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Development of Antimicrobial and Antistatic Textile for Industrial Air Management Systems

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Abstract
Textile air management systems are used in modern buildings to improve overall indoor air quality. During use and storage, industrial textiles are negatively affected by microbes. Adding biocide to synthetic fibres can control the detrimental effects of antimicrobial finishing on textiles. Antimicrobial textiles have seen a rapid increase in demand due to consumers' concern over hygiene and active lifestyles as well as with the aim to improve overall functionality. An antimicrobial treatment with a long lifespan, that is, resistant to washing, is presented in this paper. A new commercial antimicrobial product named *Si Bac-Pure* was used in woven polyester fabrics to treat them against bacteria. The antimicrobial activity was measured after twenty washing and drying cycles. Good antimicrobial and antifungal activity is produced in treated fabrics after treatment with the stated finishing agents. The antimicrobial treatment has significant antistatic properties that are important for industrial air management systems.

Keywords
Air management systems, antimicrobial treatment, antistatic effect, functional textiles.

1. Introduction

Dangerous microorganisms in the surrounding environment, such as viruses, bacteria and fungi pose a serious threat to public health. After the SARS-CoV2 (COVID-19) pandemic, consumers are more than ever aware of the importance of sufficient and effective ventilation and clean air, which is likely to play a critical role in preparation for future outbreaks. An easy way for the COVID-19 virus to spread, for instance, is by droplets or aerosols that stick to surfaces, which are then touched by a recipient [1,2]. Currently, a wide variety of applications and purposes are served by the use of fabrics. Due to increased demand for hygienic and clean fabrics, the use of antiviral and antibacterial textile materials is growing. The fabric industry already has significant segments related to medicine, health, and hygiene, and is expanding its capabilities. Antimicrobial compounds can be applied to a textile substrate using a variety of processes, including spray, foam, coating, pad-dry-cure, and exhaust [3–6].

A steady increase in the production of protective, medical, and industrial textiles made from polyester fibres has been seen in recent years. The majority of these materials must have antimicrobial properties. However, the hydrophobic properties and low surface energy of polyester make surface treatment incredibly challenging [7]. The majority of antimicrobial substances, such as silver, zinc oxide, triclosan, copper compounds, etc., used to finish commercial textiles are biocides [8–13]. In addition to improving the air quality and reducing the risk of airborne infections, anti-microbial treated fabrics prevent the growth and spread of microorganisms.

Air management systems are used in modern buildings to improve overall indoor air quality, and the aforementioned key trends can drive the growth of air supply system installations [14]. The global air duct market is segmented into three parts by the type of prevailing material - sheet metal (galvanized steel and aluminium) ducts, flexible non-metallic ducts, and textile ducts. Galvanized steel ducts still dominate in the market, however, the rising prices of raw materials, especially metals, are leading to long-term market forecasts of a lower demand than prior to the material price increase. Textile ducts, on the other hand, are extremely promising and their demand is growing. Therefore, it is important to implement technological innovations to give textile ducts antistatic, antimicrobial, wrinkle resistance and stiffness properties that are the same as or superior to those of sheet metal ducts [15].

Many research works dedicated to fiber types, application methods, performance analysis, fabric structures, and types of finishing agents used for antimicrobial purposes can be found in literature [16–21]. However, there is a lack of published investigations in the field of the antimicrobial and ani-static polyester-based textiles used for air management systems.

