perfect medium for the growth of pathogenic microorganisms. These microorganisms can pose a serious health risk to individuals and threaten their well-being [3]. Additionally, once the microorganisms propagate on the cotton fabric, the fibers may degrade and become discolored. Therefore, modifying cotton fabrics by coating with a functional additive to prevent degradation and gain new functional properties, such as improved color and wash fastness, controlled hydrophobicity, or antimicrobial properties, is needed [4-6].

The development of antibacterial surfaces through green, sustainable approaches has become an important research trend driven by growing concerns about environmental impact, material safety, and long-term functionality. Among various antibacterial agents, silver nanoparticles (AgNPs) remain one of the most widely explored due to their broad-spectrum antimicrobial activity [5-8]. In recent years, plant-extract-mediated synthesis has emerged as an attractive alternative to conventional chemical routes, enabling AgNP formation under mild conditions while reducing the use of

hazardous reagents [9-12]. Despite extensive reports on green-synthesized AgNPs, most studies focus solely on antibacterial performance, with limited consideration of how additional surface modifications affect their effectiveness.

In practical applications, antibacterial surfaces are often required to exhibit multiple functionalities simultaneously, such as water repellency, durability, or self-cleaning activity [13,14]. Hydrophobic surface modification is therefore frequently applied to AgNP-functionalized substrates to improve resistance against moisture and contamination [15]. However, introducing hydrophobic layers may unintentionally affect antibacterial performance by altering nanoparticle accessibility, surface wettability, and ion diffusion pathways. This potential trade-off between antibacterial activity and hydrophobicity has received limited systematic attention, particularly in systems prepared via green synthesis routes.

Cotton, as a cellulose-based substrate rich in surface hydroxyl groups, provides a convenient model for investigating functional surface modification strategies. Green *in situ* synthesis of AgNPs on cotton enables direct nanoparticle immobilization without additional binders, while post-synthesis surface treatment allows tailoring surface wettability. Bamboo leaf extract (BLE), which contains phenolic and flavonoid compounds, has been reported as an effective bio-reducing agent for AgNP synthesis [16,17]. In parallel, naturally derived organic acids, such as cinnamic and myristic acids, have attracted attention as non-fluorinated, hydrophobic modifiers, offering environmentally benign alternatives to conventional fluorinated or organosilane coatings [18,19].

In this context, the present study aims to investigate a green, surface-based approach for preparing AgNP-coated cotton, followed by hydrophobic surface modification using naturally derived organic acids. Rather than emphasizing extensive nanoparticle characterization, this work focuses on the functional consequences of combining antibacterial and hydrophobic treatments within a single system. By examining antibacterial activity and surface wettability before and after hydrophobic modification, this study highlights a system-level trade-off that is relevant to the design of multifunctional antibacterial surfaces prepared via sustainable routes.

Materials and methods

Materials

Silver nitrate ($AgNO_3$, M.W. 169.87 g/mol) as a precursor of AgNPs, sodium dodecyl sulfate (SDS), and N, N-dicyclohexylcarbodiimide (M.W. 206.33 g/mol) were supplied by Sigma-Aldrich. Myristic acid and ethanol were obtained from Merck. White cotton fabrics were obtained from PT. Primissima, Indonesia. An extract of the *Tingi* plant (*Ceriops tagal*), a natural dye, was purchased from the Gama Indigo Workshop Gallery in Yogyakarta, Indonesia. Bamboo leaves (*Gigantochloa apus*) were collected from a bamboo yard in Yogyakarta, Indonesia.

Fabric dyeing

Before the dyeing process, the cotton textiles with dimensions of 20×60 cm^2 (21.6 g) were soaked in clean water for 30 min. After drying at room temperature, the fabrics were then dipped in a dye bath (500 mL). The dyeing process was conducted for 1 h with intermittent stirring. After being removed from the dye bath, the dyed fabrics were squeezed to remove excess dye. After that, the dyed fabrics were soaked in a mordant solution (70 g/L) at room temperature for 30 min, then rinsed with tap water and dried at room temperature.

Preparation of Bamboo Leaf Extract (BLE)

Dry bamboo leaves of approximately the same size were gathered and cleaned with water to remove any dust or dirt that might have adhered to their surfaces. After drying, they were sliced into small pieces to prepare for extraction. About 5 g of washed bamboo leaves were extracted with 100 mL of distilled water for 30 min at 100 °C [16]. The extract was then collected and filtered through the Whatman 42 filter paper.

Synthesis of silver nanoparticles

AgNPs were synthesized by adding 2 mL of BLE (50 g/L) into $AgNO_3$ solution. BLE was added dropwise to the solution at 10-minute intervals, and the reaction was allowed to proceed at 60 °C under constant stirring for 60 min. The concentrations of $AgNO_3$ and BLE were varied, i.e., 4.7, 5.2, 6.2, and 6.5 mM for $AgNO_3$ and 0.5%, 1%, 2%, and 3% for BLE, to examine the optimum conditions. The synthesized colloidal AgNPs were then characterized using a UV-visible spectrophotometer (Genesys 10s UV-Vis

Spectrophotometry) in the 200 - 600 nm wavelength range.

***In situ* preparation of AgNPs-loaded cotton fabric**

Dyed cotton fabric (3×6 cm^2) was immersed in silver nitrate solution and heated at 60 °C. BLE was added dropwise to the mixture at specific time intervals, and the reaction was allowed to take place with stirring for 60 min. After that, the cotton fabric was removed from the solution, rinsed with distilled water, and allowed to dry at room temperature. The process was repeated with varying concentrations of silver nitrate solutions (4.7, 5.2, 6.2, and 6.5 mM), and the resulting coated cotton fabrics were labeled Ct-1, Ct-2, Ct-3, and Ct-4, respectively. In contrast, the uncoated cotton was labelled as Ct-0.

Preparation of hydrophobic cotton with myristic acid

The hydrophobic surface was prepared using the liquid phase deposition method. An ethanol solution of myristic acid was prepared by adding 20% N,N-dicyclohexylcarbodiimide relative to the acid concentration. The cotton or cotton/AgNPs were then immersed in the solution at 75 °C for 3 h on a hot plate [20]. Afterward, the fabrics were left to dry at room temperature.

Characterization

Surface morphology and elemental composition of cotton fabric samples were examined using scanning electron microscope-energy dispersive X-ray spectroscopy (SEM-EDX) (JSM-6510LA, Phenom ProX desktop series Thermofisher, and JSM-IT700HR for elemental mapping). Samples were initially coated with a thin layer of Au particles using a sputtering machine. Moreover, the interaction between components in the cotton surface was studied using an X-ray photoelectron spectroscopy (XPS) Axis Ultra DLD, Kratos, UK, equipped with an Al Kα X-ray source (1486.6 eV) at 9 mA for emission and 10 kV for anode HV. Meanwhile, FTIR analysis was employed using a Spectrum Two FT-IR Spectrometer to investigate the functional groups present in the samples.

Antibacterial activity

The antibacterial activity was examined against *Streptococcus aureus* and *Escherichia coli* bacteria using the inhibitory zone method. After the samples were prepared in circular shapes with a diameter of 1.0 cm, they were placed on an agar medium containing *S. aureus* and *E. coli*. The agar medium plates were then incubated at 37 °C for 24 h. The antibacterial activity of the samples was examined by measuring a zone of inhibition surrounding the sample on the incubated plates. Each sample was measured in four replications, and the mean value was reported.

Hydrophobicity by water contact angle

Water contact angles (WCA) were determined by taking images of a 10 μL water droplet on the cloth using a smartphone camera in macro mode. The obtained images were then converted to "B&W" mode and processed using ImageJ software. Three separate spots on the cloth's surface were used to assess WCA, and the mean value was reported.

Results and discussion

Synthesis of AgNPs in solution

The development of AgNPs was indicated by the emergence of a yellowish-brown tint. It is due to the localized surface plasmon resonance (LSPR) absorption of AgNPs upon exposure to visible light [21,22]. The LSPR band was examined using a UV-vis spectrophotometer and is presented in **Figure 1**. This LSPR phenomenon gives rise to absorption peaks in the 400 - 450 nm wavelength region. The resulting absorption increased with increasing concentration of the precursor $AgNO_3$ solution (**Figure 1(a)**). Similarly, the higher the concentration of BLE, which also corresponds to a higher phenolic content, the higher the peak intensity (**Figure 1(b)**), indicating that the higher the concentration of AgNPs formed.

