Heliyon 10 (2024) e37120

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A multi-functional coating on cotton fabric to incorporate electro-conductive, anti-bacterial, and flame-retardant properties

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ARTICLE INFO

Keywords:
Cotton fabric
Electrical conductivity
Anti-bacterial
Flame retardancy
Multi-functionality

ABSTRACT

Multi-functional textiles have become a growing trend among smart customers who dream of having multiple functionalities in a single product. Thus, this study aimed to develop a multi-functional textile from a common textile substrate like cotton equipped with electrically conductive, anti-bacterial, and flame-retardant properties. Herein, a bunch of compounds from various sources like petro-based poly-aniline (PANI), phosphoric acid (H_3PO_4), inorganic silver nanoparticles (Ag-NPs), and biomass-sourced fish scale protein (FSP) were used. The coating was prepared via in-situ polymerization of PANI with the cotton substrate, followed by the dipping in AGNPs solution, layer-by-layer deposition of FSP and sodium alginate, and finally, a dip-dry-cure technique after immersing the modified cotton substrate into the H_3PO_4 and citric acid solution. The key results indicated that the fabric treated with PANI/Ag-NPs/FSP/P-compound exhibited a balanced improvement in all three desired properties as the electrical resistance was reduced by 44.44 % while showing superior bacterial inhibition against gram-positive bacteria (*S. aureus*) and gram-negative bacteria (*E. coli*), and produced dense-black carbonaceous char residues, indicating its flame retardant properties as well. Thus, such amicable developments made the cotton textile substrate a multi-functional textile, which showed potential to be used in medical textiles, wearable electronics, fire-fighter suits, etc.

1. Introduction

In recent times, multi-functional textiles have become one of the most time-demand research areas in the material science field. It is a smart call from the end-users as they expect that a single textile product will be equipped with a good number of novel functionalities to perform multi-dimensional tasks needed for a specific field of use. Very recently, several research groups have already come up with such developments on varied textile substrates, namely cotton [1,2], polyester [3], polyamide [4], etc. in integrating multi-functional properties like flame retardancy, anti-bacterial activity, electro-conductivity, hydrophilicity, hydrophobicity, and so on [1–4].

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https://doi.org/10.1016/j.heliyon.2024.e37120
Received 10 May 2024; Received in revised form 26 August 2024; Accepted 28 August 2024
Available online 29 August 2024

Cotton fabric is a premium choice for users due to its amicable properties like delicate hand-feeling, outstanding air-permeating, and wicked nature, and is widely used in regular apparel to advanced application areas like healthcare and protective apparel industries [5–7]. However, to ensure a multi-dimensional usage of cotton textiles, the textile substrate should be endowed with prerequisite functionalities like flame retardant, anti-microbial proprieties, and so on at a satisfactory level. This is because a cotton textile lacks flame-resistant properties connected to its organic polymer structure containing hydrocarbon moieties, which are readily flammable in a fire source. Moreover, cotton is susceptible to microbial attack due to its polysaccharide configuration and moisture absorption properties, resulting in a favorable condition for microbial growth [8]. Apart from these, like other common textiles, cotton also behaves as an insulator of electrical conductivity, which also confines its application in e-textile-based electronic devices. However, the development of cotton textile-based electronic devices like wearable and flexible supercapacitors [9–11], fire alarming sensors [12,13], human-health monitoring sensors [14,15] etc. have seen enormous rises in recent time.

Thus, to overcome the aforementioned shortcomings and to ensure multi-dimensional applications of cotton textiles, cotton has undergone numerous experiments over the last decade using different classes of compounds likely with an organic, inorganic structure, or their hybridization. For example, Tissera et al. [16] fabricated the electrically conductive cotton fabric through in situ one-pot oxidative polymerization of an organic compound, namely an intrinsic conductive polymer like polyaniline (PANI). Here, the polyaniline (PANI) nanofibers, grafted onto the cotton surfaces via a simple heterogeneous polymerization method, exhibited significantly enhanced electrical conductivity compared to PANI nanoclusters. In another work [17], polyaniline (PANI) was fabricated onto the cotton fabric surface through a two-step in-situ polymerization process using hydrochloric acid and ammonium persulfate (APS) as a dopant and oxidant, respectively. This two-step polymerization process facilitated PANI monomer penetration into the fibers, ensuring good conductivity and EMI shielding of the PANI/cotton composite fabric.

In the meantime, inorganic compounds, namely carbon compounds and metallic nanoparticles were extensively experimented to endow the textile substrate with numerous functionalities. Among them, silver nanoparticles (Ag-NPs) have shown immense practicality in imparting multi-functional properties namely anti-bacterial, ultraviolet-protection, electro-conductivity, and so on to a varied range of polymer substrates due to their inherent characteristics [18], while its greener synthesis methods [19,20] make the Ag-NP a superior choice over others. For example, Pakdel et al. [21] introduced silver nanoparticles (Ag-NPs) to endow the cotton textile with electromagnetic wave attenuation and anti-bacterial properties where they claimed that Ag-NP played the key role in attaining these functionalities. Alongside, a kind of hybridization like co-application of PANI and Ag-NPs was also realized, which revealed that such application could intensify the electrical conductivity of a typical cotton textile by facilitating the transfer of electrical charge along the fibers via forming a network of conductive pathways allowing electrons to flow [22,23].

