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DETERMINING THE EFFECTIVENESS OF USING A COMPOSITION OF BIOSURFACTANTS IN TECHNOLOGIES FOR ANTIMICROBIAL TREATMENT OF FLEECE MATERIALS FOR MILITARY AND CIVIL PURPOSES

Olga Paraska
Corresponding author
Doctor of Technical Science, Professor*
E-mail: olgaparaska@khmnu.edu.ua
Vita Nehorui
PhD Student*
Andriy Gorban
Doctor of Medical Science
Department Hygiene, Social Medicine, Public Health and Medical Informatics
University Petro Mohyla Black Sea National University
68 Desantnykiv str., 10, Mykolaiv, Ukraine, 54000
Tomasz Buratowski
Doctor of Technical Science, Professor
Department Robotics and Mechatronics
AGH University of Science and Technology in Krakow
Mickiewicza ave., 30, Krakov, Poland, 30059
*Department Chemistry and Chemical Engineering
Khmelnytskyi National University
Instytutska str., 11, Khmelnytskyi, Ukraine, 29016

This study's object is the processes of antimicrobial treatment of fleece materials for military-civilian purposes. The issue addressed is the high vulnerability of fleece materials to bacterial and fungal contamination in intensive use. This reduces their hygienic characteristics, durability, and safety.

The effectiveness of using the composition of biological surface-active substances (biosurfactants) with a concentration of 2.5 g/l has been carried out for the technologies of antimicrobial treatment of fleece materials for military-civilian purposes. The effect of biosurfactant composition on the preservation of antimicrobial activity against a wide range of microorganisms (Acinetobacter spp., Enterococcus faecalis, Micrococcus spp., Staphylococcus epidermidis, Proteus vulgaris, Aspergillus) was studied.

The results indicate a decrease in the bacterial load to the level of 101–102 CFU/ml and a significant reduction or complete elimination of fungal contamination (up to 103 CFU/ml). The findings are attributed to the ability of biosurfactant to destroy cellular membranes of microorganisms, which provides increased biocidal resistance of the material.

A feature of the results is the achievement of a pronounced antimicrobial effect while maintaining the physical and mechanical properties of the fabric. After treatment, a slight increase in bending stiffness (10–20%) was observed, the wrinkle resistance coefficient was 44–72%. This ensures the proper level of comfort and functionality of the products.

The practical significance relates to the possibility of implementing the designed technological solutions in the production of military and civilian clothing, which is operated under conditions of increased requirements for hygiene, thermal insulation, and durability, enabling consumer protection from microbial contamination

Keywords: biosurfactant, fleece products, antimicrobial treatment technologies, military clothing, antimicrobial finishing

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1. Introduction

Under current conditions of the growing need for highly efficient functional textiles, especially for military and civil purposes, the problem of microbiological safety of fabrics is becoming increasingly important [1, 2]. People are constantly in contact with textile materials in everyday life, which leads to high requirements for their hygiene and safety. During operation, textile products become contaminated, and as a result of heat generation, sweat secretion, and other metabolic processes, conditions favorable for the reproduction of microorganisms are created. Excessive bacterial contamination can lead to unpleasant odor, mold formation, color change, and deterioration of the operational properties of the material, as well as pose a threat to human health because of the possible penetration of pathogenic microorganisms through the skin [3].

Antimicrobial treatment of textile products is an important area for the development of the modern textile industry. This issue is especially relevant for fleece materials, which, due to their porous structure and ability to accumulate moisture, create favorable conditions for the growth of bacteria and fungi, which reduces the hygiene and operational properties of products.

Over the past decades, fleece materials have been widely used in the production of clothing, military and civilian equipment, medical textiles, furniture material, and technical textiles. Specifically, because of their unique properties: low thermal conductivity, lightness, softness, resistance to deformation, and quick drying. Fleece is made mainly from

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polyester, in particular polyethylene terephthalate, which provides high wear resistance and durability of the material.

Fleece materials, which are widely used in the production of thermal insulation clothing and equipment, are characterized by high porosity, the ability to retain moisture, and therefore a favorable environment for the development of pathogenic microflora. These properties determine the need to provide such materials with antimicrobial properties, in particular by surface treatment with specialized agents.

Among the numerous antimicrobial agents, compositions based on biopolymers and inorganic nanoparticles attract special attention, which are able to provide long-lasting action, compatibility with textile fibers, and environmental safety [4, 5]. It is known that biopolymers, in particular chitosan, sodium alginate, gelatin, play a role as matrices or stabilizers for the formation of antimicrobial compositions with nanoparticles of silver, copper, zinc [1, 6]. Among the promising advancements of recent years in textile finishing technologies is the use of multicomponent antimicrobial compositions based on natural polymers and nanoparticles, which make it possible to achieve a synergistic effect [1, 7]. For example, biosurfactant compositions containing functional agents of natural origin, which contribute to the uniform distribution of active substances on the surface of the textile material. However, the interaction of biosurfactant compositions with fleece fibers, as well as their effect on biocidal resistance under real operating conditions, remain insufficiently studied.

Biopolymer compositions based on biosurfactants demonstrate the ability not only to enhance the antimicrobial protection of fleece fabrics but also provide a long-term protective effect. At the same time, they preserve the physical and mechanical properties of the material, which is important for functionality and ease of use. The mechanisms of action of biosurfactants are based on interaction with cell membranes of microorganisms, disruption of their integrity, and causing the death of pathogenic cells, which confirms their effectiveness as antimicrobial agents for textile processing.

Despite the positive properties of biosurfactants, their introduction into fleece materials remains insufficiently studied. Existing methods of antimicrobial treatment often do not provide a long-term protective effect and can also affect the comfort and strength of the fabric. Therefore, it is a relevant task to design and analyze innovative biopolymer compositions based on biosurfactants in antimicrobial textile treatment technologies that provide long-term biocidal resistance and do not violate the physical and mechanical properties of fleece.

2. Literature review and problem statement

Global textile fiber production is growing annually. In particular, it reached 124 million tons in 2023, with an increase of 7% compared to 2022 (from 116 million tons), and the share of polyester, the basis for fleece, was about 75 million tons, i.e., 57% of all fibers [8]. The growth in demand is associated with the expansion of the scope of application of fleece materials, especially in products that have to contact the skin under extreme conditions. In particular, this applies to sports equipment, protective clothing, medical and military textile products. At the same time, the disadvantage of fleece is its poor resistance to the development of microorganisms, the ability to accumulate moisture, form biofilms, and cause unpleasant odors or skin irritation.