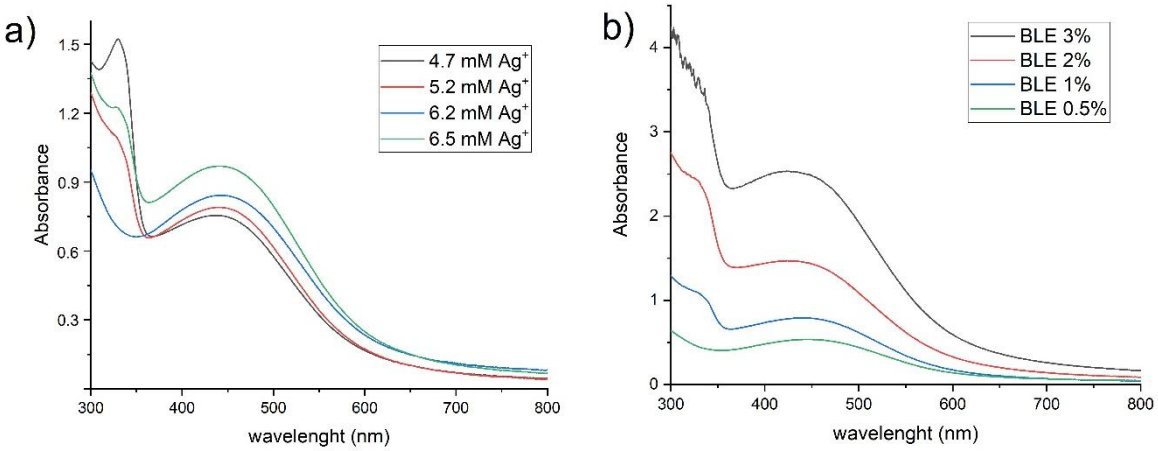

Figure 1 The UV-Vis absorbance spectra of AgNPs prepared with varying (a) $AgNO_3$ concentration and (b) BLE concentration.

It was observed that the formation of AgNPs occurred after 60 min of reaction. However, the formation of AgNPs continues to occur, as indicated by the increasing absorbance and the hypsochromic shift of the absorption peak from 445 - 422 nm. The low-intensity and broad absorbance peak centered at 445 nm observed on day 1 (**Figure 2**) suggests a low concentration of AgNPs and a broad range of particle sizes. After 3 days, the peak became narrower, and the absorbance peak was higher. This indicates that more AgNPs with more consistent size distributions were generated. Further observation revealed that the intensity of the peak continues to increase over time. However, after the 83rd day, the increase is no longer significant, and the absorbance remains almost the same, which can be explained by the fact that all Ag^+ from the precursor has been fully reduced to form AgNPs. Meanwhile, the absorbance peak at around 360 nm of the phenolic functional groups from BLE decreased as the concentration of AgNPs increased. Thus, these data further confirm the role of phenolic compounds in BLE as reducing agents in the formation of AgNPs, which is in accordance with previous studies on the use of plant extracts as reducing agents [23]. Therefore, BLE can be used to synthesize AgNPs, resulting in AgNPs with good stability that last for more than 80 days.

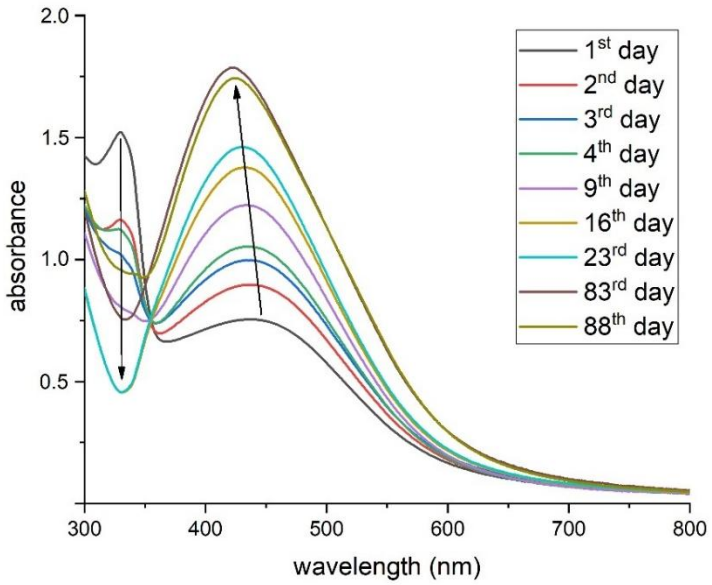

Figure 2 The UV-Vis spectra showing the formation and stability of AgNPs.

As reported elsewhere, during synthesis, the hydroxyl groups of the phenolic compounds initially form an intermediate complex with Ag^+. Then, the Ag^+ ions withdraw electrons from the hydroxyl groups and form AgNPs. Meanwhile, the phenolic compounds were oxidized into quinones. These quinone compounds then attach to the AgNPs surface and stabilize the nanoparticles [10,24-26].

***In situ* synthesis of AgNPs-loaded cotton fabrics**

In the *in situ* synthesis of AgNPs-loaded cotton, the microfibrillar cotton network, which expands in aqueous solution, allows Ag^+ ions to permeate into the cotton fibers. Additionally, this process produces nanoscale channels that facilitate the Ag^+ reduction reaction and regulate particle growth [27]. Both phytochemical compounds in BLE and the building units of the cotton fabrics work to stabilize the AgNPs. The larger nanoparticles are typically confined in the polymeric structure of the cotton fiber. On the other hand, smaller nanoparticles are easily attracted by porous cotton fiber structures and then entrapped by plant extract compounds and cotton fiber structures [28].

Following the incorporation of AgNPs, the fibers turned darker (**Figure 3**). The higher the concentration of $AgNO_3$, the darker the fabrics obtained. This indicates that the density of attached AgNPs on fabrics increases, as previously reported [29].

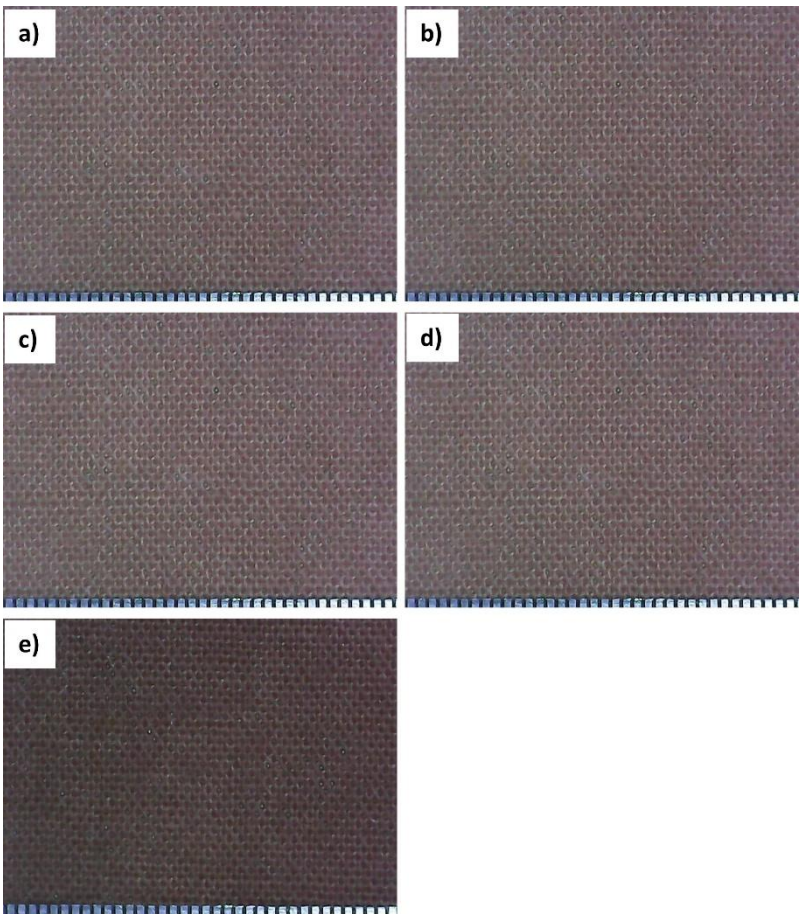

Figure 3 Digital images of (a) *Tingi* dyed cotton fabric (Ct-0), and AgNPs-loaded *Tingi* dyed cotton fabric with different $AgNO_3$ precursor concentrations (b) 4.7 mM (Ct-1), (c) 5.2 mM (Ct-2), (d) 6.2 mM (Ct-3), (e) 6.5 mM (Ct-4).