Meanwhile, to develop a flame-retardant cotton textile, researchers have attempted a varied range of techniques, and formulations and experimented with various types of flame-retardant compounds derived from synthetic, biomass, and mineral sources. For example, Wan et al. [24] came up with some petro-based cheaper compounds, namely phosphoric acid thiourea to synthesize a flame-retardant compound containing necessary flame inhibition elements like phosphorus, nitrogen, and sulfur. They have experimented with this compound on the cotton textile substrate and found that such finishing could bring a notable decrease in peak heat release rate and total heat release while preserving the mechanical properties of cotton textiles. However, in a recent study, Song et al. [25] developed a sustainable flame-retardant coating for cotton fabrics using biomass-derived compounds like fish scale protein (FSP) and phytic acid (PA) in a layer-by-layer self-assembly. Herein, they claimed that this novel approach not only was an environmentally benign application technique but also showed great promise in achieving remarkable flame-retardant performance with a limiting oxygen index (LOI) value of 31.1 %, reduction in total smoke emission by 139 % and enhanced charring. In addition, the protein content of fish scale has already exhibited growth inhibition efficacy against a variety of microorganisms, along with bacteria and fungi [26,27], and thus, can potentially be used in developing antimicrobial textiles. Meanwhile, the combination of sodium alginate and fish scale protein facilitates the deposition of the latter onto the textile surface due to the gelation behavior of sodium alginate, in which a gel-like matrix is formed to entrap and immobilize proteins [28], and also can help to form a thick coating. On the other hand, the presence of sodium alginate in a typical coating formulation can surely boost the flame inhibition activity since sodium alginate (SA) can play the role of a carbon source due to its long-chain aromatic and poly-alcoholic structure [29]. However, a unique multifunctional coating based on polyaniline (PANI), Ag nanoparticles (AgNPs), fish scale protein (FSP), and phosphoric acid is rarely reported.

Thus, being inspired by the future direction concerning the potential use of multi-functional textiles, we aim to incorporate three different novel functionalities, namely electro-conductivity, antimicrobial, and flame retardancy on a widely-used textile substrate like cotton fabric as such attempt is yet to be reported. The key challenge lies in effectively integrating these properties without compromising their performance, necessitating a balanced and synergistic approach. Herein, we have reported the development of a multi-functional cotton fabric based on polyaniline (PANI), Ag nanoparticles (AgNPs), fish scale protein (FSP), and phosphoric acid. First, the cotton surface was modified by PANI by oxidative polymerization, and then, AgNPs were embedded into the PANI-modified cotton substrate in the soaking method. Subsequently, fish scale protein (FSP) in the presence of sodium alginate was deposited in a layer-by-layer deposition followed by the dipping in phosphoric acid solution.

2. Experimental

2.1. Materials

Ready-for-dyeing cotton fabric with a twill woven structure was collected and each sample with a dimension of 10×10 cm^2 was cut, which individually weighed ca. 3g. Aniline ($C_6H_5NH_2$) and phosphoric acid (H_3PO_4) used in this experiment were bought from Millennium Supplier, Dhaka, Bangladesh. The silver nitrate ($AgNO_3$) used in this work was bought from Labtex, Dhaka, Bangladesh.

Raw fish scale as a waste biomass was collected from a local fish market. The rest of the chemicals e.g., sodium per-sulfate ($N_2S_2O_8$), hydrochloric acid (HCl), ammonia ($NH_3.H_2O$), sodium alginate ($NaC_6H_7O_6$), glucose ($C_6H_{12}O_6$), and citric acid ($C_6H_8O_7$) were procured from a local supplier.

2.2. Preparation of Cotton/PANI

At first, 17 mL of 0.1M aniline was taken with distilled water in a beaker to make a 200 mL solution with a final conc. of 8.5 % aniline followed by heating at 70 °C until aniline was completely dissolved. Thereafter, four 10 cm × 10 cm cotton fabric samples were dipped into the earlier-mentioned solution. In another beaker, 25 mL of 3M HCL was added dropwise along with 0.05 M $Na_2S_2O_8$ to make a 100 mL solution. After that, the aniline solution along with cotton fabric samples was taken in an ice bath. Here, an oxidative polymerization of aniline occurred as the solution was kept still at 0 °C for about 120 min.

