ORIGINAL ARTICLE

Annals of Agricultural and Environmental Medicine 2025, Vol 32, No 4, 443–452
www.aaem.pl

Survivability of microorganisms on synthetic and semi-synthetic textile materials used in the production of special purpose clothing in various humidity and temperature conditions

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A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article

Górny RL, Gołofit-Szymczak M, Cyprowski M, Ławniczek-Wałczyk A, Stobnicka A, Sawicka D, Krzemińska S, Greszta A, Dąbrowska A. Survivability of microorganisms on synthetic and semi-synthetic textile materials used in the production of special purpose clothing in various humidity and temperature conditions. Ann Agric Environ Med. 2025;32(4):443–443. doi: 10.26444/aaem/215225

Abstract

Introduction and Objective. The appropriate selection of the type, composition and finish of textile materials under specific conditions of temperature and humidity influences the possibility of their microbial colonization. The aim of the study is to test the survivability of microorganisms on textile materials in different microclimate conditions.

Materials and Method. To test the survivability of bacteria (Staphylococcus aureus, Escherichia coli, Bacillus subtilis, and Streptomyces albus), virus (bacteriophage PhiX174), and fungi (Cladosporium cladosporioides, Aspergillus versicolor, and Penicillium melinii), five man-made (viscose) and synthetic (polyester, polypropylene, polyacrylonitrile, polyamide) fabrics made of homogeneous fibres (100% the same fibres), as well as five fabrics made of mixed fibres (i.e. polyester with addition of viscose, carbon, aramid, and anti-static fibres) kept in low (60%) humidity and at room (~24 °C) and elevated (~40 °C) temperature of the air were used.

Results. The study showed different microbial survivability patterns. In the case of bacteria and bacteriophage, fibre admixtures added to synthetic materials usually reduced their survivability. In the case of fungi, synthetic, mainly polyester, as well as doped polyacrylonitrile and polyamide materials, supported the survivability of their conidia.

Conclusions. Under specific microclimatic conditions, the textile material can be selected in a way that limits the survivability of harmful microorganisms, which may be deposited on it. And *vice versa,* by changing the microclimatic conditions when wearing clothes made of a specific fabric, one can ensure that the presence of microorganisms will be eliminated or at least their survivability will be significantly reduced.

Key words

microorganisms, survivability, textile materials, antimicrobial action, fibre admixtures, air humidity and temperature

INTRODUCTION

Today's consumers demand high performance from textiles, regardless of whether the need for sophisticated fabrics is for high quality apparel, home textiles (bedding, upholstery, towels, carpets, curtains etc.), outdoor, or special purpose (e.g. medical, military, food packaging, air filtration, water purification, sewage treatment etc.) applications. However, the quality of manufactured products may be significantly reduced by the unfavourable effects of microorganisms. Microorganisms can attach to and grow on textiles during their use as well as storage, and this type of direct impact can be detrimental to both the fabric and the wearer [1, 2].

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Received: 23.10.2025; accepted: 05.12.2025; first published:

The growth of microorganisms on textiles may result in unfavourable changes of subjective (e.g. unpleasant odors) and objective, usually physical (decrease of strength, firm fabric stains and discoloration), character. Microorganisms (mainly *Aspergillus*, *Penicillium*, and *Microsporum* fungal genera, as well as *Bacillus*, *Streptomyces*, *Pseudomonas*, *Escherichia*, and *Staphylococcus* bacterial genera), can deteriorate fabrics that may result in the decomposition of fibrous material, leading to decay of textile [3–6].

Microbially-contaminated textiles, especially those acting as a carrier in transmitting pathogens (primarily in the healthcare environment) or their active emission source (e.g. after biofilm formation on their surfaces), may also be responsible for adverse health outcomes in wearers. Among the most frequently observed adverse effects are allergic reactions, irritations, atopic dermatitis and psoriasis, dermal infections, cross-infections, and infectious diseases [5–9].

An ideal antimicrobial treatment of textile materials should be effective against a broad spectrum of microbial species, reveal low toxicity to users, durability to repeated washing, dry cleaning, and hot pressing, properly preserve moisture transfer and thermal regulation, protect the initial quality and appearance of the fabrics. The finishing action should also be compatible with textile chemical processes like dyeing, be economically effective and environmentally friendly [8, 10–12]. The most widely used method to control microbial pollution on textile materials is the introduction of antibacterial, antifungal, and antiviral functions through special finishing of fibres and/or final textile products. Antimicrobial finishing processes have three different mechanisms: controlled release, regeneration principle, and blocking effect. In controlled release mechanisms, antimicrobial agents are slowly released in a controlled manner from a reservoir located either on the surface of the fabric or inside the textile material in the interior of the fibre. Such a finish is effective against microorganisms present on the fibre surface and in the surrounding environment. In the regeneration mechanism, an active germicidal substance, usually in microencapsulated form, is applied to the fabrics. Regeneration occurs when the covalent bonds in the chemically modified fibre are broken down by chemicals (e.g. bleaching substances during laundering) or photochemical action (e.g. exposure to ultraviolet radiation). This type of finish defends against microorganisms on the textile surface, but not in the neighbouring environment. Blocking mechanism uses films or coatings that are resistant to the passage of microbes into the fabric or have direct surface contact activity against microbial proliferation [2, 10, 13]. There are a variety of antimicrobial agents that are used for fast, effective, and efficient action on textile microbiota. These agents can be grouped as synthetic including inorganic (metal-based native and oxide nanoparticles), organic compounds (triclosan, polyhexamethylene biguanide, quaternary ammonium compounds, *N*-halamines), and carbon quantum dots made from carbon, graphite or graphene nanotubes, as well as natural ones, including plant extracts, such as acemannan from aloe vera, azadirachtin from neem, curcumin from turmeric, punicalagin from pomegranate, methanolic extracts from walnut, and essential oils from thyme, eucalyptus, jasmine, lavender or rose, and animal – chitosan, alginate, collagen hydrolysate [2, 7, 14].

