Research Article

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Washing-dependent antistatic performance of antimicrobially finished woven polyester fabric for textile air distribution systems

https://doi.org/10.1515/aut-2025-0079
Received August 31, 2025; accepted May 26, 2026;
published online July 13, 2026

Abstract: In textile air distribution systems, functional properties such as antimicrobial and antistatic performance are typically introduced into the fabric through separate methods. In this study, a novel silica-based benzalkonium chloride (BAC) finish, originally developed for antimicrobial performance, was further evaluated for its secondary antistatic effect (earlier detected by the authors) on woven 100 % polyester fabric after 0, 1, 2, 5, and 10 washing cycles. The unwashed finished fabric exhibited acceptable antistatic properties according to the requirements for protective clothing. FTIR analysis confirmed the presence of silica and BAC on the finished fabric sample surface. However, the antistatic effect progressively declined with washing, with surface resistivity approaching that of the unfinished fabric. FTIR band intensities characteristic of silica and BAC decreased in washed finished fabric samples, confirming a partial wash-out of both components from the fabric surface. Since silica nanoparticles are electrical insulators, the observed antistatic effect is more likely attributable to BAC. A single finish Integrating both antimicrobial and antistatic properties into a 100 % polyester fabric with one finishing may facilitate end-of-life recycling and improve the sustainability profile of fabrics for textile air distribution systems.

Keywords: antistatic textiles; surface resistivity; antimicrobial textiles

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1 Introduction

According to statistical studies [1], [2], people in developed countries spend up to 90 % of their time indoors. The exposure to indoor air pollutants distinctly impacts both human health and workplace effectiveness [3]. Thus, indoor air quality (IAQ) is important for public health and exposure assessment. The control and regulation of indoor environmental parameters – specifically temperature, humidity, air movement, and air quality – are essential for occupant health and comfort, as deviations can lead to respiratory issues, discomfort, or even chronic diseases. These factors, especially in modern work environments, are typically managed through heating, ventilation, and air conditioning (HVAC) systems, which regulate temperature and humidity, ensure appropriate air movement, and filter out pollutants. This supports the emphasis on HVAC system performance and the control of indoor pollutant sources in environmental health policies and research [4]–[8].

HVAC systems ensure IAQ [9]. Air distribution ducts deliver the air within the building in all mechanical ventilation systems. Dust, bacteria, and other contaminants can accumulate inside the ducts, which may negatively affect IAQ, so standards and hygiene guidelines exist to ensure hygiene in air distribution systems [10]–[12]. Metal ducts are considered standard due to their airtightness, fire resistance, and durability [13]–[17], but they present challenges with respect to cleaning [18]. Textile ducts, or textile air distribution systems, are an emerging alternative to metal ductwork, with increasing application but limited standardization. Their use is permitted under regulatory standards to ensure safety and performance [19]–[21]. Textile air distribution systems are increasingly popular due to their light weight, easy washing, antimicrobial finishes, and quick installation. They also diffuse air evenly and in customizable patterns at low velocities, reducing drafts [22]. PET (polyethylene terephthalate), a durable and lightweight polyester textile, is commonly used for production of these ducts. Recycled PET [23] is increasingly used for its reduced environmental impact and contribution to sustainable building.

While polyester fabrics, especially recycled PET, offer durability and moisture resistance, ensuring hygienic conditions within these textile air distribution systems require advanced finishing technologies. Antimicrobial (antibacterial and antifungal) properties in textiles can be achieved applying various finishes: synthetic agents, metallic nanoparticles, polymer-based coatings, natural agents and physical treatments: plasma, microencapsulation, layer-by-layer assembly [24]. Traditionally, zinc pyrithione is a widely used antimicrobial finishing agent due to its effective microbial resistance [25]. However, recent European Union regulatory restrictions on its use in cosmetic products [26] and European Chemicals Agency consultations on potential candidates for substitution and on derogation conditions in other application areas [27] have prompted the search for alternative industrial solutions.