2.3. Conversion of $AgNO_3$ into Ag-NPs

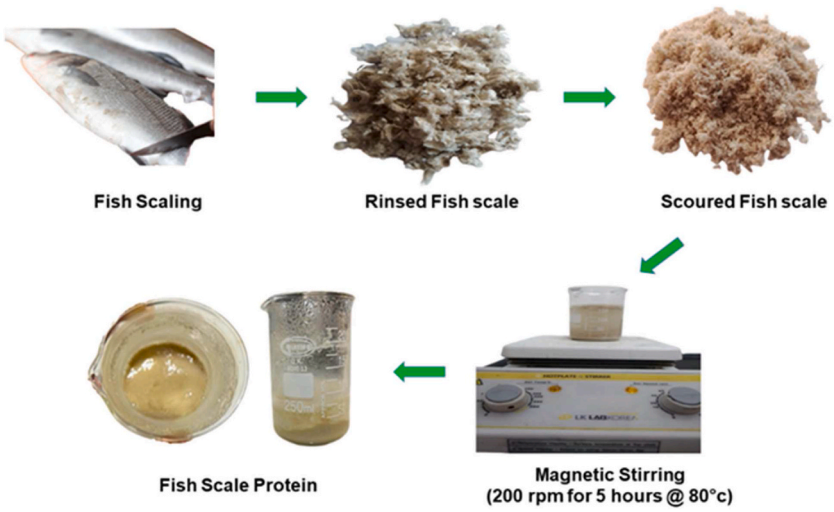
The preparation of AgNPs was carried out according to a previously reported method with a slight modification [30]. First, we prepared two solutions of 3.5g $AgNO_3$ with 200 mL distilled water with a conc. of 1.75 % $AgNO_3$ and 1.4g NaOH with 200 mL distilled water with a conc. of 0.7 % NaOH on two different beakers, respectively. Then, these solutions were mixed and $NH_3.H_2O$ was added dropwise until the complete dissolution happened. This caused the formation of silver ammonia solution which was absorbed into cotton fabric samples and the samples were immersed in the solution for about 60 min. Finally, Ag nanoparticles (Ag-NPs) were formed onto the cotton/PANI fabric surfaces when the samples were treated with glucose solution made by mixing 1g glucose in 100 mL distilled water and kept for about 40 min at room temperature. Here, glucose acted as a reducing agent to form Ag-NPs.

2.4. Preparation of FSP

At first, raw fish scales purchased from the fish market were washed with cold and hot water to remove mucus, fat, and impurities. It was then immersed in a 5 % NaOH solution for 30 min at 80 °C. The cleaned fish scales were dried and stored for future use. In a 500 mL three-necked flask, 9 g of dry product was blended with 200 mL of deionized water with a conc. of 4.5 % FSP and stirred at 200 rpm for 5 h at 80 °C. After cooling, the mixture was filtered through filter paper to separate insoluble parts, and soluble residues (FSP) were preserved in the freezer to use in the next process. The preparation of FSP was presented in Scheme 1.

2.5. Layer-by-layer deposition

In the beginning of layer-by-layer deposition process, we prepared two different polyelectrolyte solutions. In the first beaker, 5g of FSP was taken to make a 1 L solution in the presence of deionized water. In another beaker, 10g of sodium alginate (Na-Alginate) was taken to prepare 1 L of solution. These two beakers were kept on magnetic stirring at 200 rpm in an ambient atmosphere overnight. For the layer-by-layer deposition, samples no 3 and 4 (i.e., S3 and S4) were alternatively immersed into the FSP and Na-alginate (SA) solution. In the first cycle, samples were dipped into the FSP solution for 5 min and then subjected to cold wash for 30 s, and later on, dipped in SA solution for another 5 min followed by a wash with cold water for 30 s. In this way, another 9 cycles were built up onto the textile surface. The aforementioned deposition technique was sketched out in Scheme 2a.



Scheme 1. Preparation of FSP.

2.6. Dipping with phosphoric acid

At this stage, 100 mL solution was made by adding 10 mL phosphoric acid with 90 mL distilled water. Then sample no 4 was taken in this solution and kept dipping for 30 min. Then 100 mL solution of citric acid was made by adding 10 g of citric acid with 100 mL of distilled water. Then half of this solution was taken in two beakers and samples no 3 and 4 were dipped into that beaker individually for 30 min. Then both of the samples were dried for 30 min at 80 °C. Afterward, curing was done for 3 min at 160 °C. The dipping procedure was depicted in Scheme 2b. Finally, the weight gain in terms of dry-weight pick-up % was calculated using the following formula:

$$\textbf{Weight gain } \% = \frac{W_1\text{-}W_0}{W_0} \times 100$$

Here, W_1 and W_0 represent the weight gain % of treated and control cotton fabric samples, respectively. The formulations used in the coating preparation and the weight gain % are summarized in Table 1.

2.7. Characterization

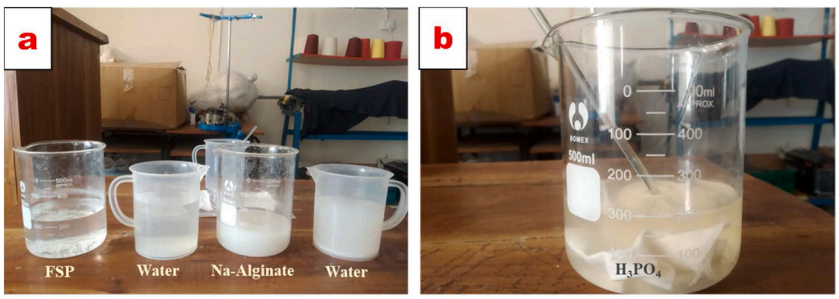
The surface morphology of cotton fabric samples was perceived using scanning electronic microscopy (SEM) (JSM-6700F, JEOL, Japan) whereas the elemental analysis of selected elements present on the fabric surface was observed on an energy dispersive X-ray (EDX) analyzer. The fabric specimens were sputter-coated with a conductive gold layer to avoid charge accumulations before testing.

ATR-FTIR (Attenuated Total Reflectance-The Fourier Transform Infrared Spectroscopy) was used to identify the chemical bonds formed onto the textile surface after the treatment process using a Thermo Nicolet Avatar 6700 FTIR equipped with an attenuated total reflectance device. Fabric specimens were tested using a thin KBr disk and the wavenumber range was set from 4000 to 500 cm^{-1}.