The antimicrobial agents used to protect textile products against the unfavourable effects of microorganisms act through damage or inhibition. These agents can: damage or inhibit the synthesis of the cell wall, damage cellular transport by inhibiting cell membrane function, inhibit the synthesis of the proteins that make up the cells and enzymes, inhibit nucleic acid synthesis preventing the survival and proliferation of the cell, as well as inhibit metabolic processes leading to the death of the microorganism [13, 15].

The ecological footprint of antimicrobial textiles has gained increasing attention, raising concerns about contribution of biologically active agents to the ecosystems [2]. The average life expectancy of textile products is two years, after which become waste loads in landfills [13]. Textile production inextricably involves the creation of toxic and environmentally hazardous chemicals resulting from their necessary use in the production process. The most dangerous of these include: chlorinated solvents, aliphatic and aromatic hydrocarbon solvents, oxygenated solvents (alcohols, glycolics, ethers, esters, ketones, aldehydes), animal-based, oil-based, and synthetic-based greases, used oils, dyes and pigments (the latter can contain organohalogens such as fluoro-, chloro-, bromo- or iodo-carbon bond, and contains toxic elements such as lead, cadmium, mercury, chromium, cobalt, nickel, arsenic, and selenium), as well as organic compounds (e.g. benzyte, methane, paraffin) and native/oxide nanoparticles (nano-silver, copper, gold, zinc, gallium, titanium, magnesium, alginate) [1, 6, 7, 10, 12, 13, 15–19]. The majority of these substances, if not all of them, unfortunately have a negative impact on humans and the environment; in humans being responsible for shortness of breath, asthma and allergies, diseases of the kidney, lung, and nervous system, impairment in foetus development, infertility in men, memory and hearing loss, depression, headache, skin disorders, as well as toxic and carcinogenic effects [7, 13, 14].

Due to the health hazards described above and the ecological footprint left by the production and disposal of antimicrobial textiles, alternatives should be sought to the biologically active and often toxic substances that can be released into the environment [2]. Among such solutions is the use of fibre admixtures in textile production, one of the main roles of which will be to limit microbial growth. These admixtures can be selected with consideration of the environmental conditions in which the textiles will be used. The main factors to be considered are the humidity and temperature of the environment in which the textiles are used. The aim of this study, therefore, is to test the survivability of microorganisms on man-made and synthetic textiles made of homogeneous (100% the same fibres), as well as mixed (i.e. with admixtures of carbon, aramid, and antistatic) fibres used for the production of special purpose clothing in low (i.e. < 30%) and high (i.e. > 60%) air humidity, and at room (~24 °C) and elevated (~40 °C) temperatures.

MATERIALS AND METHOD

Eight reference microbial strains were used in the study: from bacteria – *Staphylococcus aureus* (ATCC 6538P), *Bacillus subtilis* (ATCC 6633), *Escherichia coli* (ATCC 25922), and *Streptomyces albus* (ATCC 3004); from fungi – *Penicillium melinii* (ATCC 10469), *Aspergillus versicolor* (ATCC 9577), and *Cladosporium cladosporioides* (ATCC 58991); and from viruses – bacteriophage PhiX174 (ATCC 13706-B1). *S. aureus* is a Gram-positive coccus with pathogenic properties mainly related to biochemical activity, and the production of several enzymes and toxins. Human infection usually occurs through direct contact and/or inhalation of vegetative cells. *B. subtilis* is an endospore-forming Gram-positive rod, a bacterium which is not considered a human pathogen. However, it is common in plant as well as animal products, and due to its ability to produce proteolytic enzymes (subtilisins), individuals exposed to dust containing these bacteria may develop *alveolitis allergica*, asthmatic symptoms or skin inflammation.

E. coli is a Gram-negative rod-shaped bacterium, a common inhabitant of the lower intestinal tract of humans and other vertebrates. It can also be present in soil and water as the result of faecal contamination, and therefore its presence has been used as an indicator of poor water and food quality. *E. coli* acts as a pathogen responsible mainly for urinary tract infections and intestinal diseases.

S. albus is Gram-positive, mycelium-forming actinomycete which is able to withstand desiccation and survive at a low moisture content of the substrate. It is widely distributed in nature, being common in soil, dust, straw, fodder, compost, and on plant surfaces. Inhalation of *S. albus* propagules may lead to respiratory diseases (including allergic alveolitis) [20].

P. melinii represents moderately xerophilic filamentous fungi. The mould is ubiquitous in the environment and can be found both indoors and outdoors. Its pathogenicity is low, and mycotoxin production has not been reported; however, the production of griseofulvin or penitrem A is quite likely.

A. versicolor is a cosmopolitan mould, isolated primarily from soil and plants, but also often found in buildings with water damaged and ventilation problems. Its pathogenicity is connected primarily with opportunistic infections in nails, ears, and skin. Its conidia can trigger inflammation in the lungs. It is also known to produce mycotoxins. *C. cladosporioides* is a fungus widely present in soil, plant debris, and on leaf surfaces, as well as is frequently isolated from the air, including buildings with elevated humidity levels. It can cause allergies, asthma, and pulmonary infections [21].

The bacteriophage PhiX174 is a model virus for laboratory studies requiring living nanosized particles. Its structure (shape) resembles a ball with five molecules of the G protein and one molecule of the H protein, forming spikes at each vertex, which resembles the SARS-CoV-2 virus. Its size – diameter about 32 nm – make this bacteriophage a very good model of a microorganism for testing, e.g. medical masks in terms of their effectiveness in protection against viruses that cause respiratory infections, as well as clothing protecting against infective agents in terms of its resistance to penetration of contaminated liquids under hydrostatic pressure. This bacteriophage has also been used in different research, e.g. in testing polyethylene films [22].

Microbial survivability studies were conducted on 10 different textile materials. These included five man-made (viscose) and synthetic (polyester, polypropylene, polyacrylonitrile, polyamide) fabrics made of homogeneous fibres (100% the same fibres), as well as five fabrics made of mixed fibres (i.e. polyester with addition of viscose, carbon, aramid, and antistatic fibres). The technical parameters of the tested materials were characterized by determining the fabrics' surface mass (mass per unit area), thickness, and air permeability (according to the Polish Standards: PN-EN 12127:2000 [23], PN-EN ISO 5084:1999 [24], and PN-EN ISO 9237:1998 [25], respectively). Their full characteristics are provided in Table 1.

