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Development of Antimicrobial Cotton Fabric Impregnating AgNPs Utilizing Contemporary Practice

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Abstract: Multifunctional fabrics using conventional processes have piqued increasing global interest. The focus of this experiment was to assess the modification of the cotton fabric surface by utilizing silver nanoparticles (AgNPs) and introducing functional properties along with sustainable dyeing performance. A single-jersey knitted fabric composed of cellulose-enriched 100% natural fiber (cotton) with an areal density of 172 GSM was used in this study. The standard recipe and test methods were employed. FTIR-ATR spectra were used to determine the fixing of AgNPs onto the fiber surface. A comparative assessment was conducted in response to the distribution of color, color fastness to wash, water, perspiration, rubbing, and light. Scanning electron microscopy (SEM) was used to characterize the surface of nano-Ag-deposited specimens. In terms of functional properties, antimicrobial activity was scrutinized. Our findings reveal that the nanoparticles impart remarkable antibacterial effects to cellulose-enriched fabric against *S. aureus* (Gram-positive) and *E. coli* (Gram-negative). Direct dyes were used for dyeing the proposed samples, resulting in enhanced dyeing performance. Except for light fastness, the samples dipped with AgNPs showed outstanding color levelness and color durability characteristics. The developed fabrics can be applied in a wide range of functions, including protective clothing, packaging materials, and healthcare, among others.

Keywords: AgNPs; antibacterial activity; cotton fabric; direct dyeing; functional properties

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1. Introduction

Fabrics made from cotton fibers are generally renowned for having outstanding attractive attributes, such as sharp absorbency, good breathability, and comfortable wear. Comparatively, while the strength of cotton fabric is less, and its durability is below the satisfactory level, it is nevertheless leading the world owing to its unique properties. In the modern era, smart-looking cotton fabrics are demanded that have functional properties, along with both durability and comfortability. The use of nanotechnology opens up several possibilities for acquiring these advanced properties in cotton clothing [1–4].

In textile manufacturing, functional finishes have become more significant in the acquisition of multifunctional properties. Most implemented functional finishes are antistatic, durable, antimicrobial, dirt resistant, flame resistant, water repellent, wrinkle recovering, self-cleaning, and offer ultraviolet protection. Modification of textile surfaces has an excellent impact on improving these functional values. In recent years, the use of noble

metal nanoparticles in the development of multifunctional fabrics has proven to be one of the most significant methods [5–7]. Each of these nanoparticles has the ability to provide extraordinary effects on the fabric surface; for instance, ZnO is used for UV-protective clothing, silver for antimicrobial purposes, TiO_2 for self-cleaning fabrics, and silver and ZnO for conductive textiles [8–11].

All of these nanoparticles are implemented particularly on cotton fabric surfaces, because they are suitable for manufacturing garments for sports, leisure, and healthcare products such as bandages, absorbent pads, gauze dressings, wadding, surgical gowns, uniforms, etc. [12]. Nevertheless, the moisture content of cellulose-enriched cotton is so high that it makes fibers more susceptible to microbial attack, and becomes a perfect medium for bacterial and fungal growth [13,14]. Having been historically acknowledged as robust biocides with antimicrobial activity, silver nanoparticles have greater opportunities for use in textile resources. Higher antimicrobial efficiency is achieved when the particle size becomes smaller [15]. Furthermore, due to their localized surface plasmon resonance (SPR) capabilities, metal particles may offer greater coloring [16,17]. Anisotropic Ag nanoparticles (AgNPs) exhibit a wide range of vivid hues, as a result of their surface plasmon resonance (SPR) [18,19]. Altering the dimensions and structure of the AgNPs may easily modify such features. As a result, various methodologies for the synthesis of AgNPs have been developed, including physical, chemical, and biological techniques [20]. Additionally, for the safe dyeing of cotton, anisotropic AgNPs with well-tailored SPRs can offer an alternative solution to natural dyes. Anisotropic AgNPs can thus be utilized not only to dye cotton fabrics with attractive and varied hues, but also to make them antimicrobial [18].

As they offer higher resistance to microbes without changing the color of the fabric significantly, AgNPs are applied to cotton fabric surfaces in order to enhance their antimicrobial properties. However, the application process needs a great deal of attention, because the synthesis and the application of nanoparticles are an accumulation process. Failing to synthesize and apply the nanoparticles via appropriate processes can lead to the loss of their distinct characteristics [21,22]. In order to avoid this problem, the in situ synthesis process is better to apply nanoparticles precisely onto the fabric surface, where the cotton fabric is used as the medium to stabilize and grow AgNPs.

Some researchers have utilized the in situ application method to impregnate AgNPs into the cotton fabric. The AgNPs are used to coat the cotton fabric, where the starch aldehyde converts silver nitrate to metallic silver, while also adhering the nanoparticles to the fabric surface. Another study proposed employing ultrasonic irradiation to sonochemically encapsulate silver nanoparticles (AgNPs). The AgNPs, which were made via a fungal process on cotton textiles, had potent antibacterial properties. It was found that the enhanced antibacterial activities of plasma-treated cotton fabric can be developed via in situ synthesis of AgNPs. In situ production of AgNPs from silver nitrate salt and aloe vera can provide UV protection and antimicrobial action in cotton fabrics. By eliminating the separate reaction time, in situ production of AgNPs results in adequate particle deposition [9,22–32]. Almost all of the relevant studies evaluated antimicrobial activity, but very limited literature was observed for wash durability. Antimicrobial activity levels can be changed based on particle size, shape, concentration, and pre- and post-deposition surface modification. Better wash durability was detected in the present study. No works observed in literature considered the degree of color levelness measurement in AgNP-impregnated cotton fabrics.