Antimicrobial treatments reduce the risk of airborne infections and improve air quality by preventing the growth and spread of microorganisms in the air. The use of anti-microbial agents can reduce unpleasant odours in the air by controlling the growth of bacteria that cause them. Textile materials can be treated with various anti-microbial agents, such as silver nanoparticles, silver chloride, silver zeolites, benzalkonium chloride, triclosan, zinc pyrithione, chitosan, copper-based compounds, polyhexamethylene biguanide, N-halamine compounds, chlorine dioxide, and more. However, the use of certain antimicrobial reagents in textile finishing can have negative consequences on the environment. For instance, quaternary ammonium salts and derivatives as well as triclosan can end up in water biotopes and disrupt the natural balance. Additionally, there is a concern regarding the release of nanoparticles from antimicrobial textiles. These nanoparticles can enter the human body and accumulate in various tissues by easily penetrating cell walls [22,23]. Si Bac-Pure, the anti-microbial agent utilized in this study, was selected due to its sustainable functional finish and its antivirus and antimicrobial properties. This treatment effectively combats bacteria, fungus, mold, and unpleasant odors for multiple washes. Si Bac-Pure provides long-lasting hygiene, freshness, and cost-effective value to textiles. The active substance in Si Bac-Pure has received approval from the US EPA and is registered in REACH. It does not contain any substances listed on the SVHC list nor does it contain metal ions. Si Bac-Pure demonstrates excellent results in eliminating various bacteria types (both gram positive and gram negative). Furthermore, it is completely safe for human use and has been registered by the World Health Organization [24]. Electrostatic forces can be used to attract and retain particles in air management systems that are treated with anti-microbial agents. Fabrics can be made more durable by treating them with anti-microbial agents, so that repeated washing and use will not harm them.

The objective of this paper is the development of woven fabrics with specific antimicrobial properties and additional antistatic properties with the view to be used for air management systems. The antibacterial effect against *Staphylococcus epidermidis, Escherichiae coli, Staphylococcus aureus, Klebsiella pneumoniae, Pseudomonas aeruginosa and Proteus mirabilis* was evaluated and the antifungal effect against *Candida albicans* assessed. A number of bacteria were used for practical purposes, as developed air ducts may be used in different industries.

2. Materials and Methods

2.1. Materials

Plain woven fabric was manufactured using polyester 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. Antimicrobial treatment

The woven samples were subjected to treatment with Si Bac-Pure, which is a technology developed by a Portuguese company called Smart Innovation, Lda. One of the advantages of this technology is the ease of application as well as its non-toxicity [24]. There are neither heavy metals nor silver used in the manufacture of this product, and it is an eco-friendly product as well. Benzalkonium chloride (BKC) is the active antimicrobial agent in this product. By using the wet impregnation method, BKC was applied to the textile materials in order to cover them with the compound. The antimicrobial treatment included: 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. There was then a 15 minute drying period at 120 °C, followed by the application of the product.

2.3. Washing and drying

The samples were washed and dried 20 times after the antimicrobial treatment, and then their antimicrobial activity was determined. The specimens had to be washed for 15 ± 0.5 min at 40 ± 2 °C using 3 g/l washing powder, following ISO 6330:2012 [25]. Afterwards, the specimens 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 hours in a standard atmosphere.

2.4. Reference culture preparation for antimicrobial testing

Reference cultures of micro-organisms such as *Staphylococcus epidermidis (*ATCC 12228), *Escherichia coli* (ATCC 25922), *Staphylococcus aureus* (ATCC 25923), *Klebsiella pneumoniae* (ATCC 13883), *Pseudomonas aeruginosa* (ATCC 27853), and *Proteus mirabilis (*ATCC 12459) were used to determine the antimicrobial activity effect of the textile fabric and *Candida albicans (*ATCC 10231) to determine its antifungal activity effect. Reference bacterial cultures were grown for 20-24 hours at 37.0 °C. Reference *Candida albicans* fungus cultures were grown for 3 days at 25.0 °C. Suspensions of the micro-organisms grown were prepared. The turbidity of the micro-organism suspension was determined by the McFarland standard, which measures the number of micro-organisms in 1 ml of suspension. In 1 ml of the microorganism suspension prepared for the experiment, it should be about 1.5×10^8 CFU/ml [CFU=colony-forming unit].