Furthermore, the surface morphology and chemical composition of the treated fabrics were examined using SEM-EDX spectroscopy (**Figures 4** and **5**). Pristine cotton fabrics have a clear, clean, and smooth surface (**Figure 4(a)**). The *Tingi*-colored cotton fabric (**Figure 4(c)**) exhibits a rough surface, which may be attributed to the residue from the dyeing process. The surface of AgNPs-loaded *Tingi*-dyed cotton (**Figure 4(e)**) is similar to that of *Tingi*-dyed cotton (**Figure 4(c)**), but with the presence of AgNPs. The EDX data shows a peak at 3 keV, which is the characteristic peak of AgNPs with a percentage of 2.98% (**Figure 4(f)**). The

SEM-EDX mapping further confirmed the presence of AgNPs, as shown in **Figure 5**. The elemental mapping images also showed that AgNPs were evenly distributed over the cotton surface.

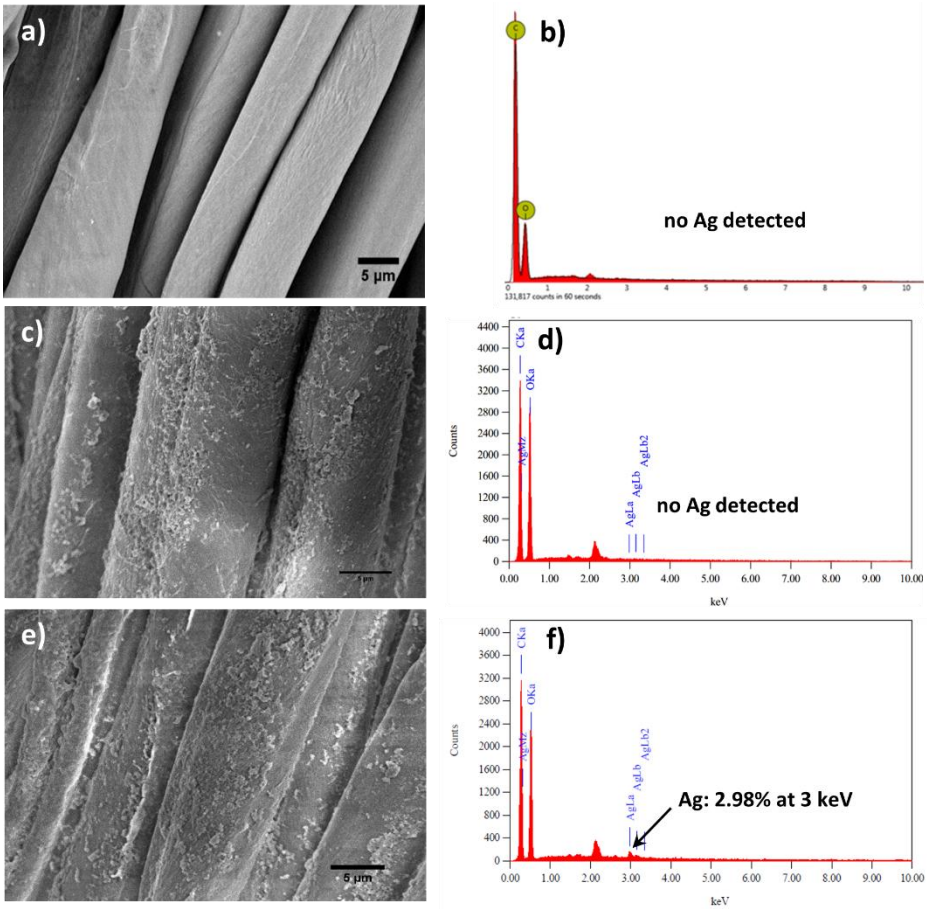

Figure 4 SEM images and EDX spectra of (a), (b) untreated cotton, (c), (d) *Tingi*-dyed cotton, (e), (f) AgNPs-treated *Tingi*-dyed cotton. Scale bar 5 µm.

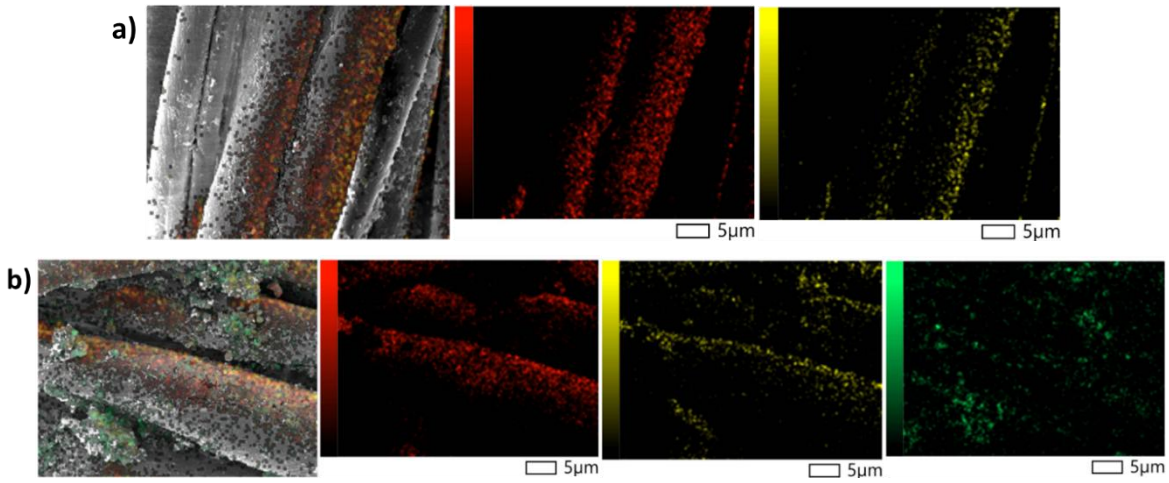

Figure 5 SEM-EDX spectral mapping of C (red), O (yellow), and Ag (green). (a) *Tingi*-dyed cotton fabric, (b) AgNPs-treated *Tingi*-dyed cotton fabric. Scale bar 5 µm.

Green hydrophobic AgNPs-cotton fabric

In order to produce a cotton fabric with a hydrophobic surface, the AgNPs-treated cotton was further coated with myristic acid (MA). The MA coating made the color of the cloth darker due to the heat generated during the coating process (**Figure 6**). **Figure 7** shows the FTIR spectra of the *Tingi*-dyed cotton and myristic acid-coated *Tingi*-dyed cotton. Both spectra show a band at 3,330 cm^{-1}, associated with the stretching of hydroxyl groups. The spectral bands at 2,893 and 1,313 cm^{-1} refer to the stretching and deformation vibrations of C-H groups in the glucose unit of cellulose [30] from the cotton fabric. The absorption band at 1,623 cm^{-1} is due to the C=O vibrations of carbonyl groups in myristic acid or amide in the dye. The absorption band from the -C-O- groups of secondary alcohols and ethers in the cellulose chain backbone appears at 1,025 cm^{-1}. The band at 1,162 cm^{-1} is attributed to the beta-glycosidic linkage between glucose units [31]. Apart from the carbonyl groups (1,623 cm^{-1}), the presence of myristic acid in the fabric is indicated by a vibration peak of -C-H bending of methylene groups at 1,540 cm^{-1}.