In this study, our approach was to load the cotton fabric with AgNPs by applying an in situ synthesis process. Alkali treatment played a significant role in this experiment. This study discusses the surface modification of the sample fabric after deposition of AgNPs, based on SEM analysis, as well as the reaction between cellulose structure and silver ions, via FTIR analysis. The experiment also shows the antibacterial effectiveness and washing stability, which were tested against the Gram-positive bacterium *Staphylococcus aureus* and

the Gram-negative bacterium *Escherichia coli*. The influence of the presence of AgNPs on the color change of dyed fabrics is also evaluated.

2. Materials and Methods

2.1. Materials and Chemicals

The cellulose-enriched cotton fabric employed in this experiment was obtained from a local market. Table 1 indicates the whiteness index, brightness index, color coordinates, and areal density of the scoured/bleached cotton fabric. A combed yarn of 16.3 tex was used to fabricate the fabric. The geometrical properties of the fabric are stated in Table 2. Silver nitrate ($AgNO_3$, 99.9% pure), sodium hydroxide pellets (NaOH, 99.8% pure), ascorbic acid ($C_6H_8O_6$, extra-pure), and acetic acid (CH_3COOH) were bought from Merck, Darmstadt, Germany. Direct dyes such as C.I. Direct Red 13, C.I. Direct Blue 8, and C.I. Direct Yellow 8 were obtained from DyStar Chemicals Limited, International Business Park, Singapore. Figure 1 demonstrates the chemical structures of C.I. Direct Red 13, C.I. Direct Blue 8, and C.I. Direct Yellow 8.

Table 1. WI, BI, color coordinates, and areal density of pretreated (NaOH- and H_2O_2-treated) cellulose-enriched cotton fabric.

WI	BI	L*	a*	b*	c*	H	Areal Density
68.38	94.19	93.68	−0.30	3.67	3.68	94.74	172 g/m^2

Table 2. Geometric parameters of the fabric.

Course per Inch (CPI)	Wales per Inch (WPI)	Stitch Length (SL)
48	37	2.75 mm

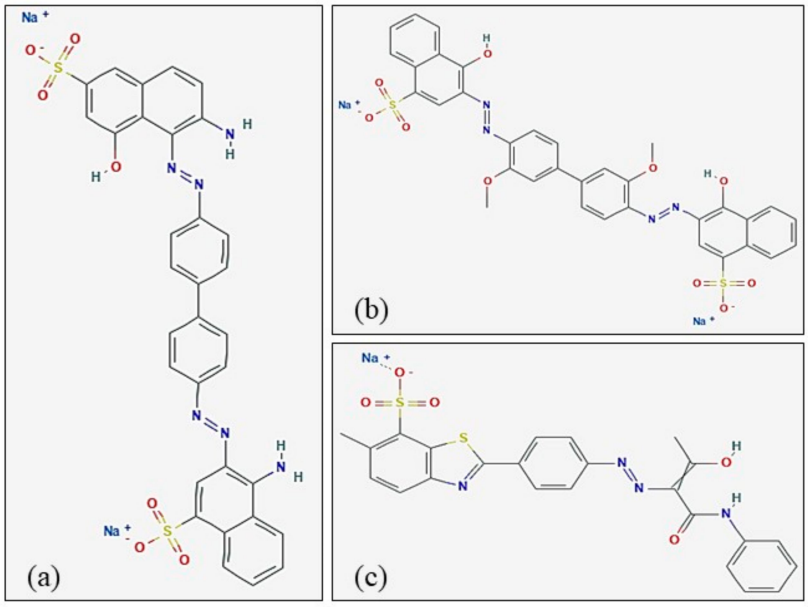

Figure 1. Chemical structure depiction of (**a**) C.I. Direct Red 13, (**b**) C.I. Direct Blue 8, and (**c**) C.I. Direct Yellow 8.

All necessary chemicals were obtained from Redox Chemicals Ltd. in Westlink Tech-park, Singapore, including soda ash (Na_2CO_3), Glauber's salt ($Na_2SO_4 \cdot 10H_2O$), leveling agent (IRSO), and soaping agent (GASOP-100-RUBY). All of the dyes and chemicals used were of analytical grade, without the need for additional decontamination.

2.2. Methods

2.2.1. Combined NaOH and H_2O_2 Treatment

The raw (grey), primarily collected cellulose-enriched cotton fabric was subjected to the same bath-scouring and bleaching process as employed in the recipe mentioned in Table 3, employing the exhaust method.

Table 3. Recipe for combined NaOH and H_2O_2 treatment of the raw fabric.

