Bio-materials for sustainable textile-based sensing applications

Igor Tyurin[1*], *Salikh* Tashpulatov[2], *Irina* Leonova[3], *Arthur* Kuzmin[1], and *Elena* Andreeva[1]

[1]Kosygin University, Sadovnicheskaya str. 33, 115035 Moscow, Russia
[2]Tashkent Institute of Apparel and Textile Industry, 5 Shoxdjaxon str., 100100 Tashkent, Uzbekistan
[3]Seven pieces Ltd, Ryazan Avenue 97k2, Moscow, Russia

Abstract. The paper is devoted to the production of biodegradable nonwovens (films) based on bacterial cellulose, the study of its physical and mechanical properties and the possibility of designing garments made from this fabric. As a result of the research, samples of bacterial cellulose films of different thicknesses were obtained, the relationship between changes in film thickness and cultivation time was established, the structure of biodegradable films was determined, the values of microfibrils forming them were revealed, and the physical and mechanical properties of bacterial cellulose were studied. A comparative analysis of the obtained biomaterials with commercial samples of composite eco-materials was carried out using synthetic leather made from Mexican cactus waste. The data collected is valuable for further research in the design of eco-friendly and biodegradable materials for both casual wear and textiles, as well as smart biomaterials for the engineering of sustainable textile-based sensors.

1 Introduction

Nowadays, the application of biotechnology in the manufacture of various products is becoming increasingly popular [1,2], making it possible to design clothing and textiles with increased functionality [3-5] and a wide range of sensory functions. The development of biodegradable materials for various applications is particularly promising in this area: from the medical and pharmaceutical fields to the manufacture of high-tech products with the advantage of eco-friendly technology.

The textile and light industry faces urgent problems of increasing the competitiveness of manufactured products [6], the solution of which is primarily connected with the introduction of innovative technologies and materials, including the design of "smart" clothing. The integration of biotechnology into the textile industry is becoming both a source of unique product development and an incentive for the financial and economic growth of individual companies and sustainable industrial development as a whole [7].

One of the most important aspects of "sustainable" product development is the use of environmentally friendly and/or biodegradable materials. There are several areas of production of bio-based materials for textile applications. They can be structurally divided

* Corresponding author: iniruyt1409@gmail.com

into three directions. First is biomaterials that meet two criteria: the composition is based only on natural components and the production is classified as "clean" and "environmentally friendly". Second is eco-materials which are described by meeting only one parameter: either the material is made of 100% "nature-like" composition, or the production of the material is "environmentally friendly". The third direction is eco-composites, which are characterized by the partial presence of "nature-like" components in their composition.

One of the most interesting examples of bio-based materials is bacterial cellulose (BC), which is the result of the interaction between bio- and textile technologies. Biocellulose is a polymer composed of nanofibrillar structures with a microporous structure [8]. On the other hand, this makes it possible to modify it and, as a result, to produce various composites with much better properties. Compared to plant cellulose, BC does not contain lignin or hemicellulose and is therefore quite pure, neutral, and biocompatible [9,10].

According to [11], BC membranes accelerate epithelialization and prevent infection. In addition, BC biocomposites have the potential to regulate cell adhesion; ultrathin BC films can also be used in the construction of diagnostic sensors due to their ability to immobilize multiple antigens.

This is a sort of natural skin-like fabric. It is formed on the surface of the air–liquid contact of a symbiotic culture of bacteria and yeast with polysaccharides. The cultivation method is sustainable and does not require any energy-intensive processes. BC films are synthesized by members of *Agrobacterium*, *Aerobacter, Sarcina, Pseudomonas, Alcaligenes* and *Myxedema, Komagataeibacterxylinus, Komagataeibacterhansenii, Komagataeibacter intermedius* [12].

A vivid example of eco-composites is the use of vegetable waste in the production of artificial (synthetic) leather. These are composites made of plant fibers from pineapple, cactus, and mushroom leaves, the percentage of which in the composition of the finished material varies from 20 to 55%. The composite material is based on polylactic acid (PLA) biopolymers, modified polyurethane (PU), etc. [13].

In order to generate the methods for designing smart biomaterials with sensory functions based on resource-efficient technology, we aimed to obtain samples of some biomaterials and investigate the samples of eco-composites. Biodegradable nonwovens (films) based on bacterial cellulose (BC) were used as samples of biomaterials; samples of artificial leather made from cactus waste were chosen as samples of eco-composites.

2 Materials and methods

BC films were obtained as follows. The symbiotic culture derived from the synthesis of the acetic acid bacteria *Acetobacter xylinum* and the osmophilic yeast strain *Schizosaccharomyces pombe* was placed in containers with a pre-prepared nutrient medium. Cultivation was carried out under static conditions of 25-26 ºC. The resulting BC films were removed from the containers with nutrient medium and symbiotic culture after 1, 2, and 4 weeks. Next, an initial cleaning of the bacterial films was performed to stop bacterial growth, followed by cleaning in distilled water to remove the residual solution. The next step was to dry the obtained films on wooden racks for 2 – 4 days.

