



Synergistic Modification of Cotton Fabric with Polyamidoamine Dendrimer and Cationic Gemini Surfactant for Enhanced Functional Performance

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Article Information	Abstract
<p>Article history:</p> <p>Received: 2026-02-18</p> <p>Accepted: 2026-06-01</p>	<p>This study investigates a novel and synergistic approach to functionalize cotton fabric using a second-generation Polyamidoamine (PAMAM) dendrimer and a cationic Gemini surfactant. The modification was efficiently carried out via the pad-dry-cure method using various concentrations of the two agents. The optimal treated fabric was identified through a comprehensive staining test utilizing model anionic (C.I. Acid Red 1) and cationic (C.I. Basic Blue 9) dyes. The optimal sample demonstrated a significant enhanced ionic interaction with model dyes as evidence of surface charge modification, showing a 500% increase in color strength with the anionic dye (AR1) and a 27.6% increase with the cationic dye (BB9), confirming successful surface charge modification. The dyes were used as ionic identifiers to evaluate surface charge alteration rather than to assess textile dyeing performance. Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy confirmed the effective incorporation of both the dendrimer and Gemini compounds onto the cotton surface. Beyond staining, the modified fabric exhibited remarkable functional and mechanical enhancements. Stress-strain analysis revealed a significant 50% increase in elongation compared to raw cotton. Complete inhibition (100% reduction) was achieved against both Gram-positive (<i>Staphylococcus aureus</i>) and Gram-negative (<i>Escherichia coli</i>) bacteria. Furthermore, after 10 washing cycles (Standard Test Method Two), the modified fabric retained substantial activity, maintaining a 60% reduction against <i>S. aureus</i> and a 70% reduction against <i>E. coli</i>. These results highlight the powerful synergistic effect of the PAMAM dendrimer and Gemini surfactant, establishing a straightforward method for producing cotton textiles with combined superior staining affinity, potent durable antimicrobial activity, and improved mechanical flexibility.</p>
<p>Keywords:</p> <p>Poly (amidoamine) dendrimer (PAMAM), cationic Gemini surfactant, surface modification, cellulosic materials, antibacterial activity.</p>	

1 INTRODUCTION

Cotton is the most consumed natural fiber in the world, and its handcrafted materials are necessary in human life, and for this reason, modifying cotton fabrics was essential[1]. Coloration is the first example of cotton improvement and up to now various treatments such as mercerization, Singeing, de-sizing, scouring, bleaching and for improving chemical and physical properties have been studied. Moreover, cross-linking finishes for achieving the durability and appearance retention of cotton textile, besides these treatments, were essential[2]. Despite the introduction of manmade fibers, cotton still has high consumption in different fields of textile, medical and agriculture due to its phenomenal properties such as water absorbency, nontoxicity, biocompatibility, biodegradation and softness[3]. However, crease resistance and resistance toward microbes, besides low dye ability towards anionic dyes, are the demerits of cotton fabrics [4]. Specifically in the antibacterial field, in order to improve cotton properties, different materials such as inorganic nanoparticles, polysaccharides, cationic surfactants, enzymes

and amine-terminated dendrimers were applied on cotton fabrics via immersing, pad-dry-cure and spraying methods[5]. For instance, in one of the latest studies, carboxymethyl chitosan (CMC) and (3-carboxypropyl) trimethylammonium chloride (CPTC) were used as raw materials to prepare an antibacterial cotton fabric with excellent laundering durability[6]. Lan et.al. used chitosan oligosaccharide in order to modify cellulosic fibers and the results showed 100 % antibacterial and 98.38 % antiviral activity after 20 washing cycles[7].

A recent enzyme treatment for antibacterial activity of cotton goods, Termamyl® 2X and Bioprep® 3000L were applied on cotton textiles for their antimicrobial activities, the results revealed that Bioprep® 3000L enzyme has higher antimicrobial activity compared to the Termamyl® 2X against *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Escherichia coli* and *Candida albicans* and due to its high potential of antibacterial application, it can be replaced instead of many synthetic antibacterial compounds. In terms of nanomaterials, cotton samples loaded with AgNPs- or

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AgNPs/ZnONPs or AgNPs/ZnONPs/CuNPs gave good antibacterial properties even after 20 washing cycles[8].