Chemicals/Parameters	Amount
Wetting agent	1.0 g/L
Sequestering agent	0.5 g/L
Detergent	1.0 g/L
Sodium hydroxide (NaOH)	10 g/L
H_2O_2 stabilizer	0.5 g/L
Bleaching agent (H_2O_2)	1.0 g/L
Material–liquor ratio	1:10
Temperature	60 °C
Time	60 min

2.2.2. Impregnation with AgNPs

The fabric was dipped in 1 M $AgNO_3$ solution at 25 ± 2 °C for 10 min. Then, the fabric was immersed in 0.01 M ascorbic acid for 20 min. The scoured and bleached fabric was impregnated in sodium hydroxide (NaOH) (1 M) at a material-to-liquor ratio of 1:20 for 20 min, before being dipped in $AgNO_3$ solution.

2.2.3. Dyeing

Briefly, an infrared lab sample coloring machine (XIAMEN RAPID, Fujian, China) was used to dye the samples via the exhaust technique at 60 °C for 60 min. The dye bath was then cooled to 40 °C before being rinsed at room temperature. Afterwards, washing was carried out with ISO standard soap of 0.5 g/L at 70 °C for 10 min, in order to eliminate unstable dye from the fabric exterior. The fabric-to-liquor ratio was maintained at 1:10 when dyeing and soaping. After soaping, squeezing was performed, and samples were dried on a flat dryer machine (MESDAN, Brescia, Italy). The recipe of direct dyeing is described in Table 4. The process curve of direct dyeing is shown in Figure 2. The dyed sample without AgNP impregnation was denoted as CF-0A, and the AgNP-impregnated samples was denoted as CF-1A.

Table 4. Recipe for the direct dyeing of cotton fabric.

Chemicals/Parameters	Amount
Soda ash	5 g/L
Glauber's salt	10 g/L
Leveling agent	1 g/L
C.I. Direct Red 13	0.091% (on the weight of fabric)
C.I. Direct Blue 8	0.075% (on the weight of fabric)
C.I. Direct Yellow 8	0.0620% (on the weight of fabric)
Material–liquor ratio	1:10
Temperature	60 °C
Time	60 min

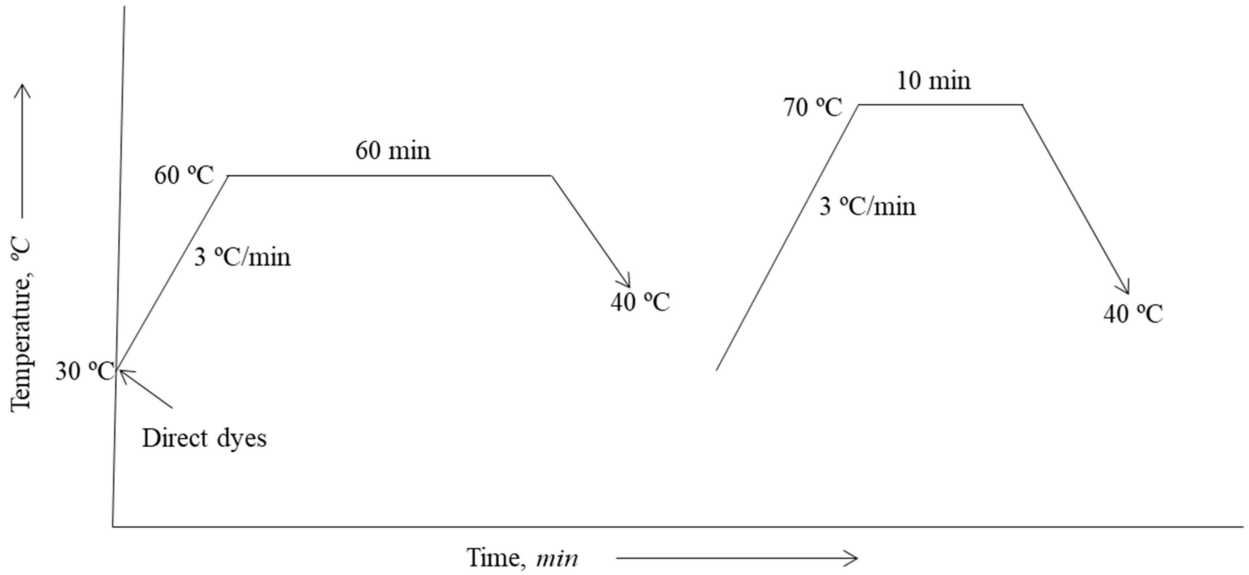

Figure 2. Process curve of direct dyeing.

2.2.4. Scanning Electron Microscopy (SEM)

An FEI Quanta 200 FEG (FEI Company, Hillsboro, OR, USA)—a high-resolution field-emission scanning electron microscope (SEM) with a Schottky-type electron gun—was used to capture images of the knitted specimens for analysis of their morphological changes due to deposition of AgNPs. The microscope vacuum system consists of one turbomolecular pump (TMP, 240 L/s), two ion getter pumps (IGPs), and two mechanical pre-vacuum pumps (PVPs). The working distance can be controlled from 10 to 2 mm. The motorized sample stage can be adjusted ±25 mm in the X, Y, and Z directions, and rotated 360°. The microscope is controlled via a 32-bit graphical user interface in the Windows XP environment. The morphological changes and distribution of silver nanoparticles on the fabric surface can be detected via SEM.