Water is essential for the fungal colonization of textiles, acting as a medium for enzymatic activity, enabling hyphal growth, and influencing water activity and moisture content of the textile. Fungi secrete enzymes that require water to break down the textile substrate, while also needing water for their own metabolic processes and growth, making moisture control a primary method for preventing fungal growth on textiles. Water activity is generally temperature-dependent, with values typically increasing with rising temperatures for most products because higher temperatures increase the energy of water molecules, allowing them to become less bound and more available [26]. Taking the above into consideration, the survivability testing was performed in low (< 30%) and high (> 60%) relative humidity (RH) simulating 'dry' and 'wet' environmental conditions. Special-purpose clothing is used both under normal ambient temperature conditions (so-called room temperature) and in conditions where the air temperature in the environment may increase significantly due to (more or less) natural changes in the environment or specific working or use conditions. Therefore, this study tested combinations of both environmental parameters by simulating four usage variants, i.e. 24 °C/30%, 24 °C/60%, 40 °C/30%, and 40 °C/60%.

The antimicrobial activity test procedure was carried out according to the International Standard ISO 22196:2011 [27]. Briefly, flat samples of 10 tested materials, with a surface area of about 16 cm^2 each, were placed into separate Petri dishes with the test surface uppermost, and subsequently inoculated with 0.04 ml of the test microbial inoculum. The dishes with the samples were covered with a piece of polyethylene film that was gently press down to spread inoculum to the edges, paying attention that the test inoculum did not leak beyond the edges of the cover film. The same procedure was followed by the control sample, which was an empty sterile Petri dish without any microbiological material placed in it. The concentrations of microbial inocula were as follows (CFU means colony-forming unit, PFU means plaque-forming unit): *S. aureus* – 5.5×10^8 CFU/cm^3, *B. subtilis* – 4.9×10^8 CFU/cm^3, *E. coli* – 2.7×10^8 CFU/cm^3, *S. albus* – 3.5×10^8 CFU/cm^3, *A. versicilor* – 1.1×10^8 CFU/cm^3, *C. cladosporioides* – 1×10^8 CFU/cm^3, *P. melinii* – 2.6×10^8 CFU/cm^3, and bacteriophage PhiX174 – 2.4×10^5 PFU/cm^3.

Immediately after inoculation of the control and tested specimens, the samples were divided into four groups and incubated separately for 24 h at the following temperature and humidity conditions: 24 °C/30%, 24 °C/60%, 40 °C/30%, and 40 °C/60%. After incubation, the microorganisms from control samples were washed away by adding 5 ml of soybean casein digest broth with lecithin and polyoxyethylene sorbitan monooleate (SCDLP) to the Petri dish, and the microorganisms were completely washed at least four times by using a pipette to collect and release the applied neutralizer. In turn, the microorganisms from the inoculated material samples were placed in 10 ml test tubes filled with 5 ml of SCDLP and then eluted by vortexing for 5 minutes. All suspensions thus obtained from the control and test samples were elaborated by performing 10-fold serial dilutions of the SCDLP in phosphate-buffered physiological saline, with subsequent plating of these aliquots on trypticase soy agar for bacteria, Sabouraud agar for fungi, and nutrient agar with *E. coli* lawn for bacteriophage (all nutrient media: Becton Dickinson & Co., Sparks, USA) and incubation for 24 h at 37 °C, 30 °C, and 37 °C, respectively. After this incubation, the number of microbial colonies in control ($C_{cont.}$) and test (C_{CFU} or C_{PFU}) samples was determined for each test specimen in accordance with the following equation:

$$C_{Cont.} \text{ or } C_{CFU/PFU} = (N/10^{-D})\ (V_1/V_2)$$

where: N – the average number of viable microorganisms recovered per cm^2 per test specimen, D – the dilution factor, V_1 – the volume of extracting solution [ml], V_2 – the volume of sample inoculated on agar [ml].

When the test was deemed valid, the antimicrobial activity, R, was calculated using the following equation:

$$R = U_t - A_t$$

where: U_t – average of the common logarithm of the number of viable microorganisms, in CFU/cm² or PFU/cm², recovered from the untreated test specimens after 24 h; A_t – average of the common logarithm of the number of viable microorganisms, in CFU/cm² or PFU/cm², recovered from the treated test specimens after 24 h.

All tests for control and textile material samples were performed in duplicate. All experimental data were statistically processed. After checking the normality of data distributions with the Shapiro-Wilk test, the collected data were statistically elaborated using ANOVA, followed by Scheffe's and Fisher's tests, *t*-test, and Pearson correlation analysis, using Statistica, version 10. (StatSoft, Inc., Tulsa, OK, USA). Probability values were treated as statistically significant at $P < 0.05$.

RESULTS

The results of the textile fabric mass per unit area test are presented in Table 1. The highest mass per unit area was found in the fabric made of 100% viscose ('Jersey Ecru' – J), while the lowest was found in the fabric made of 100% polyamide ('Markizeta' – N). Regarding the mass per unit area parameter, it should be noted that in none of the 10 cases tested did the manufacturer's declared mass per unit area correspond to the actual laboratory-determined value. The largest difference in this respect was found for the fabric made of combination of polyester fibres (99.7%) with a carbon fibre admixture (0.3%) ('Hydrofil 1A/150' – E), for which the difference was 92.9 g/m², which exceeded the declared mass per unit area by 66%. Of the tested materials, acrylic fabric (M) had the highest thickness (1.35 mm), while fabric made of a combination of polyester fibres (99.7%) with a carbon fibre admixture (0.3%) ('Riplay 171' – G) had the lowest thickness (0.16 mm). Moreover, the air permeability tests revealed that the highest parameter was demonstrated by the fabric made of 100% polyamide (N) (3856.7 mm/s) and the lowest (17.1 mm/s) by the fabric made of polyester fibres (98%) with a carbon fibre admixture (2%) ('Buxton 153' – F). It should also be noted that one of the tested fabrics, made of a combination of polyester fibres (99.7%) with a carbon fibre blend (0.3%) (G), was completely impermeable to the air.