The structural scheme of the obtained bacterial cellulose films is shown in Figure 1.

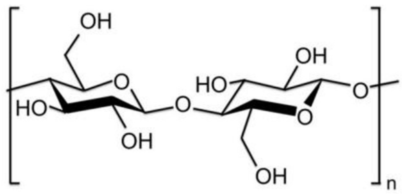

Fig. 1. Structural scheme of BC films.

The BC structure was examined using a Bresser National Geographic microscope (Germany). It was found that the obtained samples of the bacterial films have a flat and smooth surface (Fig. 2), compared to textiles with rough surfaces, in particular, cotton cellulose with heterogeneous surfaces due to the phase structure of yarns, weave, as well as the formation of pills.

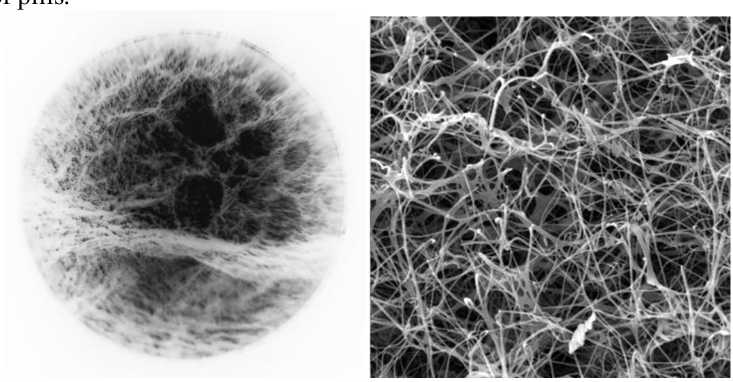

Fig. 2. Micrograph of BC films obtained at x100, x1000 magnifications.

Examination of the BC structure at 1000X magnification reveals that the chaotically arranged microfibrils form a grid of irregular structure. In the process of BC cultivation, the rate of change in film thickness over 4 weeks was studied.

3 Results and discussion

The practical analysis showed that the diameter of microfibrils varied in the range of (18.5 ± 3.2 nm), (33.6 ± 5.8 nm), (74.8 ± 11.2 nm). The standard deviation was 112.5, 142.4, and 131.7, respectively. The sample size studied was 1000 microfibrils in a sample of the BC film.

The diagram of the relationship between the change in film thickness and the cultivation time is shown in Fig. 3.

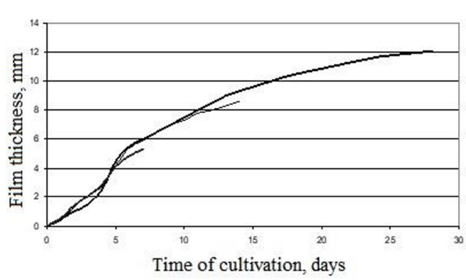

Fig. 3. Graph of the dependence of the change in film thickness (mm) on the time of cultivation (days).

The next step was to investigate the physical and mechanical properties of the BC films and determine the values of tensile strength, elongation at break and under load. The indicators were determined according to GOST R 53226-2008. The results of the physical and mechanical properties are presented in Table 1.

Table 1. Physical and mechanical characteristics of BC films.

Sample number	Wet film thickness, mm	Dry film thickness, mm	Elongation at break, %	Breaking load, MPa
1	5.62	0.72	4.2	4.8
2	9.36	0.90	12.2	5.6
3	12.10	1.1	7.6	6.8

According to the results of the study, it was found that the best indicators of physical and mechanical properties possess the sample of the bacterial film obtained as a result of cultivation for 14 days. It is also noted that the 3d sample of the film, despite relatively high values of tensile strength in uniaxial extension, exhibits increased brittleness in bending.

The comparative analysis with samples of eco-composites is based on the results of the study of the physical and chemical properties of artificial leather. The structure of the cross-section of the sample of commercial artificial leather of the brand Desserto® made from cactus waste is shown in Fig. 4 and consists of a top layer of PU dye coating (Fig. 4a), a middle layer of composite foam based on Mexican cactus waste (Fig. 4b), and a bottom layer of textile backing (Fig. 4c).

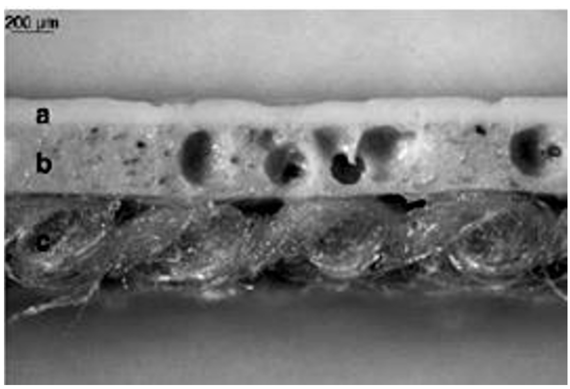

Fig. 4. Structure of a cross section of a sample of commercial artificial leather brand Desserto®, based on cactus waste [14].