Among diverse novel technologies, applications of biomaterials have been explored in the textile industries due to their unique properties[9]. Dendrimers as one of the nano-size materials are macromolecules which can play a significant role in modifying textiles[10]. Dendrimers are unique in that they possess a hollow structure, internal cavities, and multifunctional surfaces that allow for the control of macromolecules and acceptance of small molecules in host-guest chemistry[11]. They also dissolve quickly, making them more effective than other polymers in various fields, particularly in nanomedical applications[12]. Additionally, amine-terminated dendrimers have antimicrobial properties due to the abundance of amino functional groups[13]. The toxicity of dendrimers depends on the number of generations, with lower generations being less toxic[14]. Various researches have been done on projects on modifying cotton using dendrimers and mostly flame retardancy[15], salt free dyeing[16] and antimicrobial[17] properties were investigated. In a study, two generations of poly (propylene imine) dendrimer were grafted on cotton fabric using citric acid as a cross linking agent and as a result, the treated fabric investigated a 99% reduction in bacterial counts against *S. aureus*, *E. coli* and *C. albicans* and after 5 cycles of washing, the antibacterial activity were maintained[18].

Twin surfactants, or Geminis, have two hydrophilic ends and two hydrophobic chains connected by a spacer[19]. The Cationic type of Geminis besides having a lower minimum inhibitory concentration (MIC), have a better performance in reducing surface tension and creating antibacterial properties[20]; in terms of antibacterial activities, quaternary ammonium salts have the best results[21]. The hydrophobic chain with 10 carbons has the strongest activity against bacteria, and as the spacer length increases, the antibacterial property of the surfactant decreases[22]. In 2023 a novel two-step modification strategy including oxidation process and following grafting process was reported to functionalize cotton fibers with quaternary ammonium salts in order to fabricate a functional daily health-care textile with durable antibacterial performances[23].

In order to show the presence of the materials used in the treatment, staining with two different anionic and cationic dyes were applied and the spectrophotometer data of the samples were studied [24].

Although cationization of cotton using various quaternary ammonium compounds has been widely reported, the simultaneous integration of PAMAM dendrimer and cationic Gemini surfactant in a single finishing system has not been systematically investigated. The present study aims to explore the synergistic interaction of these two polycationic systems to develop a multifunctional cotton fabric with durable antibacterial activity and improved mechanical performance.

2 Experimental

Samples with different concentrations of PAMAM (Poly Amidoamine dendrimer 2nd generation), Gemini (quaternary ammonium salt) were kindly donated by Delta-dolsk company, Poland and as shown in details in Table1 and their

combination were prepared (Table 2). Pad-dry-cure (Ernst Benz-Textile Mashinen) process was followed by 100% pick-up of padder rollers, drying at 100°C for 1 minute and curing for 3 minutes at 160°C.

Table 1 Characterization of cationic Gemini surfactant

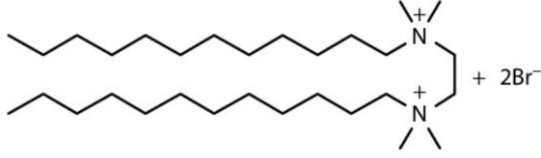
Name	Dodecyl-[1-[Dodecyl(dimethyl)Azaniumyl] Hexan-2-yl] Dimethylazanium;Dibromide
structure	

Table 2 Modified samples data by various concentration of dendrimer and gemini surfactant

Sample coding	concentrations	
	Dendrimer (%)	Gemini (%)
Neat	0	0
d 0.5	0.5	0
d 1	1	0
d 2	2	0
G 0.05	0	0.05
G 0.1	0	0.1
d 1/ G 0.05	1	0.05
d 1/ G 0.1	1	0.1

The presence of PAMAM/Gemini on samples was proved by ATR (Nicolet iS10 / Thermo SCIENTIFIC /USA) and staining test; aqueous solutions with 1% O.W.F of two model dyes, C.I. Acid Red1(AR1) and C.I. Basic Blue9 (BB9), were prepared for staining test and samples were stained with liquor to good ratio (L: G) of 50:1 at boiling temperature for 45 minutes. The staining procedure was conducted solely to evaluate electrostatic interactions between the modified cotton surface and oppositely charged dye molecules. The selected dyes were used as ionic indicators of surface modification rather than for conventional textile dyeing evaluation. A reflective spectrophotometer (Color-Eye 7000A / Gretag Macbeth) was used to obtain the colorimetric data of the samples using Equation 1.

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

All staining experiments were performed in triplicate and averaged values were reported. The antibacterial performance of the Neat, treated and washed cotton fabric after 10 cycles based on the standard test method two were tested against *S. aureus* and *E. coli* bacteria using AATCC-100 antibacterial test approach.