The surface resistance of the treated fabric samples was measured according to the standard testing method ASTM D4496 by using an electrical mega ohm meter under specific temperature, relative humidity, and di-electric ratio. In mega ohm meter the line terminal was placed at one side of the test sample and the earth terminal was placed at the opposite end of the sample. Here the test was carried out at room temperature (26 °C) and the relative humidity was 65 ± 2 %. The test had a dielectric absorption ratio (DAR) of 1.5. Throughout the test, the distance between the two ends of the samples attached to the mega ohm meter remained constant. A specific voltage (2950 V) of the HVI tester was applied to carry out the test. Test voltage (2950 V) was applied for 15 s to get the resistance data from the mega ohm meter.

The antibacterial activity of cotton textiles against two different bacterial species *Staphylococcus aureus* [Gram positive] and *Escherichia coli* [Gram negative] was assessed following the ASTM E2149–01:2001 standard (ASTM International 2001). According to this protocol, 1 g of samples was weighed and ready for antibacterial testing. The bacteria were grown on plates at 37 °C for 24 h. For gram-positive bacteria, Mannitol Salt Agar (MSA) plates were used and for gram-negative bacteria MacConkey agar (McA) plates were used. The colonies that were formed were subsequently introduced with nutrient broth (NB). The cells were harvested and added to 50 mL of normal saline to bring the concentration of bacteria down to the McFarland standards of 0.5 (~ OD 0.1 at 600 nm/10^8 cfu/ml). After this resuscitation, 1g of fabric was immersed in a 50 ml liquid solution containing around 10^8 bacterial cfu/ml. Following that, the glass jars containing the 50 ml bacterial solution were placed in an incubator shaker set at 37 °C for an hour. The glass jars containing the fabric and bacterial solution were taken out of the incubator. The liquid samples were then diluted 10- to 1000-fold, and 100 μl was placed on nutrient agar plates and incubated for 24 h at 37 °C. In comparison to the control plate (only bacteria), this application is assessed when leading to a decrease or increase in the number of bacteria.

For the flame retardancy test, the burning time of cotton fabric samples was recorded using a non-standard method. This test was carried out at a room temperature of 25 °C with a specific humidity of about 65 % using a methane flame source. The burning time was also measured after 10 wash cycles. Herein, the wash process was carried out following an AATCC test method 61 (2A)-1996 in the presence of non-ionic detergent in an ambient atmosphere at 38 ± 3 °C. Here, each cycle of the wash process is equivalent to 5 times home laundering.



Scheme 2. Layer-by-layer deposition (a) and dipping process of cotton fabric (b).

Table 1
Formulations and weight gain % of cotton fabric samples.

Sample	PANI (mL)	$AgNO_3$ (g)	FSP (g)	H_3PO_4 (mL)	Weight gain %
Cotton-control (S-0)	–	–	–	–	0
Cotton/PANI (S-1)	17	–	–	–	4.33
Cotton/PANI/AgNPs (S-2)	17	3.5	–	–	7.8
Cotton/PANI/AgNPs/FSP (S-3)	17	3.5	5	–	13.42
Cotton/PANI/AgNPs/FSP/H_3PO_4 (S-4)	17	3.5	5	10	16.75

3. Results and discussion

3.1. Scanning electron microscope and energy disperse spectroscopy

To investigate the surface morphology and the chemical composition of as-prepared coatings, both the control and treated fabric samples were examined by SEM along with EDS, as presented in detail in Figs. 1 and 2. From the SEM images, it is perceived that the control cotton fabric (S-0) has an intricate structure and is relatively smooth in appearance under a 10-μm scale with 2.50 KX magnifications. After being treated with PANI, the surface gets covered in the presence of PANI molecules and the surface becomes relatively rough for S-1. Next, S-2 illustrates the morphology of the fabric sample that is modified by $AgNO_3$ contributing to a plentiful micro-nano rough structure, and confirms the possible deposition of Ag-NPs onto the fabric surface. However, after the treatment with FSP (S-3), the surface became smoother than the $AgNO_3$-treated fabric sample (S-2). This is because, during the treatment with FSP in a layer-by-layer deposition, some particles like PANI, and Ag-NPs were moved to the interior of the fabric or covered by the deposited moieties, which ultimately tends to lower the roughness of the coating and led to a nearly smoother coating. Meanwhile, after the modification by phosphoric acid, the surface of the FSP-treated fabric sample became even smoother than the S-3 and it is clear that most of the molecules moved to the interior and made strong bonds with the fibers, as shown in S-4.

The chemical elements available in the pristine cotton fabric and treated cotton fabric were determined by EDS to further confirm the deposition of coating ingredients. From the EDS analysis, it is seen that the pristine cotton (S-0) contains only C and O elements with an amount of 48.82 % and 51.18 %, respectively. Meanwhile, the PANI-treated fabric sample comprehends three different elements with an amount of C = 41.44 %, N = 9.92 %, and O = 48.65 %. Subsequently, after being treated with $AgNO_3$, the fabric surface (S-2) shows the presence of C = 40.06 %, N = 0.18 %, O = 59.09 %, and Ag = 0.67 % elements. Later, the fabric sample was treated with FSP (S-3) and thus, it claimed the presence of phosphorus element by P = 5.21 % as shown in Fig. 2. Finally, being treated with phosphoric acid, surface composition revealed the presence of all desired elements available from the applied compounds in a proportion like C = 43.08 %, O = 51.55 %, P = 5.09 %, and Ag = 0.28 %, which ultimately confirms the successful preparation of coating onto the cotton substrate.