In response, innovative benzalconium chloride (BAC)-based antimicrobial finish [28] has emerged as a promising candidate. Unlike conventional encapsulated treatments, this novel approach utilizes silicone nanoparticles to transport BAC directly onto the fabric surface, enhancing antimicrobial efficacy [29], maintaining the non-growth zone under the sample until up to 20 washes. The tested knitted textile samples included various fiber compositions: 100 % wool, wool/acrylic blends (70/30, 50/50, 30/70), 100 % acrylic, a cotton/acrylic blend (50/50), and 100 % cotton [29]. Moreover, earlier by authors of this paper it was found that this antimicrobial finish provided not only good antimicrobial efficacy, but also an additional benefit such as some antistatic properties [30], tested on woven 100 % polyester fabricsamples. Antistatic properties are important to prevent dust accumulation in textile air dispersion systems and to maintain optimal airflow and IAQ. This finish is an alternative to the achievement of antistatic properties in textile by incorporating metalized or carbonized yarns [31], which effectively dissipate static charges but complicate recycling processes due to material heterogeneity and the presence of non-textile components [32].

Silica-based BAC antimicrobial finish applied to polyester fabrics inhibits microbial growth (antibacterial against *Staphylococcus epidermidis*, *Staphylococcus aureus*, Escherichiae coli, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae* and *Proteus mirabilis*, antifungal against *Candida albicans*) as expected but also imparts a novel antistatic effect [30]. Although initial study [30] demonstrates these antistatic properties partially persisting after washing, further investigation is necessary to analyze the performance of the antistatic effect. The initial research mainly focused on analysis of antimicrobial properties, and the antistatic effect was measured in wide intervals between washing cycles (0, 1, 20). This study aims to further explore the effects of antimicrobial finish on polyester fabrics for textile air distribution systems, focusing on its impact on antistatic property and applying narrower intervals between washing cycles. A more detailed analysis clarifies how antistatic properties change after finishing and consecutive washing. This approach provides essential data to inform the design and use of textile materials emphasizing properties that support and enable recycling.

2 Experimental

2.1 Materials

Plain woven fabric for samples was manufactured using 100 % polyester (PET) multifilament 33 tex × 2 yarns and polyester multifilament 33 tex yarns in the warp and weft. The warp and weft densities of the fabric used were 28.5 cm^{-1} and 15.2 cm^{-1}. The surface density of the fabric was 245 ± 8 g/m^2 and the thickness 0.35 ± 0.01 mm.

2.2 Methods

2.2.1 Antimicrobial treatment

The woven fabric samples were treated with Si Bac-Pure, a silica-based functional textile finish [28] engineered for durable not only antibacterial but also antiviral and antifungal efficacy, and could be described to have antimicrobial effect. Its active ingredient, benzalkonium chloride, is an organic quaternary ammonium compound [33]. Application: wet impregnation method (mixing 41 ml/l Si Bac-Pure with 7 ml/l auxiliary Smart Fix into an aqueous solution at 30 °C, with a bath pH of 6–6.5 and absorption rate of 70 %, for 15 min), followed by a 15 min drying period at 120 °C.

2.2.2 Washing and drying

Treated samples were washed and dried (0, 1, 2, 5, 10) times after the Si-Bac Pure treatment. One washing cycle consisted of two steps: the samples were washed for 15 ± 0.5 min at 40 ± 2 °C using 3 g/l washing powder, following ISO 6330:2012 standard [34]. After that, the samples were rinsed three times with water at 20 ± 2 °C. The rinsing procedure took 1 ± 0.1 min each. Upon rinsing, the specimens were spin-dried for 1 ± 0.1 min and dried for 24 h in a standard atmosphere.

2.2.3 Determination of electrostatic properties

There is currently no textile ventilation-specific standard governing anti-static properties. Therefore, EN 1149-5: 2018 standard [35] which specifies performance and design requirements for materials to be used in the production of protective clothing with electrostatic dissipation for prevention of incendiary discharge, was adopted for assessment in this context. The samples (5 finished samples and one unfinished sample) were conditioned for 24 h prior to measurement and test was performed in the following atmosphere: air temperature (23 ± 1) °C and relative humidity (25 ± 5) % according to EN 1149-1: 2006 standard [36] and surface resistance was measured using Teraommeter Eltex 6206, at a voltage of 100 V.