In work [1], a comparative analysis of synthetic and natural antimicrobial agents used for the safe processing of textiles was conducted. The potential of natural biopolymers and nanoparticles in the creation of environmentally friendly and effective antimicrobial compositions is shown. However, the authors emphasize the need to expand the range of bioactive substances and optimize their fixation technologies to ensure stability during operation.

In view of this, more and more attention is paid to biosurfactants. In [6], the antimicrobial activity of biosurfactants is characterized and their potential in biomedical applications is analyzed. The authors emphasize the importance of low toxicity, high biodegradability, stability under harsh conditions, and the ability to effectively adsorb on surfaces. It is this approach that contributes to the prospects of introducing biosurfactants in the technologies for designing modern antimicrobial systems for the treatment of textile materials, including those used in healthcare. However, a number of aspects remain unresolved. In particular, the mechanisms of interaction of biosurfactants with different types of textile fibers are not well understood, which may affect the effectiveness of their fixation and preservation of activity. The compatibility of biosurfactants with other types of textile treatments, such as dyeing, water-repellent, or flame-retardant impregnations, which is critically important for practical application, has not been considered. Possible reasons for the outlined aspects are the focus on the biosurfactant – microorganism model without taking into account the specificity of textile substrates, as well as the limited set of techniques capable of assessing long-term action under operational conditions. The combination of these factors determines the areas of further research necessary for the adaptation of biosurfactants to technologies for antimicrobial treatment of textile materials for military and civil purposes.

Given the climatic conditions of Ukraine, which are characterized by a cold and temperate climate with pronounced seasonal temperature fluctuations, fleece fabrics and materials are widely used in domestic textile production. Enterprises engaged in the supply, processing, and sewing of fleece fabrics are actively working in the market of fleece materials in Ukraine.

Corporate catalogs “TK-Style” [9] contain detailed primary information about the names of fleece fabrics, density, availability, positioning, terms of delivery, ss well as the assortment, the efficiency of updating, which allows consumers to quickly find the necessary range of fleece fabrics. The “Van Tex” catalogs [10] describe the technologies for processing military and civilian materials in accordance with quality standards. The existence of a wide range of fleece is confirmed, the directions of technological capabilities (processing, types of finishing, sewing), and a list of partners are given. Materials by “Grand Textile” [11] demonstrate product positions with detailed parameters of fleece fabrics. “Textile Contact” [12] is distinguished by its extensive logistics and market reviews, which are of a promotional nature. They contain analytical reviews of price demand, logistics capabilities, and the existence of several sales channels. Products by the “Comotec” trademark [13] have functional finishes, including antibacterial, which are introduced in the Ukrainian market. Potential specialization is technologies for creating functional coatings, in particular antibacterial, hydrophobic, and other finishes). Collectively, these sources illustrate the structure of the offer and the need to use a wide range of fleece fabrics of proper quality.

However, despite the growing demand, the production volumes of these materials remain insufficient to fully meet the needs of the market, which makes the further development of technologies and the introduction of innovative solutions to improve the quality and functionality of fleece products relevant. Thus, there is a scientific and practical need for a comprehensive study on the effect of antimicrobial composition of biosurfactants on the properties of fleece materials, in particular their biocidal resistance, which is a key factor in enabling microbiological safety in textile products for military and civilian purposes.

In [14], a review of current advances in the development of antimicrobial and anti-inflammatory cotton fabrics using nanostructures is provided. The authors note the high efficiency of nanomaterials in protecting fabrics from pathogens but emphasize the need for further study of their safety for humans and stability in long-term use. At the same time, key issues related to the long-term safety of nanoparticles for humans and their stability during repeated use remain unresolved. The environmental risks associated with the possible release of nanostructures into the environment during washing or disposal of products, as well as the technological aspects of scaling up the developed solutions, are also insufficiently studied. This may be due to the lack of standardized methods for assessing long-term effectiveness and safety, and the narrow specialization of research, which is focused mainly on biocidal activity.

Study [15] reports the design of innovative textile materials treated with TiO_2-AgNPs nanoparticles using succinic acid as a crosslinking agent. The results confirm the high antimicrobial activity of the materials, which opens up prospects for their use in the medical field. However, the mechanisms of stabilization of nanoparticles on the surface of the fibers, their effect on the physical and mechanical properties of the fabric, as well as the potential toxicological risks associated with the possible release of nanoparticles during operation have not been sufficiently studied. The lack of research on scaling up TiO_2-AgNPs technology to the industrial level determines the need for further work in this area, taking into account hygienic, technological, environmental, and economic requirements.

In work [16], the authors investigate textiles treated with antimicrobial substances for use at medical institutions. The review shows the effectiveness of such materials in preventing infections, but problems related to insufficient biostability, and instability of antimicrobial agents remain unresolved. The authors emphasize the need to improve fixation methods to increase the durability of the treatment.

However, the widespread practical implementation of biosurfactants in technologies for antimicrobial treatment of fleece materials, in particular for military and civil purposes, is hampered by a number of scientific and technical barriers: insufficiently studied mechanisms of action, instability of the antimicrobial effect under operating conditions, problems of fixation on the fibrous base, as well as the need for standardized methods for assessing effectiveness.

In this regard, there is a need for a comprehensive analysis of the use of biosurfactant compositions as a basis for creating safe, functional, and durable products in technologies for antimicrobial treatment of textile materials for military and civil purposes.

3. The aim and objectives of the study

The aim of our work is to determine the effectiveness of technology for antimicrobial treatment of fleece fabrics with a biosurfactant composition to ensure their hygiene, improve functional properties, and expand the possibilities of use in the military, medical, and sports industries. The implementation of this goal will make it possible to design textile materials with a long-lasting biocidal effect, adapted for operation under extreme conditions, which will meet modern requirements for safety, comfort, and multifunctionality.

To achieve this aim, the following objectives were accomplished:

– to assess the biocidal resistance of fleece fabrics after treatment by testing their resistance to bacterial and fungal damage;

– to determine the effect of antimicrobial agents on physical and mechanical properties to establish the optimal balance between protective and operational characteristics.

4. The study materials and methods

The object of our study is the processes of antimicrobial treatment of fleece materials for military and civil purposes.

The subject of the study is the composition of biosurfactants in the technologies of antimicrobial treatment of fleece materials for military and civil purposes.