3.2. Attenuated total Reflectance-FTIR

Table 2 exhibits the list of chemical bonds and relevant standard peaks of these bonds detected in the attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) and their corresponding graphs are presented in Fig. 3. For example, C-H peaks within 3000–2800 cm^{-1} [31], O-H peaks within 3416–3402 cm^{-1} [32], C-O peaks within 1382–1036 cm^{-1} [33], C=O peaks within 1800–1700 cm^{-1} [34], C=C peaks within 1622–1612 cm^{-1} [32], Ag-O peaks at 445 cm^{-1} [35], -C(=O)N- or amide peaks at 3675 cm^{-1} [33], P-O-H peaks at 945 cm^{-1} [36], P=O peaks at 1187 cm^{-1} [37] were found.

Here, the main component of pure cotton fabric is cellulose, which is composed of long chains of glucose molecules and thus, from the ATR-FTIR graphs strong absorbance peaks in the fingerprint region 2999, 2980, 2985, 2980, and 2999 cm-1 for S-0, S-1, S-2, S-3,

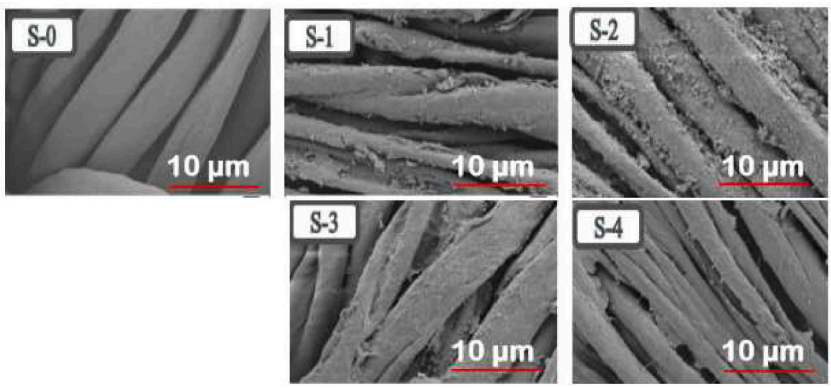


Fig. 1. SEM images of cotton fabric samples.

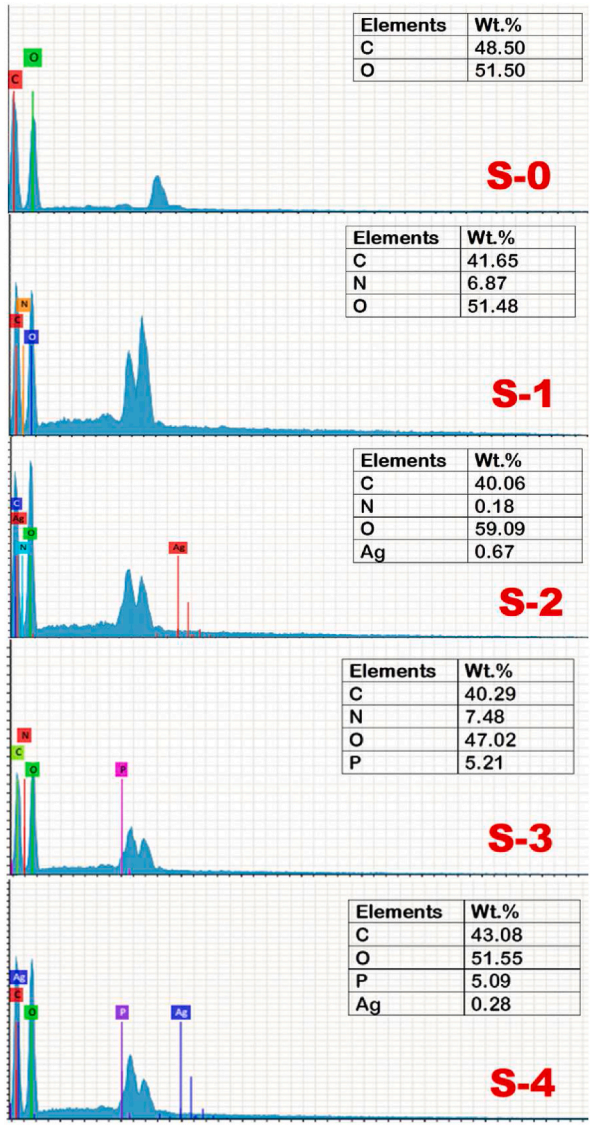


Fig. 2. Elemental analysis of cotton fabric samples from the EDS test.

Table 2
FTIR absorption bands of cotton fabric samples.