2.5. Determination of the antibacterial and antifungal activity

Antibacterial and antifungal activity of the samples was revealed using the agar diffusion plate test method. The standard method ISO 20645:2004 [26] was used in the present study. The antibacterial activity of the textile fabric was evaluated against *Staphylococcus epidermidis, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumoniae* and *Proteus mirabilis* before and after 1, and after 20 washing cycles**.** The antifungal activity of sterile textile tissue was determined against *Candida albicans.* Textiles such as woven, knitted and flat are subject to ISO 20645:2004, which specifies a procedure for determining the effectiveness of antibacterial treatments. In addition to testing fibres incorporated with antibacterial agents, ISO 20645:2004 also applies to hydrophilic, air-permeable materials. This procedure requires a

Mean value of inhibition zone (mm)	Growth [a]	Description	Assessment
> 1 1-0 0	None None None	Inhibition zone exceeding 1 mm, no growth [b] Inhibition zone up to 1 mm, no growth [b] No inhibition zone, no growth [c]	Good effect
0	Slight	No inhibition zone, only some restricted colonies, growth nearly totally suppressed [d]	Limit of efficacy
0 0	Moderate Heavy	No inhibition zone, compared to the control growth reduced to half [e] No inhibition zone, compared to the control no growth reduction or only slightly reduced growth	Insufficient effect

Note: a) Bacterial growth in the nutrient medium underneath the specimen

Table 1. Assessment conditions of the antimicrobial and antifungal effect in the agar diffusion test

minimum amount of diffusion of an antibacterial solution into test agar. Strips of sterile textile fabric were cut into 12 × 12 mm pieces for the ISO 20645:2004 test. Then, 10 ml of liquid 45 °C TSA (tryptic soy agar) and 1 ml of bacterial suspension were added to each sterile Petri dish. The contents of the Petri dish were mixed. After the agar hardened, samples of textile materials were positioned on the agar surface in a Petri dish using sterile tweezers. Test samples were incubated on tryptic soy agar (TSA) for 24 h at 37 °C. After incubation, the Petri dishes with samples were maintained at room temperature for 24 h. Finally, the inhibition zone was calculated using equation 1 [3].

$$H = \frac{D - d}{2} \qquad (1)$$

Where, H represents the inhibition zone, D the total diameter of the sample, and d is the diameter of the sample. The unit of measurement is in mm.

The criteria for the evaluation of the antimicrobial and antifungal effect by the agar diffusion test [3] are stated in Table 1.

b) A partial consideration shall be given to the extent of the inhibition. If an inhibition zone is large, it may indicate that there are significant reserves of active substances or that the product has not been adequately bonded to the substrate.

c) Absence of growth even in the absence of inhibition zones may be a good effect, as such a zone may not have formed due to low diffusibility of the active substance.

d) ″As good as no growth″ indicates the limits of efficacy.

e) A reduction in bacterial expansion indicates a reduction in the number of colonies or in the diameter of the colonies.

2.6. Determination of antibacterial activity in liquid nutrient medium

After establishing that, in the case of certain bacteria, there is no non-growth zone around small samples, it was decided to expand the study with larger samples. Therefore, the analysis of the antibacterial activity of textile fabrics in liquid nutrient medium-triptic soy broth (TSB) was extended. The assay in the liquid nutrient medium allows to increase the size of the test sample by increasing the amount of antibacterial agent in the nutrient medium (TSB). The standard method SN 195920-1992 [27] was used for this test. The strips of sterile textile fabric were cut into 12×60 mm pieces. For each sample, 5 sterile tubes with 10 ml of triptic soy broth (TSB) were used. 1 sample 12×60 mm strip was added to 1 tube, 2 sample 12×60 mm strips to 2 tubes, 3 sample 12×60 mm strips to 3 tubes, and 4 sample 12×60 mm strips to 4 tubes. Then, 0.1 ml of the test bacterial suspension was added to each tube. Test samples were incubated in tryptic soy broth (TSB) for 24 h at 37 °C. After incubation, Petri dishes with samples were kept at room temperature for 24 h. After culturing the sample, the TSB was assessed for signs of bacterial growth: TSB was cloudy - bacteria growing; TSB was clear – bacteria did not grow. The samples were evaluated as follows: the sample of a textile fabric that was antibacterially active – bacteria do not grow, TSB is clear, and the sample of textile fabric that was antibacterially inactive – bacteria growing, TSB is cloudy. The controls are presented as follows:

- KS + - TSB cloudy, *S. epidermidis* grows (0.1 ml of *S. epidermidis* suspension was added to the tube with TSB);
- KS– - TSB clear, *S. epidermidis* does not grow (0.1 ml of *S. epidermidis* suspension and their growth inhibitors were added to the tube with TSB).
- KE + - TSB cloudy, *E. coli* grows (0.1 ml of *E. coli* suspension was added to the tube with TSB);
- KE–- TSB clear, *E. coli* does not grow (0.1 ml of *E. coli* suspension and their growth inhibitors were added to the tube with TSB).

2.7. Determination of electrostatic properties

The EN ISO 1149-1 :2006 standard [28] specifies a test method for materials to be used in the production of protective clothing with electrostatic dissipation for prevention of incendiary discharge. A surface resistance of $\leq 2.5 \times 10^9\ \Omega$ was the minimum compliance value according to this standard. Electrostatic properties of a material are determined in order

Table 2. Antimicrobial activity test of the unwashed and washed textile fabric prepared – evaluation of bacterial and fungus growth

Sample identification	Activity	Reference cultures	Growth	Inhibition zone, mm	Efficacy
Before antimicrobial treatment	Antibacterial	ATCC 12228	none	0	NE
		ATCC 25922	none	0	NE
		ATCC 25923	none	0	NE
		ATCC 13883	none	0	NE
		ATCC 27853	none	0	NE
		ATCC 12459	none	0	NE
	Antifungal	ATCC 10231	none	0	NE
Sample 0	Antibacterial	ATCC 12228	none	8.1	GE
		ATCC 25922	none	2.1	GE
		ATCC 25923	none	7.0	GE
		ATCC 13883	none	3.0	GE
		ATCC 27853	none	3.8	GE
		ATCC 12459	none	1.3	GE
	Antifungal	ATCC 10231	none	1.8	GE
Sample 1	Antibacterial	ATCC 12228	none	1.3	GE
		ATCC 25922	none	0	GE
		ATCC 25923	none	1.1	GE
		ATCC 13883	none	0	GE
		ATCC 27853	none	0	GE
		ATCC 12459	none	0	GE
	Antifungal	ATCC 10231	none	0	GE
Sample 2	Antibacterial	ATCC 12228	none	0	GE
		ATCC 25922	none	0	GE
		ATCC 25923	none	0	GE
		ATCC 13883	none	0	GE
		ATCC 27853	none	0	GE
		ATCC 12459	none	0	GE
	Antifungal	ATCC 10231	none	0	GE

[NE= No efficacy; GE= Good effect]

to understand its electrical behaviour, especially the build-up and discharge of static electricity. By attracting and retaining particles through electrostatic forces, electrostatic properties contribute to the effectiveness of air filtration systems.

2.8. Sample identification

The samples were identified as sample 0 – antibacterial textile fabric before washing, sample 1 – antibacterial textile fabric after 1 washing cycle, and sample 2 – antibacterial textile fabric after 20 washing cycles. These identifications were applicable for antifungal activity as well.

During the experiments, the standard atmospheric conditions were 20±2 °C and 65±4 °C, respectively, as stipulated by ISO 139:2005 [29].

3. Results and Discussion

3.1. Antibacterial and antifungal activity based on ISO 20645:2004 standard

The antibacterial activity level of the polyester woven textile fabric against *Staphylococcus epidermidis, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumoniae* and *Proteus mirabilis* before and after 1 and 20 washing cycles is presented in Table 2 and Figure 1. The level of antifungal activity of the textile fabric against *Candida albicans* before and after 1 and 20 washing cycles is presented in Table 2 and Figure 2. The antibacterial and antifungal effect is assessed as good, but with limited efficacy or an insufficient effect according to the growth of the tested bacteria *Staphylococcus epidermidis, Escherichia coli, Staphylococcus aureus, Klebsiella pneumoniae, Pseudomonas aeruginosa* and *Proteus mirabilis* and the fungus *Candida albicans* under the sample and around the sample.