It is assumed that the antimicrobial composition based on biosurfactants provides a stable coating on the surface of the fleece material and contributes to the preservation of biocidal activity.

The assumptions adopted in the study are:

– uniformity of composition application is achieved by observing a certain technological regime;

– the effect of treatment on the mechanical properties of the fabric is insignificant;

– fixation of active components is carried out through hydrophilic interactions and intermolecular bonds.

Our study on the influence of the composition of biosurfactants on the hygienic properties of textile products for military and civil purposes was carried out on samples of fleece fabrics that are represented in the Ukrainian market in accordance with the quality standards ISO 105, ISO 5077, EN 340:2004, ISO 14184-1. The characteristics of fleece fabrics are given in Table 1.

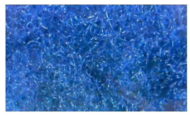
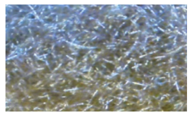
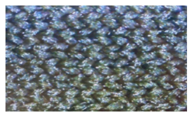
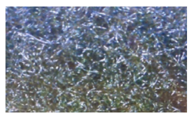
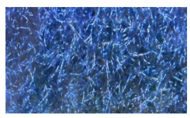
Before antimicrobial treatment, a visual assessment of the structure of the samples was carried out in the usual form and under an Andonstar ADSM301 optical microscope to identify differences in the fiber composition, surface structure, and weave density. Antimicrobial treatment of fleece samples was carried out by impregnation in an aqueous solution of an antimicrobial composition based on biosurfactant (at a concentration of 2.5 g/l) containing non-ionic biosurfactant, cationic bioSA [3, 17]. The composition is prepared by mechanical mixing of the calculated amount of starting components.

The treatment of fleece textile materials was carried out by the impregnation method: fabric samples were immersed in the prepared biosurfactant solutions and kept for 10 minutes at a temperature of 20°C. After impregnation, the samples were plused and dried at a temperature of 20°C until completely dry.

The antimicrobial properties of biosurfactant composition were studied by measuring the effect on the microflora found on fleece material samples. Analysis included determining the number of colonies of bacteria (*Acinetobacter, Enterococcus faecalis, Enterobacteria, Micrococcus, Staphylococcus*) and fungi (*Aspergillus*).

Table 1

Characteristics of fleece materials

Sample	Images of general appearance of fabrics	Image of a fabric sample under a microscope	Composition	Application
No. 1			100% PE*	Outerwear production
No. 2			100% PE	Camouflage uniform for cold climatic conditions, insulated layers for equipment for military personnel
No. 3			85% PE 15% PA**	Sportswear – thermal underwear for winter sports
No. 4			100% PE	Insulated overalls for walking. Fleece hats, gloves, and scarves
No. 5			100% PE	Sweaters, trousers, and overalls for outdoor activities (fleece sweaters, vests)

*Note: *PE – polyester, **PA – polyamide.*

Acinetobacter spp. are gram (–) bacteria that commonly cause infections of the respiratory tract, blood (sepsis), skin, soft tissue, and urinary tract, especially in immunocompromised patients. *Enterococcus faecalis* is a gram (+) bacterium that is part of the normal intestinal flora but becomes pathogenic under certain conditions, causing urinary tract infections, endocarditis, peritonitis, and sepsis. *Micrococcus spp.* is a gram (+) bacterium, mainly saprophytic, that lives on the skin and mucous membranes and may perform a protective function but in rare cases causes endocarditis or infected wounds. *Staphylococcus epidermidis*, a member of the normal skin flora, sometimes becomes pathogenic and can cause infections associated with medical devices, endocarditis, and sepsis. *Proteus vulgaris* is a gram (–) organism that is normally part of the normal intestinal flora but can cause urinary tract infections, kidney stones, and sepsis.

The genus *Aspergillus* includes over 200 species, some of which are pathogenic to humans. They can cause allergic bronchopulmonary aspergillosis, skin, eye (keratomycosis), ear (otomycosis), and central nervous system infections. These microorganisms were selected as test cultures to determine the effectiveness of antimicrobial treatment due to their medical significance and ability to survive on textile materials used in conditions of high humidity and pollution.

The number of microorganisms was determined by culturing tissue samples on appropriate nutrient media for 18 to 24 hours at 37°C. The number of colonies was estimated using standard quantitative analysis methods, and the results were expressed in CFU/ml.

To assess the effect of the composition on the viability and abundance of microflora, the direct effect of the composition on the microbial load was determined.

The thickness of fleece fabrics was determined using a thickness gauge, in accordance with the requirements by DSTU ISO 5084:2004 (ISO 5084:1996).

The hygienic properties of products, after treatment with compositions, were determined by the hygroscopicity of textile materials, in accordance with the requirements by DSTU GOST 3816:2009 (ISO 811-81). The hygroscopicity of fleece was characterized by the capillarity of the samples. Capillarity determines the ability of the fabric to absorb and transport moisture, which significantly affects the comfort of using finished products, especially under conditions of increased physical activity. The capillarity of textile products is characterized by the absorption of moisture by the longitudinal capillaries of the material and is estimated by the height h, mm – the rise of liquid in the sample, immersed with one end in the liquid for 1 hour.

To determine the capillarity, samples measuring 50×300 mm were fixed in a clamp so that one end remained free, and the other was immersed in a container with a dye solution. Kinetic measurement of the height of the liquid rise h was carried out at intervals of 10 minutes for 1 hour.

The stiffness of fleece fabric samples after treatment with the bio-surfactant composition was determined by the console method using the PT-2 device, in accordance with the requirements by DSTU GOST 8977:2009. For this purpose, pieces measuring 3×15 cm were cut from each fabric sample and placed in a device for measuring stiffness under the action of its natural weight of a distributed load.

Stiffness indicators (EI, $\mu N \cdot cm^2$) during bending are calculated separately for samples in the longitudinal and transverse directions according to the following formula (1)

$$B = 42{,}046\frac{m}{A}, \quad (1)$$

where B is the bending stiffness, μN·cm^2; m is the mass of the five samples, g; A is a coefficient, which is defined as a function of relative deflection f.

Relative deflection f is calculated from the following formula (2)

$$f_0 = \frac{f}{l}, \quad (2)$$

where f is the final deflection of samples; l is the length of sample ends that hang down, cm.

The length of sample ends is determined from the following formula (3)

$$l = \frac{Z_0 - a}{2}, \quad (3)$$

where Z_0 is the length of the sample, cm; a is the length of the fixed part of the PT-2 device platform, cm.