Peak Characterization	Literature review	S-0	S-1	S-2	S-3	S-4
C-H	3000–2800	2999	2980	2985	2980	2999
O-H	3416–3402	3405	3435	3411	3415	3418
C-O	1382–1036	1140	1135	1136	1136	1135
C=O	1800–1700	1715	1715	1780	1790	1790
C=C	1622–1612		1575	1590	1611	1590
Ag-O	445			466	459	473
–C(=O)N–	3675				3675	3645
P-O-H	945					900
P=O	1187					1190

and S-4, respectively and in 3405, 3435, 3411, 3415, and 3418 cm-1 for S-0, S-1, S-2, S-3, and S-4, respectively correspond to C-H and O-H bonds of glucose units were detected. Additionally, there were peaks in the region of 1140, 1135, 1136, 1136, and 1135 cm-1 for S-0, S-1, S-2, S-3, and S-4 due to the C-O bonds of the cellulose structure. After the treatment with polyaniline, the absorbance peaks of treated cotton textiles change from the pure textile substrate due to the presence of polyaniline on the fabric surface. The related data

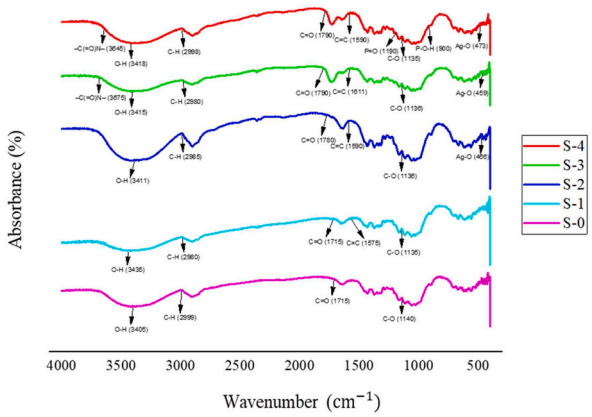


Fig. 3. ATR-FTIR line graph of cotton fabric samples.

of poly-aniline typically showed peaks in the region of 1575, 1590, 1611, and 1590 cm^{-1} in S-1, S-2, S-3, and S-4, respectively due to the presence of C=C bonds. The silver nanoparticle-treated fabric sample exhibited a new peak at around 466, 459, and 473 cm^{-1} for S-2, S-3, and S-4, respectively due to the presence of a typical Ag-O bond. Meanwhile, the FTIR data of FSP can be detected in the region of 3675, and 3645 cm^{-1} for S-3, and S-4 due to the presence of amide bonds (–C(=O)N–) in fish scale protein peptide. Finally, for the phosphoric acid-treated fabric sample (S-4), the absorbance peak appears in the region of 900 cm^{-1} due to the presence of P-O-H bonds, and peaks in the region of 1190 cm^{-1} due to the presence of P=O bonds were realized. Thus, from these aforementioned test data, it can be further speculated that the applied compounds play a pivotal role in preparing the coating composite onto the cotton fabric surface.

3.3. Electrical conductivity

The electrical conductivity data obtained in terms of a decrease in resistance % is shown in Table 3. Here, for the pristine cotton sample (S-0), the surface resistance was measured as 5.67 G-ohm. Then the PANI-treated cotton fabric sample showed a resistance value of 2.10 G-ohm. This reduction in the resistance % occurred due to its conductive properties arising from the presence of an intrinsically conductive polymer like PANI. As a result, the resistance of PANI-treated fabric (S-1) decreased by about 62.96 %. Next, the fabric sample treated with PANI and $AgNO_3$ (S-2) exhibited a further decrease in resistance %. Here, it is realized that the silver element can provide some sort of conductivity to the textile substrate, and the overall conductivity increases. Meanwhile, after being treated with FSP, sodium alginate, and phosphoric acid, electro-conductive properties were slightly compromised for both the fabric samples (i.e., S-3 and S-4) as the value of resistivity followed a growing trend which might be due to the mutual interactions among different charge particles available from the deposited coating ingredients.

The above-mentioned cotton fabric samples were further investigated to judge their capability to light an LED bulb using a circuit. Thus, a circuit with a voltage of 3 V was embedded in the textile substrate. It was found that the applied voltage could able to light the LED bulb at a different intensity corresponding to the level of conductivity of the cotton fabric sample (see Fig. 4) and, ultimately it is justified that the as-developed cotton textiles show potential to be used in e-textile-based applications.

3.4. Anti-bacterial properties

The anti-bacterial properties of cotton fabric samples was assessed by visual inspection of images received from the test (see Fig. 5). From these images, it is clearly seen that the pristine cotton textile (S-0) without any treatment exhibited no anti-bacterial activity connecting to the presence of countless surviving cells in the plate (see Fig. 5). Even, after the treatment with PANI (S-1) and $AgNO_3$ (S-2); the treated fabric samples exhibited no significant alteration in bacterial growth, especially against *E. coli* bacteria. However, a remarkable inhibition in bacterial growth was seen in the next stage after the treatment with FSP and sodium alginate in a layer-by-layer deposition. The as-treated fabric sample (S-3) exhibited almost net zero growth of bacteria since it is believed that proteins,

Table 3
Electrical resistance data of cotton fabric samples.