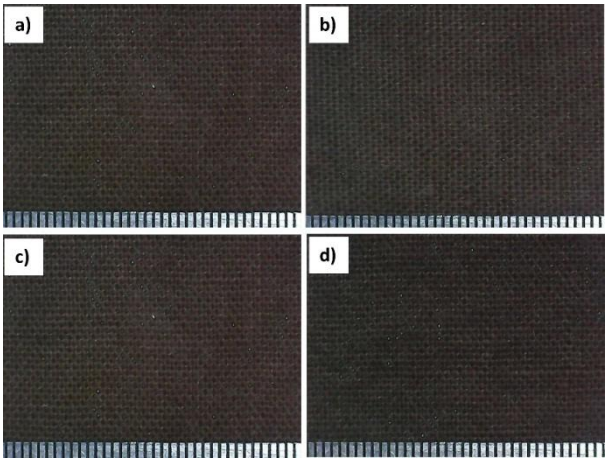

Figure 6 Digital images of myristic acid coated cotton fabric (a) dyed cotton + AgNPs + MA 1%, (b) Dyed cotton + AgNPs + MA 2%, (c) Dyed cotton + AgNPs + MA 3%, (d) Dyed cotton + AgNPs + MA 4%. MA: myristic acid.

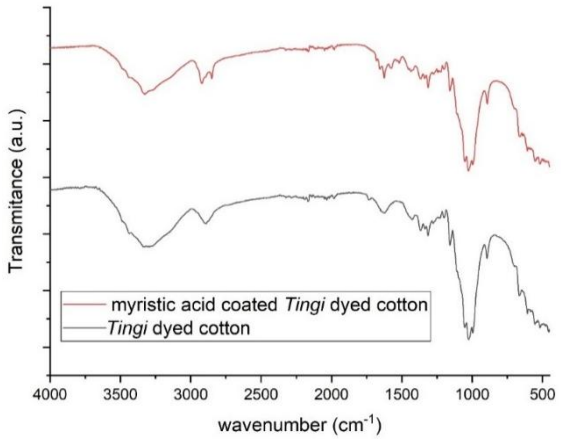

Figure 7 Infrared spectra for *Tingi*-dyed cotton and myristic acid-coated *Tingi*-dyed cotton.

The WCA data of the myristic acid-coated cotton fabric are presented in **Figure 8(a)**. The original white cotton fabric is hydrophilic. Water drops on the surface will quickly be absorbed by the fibers. Meanwhile, cotton fabrics dyed with Tingi natural dye become slightly hydrophobic, with a WCA of 122°. The hydrophobic property might be a result of the organic compounds of the dye. After coating with myristic acid, the WCA increased significantly. An almost spherical droplet with a WCA of 148° appeared on the surface of

a myristic acid-coated cloth (Ct-0 MA 3%). The hydrophobic property increases because myristic acid has a nonpolar alkyl chain. On the other hand, the carboxylate group of the acid serves as an active site that binds to the cotton surface (**Figure 10**). However, the long-chain fatty acid probably has a random orientation; thus, the acid coating was insufficient to achieve a superhydrophobic surface [32].

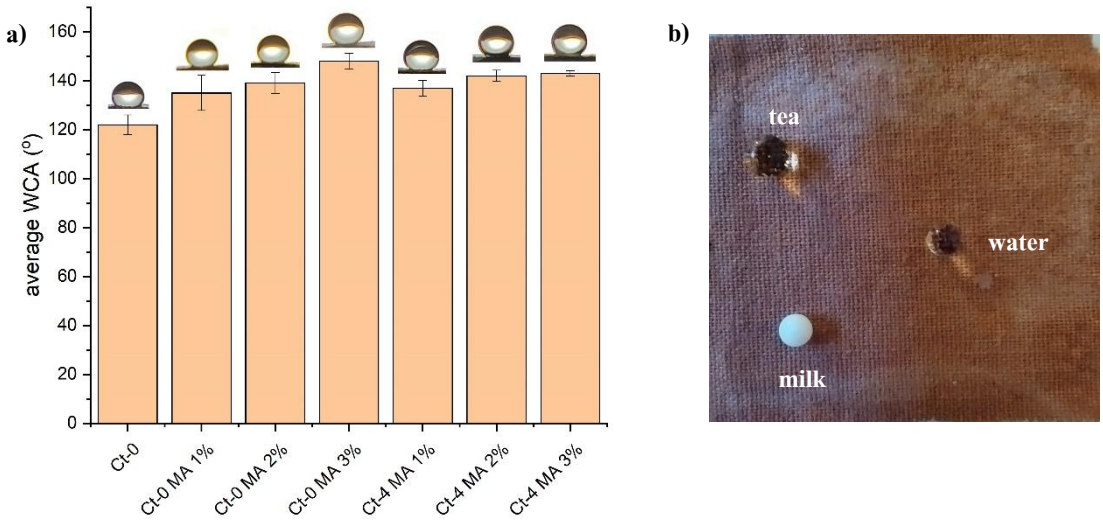

Figure 8 (a) Water contact angle of *Tingi*-dyed cotton (Ct-0) and functionalized *Tingi-dyed* cotton with *in-situ* synthesized AgNPs and myristic acid (Ct-4), (b) photograph displaying different droplets with a spherical shape on the treated cotton (Ct-0 MA 3%) surface. MA: myristic acid.

Coating with 1%, 2%, and 3% myristic acid on the dyed cotton (Ct-0) resulted in a hydrophobic surface, with a WCA of 135°, 139°, and 148°, respectively. Meanwhile, myristic acid coating on cotton/AgNPs (Ct-4) resulted in slightly lower hydrophobicity than dyed cotton without AgNPs (Ct-0). This is likely due to both AgNPs and myristic acid being attached to the fabric through hydroxyl groups on the cotton cellulose, thereby reducing the available attachment sites for myristic acid. As a result, the AgNPs-treated surface exhibited a lower water contact angle than expected. Water repellency to common liquids is also demonstrated by the spherical shape of the tea, milk, and distilled water droplets on the treated cotton surface (**Figure 8(b)**). The results showed that the green chemical myristic acid can be utilized as a hydrophobic coating on the cotton surface. This environmentally friendly hydrophobic agent can be applied as an alternative to the high-cost materials and the toxicity of organosilane and fluorine-based compounds.

Figure 9 presents the XPS spectra of *Tingi*-dyed cotton (Ct-0) and MA/AgNPs/*Tingi*-dyed cotton (Ct-4). Consistently, the survey spectrum of the *Tingi*-dyed cotton shows only C, N, and O peaks (**Figure 9(a)**). Furthermore, the C 1s XPS spectrum of *Tingi* dyed cotton (**Figure 9(b)**) showed the characteristic peaks of sp^2 C, sp^3 C, C-OH, and O-C-O with the binding energy of 283.2, 284.7, 286.3, and 288 eV, respectively. The additional peak of Ag 3d appeared on the survey spectrum of MA/AgNPs/dyed cotton (**Figure 9(c)**), confirming the attachment of AgNPs to the cotton. Meanwhile, the C 1s spectrum of MA/AgNPs/dyed cotton was deconvoluted into five distinct peaks (**Figure 9(d)**) with binding energies of 284.5, 285.2, 286.4, 287.9, and 289.1 eV corresponding to C-H or C-C, C-OH, C-O-C, C=O, and O-C=O, respectively. A decrease in the intensity of the C-OH peak in the MA/AgNPs/dyed cotton fabric compared to that of the dyed cotton confirms the interaction between hydroxyl groups on the cotton surface with AgNPs and myristic acid. The appearance of C-C, C-H, and C=O peaks in the MA/AgNPs/dyed cotton spectrum clearly verified the presence of myristic acid on the cotton surface.

The XPS signature peak of the Ag 3d doublet ($3d_{5/2}$ and $3d_{3/2}$) for the AgNPs deposited on dyed cotton is illustrated in **Figure 9(e)**. The analysis of Ag 3d exhibits the existence of 2 Ag 3d doublets at 367.8 and 373.8 eV and 369.1 and 375.0 eV, respectively. The

shifting of the second doublet peak corresponds to the Ag 3d peak to a higher binding energy compared to the characteristic peaks of metallic silver (368.2 and 374.2 eV), which could be attributed to a charge transfer between the cellulose polymer in the cotton fabric and the silver [33]. Moreover, two satellite peaks appearing at 370.1 and 376.2 eV were assigned to plasmon losses.