Examination of microbial survival on textile materials in low (i.e., < 30%) and high (i.e., > 60%) RH at room (~24 °C) and elevated temperatures (~40 °C), showed that the behaviour patterns of individual microorganisms differred and depended on the microclimatic conditions prevailing in a given environment (Fig. 1). Thus, the statistically significant differences in the survival on conditioned materials were demonstrated between:

a) for *S. aureus* – 24 °C/60% and 24 °C/30% (Scheffe's test; $P < 0.001$), 40 °C/30% (Scheffe's test: $P < 0.0001$), as well as 40 °C/60% (Scheffe's test; $P < 0.00001$);
b) for *B. subtilis* – 24 °C/30% and 40 °C/30% (Scheffe's test; $P < 0.01$), as well as 40 °C/60% (Scheffe's test; $P < 0.05$) and between 24 °C/60% and 40 °C/30% (Scheffe's test; $P < 0.01$) as well as 40 °C/60% (Scheffe's test; $P < 0.05$);
c) for *E. coli*, 24 °C/60% and 24 °C/30% (Scheffe's test; $P < 0.05$), 40 °C/30% (Scheffe's test; $P < 0.01$), as well as 40 °C/60% (Fisher's test; $P < 0.05$);
d) for *S. albus*: 24 °C/30% and 40 °C/30% (Fisher's test; $P < 0.05$) as well as 40 °C/60% (Fisher's test; $P < 0.05$);
e) for *A. versicolor*: 24 °C/30% and 40 °C/30% (Scheffe's test; $P < 0.0001$) as well as 40 °C/60% (Scheffe's test; $P < 0.001$);
f) for *C. cladosporioides*: 24 °C/60% and 40 °C/30% (Scheffe's test; $P < 0.05$) as well as 40 °C/60% (Scheffe's test; $P < 0.05$);
g) for *P. melinii*: 24 °C/30% and 40 °C/30% (Scheffe's test; $P < 0.001$) and 40 °C/60% (Scheffe's test; $P < 0.0001$) and between 24 °C/60% and 40 °C/60% (Scheffe's test; $P < 0.05$);
h) for bacteriophage PhiX174: 24 °C/30% and 24 °C/60% (Scheffe's test; $P < 0.000001$), 40 °C/30% (Scheffe's test; $P < 0.0001$) as well as 40 °C/60% (Scheffe's test; $P < 0.0001$) and between 24 °C/60% and 40 °C/30% (Scheffe's test; $P < 0.000001$) and 40 °C/60% (Scheffe's test; $P < 0.000001$).

Table 1. Characteristics of textile materials

Textile material symbol	Commercial name	Material composition	Technical parameters						
			Mass per unit area [g/m²]			Thickness [mm]		Permeability to the air [mm/s]	
			Declared	Actual					
				Mean	SD	Mean	SD	Mean	SD
A	Karo	67% polyester 33% viscose	175	187.1	1.31	0.33	0.000	54.0	2.55
E	Hydrofil 1A/150	99.7% polyester 0.3% carbon fibers	140	232.9	1.01	0.75	0.005	44.0	1.10
F	Buxton 153	98% polyester 2% carbon fibers	135	151.2	1.89	0.32	0.004	17.1	0.79
G	Riplay 171	99.7% polyester 0.3% carbon fibers	140	138.2	0.74	0.16	0.006	Impermeable	
I	Nomex Comfort	93% meta-aramid 5% para-aramid 2% antistatic fibers	165	175	1.68	0.36	0.005	101.9	8.56
J	Jersey Ecru	100% viscose	200	250.1	4.64	0.65	0.005	161.1	20.56
K	American Crêpe	100% polyester (PES)	130	149.9	1.60	0.46	0.004	453.5	34.97
L	Wigofil	100% polypropylene	150	151.8	3.07	0.54	0.009	107.7	11.14
M	Acryl	100% polyacrylonitrile	130	209.6	4.84	1.35	0.037	685.5	25.65
N	Markizeta	100% polyamide	75	70.3	1.29	0.23	0.005	3856.7	73.28