The stiffness coefficient (K_s) is defined as the ratio of stiffness value in the longitudinal direction to stiffness value in the transverse direction, formula (4)

$$K_s = \frac{B_{warp}}{B_{weft}}, \quad (4)$$

where K_s is the stiffness coefficient; B_{warp} is the stiffness when bending in the longitudinal direction, μN·cm^2; B_{weft} is the stiffness when bending in the transverse direction, μN·cm^2.

The wrinkle resistance of the fleece material after treatment with a bio-surfactant mixture was determined using the SMT-M device (standard testing method). This device makes it possible to assess the ability of the fleece material to restore its original shape after deformation caused by creasing.

To determine the wrinkle resistance coefficient of fabrics on the SMT device, it is necessary to prepare T-shaped samples and place them on the drum of the device (in the longitudinal and transverse directions). The drum is moved to the loading position, providing a specific pressure of $9.8 \cdot 10^4$ Pa (1 kgf/cm^2); the samples are left under load for 15 minutes. Then the drum is moved to the unloading position, and the samples are allowed to stabilize for 5 minutes. After that, the angle of recovery of the free end of each sample is determined using a measuring device [18].

The coefficient of invariance is calculated using formulas (5), (6):

$$K_N = 0.555 \cdot d_{warp}, \quad (5)$$

$$K_N = 0.555 \cdot d_{weft}, \quad (6)$$

where d_{warp}, d_{weft} is the arithmetic mean value of the angle of reversion of the sample in the longitudinal and transverse directions, respectively.

The data obtained make it possible to assess the suitability of fleece materials for a variety of products, taking into account their operational requirements.

5. Studying the effectiveness of antimicrobial agents and technologies in the finishing of fleece materials for military and civil purposes

5. 1. Assessing the biostability of fleece fabrics after antimicrobial treatment with a biosurfactant composition

Textile products have a significant surface area and the ability to accumulate moisture, which promotes the growth of microorganisms. This, in turn, not only accelerates the destruction of the fabric but also poses a risk to the health of consumers [19, 20]. Growing attention to consumer hygiene and safety has stimulated the development of antimicrobial textile treatment technologies. Among effective antimicrobial agents, biosurfactants, which combine the functions of wetting, cleaning, and bactericidal action, attract considerable attention [21–23]. The mechanism of action of biosurfactants is based on changing the surface properties of microorganisms and disrupting their integrity, which leads to cell death. Of particular note is the ability of biosurfactants to work effectively on hard surfaces, such as textiles, thereby providing long-lasting antimicrobial activity. This makes biosurfactants promising for use in medical, military, and household textiles, where hygiene and user safety are critical. Such approaches are important for the design of safe and effective antimicrobial materials, in particular for textiles for military and civil purposes.

A comparison of synthetic surfactants and biosurfactants shows that the latter have significantly better environmental properties [24]. These substances, unlike traditional synthetic surfactants, are rapidly degraded in the natural environment, in particular in water and soil, and have significantly lower toxicity, which makes them ideal for environmental cleaning. However, it is necessary to take into account the potential risks associated with the pathogenicity of some producer organisms, which requires additional research to ensure the safety of their use. Comparative characteristics of biosurfactants and synthetic organic agents are given in Table 2.

Table 2

Comparative characteristics of biosurfactants and synthetic organic agents

Criterion	biosurfactant	Synthetic organic agents
Origin	Biological (microorganisms, fermentation)	Chemical synthesis from hydrocarbons or aromatic compounds
Biodegradability	Complete, fast	Often low or moderate
Toxicity	Low, non-toxic to skin and environment	Possible toxicity, allergenicity
Environmental friendliness	High	Low or moderate

According to Table 2, biosurfactants have a number of significant advantages over synthetic organic agents, in particular in the field of safety for humans and the environment. Their high environmental friendliness and biodegradability make these compounds a promising alternative in production and environmental technologies [25–27].

To analyze the antimicrobial effect of biosurfactants, fleece materials were treated with aqueous solutions of biosurfactant composition with a concentration of 2.5 g/l [17].

The assessment of the antimicrobial effect of fleece materials treated with the biosurfactant composition was carried out using the impregnation method.

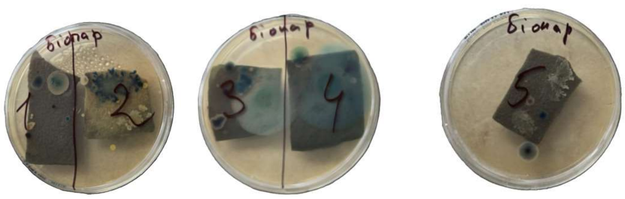
Then, the treated samples of fleece materials were placed in Petri dishes in a chromogenic medium for the isolation and differentiation of pathogens (Table 3). Incubation was carried out under aerobic conditions at 37°C for 18 to 24 hours.

Table 3

Media for isolation and differentiation of pathogens

Composition	g/l
Peptone and yeast extract	17
Chromogenic mixture	1
Agar	15

Three Petri dishes with chromogenic medium were used for each type of fleece sample. Observations showed that the largest number of microorganisms grew in samples treated with an aqueous solution of non-ionic biosurfactant, Fig. 1.



a *b* *c*

Fig. 1. Samples of fleece fabric treated with an aqueous solution of nonionic biosurfactant: *a* — samples No. 1, 2; *b* — samples No. 3, 4; *c* — sample No. 5

The results of studying the influence of microorganisms on the antimicrobial properties of fleece materials treated with an aqueous solution of a nonionic biosurfactant are given in Table 4.

Table 4

The influence of microorganisms on the antimicrobial properties of fleece materials treated with an aqueous solution of a nonionic biosurfactant with a concentration of 2.5 g/l

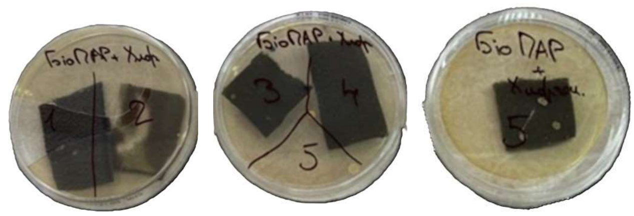
Samples of fleece materials	Microorganisms	Colony	Fungi	Colony
No. 1, No. 2	Acinetobacter, Enterococcus faecalis, Enterobacteria, Micrococcus, Staphilococcus	$1\cdot10^7$	*Aspergillius*	$1\cdot10^4$
No. 3, No. 4	Proteus vulgaris, Pseudomonas aeruginosa,	$1\cdot10^5$		
	Enterococcus faecalis	$1\cdot10^4$		
No. 5	*Enterobacteriaceae Staphylococcus saprophyticus*	$1\cdot10^4$		$1\cdot10^3$
		$1\cdot10^3$		

In samples No. 1, 2, a wide range of microorganisms was detected: *Acinetobacter, Enterococcus faecalis, Enterobacteriaceae, Micrococcus,* and *Staphylococcus spp.*, the total number of which reached $1\cdot10^7$ CFU/ml. In addition, fungal contamination with representatives of the genus *Aspergillus* was recorded at the level of $1\cdot10^4$ CFU/ml.