Sample	Resistance (GΩ) [avg. of 3 readings]	Decrease in Resistance (%)
S-0	5.67	0
S-1	2.10	62.96
S-2	1.98	65.08
S-3	3.37	40.56
S-4	3.15	44.44

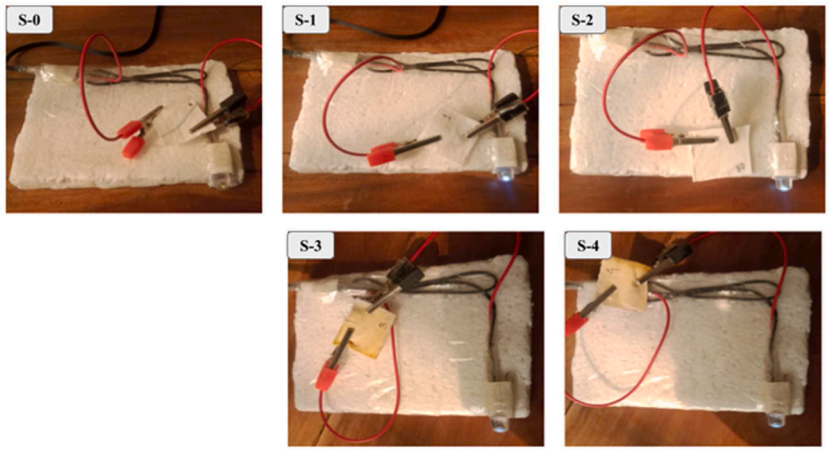


Fig. 4. Digital images of electrical conductivity test of cotton fabric during lighting an LED bulb.

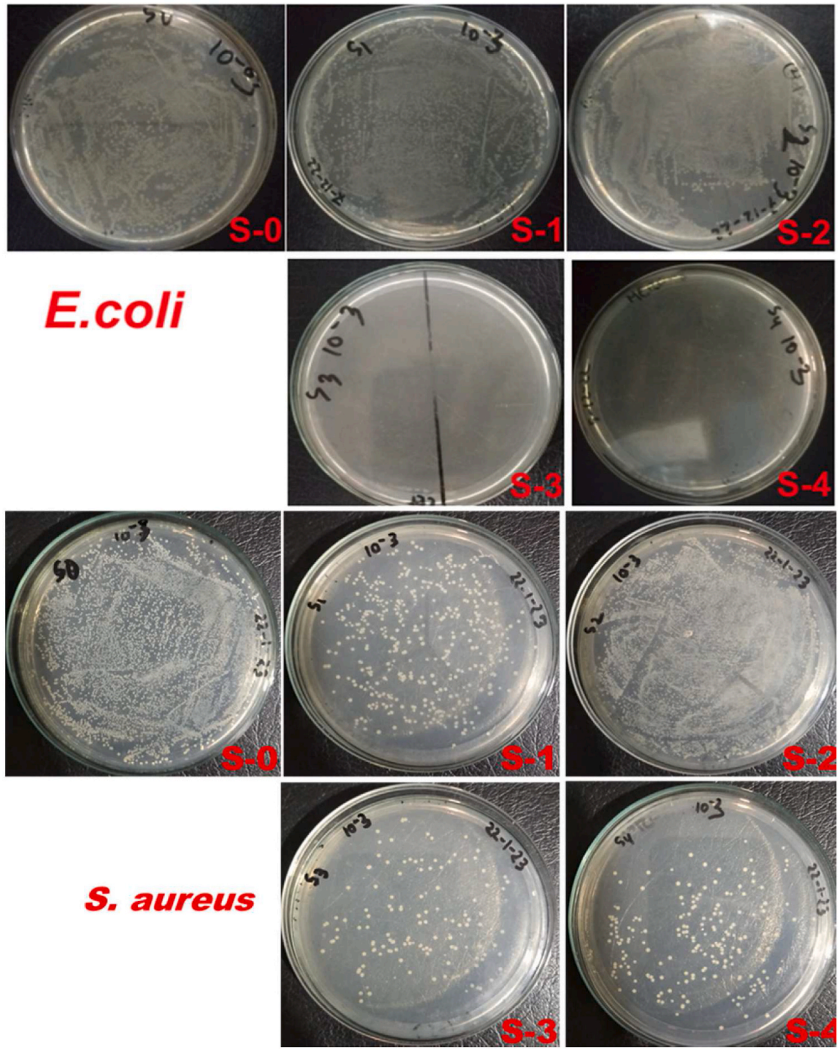


Fig. 5. Images from the anti-bacterial test.

Table 4
Burning test data of cotton fabric samples.

Sample	Burning time (s) (Before wash)	Burning time (s) (After 10 washes)
S-0	18 ± 4	18 ± 3
S-1	24 ± 3	18 ± 5
S-2	27 ± 5	19 ± 4
S-3	44 ± 5	30 ± 4
S-4	39 ± 4	26 ± 3

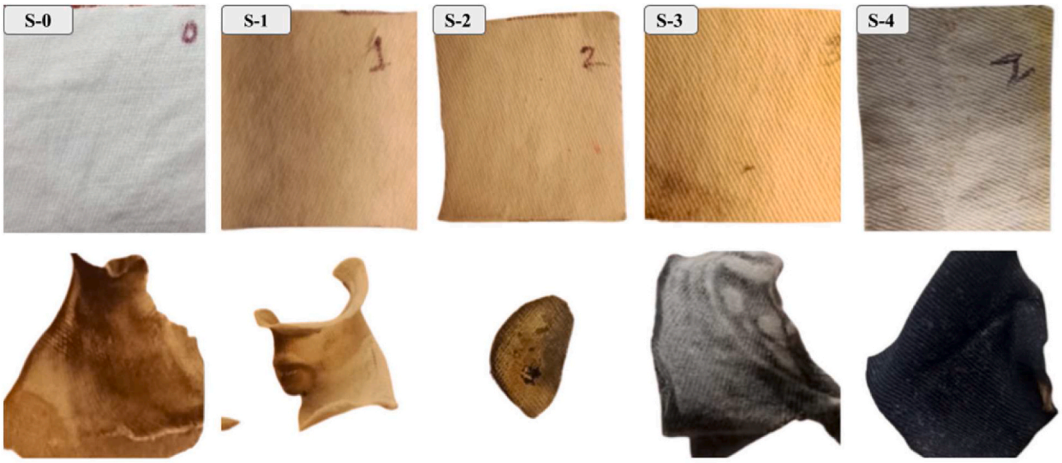


Fig. 6. Digital images of cotton fabric samples and their char residues before (top row) and after (bottom row) the burning test.