3 Results and discussions

Staining tests were performed as indicators of surface charge modification to determine the presence of PAMAM/Gemini surfactant on the cotton fabric besides obtaining the best combination of the materials. It was investigated that there is a competition between cationic Gemini surfactant and amine groups in PAMAM dendrimer to absorb hydroxyl

groups of cotton. The staining test proves the presence of dendrimer/Gemini compounds on cotton goods. Due to the cationic surface charge of the treated samples, they showed higher color absorption in AR1 (Figure 1) and lower color absorption in BB9 (Figure 2) in comparison with the raw sample. It should be noted that the objective of these experiments was not to evaluate dyeing properties, but rather to confirm the electrostatic nature of the surface modification[25].

As shown in both Figures, an increase in the PAMAM's concentration results into more absorption, about 0.86 in d 1 and 11.20% in d 2 samples comparison to the d 0.5 samples, in staining by AR1 and less absorption, -35.06% in d 1 and -34.68% in d 2, in staining by BB9. In terms of fabrics treated by Gemini, in both model dyes an increase of 24.87% in and 30.23% in color absorption of AR1 and BB9 respectively, was obtained by increasing the Gemini's concentration from 0.05% to 0.1%. This can be the result of the Gemini's structure (quaternary ammonium salt) and its intrinsic property of anionic groups adsorption. For the combinations in both model dyes the absorption on cotton was more than dendrimer treated samples and less than Gemini treated samples. Similar to other samples by increasing the Gemini's concentration, in treated samples by combined materials, the absorption of AR1 and BB9 experienced an increase of 219% and a decrease of 23% respectively.

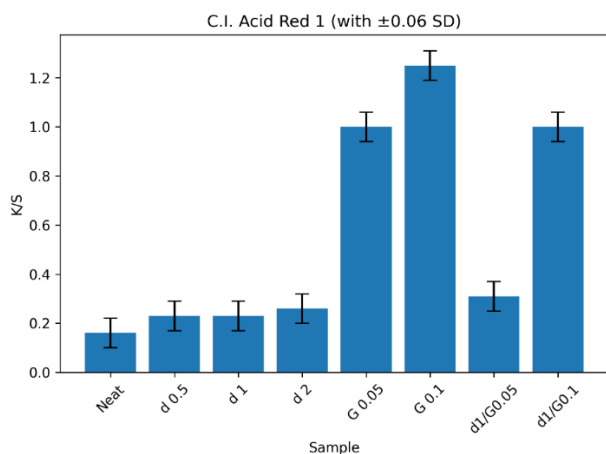


Figure 1 C.I. Acid red1 K/S data of samples by PAMAM and Gemini. (values represent mean ± standard deviation)

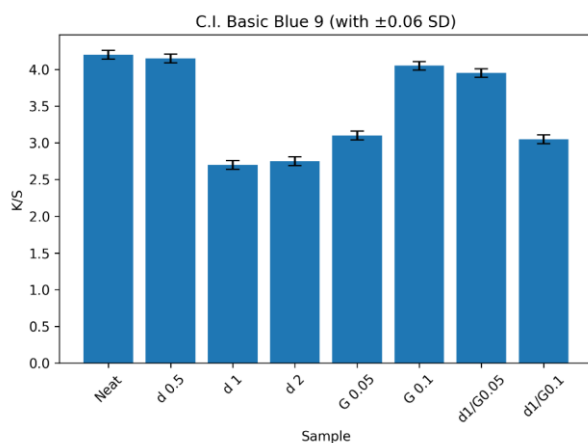


Figure 2 C.I. Basic Blue9 K/S data of modified samples by PAMAM and Gemini. (values represent mean ± standard deviation)

The sample which was treated by 1% of PAMAM and 0.1% of Gemini, d 1/G 0.1, was chosen as the optimal sample for further studies. To determine the presence of the materials on the cotton fabric, the ATR examinations of 4 samples as follow: neat sample, treated by PAMAM 1%, treated by Gemini 0.1% and treated by PAMAM 1%/ Gemini 0.1% were conducted. The results of optimal sample revealed the amide functional groups -CONH peaks at 1735 cm^{-1} (C=O stretching) and 1637 cm^{-1} (-NH bending). In the range of 3000-3500 cm^{-1} , the wide peak of -OH was changed with a double peak which indicated the NH stretching bonds formation in treated samples (Figure 3)[26].