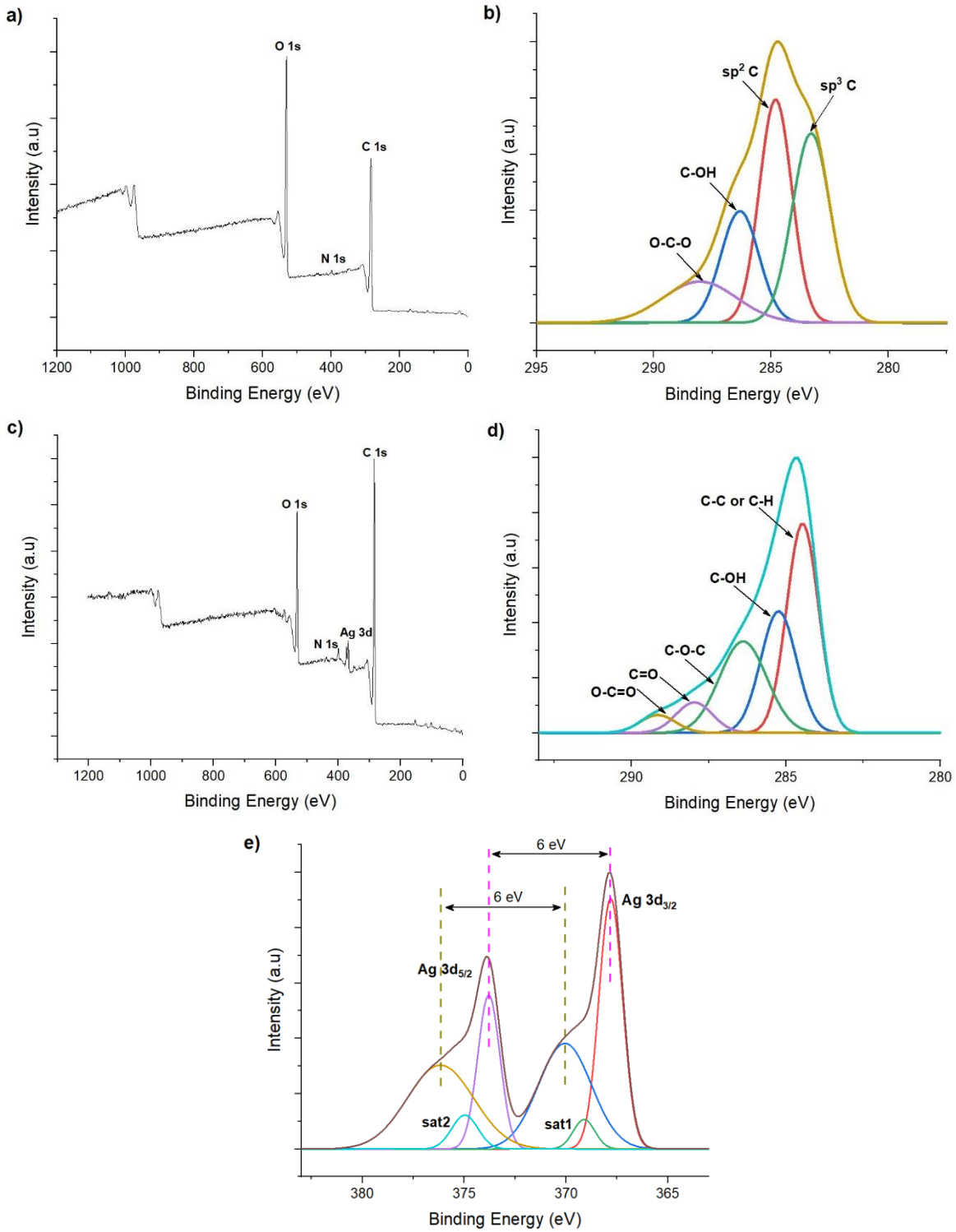

Figure 9 XPS spectra of *Tingi* dyed cotton (Ct-0): (a) survey spectrum, (b) C 1s, and MA/AgNPs/*Tingi* dyed cotton (Ct-4): (c) survey spectrum, (d) C 1s, and e Ag 3d. MA: myristic acid.

The combined SEM–EDX, FTIR, and XPS results indicate that AgNPs are immobilized on the cotton surface and subsequently covered by a myristic acid layer, which alters the surface chemistry from hydrophilic to hydrophobic. Based on the current results, we propose a conceptual mechanism for the *in-situ* incorporation of AgNPs into cotton fabrics, followed by a hydrophobic coating with myristic acid (**Figure 10**). Firstly, when the fabrics were immersed in a silver nitrate solution, a complexation and/or ion-exchange interaction between silver ions and the functional groups of cotton (-COOH and -OH) took place [26,34,35]. Following the addition of BLE, the phenolic compounds of BLE are oxidized to their quinone form, and Ag^{+} is reduced to form AgNPs. The formed AgNPs were then attached to the cotton, as confirmed by SEM-EDX and XPS, facilitated by the cotton's hydroxyl groups (reaction 1). Furthermore, the added myristic acid molecules form surface interactions between the acid's hydroxyl groups and the cotton fabric (reaction 2). The non-polar tails of the myristic acid, now attached to the cotton surface as confirmed by FTIR and XPS, create a hydrophobic surface that repels water drops.

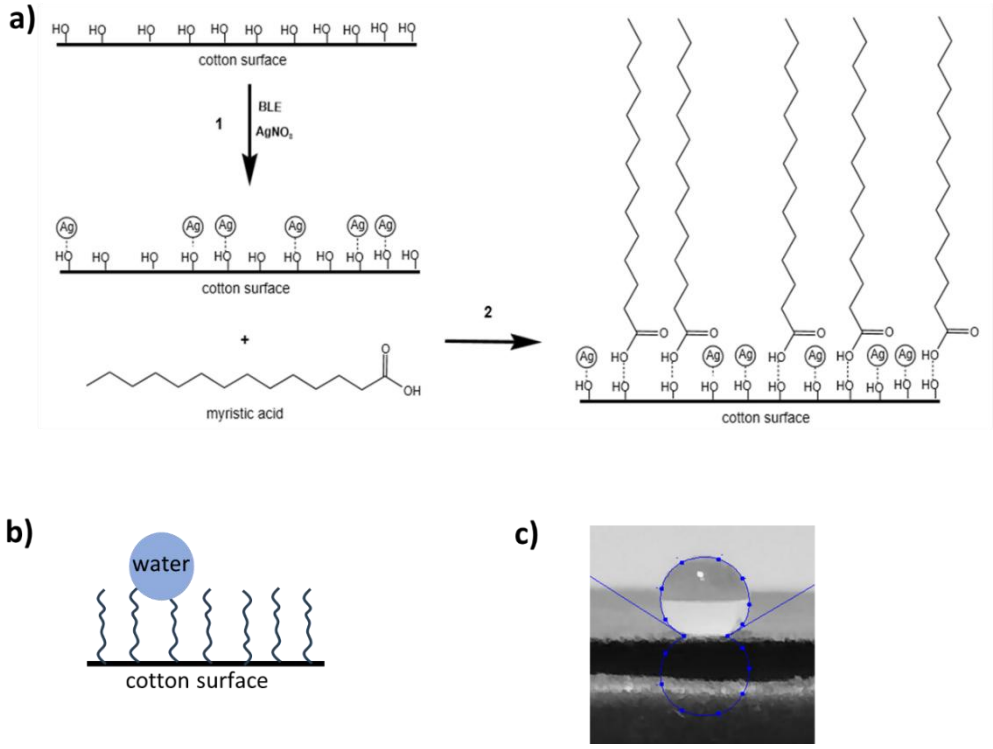

Figure 10 (a) Schematic illustration of *in situ* incorporation of AgNPs in cotton fabric using bamboo leaf extract (BLE) as reducing agent (reaction 1) and myristic acid coating (reaction 2), (b) water repellence mechanism, (c) photograph of hydrophobic cotton surface.

Antibacterial activity

The presence of AgNPs in the cotton provides antibacterial properties [36]. It is well-documented that AgNPs exhibit excellent antibacterial activity against a variety of bacterial species [37-39]. The antibacterial activity of the treated cotton in this investigation was assessed qualitatively using the zone of inhibition method. *Streptococcus aureus* and *Escherichia coli* were used as the tested bacteria, representing Gram-positive and Gram-negative bacterial strains.