Samples No. 3, 4 were characterized by a significantly lower microbiological load: *Proteus vulgaris, Pseudomonas aeruginosa* and *Enterococcus faecalis* dominated, the total number of which was $1\cdot10^5$ CFU/ml, and the level of fungal contamination was also $1\cdot10^4$ CFU/ml. This may indicate a moderate effectiveness of the applied treatment with the biosurfactant composition.

The highest antimicrobial activity was recorded in sample No. 5. Only single strains of *Enterobacteriaceae* and *Staphylococcus saprophyticus* were detected with a bacterial load of $1\cdot10^4$ CFU/ml and a fungal load of $1\cdot10^3$ CFU/ml.

In general, our results indicate the ability of biosurfactants to reduce the level of microbial and fungal contamination on fleece materials, although the degree of antimicrobial action depended on the type of sample and microflora. Therefore, an analysis of the antimicrobial action of a biosurfactant composition consisting of a mixture of nonionic biosurfactants and cationic biosurfactants was conducted [3, 17], Fig. 2.



a *b* *c*

Fig. 2. Samples of fleece fabrics treated with a biosurfactant composition with a concentration of 2.5 g/l: *a* — samples No. 1, 2; *b* — samples No. 3, 4; *c* — sample No. 5

The results of studies on the effect of microorganisms on the antimicrobial properties of fleece materials treated with a biosurfactant composition are given in Table 5.

In samples No. 1, 2, no growth of microorganisms or fungal flora was recorded. The absence of bacterial and fungal contamination load indicates complete inhibition of microbiota development, which is evidence of high antimicrobial treatment efficiency.

In samples No. 3, 4, a minimal number of *Staphylococcus epidermidis* colonies was detected – at the level of $1\cdot10^2$ CFU/ml, without detection of fungal microflora. *S. epidermidis* is a representative of the normal microbiota of human skin, therefore its presence in low concentration is not considered as a sign of microbial contamination.

In sample No. 5, the number of colonies of microorganisms was $1\cdot10^1$ CFU/ml, fungal colonies were absent. This is the lowest level of microbial load among all the samples studied, which further confirms the effectiveness of biosurfactant composition.

Table 5

The effect of microorganisms on the antimicrobial properties of fleece materials treated with a biosurfactant composition with a concentration of 2.5 g/l

Sample	Microorganisms	Colonies	Fungi	Colonies
No. 1, 2	None	–	Absent	–
No. 3, 4	*Staphylococcus epidermidis*	$1\cdot10^2$		
No. 5		$1\cdot10^1$		–

The results of microbiological analysis demonstrate a high degree of antimicrobial activity of the biosurfactant composition at a concentration of 2.5 g/l. The complete absence of growth of microorganisms in samples No. 1, 2, as well as a small number of colonies of normoflora in samples No. 3–5 indicate effective suppression of pathogenic and conditionally pathogenic microorganisms. The applied treatment ensures microbiological safety of fleece materials and has the potential for implementation in the production of fleece products with increased hygiene requirements.

5. 2. The effect of antimicrobial treatment with a biosurfactant composition on the physicochemical and moisture-exchange properties of fleece fabrics

Fleece materials are widely used in military and civilian products, in particular in textile clothing, which provides comfortable conditions for consumers. Fabric thickness is a key criterion when choosing materials for sewing military and civilian products, which must meet increased requirements for functionality, durability, and convenience.

Determining the thickness of fleece fabrics is an important stage in the study of their physicomechanical properties; the results of measuring the thickness of fleece fabrics are given in Table 6.

Table 6

Fleece fabric thickness measurement results

No. of order	Fabric thickness, mm					Average value, mm
Sample No. 1	1.79	1.81	1.75	1.82	1.3	1.69
Sample No. 2	1.71	1.75	1.7	1.4	1.71	1.65
Sample No. 3	0.91	0.9	0.92	0.98	1.0	0.94
Sample No. 4	1.8	1.8	1.8	1.8	1.8	1.8
Sample No. 5	1.82	1.85	1.85	1.9	1.95	1.87

Analysis of the results revealed that the thickness of the test samples ranges from 0.94 to 1.87 mm. The largest thickness is in sample No. 5 (1.87 mm), which is characterized by a high level of thermal insulation properties. The stability of the thickness indicators in sample No. 4 (1.8 mm) indicates its uniformity, which is also an important advantage. Thus, samples No. 4, 5 are advisable to apply for use in the production of military clothing of the winter range since they provide the necessary thermal insulation, comfort, and compliance with strict requirements for materials for military-civilian purposes. Sample No. 3 (0.94 mm) is advisable to use in combination with other materials for products where lightness and flexibility are required, for example, in the spring and summer range of clothing. An important aspect of the operation of fleece fabrics is their hygienic properties, in particular the ability to regulate humidity. The capillarity of fleece fabrics characterizes their ability to transport moisture due to capillary forces. Since the basis of fleece is polyester, a material with hydrophobic properties, the natural capillarity of these fabrics is low, which causes limited liquid absorption.

Despite this, the porous structure of fleece with micropores between the fibers enables effective moisture removal in the form of vapor. The use of specialized treatments, such as Polartec Power Dry or biosurfactant, improves this process, accelerating the removal of moisture from the skin. Owing to this combination of properties, fleece does not accumulate moisture, dries quickly, and performs the function of a moisture-wicking layer in thermal clothing, sports, and military clothing.

Research on the capillarity of fleece materials is an important stage in assessing their hygroscopic properties. This provides an optimal microclimate and comfort during intense physical exertion and in extreme operating conditions.

The results of our study of the capillarity of fleece materials before and after treatment with the biosurfactant composition are given in Table 7.