2.2.5. ATR-FTIR Spectral Analysis

ATR-FTIR spectra of direct dyed specimens, obtained using an FTIR spectrophotometer (PerkinElmer Spectrum Two, Beaconsfield, UK), revealed the AgNP–fiber fixation. Samples were carefully placed on the machine's corresponding position of Universal ATR for the assessment of AgNP–fiber bonding characteristics.

2.2.6. Color Distribution

The color distribution (degree of levelness) of each dyed sample was assessed using a datacolor spectrophotometer set to the necessary settings, with reading-1 as the standard, and the other nine as sample batches. The color difference, ΔE, was analyzed using Equation (1) [33]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔL* = L* sample − L* standard, Δa* = a* sample − a* standard, and Δb* = b* sample − b* standard; reading-1 in colored fabric was used as a reference standard, whereas other readings in the same dyed fabric were referred to as samples. Table 5 shows how ΔE values were used to indicate the degree of levelness [34].

2.2.7. Exhaustion and Fixation

Dye exhaustion and fixation percentages can be calculated using Equations (2) and (3), respectively.

$$\text{Exhaustion } \% = \frac{C_i - C_a}{C_i} \times 100 \quad (2)$$

where C_i = the original intensity of the dye in the dye bath, and C_a = the dye concentration in the dye bath after the process.

$$\text{Fixation } \% = \text{Exhaustion}\% - (\text{washing} + \text{soaping} + \text{other})\ \text{loss} \quad (3)$$

Table 5. Interpretation of ΔE values.

ΔE Values	Visual Appearance of Levelness	Extent of Unlevelness
≤0.20	Excellent levelness	Unlevelness not detectable
0.21–0.50	Good levelness	Unlevelness noticeable under close examination
0.51–1.0	Poor levelness	Apparent unlevelness
>1.0	Bad levelness	Conspicuous unlevelness

2.2.8. Color Strength

A datacolor spectrophotometer (Datacolor Spectroflash, SF 650X, Lucerne, Switzerland) was used to measure the color strength (K/S) of the dyed samples, which was based on the Kubelka–Munk hypothesis, which provides the correlation between K/S and R, as shown in Equation (4):

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (4)$$

where R is the reflectance of incident light from the dyed material, whereas K and S denote the dyed fabric's absorption and scattering coefficients, respectively.

2.2.9. Color Fastness

The chromaticity parameters were used to assess the dye–fiber bonding stability of the dyed samples. Color fastness to wash: ISO 105-C06:2010 [35]; color fastness to rubbing (dry and wet): ISO-105-X12:1995 [36]; color fastness to light: ISO 105-B02:2013 [37]; color fastness to water: ISO 105-E01:2013 [38]; and color fastness to perspiration: ISO 105-E04:2013 [39] were all determined using the Gray scale of color change and staining.

2.2.10. Antimicrobial Activity

The ASTM E2149-01 method was used to investigate the antimicrobial consequences of cellulose-enriched natural fiber for both untreated and silver-impregnated specimens. *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative) microorganisms were analyzed for antimicrobial activity. The antimicrobial properties were determined by using Equation (5) to compare the number of bacterial cells surviving after contact with the test specimen to the number of bacterial cells surviving after contact with the non-impregnated sample.

$$\text{Bacterial Reduction (BR), } \% = \frac{Y-X}{Y} \times 100 \quad (5)$$

where X is the number of surviving cells (CFU/mL) in the flasks containing test samples (nanoparticle-deposited cellulose-enriched cotton), and Y is the same for the non-impregnated variant (blank cotton), after 1 h of contact time.

3. Results and Discussion

3.1. Surface Modification of AgNPs Deposited on Samples

The morphological changes of the cotton surface were observed via scanning electron microscopy (SEM), as shown in Figure 3.

Silver nanoparticles were added to the exterior of cellulose-enriched cotton fabric in order to achieve surface modification. The SEM analysis shows the deposition of AgNPs

onto fabric, and how the fabric's surface was transformed as a result of this deposition. The image of SEM analysis of the dyed cotton fabric with and without the deposition of AgNPs is shown in Figure 3. From Figure 3a, it can be observed that the sample CF-0A has a plain surface, as it was not treated with $AgNO_3$ solution. From Figure 3b, deposition of AgNPs can be observed for the sample CF-1A. The reason the deposition of silver nanoparticles onto the sample CF-1A is the dipping of the fabric in caustic soda (NaOH) solution before impregnating it in $AgNO_3$ solution. This alkaline solution plays an effective role in depositing silver nanoparticles on the fabric surface by forming Cell-O-Na+, which works as a host for silver ions. With that, an acid reduction reaction forms nanoparticles by reducing the particle size to the nano level [22,40].