Figures 11 and **12** show the inhibition zone of the untreated and treated cotton fabric against *S. aureus* and *E. coli*, respectively. As a control, the untreated cotton (Ct-0) showed no antibacterial activity. The assay results indicate that both Gram-negative and Gram-positive bacterial strains were effectively inhibited by the treated cotton, with varying inhibition zone diameters, as shown in **Table 1**. The results are in agreement with previous research, which has shown that functionalizing cotton fabric with AgNPs can provide

antibacterial activity, with inhibition zones ranging from 0.7 to 3.0 mm against *S. aureus* and *E. coli* [40-42].

This qualitative evidence shows that the treated cotton exhibits antibacterial properties regardless of whether an outer lipid membrane is present on the bacterial cells or the thickness of the peptidoglycan layer. The results indicate that the presence of AgNPs in cotton fabric confers an antibacterial effect, resulting in either a bactericidal or bacteriostatic effect, where the bacteria are either killed or their growth is inhibited. According to the literature, AgNPs have the ability to alter the morphology of bacterial cells by damaging their cell wall and membrane [43,44]. They can also adhere to microbial cells, penetrate inside the cells, and generate reactive oxygen species (ROS) and free radicals. AgNPs have demonstrated promising antimicrobial activity against Gram-positive bacteria, including *Staphylococcus aureus* and *Brevibacterium luteolum*, as well as against Gram-negative bacteria such as *Escherichia coli* and *Pseudomonas aeruginosa* [43-45]. It should be noted that the antibacterial evaluation in this study is primarily qualitative; therefore, the results reflect comparative trends rather than absolute quantitative antibacterial efficacy.

Table 1 The antibacterial performance of cotton against *S. aureus* and *E. coli*.

Sample	Inhibition zone (mm)[a]	
	S. aureus	***E. coli***
Ct-0	ND[b]	ND
Ct-1	12.0 ± 0.0	13.5 ± 0.1
Ct-2	13.0 ± 0.0	12.8 ± 0.1
Ct-3	12.8 ± 0.1	12.0 ± 0.0
Ct-4	13.0 ± 0.1	13.0 ± 0.0
Ct-4 + MA 2%	ND	ND

[a]average of 4 replicates.

[b]ND denotes that no bacterial growth inhibition was detected.

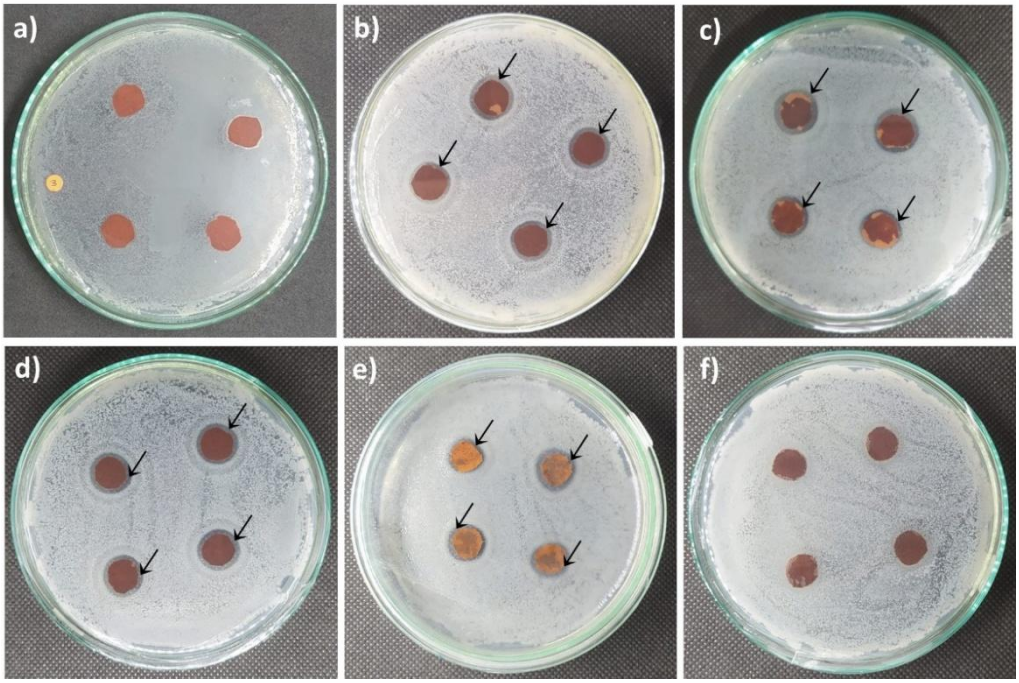

Figure 11 Antibacterial test against *S. aureus* of (a) Ct-0, (b) Ct-1, (c) Ct-2, (d) Ct-3, (e) Ct-4, (f) Ct-4 + MA 2%. The arrows indicate the zones of inhibition (clear areas with no bacterial growth).

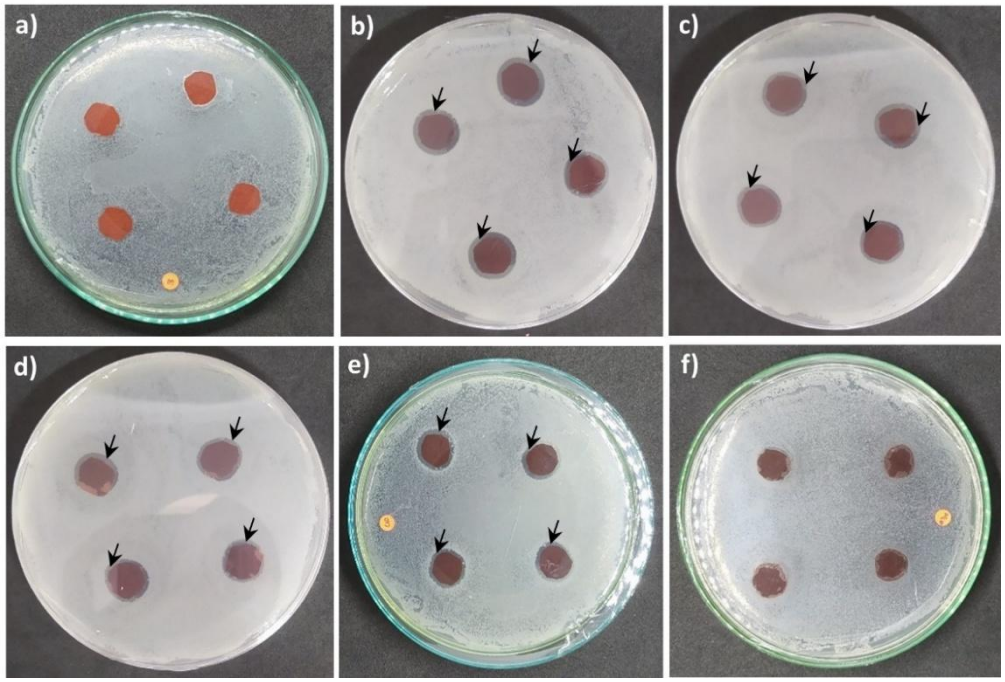

Figure 12 Antibacterial test against *E. coli* of (a) Ct-0, (b) Ct-1, (c) Ct-2, (d) Ct-3, (e) Ct-4, (f) Ct-4 + MA 2%. The arrows indicate the zones of inhibition (clear areas with no bacterial growth).

As previously reported, the release of silver ions (Ag^+) is the primary mechanism of the antibacterial effect of AgNPs [46]. The silver ions enter the bacterial cell wall and disrupt the DNA's metabolic function, resulting in bacterial death. However, the hydrophobic property of the myristic acid layer on the treated cotton fabric results in no inhibition, which may reduce the release of AgNPs from cotton. Hence, the formation of antibacterial silver ions is more difficult.

The results indicate a clear trade-off between antibacterial activity and hydrophobicity in the functionalized cotton fabrics. Cotton fabrics treated with *in situ*-synthesized AgNPs exhibited effective antibacterial performance against both *S. aureus* and *E. coli*. However, after coating with myristic acid, the antibacterial activity was no longer observed. This reduction can be attributed to the formation of a hydrophobic surface layer, which limits water penetration and suppresses the release of silver ions (Ag^+), a key component in the antibacterial mechanism of AgNPs [38,46]. Similar observations have been reported for hydrophobic antibacterial textiles, where surface water repellency reduces direct contact between AgNPs and the surrounding medium, thereby decreasing antibacterial effectiveness [47].