The surface resistivity was calculated according to equation:

$$\rho = k \times R$$

Where:

ρ – is the calculated surface resistivity, Ω

R – is the measured resistance, Ω

k – is the geometrical factor of the electrode, for this electrode the factor is 19.8

2.2.4 Structural characterization

The FTIR spectra of the fabric samples were measured using an FT-IR spectrometer (Bruker Vertex 70) in the range of 4,000–600 cm^{-1}.

3 Results and discussion

To address the durability and dynamics of the antistatic effect of silica-based BAC finishing, this study systematically evaluated the surface resistivity of silica-based BAC finished woven 100 % polyester fabrics. The intervals of 0, 1, 2, 5, and 10 washing cycles were selected to capture both the immediate impact of the first few washes where the most significant changes in surface resistivity properties are expected – and the longer-term trends in antistatic performance with continued application of washing cycles. The surface resistivity results of the finished woven fabric samples are presented as a function of the number of washing cycles. The surface resistivity measurement results for the unfinished sample are distinguished by a different color for comparison (Figure 1). This experiment enables direct comparison between unfinished and finished woven fabric samples, allowing assessment of the durability of the antimicrobial finish following repeated washing cycles.

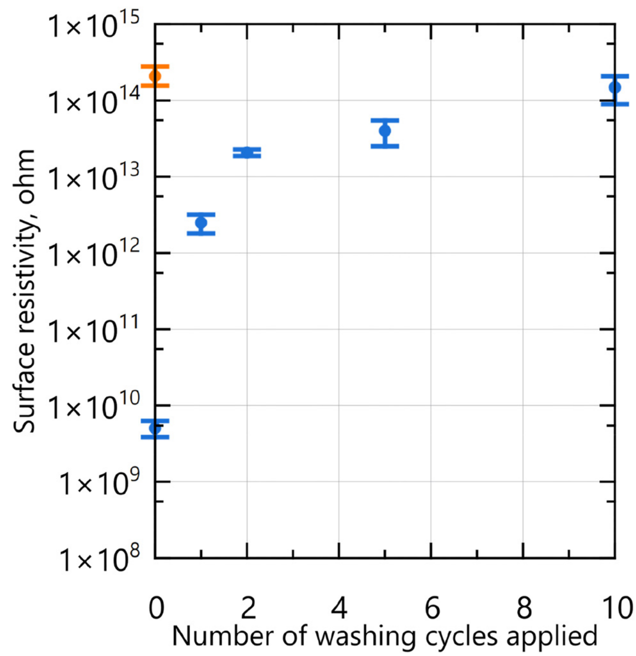


Figure 1: The relationship between the number of washing cycles (*x* axis) and surface resistivity (Ω, *y*-axis, logarithmic scale). The blue data points (five in total) correspond to experimental measurements of woven 100 % polyester fabric samples with silica-based BAC finish, while the orange data point represents an unfinished woven 100 % polyester fabric sample.

Analysis of the surface resistivity measurement data (see Table 1) as a function of the number of washing cycles reveals a distinct non-linear dependency. Initially, at zero washing cycles, the surface resistivity is relatively low (in the range of 10^9 Ω). After the first washing cycle, a sharp increase is observed, with resistivity rising by a factor of 10^3. With further washing cycles (2, 5, and 10), the increase in resistivity becomes more gradual, approaching 10^{14} Ω and suggesting a plateau (or a surface resistivity value of an unfinished woven 100 % polyester fabric). This trend indicates a rapid initial loss of antistatic performance, likely due to the removal of the functional finish, followed by a slower, asymptotic approach to a maximum value characteristic of the base material (untreated woven 100 % polyester fabric

Table 1: Surface resistivity measurement results for a) woven 100 % polyester fabric samples finished with (a) silica-based BAC finish and (b) unfinished woven 100 % polyester fabric sample.

a)