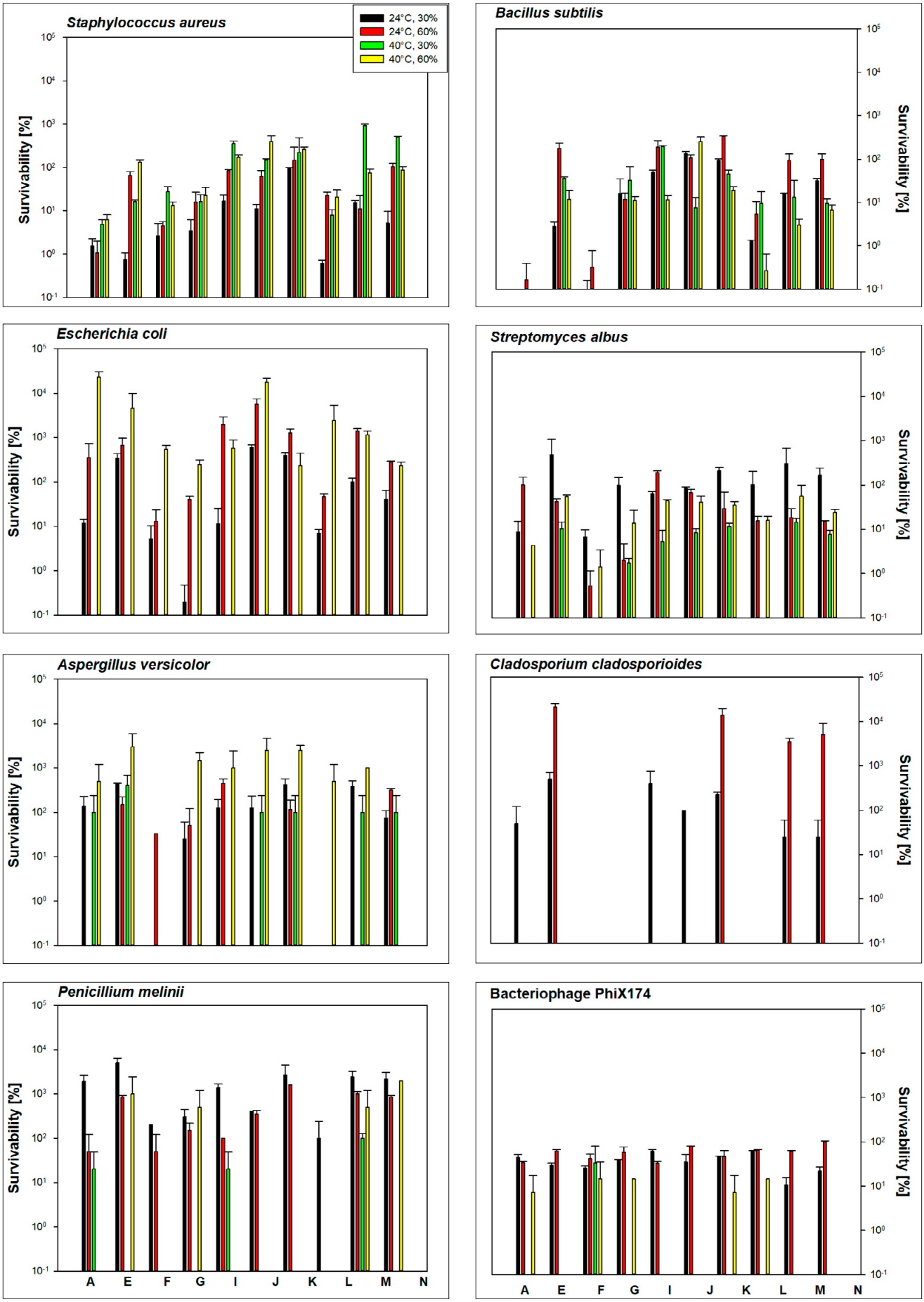

Figure 1. Survivability of microorganisms in relation to their total culturable number in the control sample in 4 air temperature and relative humidity conditions: 24 °C/30%, 24 °C/60%, 40 °C/30%, and 40 °C/60%. The capital letters on the graphs represent the following fabrics: A – polyester + viscose (33%), E – polyester + CF (0.3%), F – polyester + CF (2%), G – polyester + CF (0.3%), I – meta-aramid + para-aramid (5%) + antistatic fibers (2%), J – viscose (100%), K – polyester (100%), L – polypropylene (100%), M – polyacrylonitrile (100%), and N – polyamide (100%)

Taking into account the types of textile materials tested, statistically significant differences in the survival of microorganisms deposited on their surfaces were as follows:

a) in the case of *S. aureus* at 24 °C/30%, the highest survival rate was observed when deposited on polyester (Scheffe's test: K versus A, E, F, G, I, J, L, M, N – in all cases $P < 0.000001$); A similar relationship was observed at 24 °C/60%, where the survival rate on polyester fabric was also the highest (Fisher's test: K versus A, F, G, L, M – in all cases $P < 0.05$); whereas at 40 °C/30%, the highest survival rate was observed when these bacteria were deposited on polyamide (Scheffe's test: N versus A, E, F, G, L – in all cases $P < 0.05$) and polyacrylonitrile (Scheffe's test: M versus A, E, F, G, I, J, K, L – $P < 0.05$–0.001); at 40 °C/60%, the highest survival rate was observed when these bacteria were deposited on viscose (Scheffe's test: J versus A, F, G, L, M, N – $P < 0.05$–0.01);
b) in the case of *B. subtilis* (capable of spore production) at: 24 °C/30%, the highest survival rate of these bacteria was observed when deposited on viscose (Scheffe's test: J versus A, E, F, G, L, M, N – $P < 0.001$–0.0001), polyester (Scheffe's test: K versus A, E, F, G, L, M, N – $P < 0.01$–0.001), and aramid fabric with an admixture of antistatic fibres (Scheffe's test: I versus A, E, F, L – in all cases $P < 0.05$); at 24 °C/60%, the highest survival rate of these bacteria was observed when deposited on polyester (Scheffe's test: K versus A, F, G, J, L, M, N – $P < 0.05$–0.001) and aramid fabric with an admixture of antistatic fibres (Scheffe's test: I versus A and F – in both cases $P < 0.05$); in turn, at 40 °C/30%, the highest survival rate of these bacteria was observed when deposited on aramid material with an admixture of antistatic fibres (Scheffe's test: I versus A, E, F, G, J, K, L, M, N – $P < 0.001$–0.0001); at 40 °C/60%, these bacteria showed the highest survival when deposited on viscose (Scheffe's test: J versus A, E, F, G, I, K, L, M, N – in all cases $P < 0.001$);
c) in the case of *E. coli* at: 24 °C/30%, these bacteria showed the highest survival when deposited on viscose (Scheffe's test: J versus A, F, I, J, L, M, N – $P < 0.001$–0.0001), polyester (Scheffe's test: K versus A, F, G, I, L, M, N – $P < 0.05$–0.01), and polyester with added carbon fibres (Scheffe's test: E versus A, F, G, I, J, L, N – $P < 0.05$–0.01); At 24 °C/60%, these bacteria showed the highest survival when deposited on viscose (Scheffe's test: J versus A, E, F, G, K, L, M, N – $P < 0.05$–0.01); in turn, at 40 °C/60%, these bacteria showed the highest survival when deposited on viscose (Scheffe's test: J versus G, K, N – in all cases $P < 0.05$) and polyester with the addition of viscose (Scheffe's test: A versus E, F, G, I, K, L, M, N – $P < 0.05$–0.01);
d) in the case of *S. albus* (also capable of producing spores) at: 24 °C/30%, the highest survival rate was observed when deposited on polyacrylonitrile, polyester with an admixture of carbon fibre and 100% polyester materials, although in all these cases the differences in relation to survival on other materials were not statistically significant; at 24 °C/60%, the highest survival rate was observed when deposited on aramid material with an admixture of antistatic fibres (Scheffe's test: I versus E, F, G, J, K, L, M, N – $P < 0.05$–0.01); in turn, at 40 °C/30%, the highest survival rate was observed when deposited on polyacrylonitrile material (Scheffe's test: M versus A, F, G, L – in all cases $P < 0.05$); at 40 °C/60% these bacteria showed the same tendency as at 24 °C/30% and partially at 40 °C/30% with the highest survival on polyacrylonitrile (Fisher's test: M versus A, F, G, L – $P < 0.05$–0.01) and polyester with an admixture of carbon fibres (E versus A, F, G, L – $P < 0.05$–0.01);
e) in the case of *A. versicolor* at: 24 °C/30%, the highest survival rate was observed when these fungi were deposited on polyester fabric with the addition of carbon fibres (Scheffe's test: E versus F and L – in both cases $P < 0.05$) and plain polyester materials (Scheffe's test: E versus F and L – in both cases $P < 0.05$); at 24 °C/60%, the highest survival rate was observed when these fungi were deposited on aramid materials with addition of antistatic fibres (Scheffe's test: I versus A, E, F, G, J, K, L, M – $P < 0.05$–0.01) and polyamide (Scheffe's test: N versus A, F, J, L, M – in all cases $P < 0.05$); Also at 40 °C/30% and 40 °C/60%, these fungi showed the highest survival on polyester with added carbon fibres (Fisher's test: E versus A, F, G, I, J, K, L, M, N, and E versus F, N – in all cases $P < 0.05$);
f) in the case of *C. cladosporioides*, similarly to *A. versicolor*, at 24 °C/30%, these fungi showed the highest survival when deposited on polyester with added carbon fibres (Fisher's test: E versus A, F, G, J, L, M, N – in all cases $P < 0.01$) and aramid with an admixture of antistatic fibres (Fisher's test: I versus A, F, G, J, L, M, N – in all cases $P < 0.05$); At 24 °C/60%, these fungi showed the highest survival when deposited on polyester with added carbon fibres (Scheffe's test: E versus A, F, G, I, J, L, M, N – $P < 0.05$–0.01) and viscose (Scheffe's test: E versus A, F, G, I, J, L – $P < 0.05$ in all cases); at 40 °C/30% and 40 °C/60%, no significant differences were observed in the survival of this fungus on the tested textile materials;
g) in the case of *P. melinii*, at: 24 °C/30%, these fungi showed the highest survival when deposited on polyester fabric with added carbon fibres (Scheffe's test: E versus F, G, J, L – $P < 0.05$ in all cases); at 24 °C/60%, the highest survival rate was observed for these fungi when deposited on polyacrylonitrile (Scheffe's test: M versus A, F, G, I, J, K, L – $P < 0.01$–0.0001), polyester (Scheffe's test: K versus A, E, F, G, I, J, L, M, N – $P < 0.01$–0.000001), polyester with added carbon fibres (Scheffe's test: E versus A, F, G, I, J, K, L – $P < 0.01$–0.0001), and polyamide (Fisher's test: N versus A, F, G, I, J, K, L – $P < 0.01$–0.0001); At 40 °C/30%, these fungi showed the highest survival when deposited on polyacrylonitrile (Scheffe's test: M versus A, E, F, G, I, J, K, L, N – $P < 0.05$–0.01); at 40 °C/60%, these fungi showed the highest survival when deposited on polyamide fabric (Fisher's test: N versus A, F, G, I, J, K, L, M – $P < 0.05$–0.01);
h) in the case of bacteriophage PhiX174 at: 24 °C/30%, the highest survival of virus particles was observed when deposited on polypropylene (Scheffe's test: L versus F, N, M – in all cases $P < 0.05$) and aramid materials (Scheffe's test: I versus A, F, G, I, J, K, L – $P < 0.05$–0.01); at 24 °C/60%, the highest survival of this virus was observed when deposited on polyamide (Scheffe's test: N versus F, I, K, N – $P < 0.05$–0.01); at increased air temperature, regardless of the prevailing humidity conditions, i.e. (at 40 °C/30% and 40 °C/60%), the survival of virus particles was statistically significantly reduced, practically regardless of the type of material on which its particles were deposited.

Against this background, the results of the antimicrobial activity tests of textile materials (Fig. 2) confirm that:

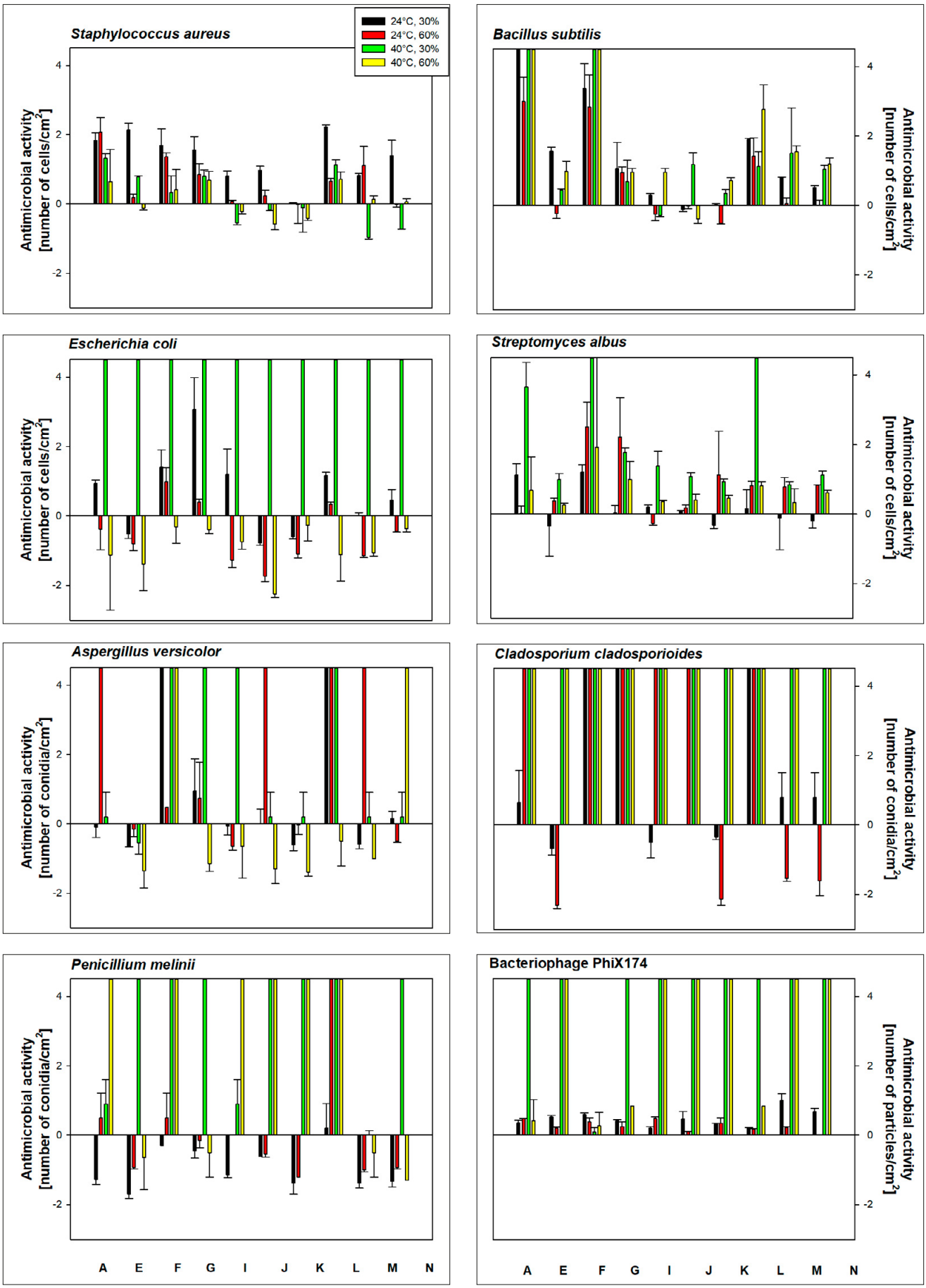

Figure 2. Antimicrobial activity of tested textile materials in 4 air temperature and relative humidity conditions: 24 °C/30%, 24 °C/60%, 40 °C/30%, and 40 °C/60%. The capital letters on the graphs represent the following fabrics: A – polyester + viscose (33%), E – polyester + CF (0.3%), F – polyester + CF (2%), G – polyester + CF (0.3%), I – meta-aramid + para-aramid (5%) + antistatic fibers (2%), J – viscose (100%), K – polyester (100%), L – polypropylene (100%), M – polyacrylonitrile (100%), and N – polyamide (100%)

a) in the case of *S. aureus*, the highest biocidal activity against its vegetative cells was observed, practically regardless of the microclimatic conditions (i.e. 24 °C/30%, 24 °C/60%, 40 °C/30%, or 40 °C/60%), for polyester materials, both native (100% PES) and those with viscose or carbon fibre admixtures, as well as polypropylene;
b) the tested textile materials demonstrated a similar relationship for *B. subtilis*. In this case, fabrics made of polyester doped with viscose and carbon fibres, as well as those made of polypropylene, exhibited the highest biocidal activity regardless of the microclimatic conditions present in the environment, although those made of 100% PES or viscose fibres supported the survival of these bacilli;
c) in the case of *E. coli*, the dependence of the degree of biocidal activity of a given material on the microclimatic conditions was particularly evident. For these Gram-negative rods, high air temperature combined with low relative humidity (40 °C/30%) had a highly biocidal effect, regardless of the type of material on which they were deposited. When analyzing the antimicrobial activity of this bacterium, it is also important to emphasize the protective effect of high air humidity on its survival, as even at low air temperature (24 °C/30%), polyester materials doped with viscose or carbon fibres, as well as aramid, polypropylene, and polyamide fabrics, demonstrated high antimicrobial activity;
d) in the case of *S. albus*, except for acrylic, pure polyester (100% PES) and PES modified with 0.3% carbon fibres (E), polyamide, and aramid materials exposed to room temperature and dry air (24 °C/30%) as well as all other materials tested at 24 °C/60%, 40 °C/30%, and 40 °C/60% revealed an antimicrobial effect on the cells of this actinomycete;
e) in the case of *A. versicolor* conidia, low air temperature and low humidity created more favorable conditions for the tested fabrics to demonstrate their antimicrobial properties against the conidia of this mould than high ambient temperature and humidity. However, in the case of two tested materials – polyamide fabric and polyester fabric modified with 2% carbon fibres – even ambient conditions of 40 °C/60% were effective in killing the conidia of this mould;
f) in the case of *C. cladosporioides* conidia, the tested materials demonstrated a killing pattern similar to that described for *S. albus* bacterium. However, in the case of fungal conidia deposited on acrylic, 'pure' polyester (100% PES), and polyester fabric modified with 0.3% carbon fibres (E), polyamide, and aramid fabrics, the antimicrobial activity of these materials was significantly less pronounced at low air temperatures (24 °C);
g) in the case of *P. melinii*, with the exception of polyacrylonitrile fabric, virtually all other tested textile materials, especially under conditions of high air temperature (40 °C) and relative humidity (60%), revealed high antimicrobial activity against the conidia of this fungus;
h) in the case of bacteriophage PhiX174, regardless of the microclimatic conditions present in the environment (24 °C/30%, 24 °C/60%, 40 °C/30%, or 40 °C/60%), all tested materials demonstrated antimicrobial activity against this virus particles. The only exception was the polyamide material conditioned at 24 °C/60%, which was neutral in this respect for the tested bacteriophage.