The findings of the antifungus activity of the textile fabric against *Candida albicans* are presented in Figure 2. The control was performed with an antimicrobial uncoated textile fabric.

All treated specimens displayed very good antimicrobial activity, as is presented in Table 2 and Figures 1. There were some variations in antimicrobial activity depending on the washing cycles; nevertheless, once treated, all fabric samples exhibited a good effect. The unwashed fabric shows a 8.14 mm inhibition zone for *Staphylococcus epidermidis* bacteria, a 2.1 mm inhibition zone for *Escherichia coli*, a 7.0 mm

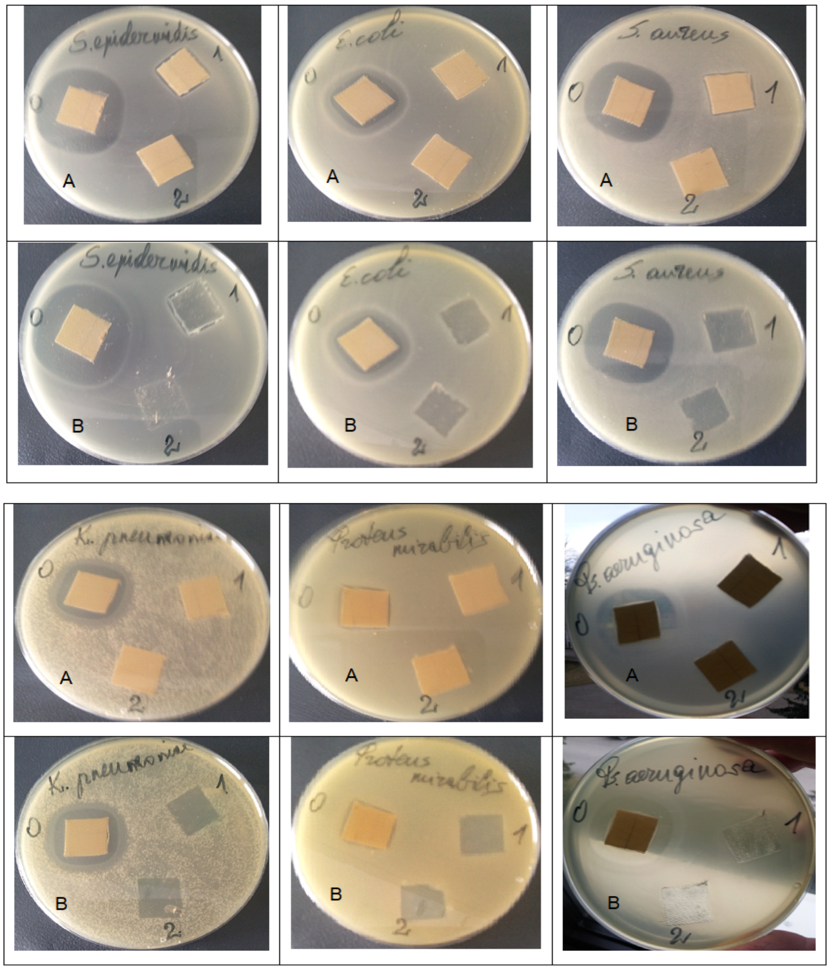

Fig. 1. Antibacterial activity of textile fabric against Staphylococcus epidermidis ATCC 12228, Staphylococcus aureus ATCC 25923, Escherichiae coli ATCC 25922, Pseudomonas aeruginosa ATCC 27853, Klebsiella pneumoniae ATCC 13883, Proteus mirabilis ATCC 12459 and Pseudomonas aeruginosa ATCC 15442: A – antibacterial activity of the samples; B – visualization of bacterial growth / non-growth under the sample (0 – sample 0; 1 – sample 1; 2 – sample 2)