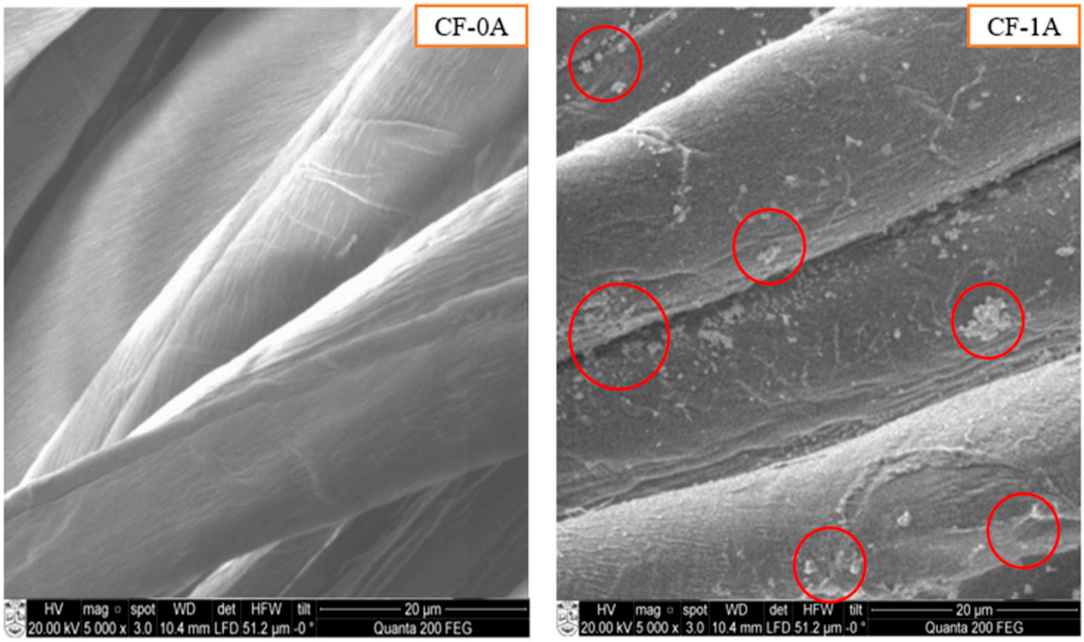

Figure 3. SEM images of the dyed cotton fabric: (**a**) without deposition of AgNPs (CF-0A); and (**b**) with deposition of AgNPs (CF-1A).

3.2. ATR-FTIR Spectra of AgNP-Deposited Samples

Using the FTIR pattern shown in Figure 4, the internal bonding of specimens with and without the deposition of AgNPs was examined. The investigation reflects the bonding phenomenon of nanosilver particles with cotton fibers. The tendencies of the two curves in the figure appear to be genuinely homogeneous, largely denoting the characteristic peaks of the major functional groups of the cellulosic structure of cotton fabrics. It can be observed that the main functional groups of the cellulosic structure include the peaks at 3323–3334 cm^{-1}, 2913–2947 cm^{-1}, 1141–11,667 cm^{-1}, and 1017–1044 cm^{-1} [23,24,41]. According to the IR table, the peaks at 3329 cm^{-1} correspond to O–H stretching, 2915 cm^{-1} is responsible for C–H deformation of $–CH_2–$, 1145 cm^{-1} indicates C–O stretching, and 1023 cm^{-1} shows the deformation of ether linkage (C–O–C).

It is apparent that no substantial modification happened on cotton because of caustic soda (NaOH) or silver treatment, which is consistent with the findings of Li Shuhui et al. [42]. Therefore, it can be stated that treating the cotton fabric with nanosilver does not influence the chemical structure of the fabric [43], ensuring that there is no chemical interlinkage between cellulose chains and silver nanoparticles [22,44]. Thus, deposition of AgNPs does not affect the chemical structure of the cotton fabric, merely causing the physical deposition of nanosilver on the fabric surface [22,43].