Sample code	Number of washing cycles	Surface resistivity, Ω
SAF1W0	0	5,08E+09
SAF1W1	1	2,49E+12
SAF1W2	2	2,07E+13
SAF1W5	5	4,00E+13
SAF1W10	10	1,48E+14

b)

Sample code	Finishing	Surface resistivity, Ω
SAF0W0	Untreated	2,07E+14

sample). The relationship is best described by a saturating exponential model. These findings highlight that while the antistatic effect is significantly reduced after the first few washing cycles, subsequent washing cycles have progressively smaller impact, with surface resistivity eventually stabilizing near the value for unfinished woven 100 % polyester fabric samples. This saturating trend was measured for 20 washing cycles in [30], and it has important consequences for the durability and long-term functionality of antistatic textile finishing investigated in this study and subjected to repeated washing cycles: 0, 1, 2, 5, 10.

3.1 FTIR analysis

FTIR spectral analysis confirms the presence of both silica and BAC components on the woven 100 % polyester fabric samples following treatment with the silica nanoparticles-based BAC finishing (Figure 2).

The spectrum is characterized by typical bands of polyethylene terephthalate (PET), confirming the polyester textile matrix. The strong ester carbonyl (C=O) stretch near 1,740 cm^{-1} and aromatic C=C stretches around 1,600 and 1,500 cm^{-1} are typical of PET. The fingerprint region (the part of the infrared spectrum between 1,500 and 500 cm^{-1}) displays ester C–O vibrations and aromatic C–H bending, consistent with polyester structure.

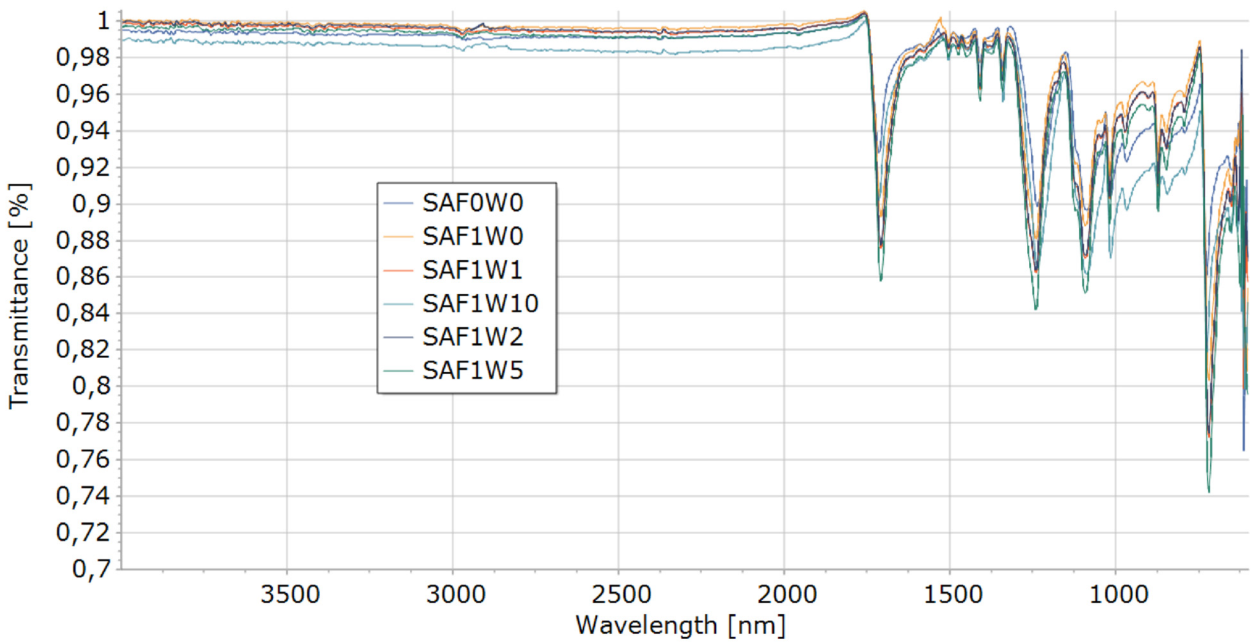
A broad Si–O–Si asymmetric stretch near 1,100 cm^{-1} and bending modes around 800 cm^{-1} indicate the presence of silica nanoparticles within the textile finish.