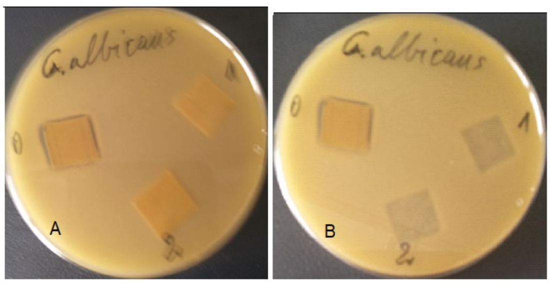

Fig. 2. Antifungal activity of textile fabric against Candida albicans ATCC 10231: A – antifungal activity of the samples; B – visualization of candida growth / non-growth under the sample (0 – sample 0; 1 – sample 1; 2 – sample 2)

inhibition zone for *Staphylococcus aureus*, a 3.0 mm inhibition zone for *Klebsiella pneumoniae*, a 3.8 mm inhibition zone for *Pseudomonas aeruginosa*, a 1.3 mm inhibition zone for *Proteus mirabilis* and a 1.8 mm inhibition zone for *Candida albicans* fungus. Based on these results, it can be inferred that the antibacterial agent BKC and the material investigated were able to form strong bonds. Thus, this antimicrobial finish can be recommended for polyester woven fabrics. Simultaneously, all treated woven fabrics displayed good antifungal activity, as is presented in Table 2 and Figure 2. A non-growth zone around the sample of unwashed fabric was found against the bacteria *Staphylococcus epidermidis, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumoniae* and *Proteus mirabilis* and against the fungus *Candida albicans.* A non-growth zone around the sample after the first washing cycle was found only against *Staphylococcus epidermidis* and *Staphylococcus aureus* bacteria. After 20 washing cycles, there was no non-growth zone around the samples. It is noteworthy that bacteria and fungus do not grow under all samples. It is important for antimicrobial finishing, however, to achieve antimicrobial activity that is resistant to washing. Results from the present clearly demonstrate that good antimicrobial activity against *Staphylococcus epidermidis* bacteria and *Staphylococcus aureus* bacteria remains after the first washing cycle. After 20 washing cycles, the developed sample showed good antimicrobial activity with no inhibition zone. The absence of an inhibition zone after 20 washing cycles indicates that the antibacterial activity of the material had decreased or disappeared. Repeated washing cycles may lead to leaching of the antibacterial agent, reducing its concentration on the textile surface and thus reducing its efficacy [30]. This antimicrobial finishing shows excellent results, especially since it a) is extremely easy to apply, b) works well with other wet finishing methods, and c) is very durable against microbes.

Samples	Resistance	Remarks	Recommendation
Without antimicrobial treatment	$1.75×10^{12}$ Ω	Higher than minimum compliance value according to the standard	Not applicable for protective textiles
Antimicrobial treated and unwashed	$1.17×10^{9}$ Ω	Good enough for this application as it is twice lower than the minimum compliance value	Could be used for non-washable systems only
Antimicrobial treated and after 1st washing cycle	$2.38×10^{9}$ Ω	On the limits of error with minimum possible	Cannot be used for protective textiles.
Antimicrobial treated and after 2nd washing cycle	---	Much higher than is required	Cannot be used for protective textiles.

Table 3. Evaluation of the electrostatic action of the unwashed and washed textile fabric prepared

3.2. Antibacterial activity based on TSB

The sample of a textile fabric is antibacterial active when bacteria do not grow and TSB is clear. On the other hand, if bacteria grow and TSB is cloudy, then the sample of textile fabric is antibacterial inactive.