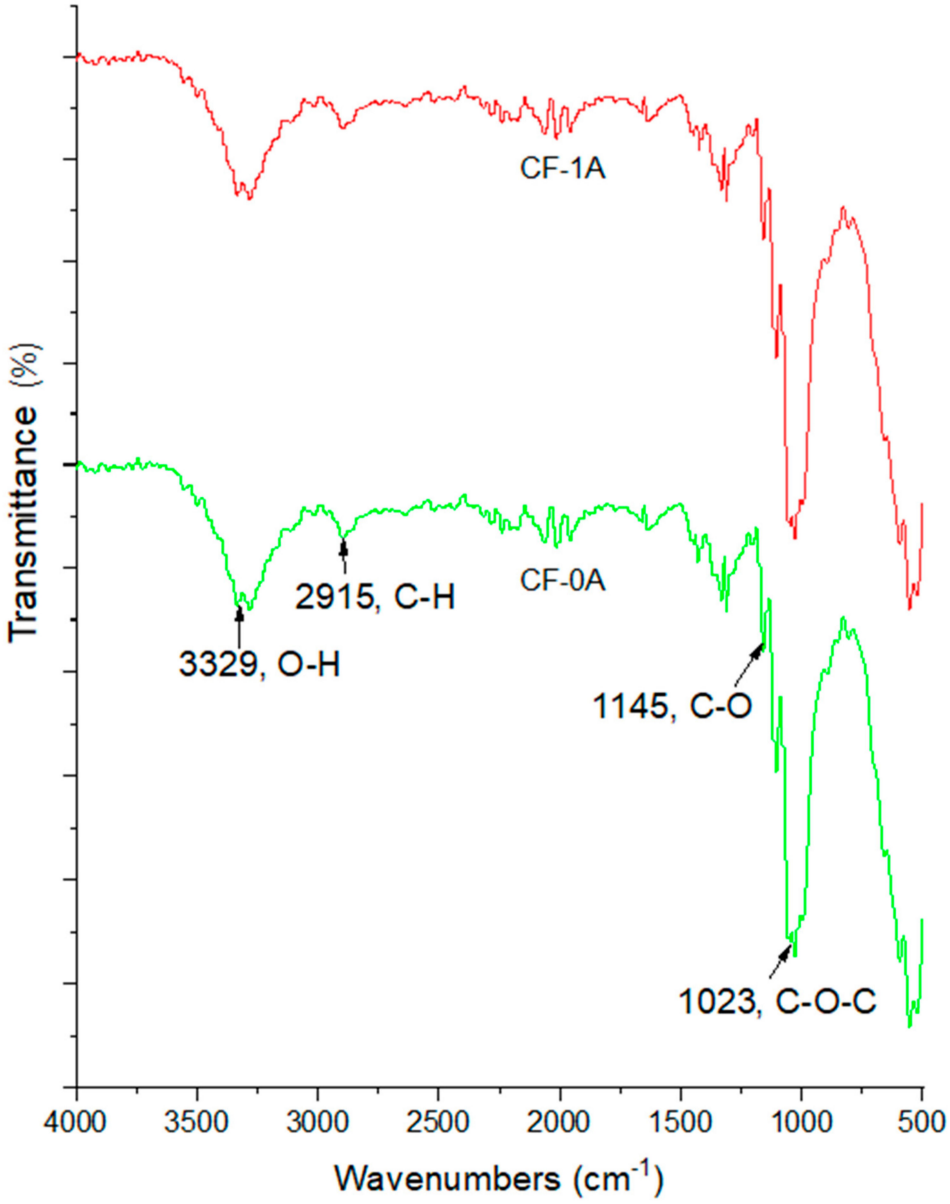

Figure 4. ATR-FTIR spectra of samples with and without deposition of AgNPs on the fabric surface.

3.3. Color Distribution

The uniformity of dye molecule allocation on the fiber surface considerably influences the levelness of color, as mentioned in Table 6.

Table 6. Distribution of color (degree of color levelness).

Sample Types	ΔE Values of Dyed Samples										Average ΔE
	R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	
		Batch Readings									
CF-0A	Standard	0.142	0.138	0.161	0.122	0.152	0.143	0.114	0.117	0.094	0.131
CF-1A		0.324	0.229	0.251	0.247	0.254	0.168	0.148	0.146	0.202	0.219

Equal distribution of dye molecules on the fiber surface is a vital indicator of the levelness of color of a dyed fabric. To confirm the natural harmonious propagation of

dye molecules on the fiber surface, the leveling agents were used in a direct dye bath in this experiment [45]. Determining the degree of color levelness of the samples CF-0A and CF-1A, Table 6 shows how homogeneously the dye molecules were distributed in the sample fabrics. The dyed sample CF-0A, without deposition of AgNPs, showed excellent color levelness, which indicates that the dye particles were distributed uniformly on the fiber surface. On the other hand, noticeable unlevelness under close examination was observed for the dyed sample CF-1A with deposition of AgNPs. Comparatively higher unlevelness—but not exceeding the acceptable limit—was identified for CF-1A, because of the deposition of AgNPs on the fabric surface, preventing the dye molecules from spreading evenly.

3.4. Color Strength, Dye Exhaustion, and Dye Fixation

Figure 5 represents the results of color strength, while Figure 6 shows the dye exhaustion and fixation of the dyed samples CF-0A and CF-1A.

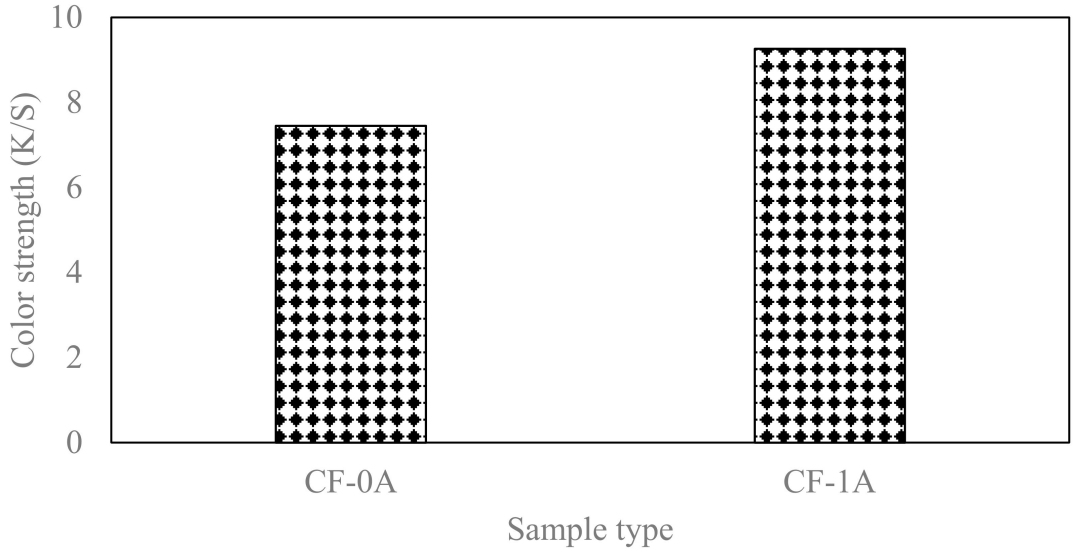

Figure 5. Color strength of the dyed fabrics.