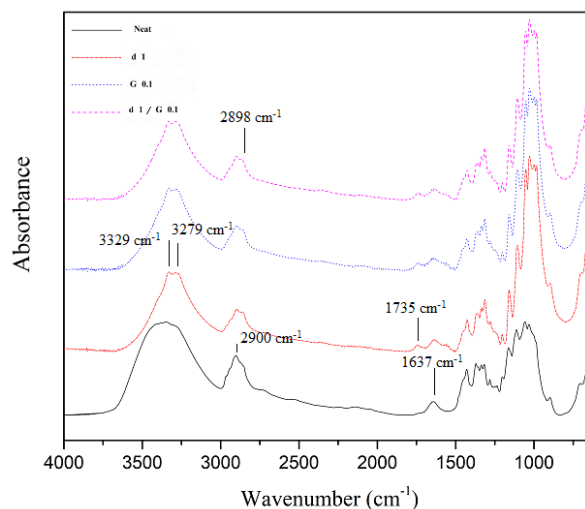


Figure 3 ATR results of Neat, modified with PAMAM1% (d1), modified with Gemini surfactant 0.1% (G 0.1) and modified with both PAMAM1%/Gemini 0.1% (d1/G0.1) fabric

The stress-strain changes of modified fabric were compared to the neat fabric. An increase of about 23% was observed in the elongation of the optimal fabric. Moreover, the maximum tolerable stress of the modified fabric was increased by approximately 8% (Figure 4).

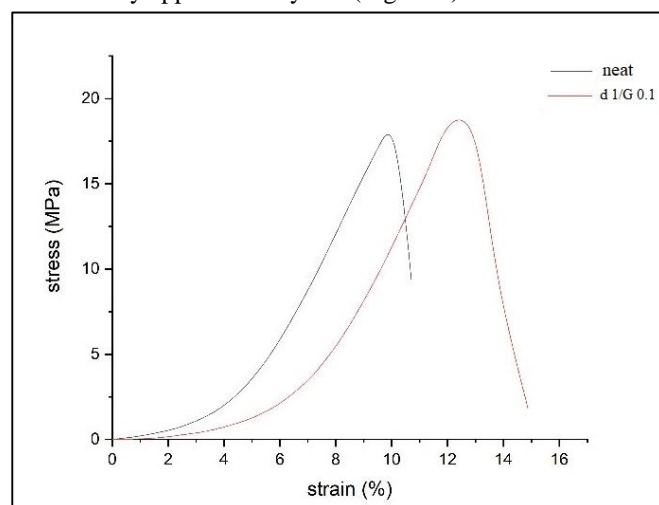


Figure 4 Stress Strain changes of modified and neat cotton fabric (weft)

Antibacterial properties of samples against *E. coli* and *S. aureus* bacteria were also measured. As a result, no growth of bacteria was observed in both gram-negative and gram-

positive, 72 hours after being in contact (Table 3). Moreover, the antibacterial characteristics were studied for *S. aureus* and *E. coli* after being washed 10 cycles in order to obtain the durability of samples against bacteria. Excellent results of 60% and 70% reduction in bacteria were observed, respectively for *S. aureus* and *E. coli*. were gained (Figure 5).

Table 3 antibacterial properties of modified sample with PAMAM 1% /Gemini 0.1 %

Name of the bacteria	Concentration of bacteria (CFU/ml)	The growth of bacteria after 72 hours
<i>E. coli</i>	1.5×10^5	No growth
<i>S. aureus</i>	1.5×10^5	No growth

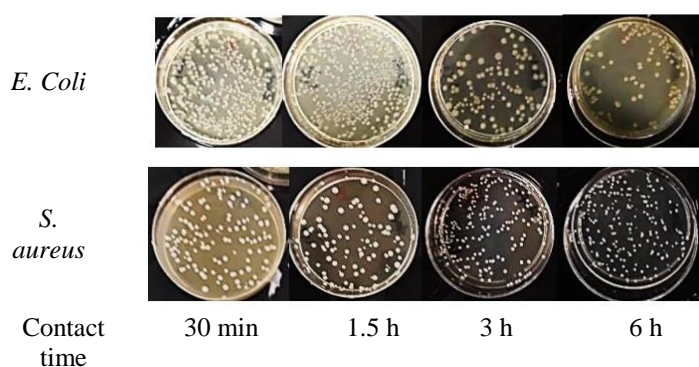


Figure 5 antibacterial activity of PAMAM 1%/ Gemini 0.1% against *E. coli* and *S.aureus* on cotton fabric after 10 cycles of washing

4 Conclusion

Surface modification of cotton goods by PAMAM dendrimer and Gemini cationic surfactant create a positive charge on the surface for antibacterial purposes. The staining experiments confirmed successful surface charge engineering and were used as diagnostic tools rather than as an evaluation of textile dyeing performance. In addition, more stress and elongation in the modified fabric was observed. The synergistic integration of PAMAM dendrimer and cationic Gemini surfactant provides a simple and effective strategy for multifunctional cotton finishing with durable antibacterial and mechanical enhancement. These goods can be used in biomedical applications as well as cotton fabrics for garments.

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