This trade-off reflects the contrary demands of hydrophobicity and antibacterial performance; while antibacterial activity benefits from accessible nanoparticle surfaces and ion diffusion, hydrophobicity requires low surface energy and restricted water contact, often leading to reduced nanoparticle accessibility. Therefore, balanced design strategies, such as layer-by-layer assembly [48], may be necessary to optimize both functionalities without sacrificing either.

This functional trade-off should be considered an important design parameter rather than a limitation. For hygienic applications, such as wound dressings and antimicrobial clothing, strong antibacterial activity is more critical than hydrophobicity. Therefore, AgNPs-functionalized cotton without an additional hydrophobic coating may be a more suitable option [49]. In contrast, for outdoor, protective, and self-cleaning applications, such as workwear, upholstery, and packaging materials, hydrophobicity and water repellency are often prioritized, and reduced antibacterial activity may be acceptable or even beneficial in minimizing silver release and environmental impact [18,32,50]. Accordingly, controlling the surface modification strategy provides flexibility in tailoring cotton fabrics for specific end-use requirements in sustainable textile finishing.

Strengths and limitations

This study provides a practical and system-level evaluation of multifunctional surface design by combining green-synthesized AgNPs with hydrophobic surface modification on a cellulose-based substrate. A key strength of the work lies in its focus on functional performance and design trade-offs rather than isolated material properties, offering insights relevant to sustainable antibacterial surface development.

Nevertheless, several limitations should be acknowledged. Quantitative determination of silver mass loading was not performed, and elemental analysis was limited to semi-quantitative techniques. In addition, separate control systems for each treatment step were not exhaustively explored, which limits detailed deconvolution of contributions from each component. Furthermore, the study does not include cytotoxicity or environmental impact assessments, and application-related implications are therefore discussed qualitatively. These limitations define the scope of interpretation and highlight opportunities for future investigations.

Conclusions

This study demonstrates a green and surface-based approach for preparing AgNP-coated cotton substrates with additional hydrophobic functionality using naturally derived materials. While *in situ* synthesized AgNPs provided effective antibacterial performance, subsequent hydrophobic surface modification significantly altered surface wettability and reduced antibacterial effectiveness. These findings reveal a functional trade-off that should be considered when designing multifunctional antibacterial surfaces *via* sustainable routes. Rather than optimizing individual properties in isolation, future research should focus on balancing surface modifications and antibacterial performance while addressing quantitative nanoparticle loading, toxicity, and long-term environmental impact.

Acknowledgements

The authors thank the UGM Research Directorate and the UGM Reputation Enhancement Team for their funding through the postdoctoral research grant under the World Class University UGM-Quality Assurance Office. MA thanks Hanna Nur Laili for technical assistance during data collection.

Declaration of generative AI in scientific writing

The authors acknowledge the use of generative AI tools (e.g., Grammarly and ChatGPT) in the preparation of this manuscript, specifically for language editing and grammar correction. No content generation or data interpretation was performed by AI. The authors take full responsibility for the content and conclusions of this work.

CRediT author statement

Mohammad Alauhdin: conceptualization; methodology; formal analysis; investigation; writing – original draft; visualization, **Rohana Adnan:** validation; resources; writing – review and editing; supervision, **Adhi Dwi Hatmanto:** conceptualization; methodology; writing – review and editing, **Indriana Kartini:** conceptualization; methodology; resources; supervision; writing – review and editing; funding acquisition.

References

[1] S Riaz, M Ashraf, T Hussain, MT Hussain, A Rehman, A Javid, K Iqbal, A Basit and H Aziz. Functional finishing and coloration of textiles with nanomaterials. *Coloration Technology* 2018; **134(5)**, 327-346.

[2] Y Wu, Y Yang, Z Zhang, Z Wang, Y Zhao and L Sun. Fabrication of cotton fabrics with durable antibacterial activities finishing by Ag nanoparticles. *Textile Research Journal* 2018; **89(5)**, 867-880.

[3] M Pigłowski. Pathogenic and non-pathogenic microorganisms in the rapid alert system for food and feed. *International Journal of Environmental Research and Public Health* 2019; **16(3)**, 477.

[4] I Kartini, SN Halimah and E Rahayuningsih. Enhanced wash-fastness of cotton fabric dyed with a composite of chitosan-natural dyes extract of *Ceriops tagal*. *IOP Conference Series: Materials Science and Engineering* 2021; **1053**, 012022.

[5] ZO Basyigit and H Coskun. Enhancing antibacterial and water-repellent properties for the production of high-performance fabrics in Home Textiles. *Fibers and Polymers* 2024; **25(5)**, 1789-1804.

[6] F Qian, M Chen, C Zhou, Z Li, R Li and X Ren. The antibacterial and hydrophobic cotton fabrics

constructed by multifunctional polysiloxane and TiO_2 nanoparticles. *Fibers and Polymers* 2023; **24(2)**, 779-787.

[7] N Sasunthon, S Laksee and P Pisitsak. Preparation of hemp fabrics with durable UV-protective and antibacterial properties using silver nanoparticles. *Journal of Nanotechnology* 2025; **2025**, 9695944.

[8] T Tandel, A Govekar and S Deogaonkar-Baride. Development of excellent antimicrobial and wash durable fabric with biosynthesized silver nanoparticles using soluble starch, maize starch and rice extract. *Journal of Applied Polymer Science* 2025; **142**, 56926.

[9] M Alauhdin, R Adnan, AD Hatmanto and I Kartini. Phytosynthesized-silver nanoparticles for functionalization of cotton fabric: A systematic literature review. *International Journal of Technology* 2024; **15(3)**, 753-769.

[10] M Rehan, GE Ibrahim, HM Mashaly, M Hasanin, HG Rashad and S Mowafi. Simultaneous dyeing and multifunctional finishing of natural fabrics with *Hibiscus* flowers extract. *Journal of Cleaner Production* 2022; **374**, 133992.

[11] M Sadeghi-Kiakhani, AR Tehrani-Bagha, FS Miri, E Hashemi and M Safi. Eco-friendly procedure for rendering the antibacterial and antioxidant of cotton fabrics via phyto-synthesized AgNPs with *Malva sylvestris* (MS) natural colorant. *Frontiers in Bioengineering and Biotechnology* 2021; **9**, 814374.

[12] H Arshad, M Saleem, U Pasha and S Sadaf. Synthesis of *Aloe vera*-conjugated silver nanoparticles for use against multidrug-resistant microorganisms. *Electronic Journal of Biotechnology* 2022; **55**, 55-64.

[13] M Khan, MA Saeed, S Ullah, MR Repon, AD Pranta, N Yunusov and MM Hossain. Development of self-cleaning and antibacterial properties on cotton fabric using silver nanoparticles and PFOTS. *SPE Polymers* 2024; **5(4)**, 568-575.

[14] Z Yu, J Liu, H He, Y Wang, Y Zhao, Q Lu, Y Qin, Y Ke and Y Peng. Green synthesis of silver nanoparticles with black rice (*Oryza sativa* L.) extract endowing carboxymethyl chitosan modified cotton with high anti-microbial and durable properties. *Cellulose* 2021; **28(3)**, 1827-1842.

[15] M Wu, B Ma, T Pan, S Chen and J Sun. Silver-nanoparticle-colored cotton fabrics with tunable colors and durable antibacterial and self-healing superhydrophobic properties. *Advanced Functional Materials* 2015; **26(4)**, 569-576.

[16] S Yasin, L Liu and JM Yao. Biosynthesis of silver nanoparticles by bamboo leaves extract and their antimicrobial activity. *Journal of Fiber Bioengineering and Informatics* 2013; **6(1)**, 77-84.

[17] N Jayarambabu, K Saraswathi, A Akshaykranth, N Anitha, TV Rao and RR kumar. Bamboo-mediated silver nanoparticles functionalized with activated carbon and their application for non-enzymatic glucose sensing. *Inorganic Chemistry Communications* 2023; **147**, 110249.

[18] J Peng, L Wu, H Zhang, B Wang, Y Si, S Jin and H Zhu. Research progress on eco-friendly superhydrophobic materials in environment, energy and biology. *Chemical Communications* 2022; **58(80)**, 11201-11219.