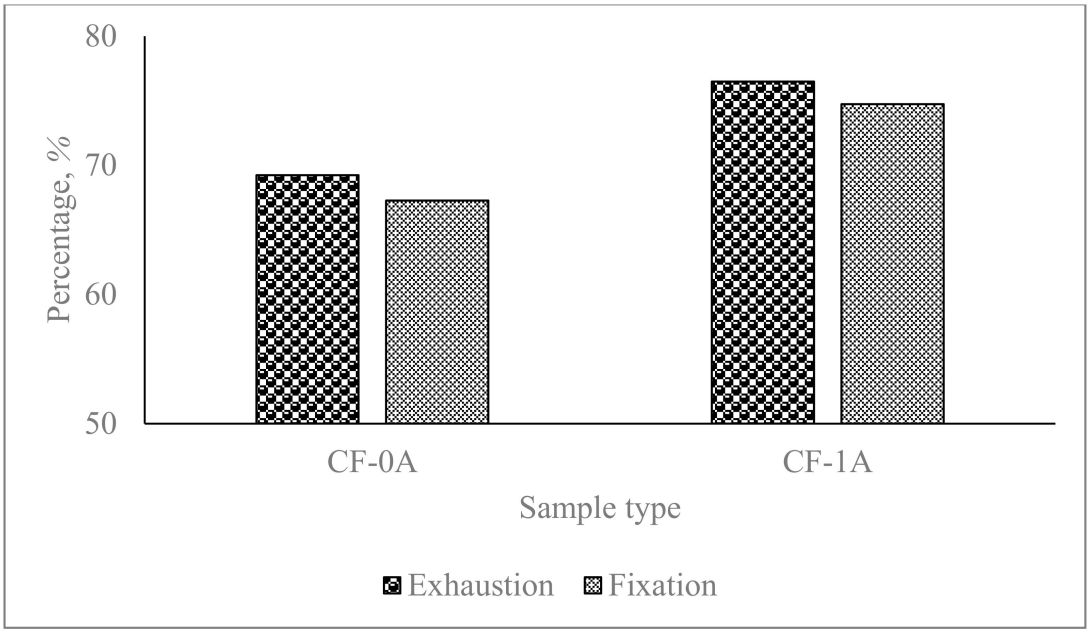

Figure 6. Dye exhaustion and fixation percentages of the dyed fabrics.

The AgNPs had a noticeable positive influence on color strength (K/S), dye exhaustion, and dye fixation, as shown in Figures 5 and 6. For sample CF-1A, a 24% increase in color strength was detected compared with CF-0A. Compared with the sample CF-0A, the dye exhaustion of the sample CF-1A was found to be 10.47% higher, while the dye fixation was 11.08%. It can be seen that the sample with deposition of AgNPs has better color strength, dye exhaustion, and dye fixation capability.

3.5. Color Fastness

Table 7 shows the color fastness to wash, water, and perspiration, while Table 8 represents color fastness to rubbing and light, of the dyed samples with and without the deposition of AgNPs.

Table 7. Color fastness to wash, water, and perspiration.

Color Fastness		Sample Code	Change in Color	Staining in Color					
				Acetate	Cotton	Polyamide	Polyester	Acrylic	Wool
Wash fastness		CF-0A	2–3	4–5	3–4	4–5	4–5	4–5	4
		CF-1A	4	4–5	4	4–5	4–5	4–5	4
Water fastness		CF-0A	3	4–5	3–4	4–5	4–5	4–5	4
		CF-1A	3–4	4–5	4–5	4–5	4–5	4–5	4
Perspiration	Acidic	CF-0A	3–4	4–5	4	4–5	4–5	4–5	4
		CF-1A	4	4–5	4	4–5	4–5	4–5	4
	Alkaline	CF-0A	3–4	4–5	4	4–5	4–5	4–5	4
		CF-1A	4	4–5	4	4–5	4–5	4–5	4

Table 8. Color fastness to rubbing and light.

Sample Types	Rubbing Fastness		Light Fastness
	Dry Condition	Wet Condition	
CF-0A	3	2–3	3
CF-1A	3–4	3	3–4

The sample without deposition of AgNPs showed a comparatively lower rating of color fastness to washing, water, and perspiration compared to the sample with deposition of AgNPs. Regarding wash fastness, mild color stains were observed for CF-1A, whereas moderate staining happened for CF-0A on the cotton and wool portions. In terms of water fastness, minor staining was observed for CF-1A on the wool part only, whereas for CF-0A moderate staining was found on the cotton and the wool portions of the multifiber fabric. For acidic and alkaline perspiration of both samples, slight color staining appeared on the cotton and wool. Almost-perfect color durability was observed for dyed fabric with deposition of AgNPs in terms of wash, water, and perspiration fastness, compared to dyed fabric without the deposition of AgNPs.