This study also examined the effect of surface area, thickness, and air permeability on the survival of microorganisms deposited on tested textiles. The results of correlations between the three aforementioned technical parameters and the survivability of microorganisms showed that only air permeability had a statistically significant positive effect, and only on the survival of *S. aureus*, *B. subtilis*, and *E. coli* bacteria, although this effect was also dependent on the microclimatic conditions in which the tested materials were conditioned. Such positive correlations with the air permeability of the tested materials were observed between the concentration of: a) *S. aureus* cells under 40 °C/60% condition ($r^2 = 0.51$ at $P < 0.05$); b) *B. subtilis* cells under conditions of 24 °C/30% ($r^2 = 0.50$ at $P < 0.05$) and 40 °C/60% ($r^2 = 0.94$ at $P < 0.05$); c) *E. coli* cells under conditions of 24 °C/30% ($r^2 = 0.48$ at $P < 0.05$), 24 °C/60% ($r^2 = 0.82$ at $P < 0.05$), and 40 °C/60% ($r^2 = 0.42$ at $P < 0.05$).

DISCUSSION

Nowadays, antimicrobial treatments are increasingly common in the textile industry The scope of application of antimicrobial textiles is very broad and encompasses many industries, including healthcare, veterinary, food processing, agriculture, and clothing and leather [2]. Applying antimicrobial finishes to fabrics and textile products not only protects against the development of pathogens but also increases the comfort of using such products. These treatments can provide benefits such as improving hygiene, controlling odour, and preserving the durability and resilience of textile products. In real-life scenarios, such as hospital linens, food industry textiles, sports apparel, footwear, and other items that require a high level of cleanliness, antimicrobial treatments can help to prevent the growth of microorganisms. They can also help to control unpleasant odours resulting from microbial contamination growth, and extend the life cycle of textile products. Laundry procedures are generally sufficient to remove microbial pollutants from textiles; however, recontamination has been shown to occur quickly, and fabrics that were almost sterile prior to use, were able to accumulate almost 50% of their eight-hour measured colony-forming units after only three hours of wear [5].

This study shows that carbon and antistatic fibre admixtures added to synthetic materials visibly reduced microbial survivability. Pure carbon fibres do not inherently have antimicrobial properties, but they can be made antimicrobial through modification. Common methods include coating them with antimicrobial substances, for example, metallic nanoparticles (especially silver), other metal compounds (e.g. titanium); however, such coatings are not necessary the most environmentally friendly. While these metals have antibacterial properties, their release into the environment from coated fibres could lead to toxicity issues for ecosystems and microbial communities, with concerns about potential human health effects from prolonged exposure [28]. Against this background, a durable functionalization of the carbon fibre surface with specific chemical groups seems to be a better solution.

Chemical treatments can introduce specific functional groups, such as hydroxyl or carboxyl groups, onto the carbon fibre surface. These groups can increase the hydrophilicity of the surface, making it more difficult for bacteria to adhere and

colonize, thereby improving its antibacterial performance [29]. Moreover, one of the main mechanisms attracting microorganisms to the materials' surfaces are electrostatic forces. Microorganisms dispersed in the environment are naturally or artificially electrically charged, and while in such a state may carry more than 10,000 elementary electric charges by individual cell [28, 30]. Carbon fibres have antistatic and conductive properties, which means they do not accumulate electrostatic charges but dissipate them. Therefore, any addition of fibres with antistatic properties will result in the limited colonization of such a modified material.

Although brands and retailers can differentiate their textiles by adding antimicrobial treatments, they need to ensure that their products meet relevant safety and efficacy standards. They must also ensure that the commercial claims placed on their products are properly substantiated with relevant testing that demonstrates their veracity, and that the antimicrobial treatments withstand a certain degree of use over time (e.g. efficacy after a given number of washes also needs to be substantiated). In the majority of cases, the antimicrobial finishes of textiles can – colloquially speaking – 'do the job'; however, biologically active agents used for this purpose pose a real environmental problem by delivering waste substances into the environment. Hence, one of the simplest solutions to decrease the amount of these pollutants around us is to use fabrics with admixtures of special fibres strongly bonded to the base material, and by changing the microclimate parameters. This will achieve an antimicrobial effect similar to the use of, e.g., chemical agents. This study shows that in many cases the survival of microorganisms can only be reduced without the chemical treatment of materials or fibres, by incorporating additives such as carbon fibres into the textile structure.

CONLUSIONS

The survivability of microorganisms on textile materials in low (RH < 30%) and high (RH > 60%) relative air humidity and at room (~24 °C) and elevated temperatures (~40 °C) revealed different patterns. In the case of bacteria and bacteriophage, fibre admixtures added to synthetic materials usually reduced their survivability. In the case of fungi, artificial, mainly polyesters, as well as doped polyacrylonitrile and polyamide materials, supported the survivability of their conidia.

Specific microclimatic conditions, i.e. low or high relative air humidity and the accompanying room or elevated ambient temperature, influence the survival of microorganisms on a given type of textile material. This observation suggests that in specific environmental circumstances, the textile material can be selected in such a way that limits the survivability of harmful microorganisms which may be deposited on it, e.g., in the case of *S. aureus* and *B. subtilis* bacteria, all fibre admixtures added to synthetic materials or use of 'pure' (100%) polypropylene fabric, reduced their survival rate. And *vice versa,* by changing the microclimatic environmental conditions when wearing clothes made of a specific textile material, it can be ensured that the presence of a viable harmful microorganism will be eliminated, or at least its survivability will be significantly reduced, for example, in the case of *C. cladosporioides* fungus, practically regardless of the type of textile material and in the cases of bacteriophage PhiX174 and *E. coli* bacterium at low relative humidity (RH < 30%), an increase in the air temperature significantly reduced survivability of these microorganisms.

Funding. The study evolved from the results obtained from research carried out within the scope of the 6th stage of the 'Governmental Programme for Improvement of Safety and Working Conditions', funded by the resources of the National Centre for Research and Development (Task No. I.PN.12: 'Electrostatic shields – modern methods of protection against infectious agents'). Programme main co-ordinator: The Central Institute for Labour Protection – National Research Institute (CIOP-PIB) in Warsaw, Poland

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