[19] R Cai, K Glinel, DD Smet, M Vanneste, N Mannu, B Kartheuser, B Nysten and AM Jonas. Environmentally friendly super-water-repellent fabrics prepared from water-based suspensions. *ACS Applied Materials & Interfaces* 2018; **10(18)**, 15346-15351.

[20] SMR Razavi, J Oh, S Sett, L Feng, X Yan, MJ Hoque, A Liu, RT Haasch, M Masoomi, R Bagheri and N Miljkovic. Superhydrophobic surfaces made from naturally derived hydrophobic materials. *ACS Sustainable Chemistry & Engineering* 2017; **5(12)**, 11362-11370.

[21] AA Hebeish, MH El-Rafie, FA Abdel-Mohdy, ES Abdel-Halim and HE Emam. Carboxymethyl cellulose for green synthesis and stabilization of silver nanoparticles. *Carbohydrate Polymers* 2010; **82(3)**, 933-941.

[22] HE Emam and MK El-Bisi. Merely Ag nanoparticles using different cellulose fibers as removable reductant. *Cellulose* 2014; **21**, 4219-4230.

[23] MC Lite, RR Constantinescu, EC Tănăsescu, A Kuncser, C Romaniţan, I Lăcătuşu and N Badea. Design of green silver nanoparticles based on

Primula officinalis Extract for textile preservation. *Materials* 2022; **15(21)**, 7695.

[24] M Rehan, S Zaghloul, FA Mahmoud, AS Montaser and A Hebeish. Design of multi-functional cotton gauze with antimicrobial and drug delivery properties. *Materials Science and Engineering: C* 2017; **80**, 29-37.

[25] P OhadiFar, S Shahidi and D Dorranian. Synthesis of silver nanoparticles and exhaustion on cotton fabric simultaneously using laser ablation method. *Journal of Natural Fibers* 2020; **17(9)**, 1295-1306.

[26] MM El-Zawahry, HSE Khatib, GM Shokry and HG Rashad. One-pot robust dyeing of cotton fabrics with multifunctional Chamomile Flower dyes. *Fibers and Polymers* 2022; **23(8)**, 2234-2249.

[27] S Nam, GW Selling, MB Hillyer, BD Condon, MS Rahman and S Chang. Brown cotton fibers self-produce Ag nanoparticles for regenerating their antimicrobial surfaces. *ACS Applied Nano Materials* 2021; **4(12)**, 13112-13122.

[28] R Mia, MS Sk, ZBS Oli, T Ahmed, S Kabir and MA Waqar. Functionalizing cotton fabrics through herbally synthesized nanosilver. *Cleaner Engineering and Technology* 2021; **4**, 100227.

[29] M Rehan, HM Mashaly, S Mowafi, AA El-Kheir and HE Emam. Multi-functional textile design using in-situ Ag NPs incorporation into natural fabric matrix. *Dyes and Pigments* 2015; **118**, 9-17.

[30] V Hospodarova, E Singovszka and N Stevulova. Characterization of cellulosic fibers by FTIR spectroscopy for their further implementation to building materials. *American Journal of Analytical Chemistry* 2018; **9(6)**, 303-310.

[31] NA Nikonenko, DK Buslov, NI Sushko and RG Zhbankov. Spectroscopic manifestation of stretching vibrations of glycosidic linkage in polysaccharides. *Journal of Molecular Structure* 2005; **752(1)**, 20-24.

[32] E Richard, RV Lakshmi, ST Aruna and BJ Basu. A simple cost-effective and eco-friendly wet chemical process for the fabrication of superhydrophobic cotton fabrics. *Applied Surface Science* 2013; **277**, 302-309.

[33] R Zeng, MZ Rong, MQ Zhang, HC Liang and HM Zeng. Laser ablation of polymer-based silver nanocomposites. *Applied Surface Science* 2002; **187(3-4)**, 239-247.

[34] Shahid-Ul-Islam, BS Butola and A Kumar. Green chemistry based in-situ synthesis of silver nanoparticles for multifunctional finishing of chitosan polysaccharide modified cellulosic textile substrate. *International Journal of Biological Macromolecules* 2020; **152**, 1135-1145.

[35] HE Emam, S Mowafi, HM Mashaly and M Rehan. Production of antibacterial colored viscose fibers using in situ prepared spherical Ag nanoparticles. *Carbohydrate Polymers* 2014; **110**, 148-155.

[36] MS Sk, R Mia, E Hoque, B Ahmed, MJI Amin, SMM Kabir and S Mahmud. Antimicrobial performance of silver–copper–zeolite microparticle-treated organic cotton fabric using versatile methods. *Surface Innovations* 2023; **11(4)**, 223-230.

[37] M Raffi, F Hussain, TM Bhatti, JI Akhter, A Hameed and MM Hasan. Antibacterial characterization of silver nanoparticles against E. coli ATCC-15224. *Journal of Material Science and Technology* 2008; **24(2)**, 192-196.

[38] K Chaloupka, Y Malam and AM Seifalian. Nanosilver as a new generation of nanoproduct in biomedical applications. *Trends in Biotechnology* 2010; **28(11)**, 580-588.

[39] G Franci, A Falanga, S Galdiero, L Palomba, M Rai, G Morelli and M Galdiero. Silver nanoparticles as potential antibacterial agents. *Molecules* 2015; **20(5)**, 8856-8874.

[40] S Ghosh, S Yadav and N Reynolds. Antibacterial properties of cotton fabric treated with silver nanoparticles. *The Journal of The Textile Institute* 2010; **101(10)**, 917-924.

[41] MS Khalil-Abad and ME Yazdanshenas. Superhydrophobic antibacterial cotton textiles. *Journal of Colloid and Interface Science* 2010; **351(1)**, 293-298.

[42] CA Arenas-Chávez, LM de Hollanda, AA Arce-Esquivel, A Alvarez-Risco, S Del-Aguila-Arcentales, JA Yáñez and C Vera-Gonzales. Antibacterial and antifungal activity of functionalized cotton fabric with nanocomposite based on silver nanoparticles and carboxymethyl chitosan. *Processes* 2022; **10(6)**, 1088.

[43] PR More, S Pandit, AD Filippis, G Franci, I Mijakovic and M Galdiero. Silver nanoparticles: Bactericidal and mechanistic approach against drug resistant pathogens. *Microorganisms* 2023; **11(2)**, 369.

[44] HH Afandy, DK Sabir and SB Aziz. Antibacterial activity of the green synthesized plasmonic silver nanoparticles with crystalline structure against gram-positive and gram-negative bacteria. *Nanomaterials* 2023; **13(8)**, 1327.

[45] M Guzman, J Dille and S Godet. Synthesis and antibacterial activity of silver nanoparticles against gram-positive and gram-negative bacteria. *Nanomedicine: Nanotechnology, Biology and Medicine* 2012; **8(1)**, 37-45.

[46] A Ivask, A Elbadawy, C Kaweeteerawat, D Boren, H Fischer, Z Ji, CH Chang, R Liu, T Tolaymat, D Telesca, JI Zink, Y Cohen, PA Holden and HA Godwin. Toxicity mechanisms in *Escherichia coli* vary for silver nanoparticles and differ from ionic silver. *ACS Nano* 2014; **8(1)**, 374-386.

[47] A Khoddami, SS Shokohi and ZM Sebdani. A facile method for anti-bacterial finishing of cotton fabrics using silver nanoparticles. *Industria Textila Journal* 2012; **63(1)**, 20-26.

[48] M Zhang, P Wang, H Sun and Z Wang. Superhydrophobic surface with hierarchical architecture and bimetallic composition for enhanced antibacterial activity. *ACS Applied Materials & Interfaces* 2014; **6(24)**, 22108-22115.

[49] A Granados, R Pleixats and A Vallribera. Recent advances on antimicrobial and anti-inflammatory cotton fabrics containing nanostructures. *Molecules* 2021; **26(10)**, 3008.

[50] Z Mazrouei-Sebdani and A Khoddami. Alkaline hydrolysis: A facile method to manufacture superhydrophobic polyester fabric by fluorocarbon coating. *Progress in Organic Coatings* 2011; **72(4)**, 638-646.