For light and rubbing fastness, moderate behaviors were noticed for the samples CF-0A and CF-1A (Table 8). For dyed fabric CF-1A with the deposition of AgNPs, dry and wet rubbing fastness were graded as moderate-to-good (i.e., 3–4) and moderate (i.e., 3), respectively. For dyed fabric CF-0A without the deposition of AgNPs, dry and wet rubbing fastness were rated as moderate (i.e., 3) and fair-to-moderate (i.e., 2–3), respectively. Regarding light fastness, the rating was recorded as fair (i.e., 3) for the sample CF-0A. Conversely, a fair-to-moderate (i.e., 3–4) rating was obtained for the sample CF-1A.

The color performance of the sample with the deposition of AgNPs was clearly superior to that of the sample without the deposition of AgNPs, as shown in Figures 5 and 6 and Tables 7 and 8. The deposited silver ions on the fabric surface act as a mordant, allowing

more dye particles to be absorbed by the fabric. Nanosilver deposition further improves the fastness qualities, since the silver ion is a metal, and metallic molecules create a covalent bond with the dyestuff [44,46]. Furthermore, the sulfonate groups (SO_3^-) of direct dye (Figure 1) produce anionic charges that are attracted toward the fiber due to the polarity formed by the silver ions on the fabric surface [47]. As a result, the dyestuff forms a strong bond with the nanoparticles, resulting in improved color fastness, as well as greater exhaustion and fixation of dye molecules. The increased dye exhaustion signifies that silver nanoparticles play a vital role in reducing dye waste.

3.6. Antimicrobial Efficiency

The antimicrobial efficiency of the cotton single jersey fabric was assessed against the Gram-positive bacterium *S. aureus* and the Gram-negative bacterium *E. coli*. The rates of bacterial reduction by cellulose-enriched cotton fabric samples loaded with and without AgNPs after laundering are shown in Table 9. As it was not loaded with AgNPs, sample CF-0A has no antibacterial action and can be considered as a piece of basic cotton fabric. Conversely, sample CF-1A exhibited remarkable bacterial reduction against both Gram-positive and Gram-negative bacteria prior to washing. Before washing, it showed a bacterial decrease of 89% for *S. aureus* and 81% for *E. coli*. The following result demonstrates washing durability, where the sample CF-1A was exposed to laundering 10 times for the lifespan test of the treated fabric. The antibacterial effectiveness decreased gradually after washing as the washing cycle lengthened. Though the efficiency decreased, after 10 washing cycles it showed up to 50% bacterial reduction (62% for *S. aureus* and 55% for *E. coli*), indicating that the sample deposited with AgNPs had greater antibacterial activity. This result was achieved because of the biocidal action of silver ions against the bacterial growth on the fabric surface [48]. It can also be observed from Table 9 that the fabric with deposition of AgNPs was more efficient against the Gram-positive bacterium than the Gram-negative bacterium. The summary of the washing durability of antibacterial activity of AgNP-deposited/impregnated cotton fabric published in literature is mentioned in Table 10.

Table 9. Antimicrobial activity and wash durability of AgNP-deposited cotton fabric.

Fabric Type	Washing Cycle	Bacterial Reduction (R%) for *S. aureus* (Gram-Positive)	Bacterial Reduction (R%) for *E. coli* (Gram-Negative)
CF-0A	No	Nil	Nil
CF-1A	No	89	81
	1	77	72
	2	74	65
	5	67	62
	7	63	57
	10	62	55

Table 10. Summary of the washing durability of antibacterial activity of AgNP-deposited/impregnated cotton fabric.

Textile Materials	Deposition/Coating Method	Wash Cycles	Antibacterial Efficiency Reduction, %	Refs.
100% cotton knitted fabric	In situ deposition	10	30.34	Present work
100% cotton knitted fabric	In situ deposition	10	39.34	[22]
Cotton fabric	Pad–dry–cure	20	45.02	[49]
Plain cotton fabric	Pad–dry–cure	10	50.00	[50]
Cotton fabric	Pad–dry–cure	10	57.41	[51]
100% cotton fabric	Pad–dry–cure	10	66.67	[52]
Cotton fabric	Impregnation by pressing	10	100	[53]

4. Conclusions

The present experiment was carried out to investigate the prospect of using silver nanoparticles on cotton fabric to improve dyeing performance and develop antimicrobial activity. The observation was performed to determine how AgNPs influence the properties of fabric in terms of the degree of color levelness, color fastness, color strength, dye exhaustion, dye fixation, and antimicrobial activity. The changes that took place in the bonding of the cellulose structure of the cotton fiber during in situ deposition of AgNPs were confirmed via SEM and ATR-FTIR. The color unevenness was found to be due to the deposition of AgNPs. The results revealed that the color strength increased by 24%, and the dye exhaustion and fixation increased by 10.24% and 11.08%, respectively, compared to the non-deposited specimens. Overall, very good ratings of color fastness were recorded regarding wash, water, and perspiration, as well as rubbing and light fastness. The antibacterial efficacy of the fabric sample coated with silver nanoparticles against the Gram-positive bacterium *S. aureus* and the Gram-negative bacterium *E. coli* was outstanding, and its durability was tested by washing it 10 times. Finally, it can be concluded that activating antimicrobial efficiency by impregnating AgNPs on cotton fabric was effectively performed, and improved the dyeing performance. The designed fabrics can be used in a variety of applications—most notably, healthcare.

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