Table 7

Dynamics of capillarity (liquid rise *h,* mm) in treated and untreated samples of fleece fabrics

Liquid lifting height in untreated fleece samples, (*h*, mm)					
Time, min	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5
1	25	25	10	10	15
5	30	30	20	15	20
10	90	50	85	70	60
20	140	90	165	150	135
30	190	135	210	190	150
40	210	150	250	230	175
50	230	170	255	250	210
60	250	180	260	280	220
Liquid lifting height in treated fleece samples, (*h*, mm)					
Time, min	Sample No. 1	Sample No .2	Sample No. 3	Sample No. 4	Sample No. 5
1	25	38	11	15	15
5	60	60	55	70	50
10	145	100	120	110	90
20	170	120	155	120	120
30	180	130	170	130	130
40	190	150	185	150	140
50	210	155	200	160	155
60	215	160	210	165	160

The results obtained allow us to assess the impact of antimicrobial treatment on the functional properties of materials and their suitability for use under conditions requiring effective moisture exchange.

Based on the data obtained, a plot was constructed for the dependence of liquid rise height *h*, mm, which characterizes the process of capillary moisture absorption by fleece material, on the time of immersion of the sample in a solution of eosin red. The results of studying the capillarity of fleece fabrics are shown in Fig. 3.

Fig. 3, *a* shows high capillary rise of liquid in untreated fabric samples. At the initial stages of the study (from 1 to 5 min) the process of liquid rise is rapid, which indicates a high ability of fibers to absorb moisture. Samples No. 1, 2 showed the highest capillary rise height already in the first minutes of the experiment, reaching from 25 to 30 mm. The maximum rise height, recorded after 60 min, is 280 mm for sample 4, which shows high capillarity.

Samples No. 3, 5 demonstrate average capillarity (260 and 220 mm, respectively, after 60 min), which may be due to differences in the structure of the fibers or their surface properties. In general, untreated fabrics are characterized by active absorption of liquid and its rapid movement through capillary channels.

Fig. 3, *b* indicates a decrease in capillary rise after fabric treatment. In the early stages (from 1 to 5 min) the liquid absorption rates are moderate, in particular, for sample No. 1 the height of rise after 1 min is 25 mm, and after 5 min – 60 mm. The maximum height of capillary rise for the treated samples (sample No. 1 – 215 mm after 60 min) is somewhat lower than that of untreated fabrics.

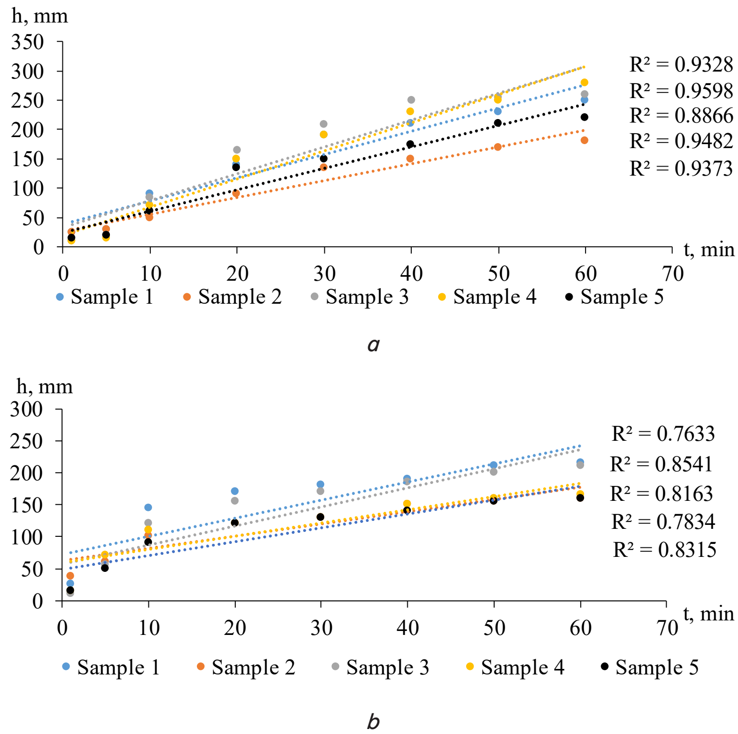


Fig. 3. Dynamics of liquid rise (*h*, mm) in: *a* — untreated; *b* — treated samples of fleece fabrics

Sample No. 2 demonstrates a high liquid rise (160 mm after 60 min), which indicates partial preservation of capillary properties even after treatment. Other samples (No. 3–5) are characterized by lower capillarity values, which may be associated with the fixation of biosurfactants in the structure of the fiber surface under the influence of antimicrobial treatment.

Analysis of the plot of the height of rise of liquid in the treated samples of fleece fabrics reveals that the ability of materials to capillary rise of liquid varies depending on their characteristics. All samples show a rapid increase in the height of rise within the first minute, indicating rapid moisture uptake. Subsequently, the capillary rise process slows down, and within 1 hour, the height of rise stabilizes.

In contrast, samples of treated fleece fabric have reduced capillarity, which can be an advantage for materials that need to provide hydrophobicity or a controlled level of moisture exchange in products. Such properties are desirable for manufacturing products with antimicrobial properties, for example, medical textiles or clothing for extreme conditions (military, athletes).

The physicochemical properties of fleece materials (stiffness, wrinkle resistance, lightness, dimensional stability) determine their wide application for sports, tourist, and military clothing. Due to these properties, fleece materials remain durable after repeated use.

The stiffness of fleece materials is determined by the density of the fabric and the type of fiber treatment, which affects their thermal insulation properties, comfort, and flexibility. Less stiff materials provide better softness and comfort, which contributes to their use for lightweight clothing and accessories. Stiffer fleeces are suitable for products with high wear resistance, such as outerwear, military, or tourist equipment. The choice of stiffness allows manufacturers to design a wide range of products for different needs.

The bending stiffness (*EI*) in the longitudinal and transverse directions, as well as the corresponding stiffness coefficients (K_s) for the studied fleece materials before and after treatment with a biosurfactant-based composition are given in Table 8.

A significant increase in stiffness indicators was recorded in samples No. 1, 2 after treatment. For sample 1, the stiffness in the longitudinal direction increased from 1,281.89 to 231,609.3 μN·cm^2, and in the transverse direction – from 3,513.93 to 635,579.1 μN·cm^2. The stiffness coefficient remained unchanged (0.36), which indicates the absence of an effect of treatment on the stiffness of the fabric.