Sample 0 and Sample 1 inhibited the growth (bacteria did not grow and TSB was clear) of *Staphylococcus epidermidis* in all tubes regardless of the sample size. Sample 2 did not inhibit the growth (bacteria grew and TSB was cloudy) of *Staphylococcus epidermidis* in all tubes regardless of the sample size. *Escherichia coli* growth was inhibited (bacteria did not grow and TSB was clear) only by sample 0. Samples 1 and 2 did not inhibit the growth (bacteria grew and TSB was cloudy) of *Escherichia coli* in all tubes regardless of the sample size.

3.3. Electrostatic property

The result of the electrostatic effect of the antimicrobial treated woven fabric, as a side effect, is presented in Table 3. The effect of washing on the electrostatic property is also evaluated and stated in Table 3. The surface resistance must be $\leq 2.5×10^{9}$ Ω (this is a minimum compliance value according to the standard).

The resistance of the woven fabric was found as $1.75×10^{12}$ Ω before antimicrobial treatment. This resistance value is not enough to be applicable for protective textiles with electrostatic dissipation for preventing incendiary discharge. The value of the resistance of the fabric decreased after antimicrobial treatment, reaching $1.17×10^{9}$ Ω. This is two times lower than the minimum compliance value, which is sufficient for protective applications. The resistance of the polyester woven fabric increased after washing, reaching $2.38×10^{9}$ Ω. This is within the limits of error with the minimum possible value, and due to that this is not recommended for protective applications. After 2nd washing, the resistance reaches much higher values than required and cannot be used for protective applications. The antimicrobial treated woven fabric could be used for non-washable antistatic air management systems only.

4. Conclusion

The findings indicate that the antimicrobial treatment of polyester fabric with Si Bac-Pure is very effective at inhibiting the growth of bacteria and provides excellent resistance to washing. From the results, the following conclusions can be made:

- The antimicrobial textile is most effective against gram-positive bacteria - *Staphylococcus epidermidis* and *Staphylococcus aureus*. Antimicrobial activity against gram-negative bacteria is weaker, but sufficient. When evaluating the antibacterial activity of the tested textile fabrics against gram-negative bacteria, it was found to be the strongest against *Escherichia coli, Pseudomonas aeruginosa* and *Klebsiella pneumoniae*, with a smaller effect on *Proteus mirabilis*.
- The antimicrobial textile fabric after 1 washing cycle retains antibacterial activity against gram-positive bacteria *Staphylococcus epidermidis* and *Staphylococcus aureus* (apparent non-growth zone around the sample, and bacteria did not grow under the sample) and gram-negative bacteria *Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumoniae*, and *Proteus mirabilis* (no apparent non-growth zone around the sample, and bacteria did not grow under the sample).
- Test data from the liquid medium confirmed the test data by the agar diffusion method. Samples 0 and 1 inhibited the growth of *Staphylococcus epidermidis* regardless of the sample size. The growth of *Escherichia coli* was inhibited only by sample 0; samples 1 and 2 had no antibacterial activity against *Escherichia coli* even at a sample size of 48×60 mm.
- The antimicrobial textile fabric inhibits the growth of the fungus *Candida albicans* around the sample (apparent non-growth zone around the sample, and bacteria did not grow under the sample).
- The antimicrobial fabric after 1 and 20 washings inhibits the growth of the fungus *Candida albicans* under the samples (no apparent non-growth zone around the sample, and bacteria did not grow under the sample).
- The antimicrobial treatment results in a positive antistatic property. However, this effect is not resistant enough to washing. The fabric developed can be used as an antistatic textile if washing is not necessary.

The results indicate that the specific structure of woven fabrics treated with an antimicrobial finish can be used for air management systems. Additionally, it displays good antistatic properties for use in non-washable applications. Future research should focus on discovering and developing new antimicrobial agents that are more effective and safer. In order to maintain their efficacy over time, antimicrobial treatments must be improved to make them washable. Air management systems require further research to optimize their efficacy and application. The integration of anti-microbial treated fabrics with air management systems to maximize their performance and efficiency is an important area for future work.

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