Alkyl C–H stretching bands at ~2,920 and ~2,850 cm^{-1} and a band near 1,470 cm^{-1} correspond to the alkyl chains and quaternary ammonium head groups of BAC, indicating its presence on the surface.

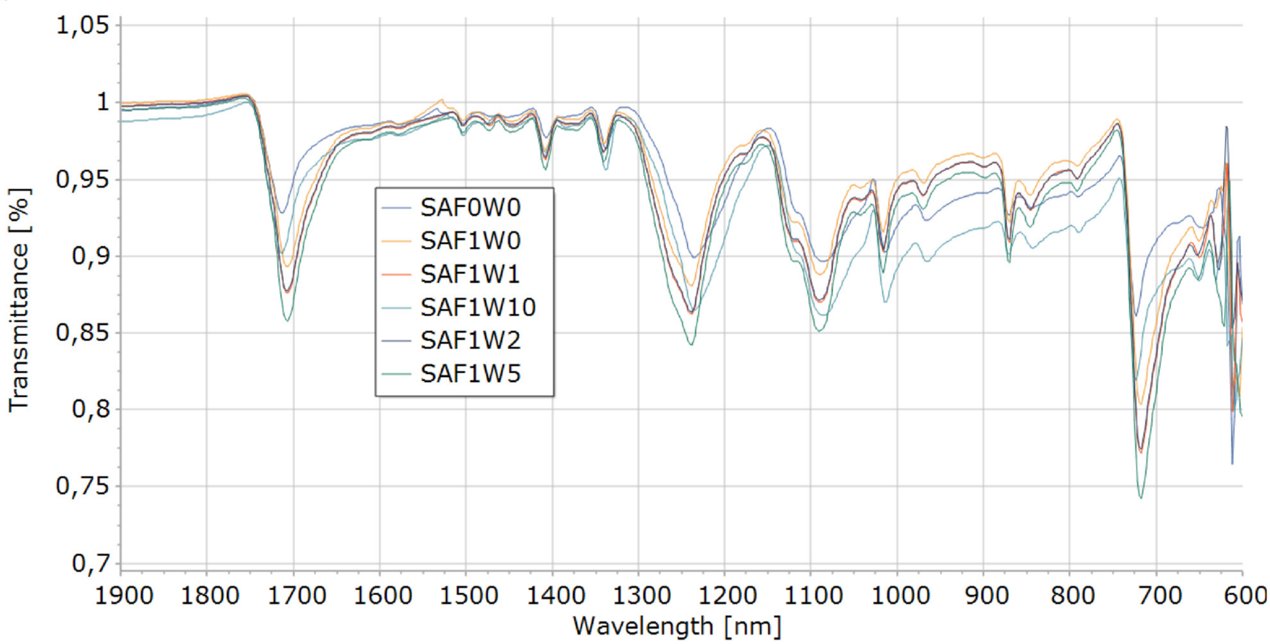
Analysis of the FTIR spectra across increasing wash cycles (Figure 2a) demonstrates a gradual reduction in the intensity of both the Si–O–Si bands (near 1,100 and 800 cm^{-1}) and the BAC-associated band 1,470 cm^{-1}. This indicates that both BAC and silica nanoparticles (with silica nanoparticles acting as the carrier of BAC in the finishing formulation) are gradually washed out from the fabric surface.

Silica nanoparticles (SiO_2 NPs) are widely used in textile finishing to provide various functional properties, such as hydrophobicity, UV protection, and enhancement of mechanical properties [37], [38]. Due to their electrical insulating nature, silica nanoparticles do not contribute directly to electrical conductivity. The durability of both antimicrobial and antistatic properties under repeated washing cycles presents distinct patterns. Antimicrobial activity demonstrates excellent wash resistance, maintaining inhibition zones after 1–20 washing cycles [30]. However, the antistatic properties demonstrated higher susceptibility to washing-induced degradation, likely due to the higher BAC concentration thresholds required for effective charge dissipation compared to antimicrobial action. Consequently, the changes in surface resistivity observed in samples finished with silica-based BAC (benzalkonium chloride) textile finish and subject to increasing number of washing cycles is attributed to the presence and concentration of BAC, with higher BAC levels corresponding to lower surface resistivity.