In sample 2, a similar increase in *EI* was observed: from 5899.98 to 148610.9 μN·cm^2 (longitudinal) and from 11,655.64 to 292,184.1 μN·cm^2 (transverse). The K_s value also did not change (0.51), which may indicate the stability of the structure during deformations.

In sample No. 3, after treatment, the stiffness indicators increased from 1,050.52 μN·cm^2 (in both directions) to 36,599.93 μN·cm^2 (longitudinal) and 28,348.17 μN·cm^2 (transverse). The stiffness coefficient increased from 1.00 to 1.29, which indicates a predominant increase in bending resistance in the longitudinal direction and an overall increase in the structural stability of the fleece material after treatment with the bio-surfactant composition.

For sample No. 4, an increase in stiffness from 3,636.12 to 75,682.8 μN·cm^2 (longitudinal) and from 4,372.20 to 145,543.8 μN·cm^2 (transverse) is also observed. However, the stiffness coefficient decreased from 0.83 to 0.52, which may indicate a decrease in the elasticity of the material or the appearance of local hard zones after treatment.

Sample No. 5 demonstrated the greatest increase in stiffness: from 5,639.68 to 345,377.9 μN·cm^2 (longitudinal) and from 8,768.01 to 315,345 μN·cm^2 (transverse). The stiffness coefficient increased from 0.64 to 1.10, which indicates an improvement in the ability of the fabric to recover after deformation.

Table 8

Flexural stiffness (*EI*, μN·cm^2) and stiffness coefficient (K_s) of fleece samples before and after treatment with biosurfactant composition

Samples of fleece materials	*EI*, μN·cm^2		K_s
	longitudinal	transverse	
Sample No. 1			
Starting	1,281.89	3,513.93	0.36
Treated with a bio-surfactant composition	231,609.3	635,579.1	0.36
Sample No. 2			
Starting	5,899.98	11,655.64	0.51
Treated with a bio-surfactant composition	148,610.9	292,184.1	0.51
Sample No. 3			
Starting	1,050.52	1,050.52	1.00
Treated with a bio-surfactant composition	36,599.93	28,348.17	1.29
Sample No. 4			
Starting	3,636.12	4,372.20	0.83
Treated with a bio-surfactant composition	75,682.8	145,543.8	0.52
Sample No. 5			
Starting	5,639.68	8,768.01	0.64
Treated with a bio-surfactant composition	345,377.9	315,345	1.10

The results of our study showed that the treatment of fleece materials with a biosurfactant composition with a concentration of 2.5 g/l contributes to a significant increase in stiffness when bending in all samples. This indicates the formation of an additional structural layer on the surface of the fabric or strengthening of the fibrous structure. Analysis of the stiffness coefficient (K_S) revealed that fleece samples No. 1, No. 2 after treatment retainestabilityty of stiffness in the longitudinal direction. Such properties are important for military and special clothing, which must combine wear resistance with comfort in use.

At the same time, samples No. 1, 5 demonstrate uneven changes in stiffness, which may limit their use for some types of military clothing, where it is necessary to maintain a balance between stiffness and flexibility. Sample No. 4, due to the increase in stiffness with a significant decrease in the stiffness coefficient, can be used under conditions where increased flexibility of the material is required.

Thus, the biosurfactant composition can be effectively used to modify the mechanical properties of fleece materials; however, its effect on wrinkle resistance indicators depends on the type of sample and requires further research to optimize the technological process.

The treated fleece fabrics, especially samples No. 1, 2, demonstrate optimal mechanical properties, which makes them suitable for use in military and special clothing, where durability, wear resistance, and functionality are important.

The determination of the creasing resistance of fleece materials was carried out to assess the ability to retain their shape after deformation, which is an important characteristic for textile materials used in clothing production. This indicator affects the operational properties of the material, in particular products retain their attractive appearance for longer; materials with high fastness are easier to wash and iron; the ability to retain shape ensures comfort in wearing and durability of the product.

During our study, a comparative analysis of the invariability of fleece materials before and after treatment with a composition based on biosurfactants was carried out. The generalized results of determining the invariability coefficient (K_N) are given in Table 9.

Comparison of invariability indicators allows us to assess the impact of antimicrobial treatment on the ability of fleece materials to restore their original shape after deformation. Analysis of the data obtained reveals changes in invariability, which indicates the prospects for further modification of the material to improve its operational characteristics.

Comparison of the results of our study on the wrinkle resistance of fleece materials before and after treatment with a biosurfactant mixture makes it possible to conclude that their consumer properties have improved as a result of treatment.

In most samples after treatment, an increase in the angle of recovery is observed, which indicates an improved ability of the material to restore its shape after deformation. In particular, in fleece sample No. 3, the angle of recovery in the transverse direction from 100° to 130°, and in fleece sample No. 4 in the longitudinal direction from 90° to 110°.

The wrinkle resistance coefficient indicators demonstrate stability or improvement in shape stability after treatment, especially in the transverse direction. For example, in fleece sample No. 3, the wrinkle resistance coefficient in the transverse direction increased from 55% to 72%, and in sample No. 4 in the longitudinal direction – from 50% to 61%.

Table 9

Coefficients of wrinkle resistance (K_N) of fleece materials before and after treatment with a biosurfactant-based composition

The wrinkle resistance of fleece materials to processing				
Fleece samples	Recovery angle, °		Coefficient of wrinkle resistance, (K_N)	
	Longitudinal	Transverse	Longitudinal	Transverse
No.1	85	130	47	72
No.2	90	120	50	67
No.3	110	100	61	55
No.4	90	110	50	61
No.5	90	90	50	50
The wrinkle resistance of fleece materials after treatment with a bio-surfactant mixture				
Fleece samples	Recovery angle, °		Коефіцієнт незминальності, (K_N)	
	Longitudinal	Transverse	Longitudinal	Transverse
No.1	90	100	50	55
No.2	110	80	61	44
No.3	100	130	55	72
No.4	110	100	61	55
No.5	100	90	55	50

Thus, treatment with a biosurfactant mixture had a positive effect on the balance of indicators of fleece materials in different directions. This provides improved uniformity of properties of fleece materials and expands their use for products requiring high performance characteristics.

Treated fleece fabrics demonstrate better ability to retain their original shape, which makes them more suitable for use in products where a combination of different properties is important, such as antimicrobial, hygienic, and wear-resistant.