peptides, and amino acids present in the fish scale are beneficial in improving the anti-bacterial activity of polymeric substrates [38, 39]. Meanwhile, after the phosphoric acid treatment, the fabric sample (S-4) also displayed an outstanding reduction in bacterial growth. However, the reduction trend of bacterial growth against *S. aureus* was a bit inferior (see Fig. 5, bottom row) compared to the *E. coli* and this might be connected to a more rigid structure of a gram-positive bacteria [*S. aureus*], which hinders the penetration of proteins and nanoparticles from abolishing them [40–42].

3.5. Flame retardancy

The flame retardant properties of treated textiles were measured in terms of calculating the burning time (i.e., time to catch fire in the presence of a fire source) of the same. From Table 4, it was seen that the burning time of the control cotton fabric was 18 s, whereas it was 24 s for S-1, 27 s for S-2, 44 s for S-3, and 39 s for S-4. Meanwhile, after 10 wash cycles burning time became slightly lower and measured at 18 s (S-0), 18 s (S-1), 19 s (S-2), 30 s (S-3), and 26 s (S-4). Here, a comparatively higher burning time was noted for S-3 (treated with FSP) and S-4 (treated with FSP and phosphoric acid) fabric samples both before washing and after 10 wash cycles; which indicates an improved level of flame-retardant effect of these fabric samples. Here, the pristine cotton fabric sample was found to be completely pyrolyzed in the burning test, leaving barely any char residue with a fluffy and porous structure (see Fig. 6). Meanwhile, cotton fabric treated with PANI had a little charring effect and the $AgNO_3$-treated fabric also had a little char residue. However, the FSP-treated cotton fabric exhibited some sort of char residues after the combustion process whereas the simultaneously FSP and phosphoric acid-treated cotton fabric sample produced a higher amount of black carbonaceous char residues leaving the burnt textile with its original woven structure (see Fig. 6) and thus, both the FSP and P-compound appeared as a flame retardant to show their efficacy. Such charring can improve the flame retardancy of the treated textile substrate by offering a barrier effect by preventing the transfer of heat and O_2 into the internal unburned area, indicating that the treated textiles revealed a certain level of flame retardancy.

4. Conclusions

This study focuses on the development of multi-functional cotton textile with some novel functionality, namely antimicrobial, electrically conductive, and flame-retardant properties. The cotton fabric surface was modified in a chemical finishing method using polyaniline (PANI), silver nanoparticles (Ag-NPs), fish scale protein (FSP), and a phosphorus compound like phosphoric acid (H_3PO_4). From the obtained data, it was found that the fabric sample treated with PANI, and Ag-NPs (S-2) exhibited the highest level of conductivity with a resistance value of 1.98 G-ohm. This was expected as the applied compounds (PANI and Ag-NPs) reasonably favor the electro-conductivity of the textile substrate due to their inherent characteristics. Meanwhile, among the formulations, the fabric

sample (S-3) treated with PANI, AgNPs, FSP, and SA revealed a maximum reduction in bacterial growth against gram-negative bacteria (*E. coli*) and gram-positive bacteria (*S. aureus)*. Regarding the flame retardant performance, the fabric sample (S-4) modified by PANI, AgNPs, FSP, SA, and phosphoric acid produces dense and carbonaceous residues; indicating a superior level of flame retardant properties utilizing barrier effect. These results suggest that the modified cotton textile has improved properties compared to the control fabric, and could have the potential to be considered in applications areas where electrical conductivity, antimicrobial protection, and flame-retardant properties are required. Although S-1 and S-2 exhibit better electro-conductivity, they lack greatly in antibacterial and flame retardant properties. Herein, among four different formulations, fabric samples S-3 and S-4 exhibit reasonable electrical conductivity, antibacterial properties as well as flame retardant properties. Thus, the as-prepared cotton textiles have real-life applications likely in making military apparel, MedTech, fire alarms, sensors, electromagnetic shielding, wearable electronics, etc. In future endeavors, such developments could be experimented on a large scale to evaluate its commercial viability and also could be considered to experiment on other kinds of textile and polymer substrates.

Ethics statement

This study required no ethical approval since we used a waste raw fish scale available in a local fish market.

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Abu Sayed Rafi: Writing – original draft, Methodology, Formal analysis, Data curation. **Al Amin Sheikh:** Writing – original draft, Methodology, Formal analysis, Data curation. **Mehedi Hasan Chaion:** Writing – review & editing, Writing – original draft. **Tanay Chakrovarty:** Writing – review & editing, Methodology, Data curation. **Md. Tanvir Islam:** Writing – review & editing, Investigation. **Chanchal Kumar Kundu:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was supported by Jashore University of Science and Technology.

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