Application of a silica nanoparticle–based BAC textile finish to 100 % polyester fabrics provides effective antimicrobial properties and reliable antistatic behavior, suitable for textile air distribution systems. As this method allows the use of 100 % polyester, it helps to avoid the separation of carbon-based or metalized yarns (as in popular two-material antistatic textiles relying on conductive fibers in the weave), resulting in more effective recycling and simplifying recovery of the material at end of life. By maintaining a uniform material composition, this approach reduces the need for energy-intensive separation steps and minimizes waste, indicating a more sustainable path for the lifecycle management of functional textiles.



a)



b)

Figure 2: FTIR spectra of silica nanoparticles and benzalkonium chloride (BAC) finished woven 100 % polyester fabric samples, 0, 1, 2, 5, 10 washing cycles applied (a), and their fingerprint region (b).

4 Conclusions

The current study demonstrates that silica-based benzalkonium chloride finish provides 100 % polyester fabric with antistatic properties (surface resistivity of $\leq 2.5 \times 10^9\ \Omega$) that, however, diminishes rapidly with increasing washing cycles applied and stabilizes at the baseline conductivity of untreated polyester. Surface resistivity measurements reveal a steep increase after the first washing cycle, followed by a gradual approach toward the surface resistivity value characteristic of the unfinishedpolyester fabric. This indicates that finish deposits a initial BAC concentration sufficient to ensure a lasting antimicrobial efficacy (up to 20 washing cycles, [30]), but that the threshold concentration required to maintain antistatic functionality is more critical and is largely affected by the first washing cycle, with subsequent washing cycles having progressively smaller effects on antistatic performance.

FTIR analysis confirms these findings by showing diminishing intensities of Si–O–Si stretching bands (~1,100 and 800 cm^{-1}) and BAC-associated quaternary ammonium signals 1,470 cm^{-1} across 0, 1, 2, 5, and 10 washes, confirming the progressive leaching of both silica nanoparticles and BAC from the fabric surface. Because silica itself is electrically insulating, the observed conductivity changes are attributable to the concentration of BAC on the fabric.

The integration of silica nanoparticles as a carrier for BAC enables effective antimicrobial functionality alongside antistatic behavior without the need for conductive fibers or metalized yarns. This single-material approach simplifies end-of-life recycling by avoiding energy-intensive separation processes typical of two-material antistatic textiles, thereby enhancing the sustainability profile of functional polyester fabrics. Future work should explore formulation strategies to improve BAC retention and extend antistatic durability under repeated washing, optimizing both performance longevity and environmental footprint.

Moreover, this study reinforces the necessity for industry-specific antistatic performance standards in the textile-based air distribution industry. Protective clothing standards that are designed to safeguard humans within garments lay down potentially higher surface resistivity thresholds than applicable to non-wearable applications, such as ducts in air distribution systems where human proximity is minimal. Establishing industry specific standards will ensure that antistatic properties are evaluated and optimized according to the safety requirements and risk profiles unique to their intended applications.

Future work should explore formulation strategies to improve BAC retention and extend antistatic durability under repeated laundering, optimizing both performance longevity and environmental footprint.

Research ethics: Not applicable.
Informed consent: Not applicable.
Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission. Rasa Gofman has prepared textile samples and analyzed the surface resistivity and FTIR measurement data, where the surface resistivity measurements were conducted by Sandra Varnaitė – Žuravliova, and together with Rimvydas Milašius concluded the findings. FTIR measurements were conducted in open access facility in Kaunas University of Technology.
Use of Large Language Models, AI and Machine Learning Tools: Perplexity was used to improve language.
Conflict of interest: The authors state no conflict of interest.
Research funding: This research was funded by Kaunas University of Technology.
Data availability: The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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