6. Discussion of results related to the effectiveness of a biosurfactant composition regarding the biocidal and physicochemical properties of fleece fabrics

The results of our studies shown in Fig. 1 and Table 4 demonstrated that fleece materials treated with an aqueous solution of non-ionic biosurfactant with a concentration of 2.5 g/l contained a variety of microflora. In samples No. 1, 2, a wide range of microorganisms was detected: *Acinetobacter, Enterococcus faecalis, Enterobacteriaceae, Micrococcus* and *Staphylococcus spp.* with a total number of colonies of up to $1{\cdot}10^7$ CFU/ml. Fungal contamination with representatives of the genus *Aspergillus* was also recorded at the level of $1{\cdot}10^4$ CFU/ml. Samples No. 3, 4 had a lower microbiological load (*Proteus vulgaris, Pseudomonas aeruginosa* and *Enterococcus faecalis* predominated – about $1{\cdot}10^5$ CFU/ml, fungal contamination – $1{\cdot}10^4$ CFU/ml). The lowest level of microbial contamination was in sample No. 5, where single strains of *Enterobacteriaceae* and *Staphylococcus saprophyticus* were recorded with a bacterial load of $1{\cdot}10^4$ CFU/ml and fungal load – $1{\cdot}10^3$ CFU/ml.

The antimicrobial treatment technology with a biosurfactant composition [3, 17] increased the resistance of fleece materials to pathogenic microorganisms (Fig. 2, Table 5). In samples No. 1, 2, no growth of microorganisms and fungal flora was recorded, which indicates complete inhibition of microbiota development. In samples No. 3 and No. 4, only single colonies of *Staphylococcus epidermidis* were detected at the level of $1{\cdot}10^2$ CFU/ml, which are a normal component of the skin microflora and are not considered as contamination. Sample No. 5 had the lowest bacterial load – $1{\cdot}10^1$ CFU/ml, fungal colonies were absent.

Thus, our results clearly demonstrate a high degree of antimicrobial activity of the biosurfactant composition at a concentration of 2.5 g/l. Applied processing technology provides effective suppression of pathogenic and conditionally pathogenic microorganisms, which is important for improving the hygienic properties of fleece materials and opens up prospects for their use for making products with increased sanitary requirements. The stability of the physicochemical characteristics (Fig. 4, Tables 7–9) is associated with the absence of aggressive action of biosurfactants on the fiber structure.

Unlike traditional synthetic biocides [14–16], the biosurfactant composition [3, 17] provides a complex effect: a pronounced antimicrobial effect against a wide range of microorganisms while simultaneously preserving the physicochemical properties of the fleece. Known studies [19, 21] demonstrate a significant deterioration in the elasticity and respiratory properties of tissues after treatment with synthetic agents, while in our case only a slight increase in stiffness by 10–20% is observed.

The features and advantages of our study are the simplicity and accessibility of the methods used to assess the antimicrobial properties of fleece materials. The proposed approaches make it possible to obtain correct, reproducible, and reliable results with high accuracy, which makes them effective for use under laboratory and industrial conditions. In addition, the study showed high efficiency of using environmentally safe biosurfactants in improving the hygienic characteristics of textile materials.

However, the results obtained are adequate for a given concentration of the biosurfactant composition – 2.5 g/l and typical laboratory test conditions. The limits of application are a limited range of fabric structures, mainly medium-density fleece. The resistance of the effect to prolonged mechanical or chemical effects, such as washing, sweat, ultraviolet radiation, requires additional verification.

The disadvantage is the use of only one type of biosurfactant composition and the lack of a multifactorial analysis of the influence of temperature, pH, and treatment modes. In the future, it is advisable to expand the range of studied conditions, test alternative biosurfactant compositions and their combinations with other ecological antimicrobial agents, ss well as expand the spectrum of studied microorganisms, in particular, including a wider range of skin microflora representatives and pathogenic species. It is important to study the durability of the antimicrobial effect and the stability of the biosurfactant composition on materials under operating conditions. Additionally, it is promising to study the effect of treatment on the physical and mechanical characteristics of fleece products, which could make it possible to optimize the technology by taking into account the preservation of consumer properties of fabrics.

When studying the effect of biosurfactant composition on the physical and mechanical properties of fleece materials, one should take into account the features of their structure – thickness, density, fiber direction, and type of weave. The pile of the material, as well as the fiber composition, significantly affect the efficiency of treatment and resistance to mechanical loads. To obtain comparable and consistent results, it is recommended to conduct research on samples with similar characteristics of fiber composition and production range.

7. Conclusions

1. The results of our assessment of the biocidal resistance of fleece fabrics showed that the treatment of fleece materials with a biosurfactant composition with a concentration of 2.5 g/l significantly reduces the microbial and fungal load. In samples No. 1, 2, no growth of pathogenic microorganisms and fungal flora was detected, which indicates high antimicrobial efficiency of the treatment. Samples No. 3, 4 contained a small number of colonies of normal microflora *Staphylococcus epidermidis*, which is not considered an indicator of contamination. The lowest level of microbial load was recorded in sample No. 5 with a complete absence of fungal contamination. The results obtained confirm the effectiveness of using the biosurfactant composition to ensure the microbiological safety of fleece materials, which makes it promising for the implementation of the technology in the production of hygienically safe textile products.

2. The treatment of fleece fabrics with a biosurfactant composition has a positive effect on their physicochemical and moisture exchange properties. Capillarity studies have shown that after treatment, the intensity of liquid rise decreases from 10–280 mm to 11–215 mm, which is an average decrease of approximately 8.03% and indicates partial preservation of moisture exchange functions while increasing the hydrophobicity of the material. This is an important factor for enabling comfort and effective humidity control in military and special-purpose products.

An increase in stiffness from 28,348.17 to 635,579.1 $\mu N{\cdot}cm^2$ after treatment indicates the formation of an additional structural layer or strengthening of the fibrous structure of the fabric, which contributes to improved wear resistance. At the same time, stiffness coefficients demonstrate the preservation or correction of elasticity, which is important for operational reliability. Analysis of wrinkle resistance indicates an improvement in the ability of fabrics to restore their shape after deformation, which increases the durability of products. The angle of recovery is from 80° to 130°.

Thus, combined modification of the physicochemical and hygroscopic properties of fleece materials using biosurfactant compositions provides an optimal balance between protective, hygienic, and operational characteristics. This contributes to the effectiveness of using biosurfactant compositions for the technologies of highly functional textile products for military and civil purposes.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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