The material composition was determined by the IR-FTIR method using the Nicolet iN10 FTIR microscope (Thermo Scientific, USA). The surfaces of the samples were analyzed in the spectral range of 675-4000 cm^{-1}. The spectra were acquired on a germanium crystal in FTIR mode by accumulating 128 scans with a resolution of 4 cm-1. The spectra were processed using the Omnic 9 software (Thermo Scientific, USA): conversion to optical density mode with automatic baseline correction [15].

Fig. 5 and Table 2 show the spectra of the artificial leather sample of the middle (composite) layer and compare them with the spectra from the library. The analysis revealed that the front side of sample No. 1 is composed primarily of polyurethane, while the back (fabric) side is made of cotton fibers. The tensile strength was measured using the Instron® 6800 and amounted to 10.6 MPa at a specimen thickness of 1.1 mm.

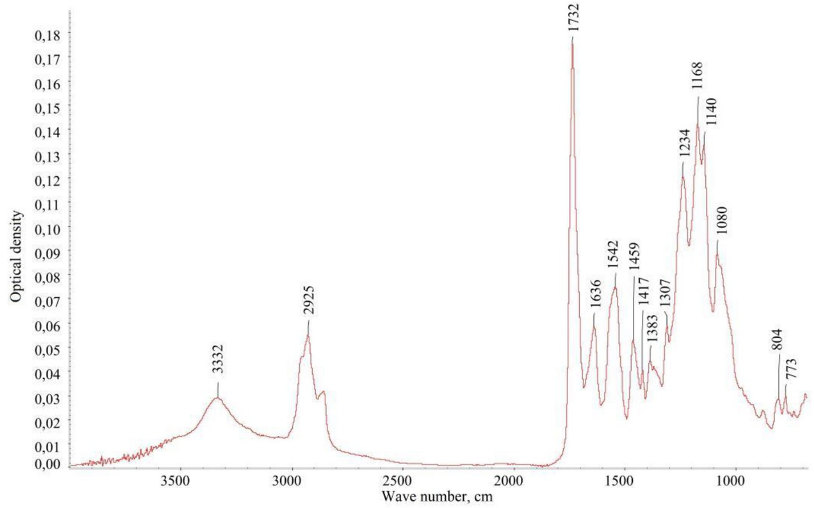

Fig. 5. IR spectra of a sample of artificial leather material of the middle (composite) layer.

Table 2. Comparison of the accuracy of the IR spectra of artificial leather samples with the studied image of the composite eco-material.

№	Coincidence with the test sample, %	Compound	Library of Materials
1	90,88	Spenlite_L-89	Coatings Technology
2	90,52	Desmolac 4125	Coatings Technology
3	89,36	NEOCRYLAX-7116	Industrial Coatings
4	89,27	Polyurethane, linear, aliphatic	HR Hummel Polymer and Additives
5	88,50	SPENSOL L52	Industrial Coatings
6	87,75	Spensol L-54	Coatings Technology
7	86,67	Desmolac 4125	HR Coatings Technology
8	86,66	SANCURE 887	Industrial Coatings
9	86,57	ESTANE 5640X660	Industrial Coatings
10	86,53	ESTANE 5712	Industrial Coatings

The results of the comparative analysis of structural, physical, and mechanical properties of biomaterials using the samples of BC films and eco-composites using the samples of artificial leather made of cactus waste indicate a lower strength (by 35-45%) of the BC samples at comparatively equal values of thickness. The analysis of the physical and chemical composition revealed the predominance of the polymer component (polyurethane) in the artificial leather samples, as opposed to the BC microfibrils, which are 100% of natural origin.

4 Conclusion

Thus, the following results are obtained in the paper:

- ✓ the method for obtaining samples of bacterial cellulose films of various thicknesses is described;

- ✓ the relationship between the change in bacterial cellulose film thickness and cultivation time was established;
- ✓ the structure of the bacterial cellulose films obtained was defined taking into account the values of the microfibrils forming them;
- ✓ it was established that the best indicators of physical and mechanical properties possess the sample of bacterial cellulose obtained as a result of cultivation for 14 days.

The bacterial cellulose films obtained from this study can be widely used due to their improved mechanical, physical and chemical, catalytic, optoelectronic, and magnetic properties, porosity, water absorption, formability, biodegradability, and natural renewability [8, 9, 10, 11]. The biodegradable nonwovens based on them are suitable for designing garments for both household and medical applications [16]. By introducing forming elements into the structure of biodegradable films, such as introducing preforms before drying, various authentic structures and textures can be created. By incorporating nanoparticles of various substances (Au, Ag, ZnO, Fe3O4, V2O5, TiO2) into the culture composition, it is possible to generate a composite with special properties suitable for biosensors, materials capable of absorbing electromagnetic radiation, photocatalysis and possessing antibacterial activity [17-19].

Further research in the design of environmentally friendly and biodegradable materials intended for the manufacture of clothing [20] is aimed at studying the forming, physical and mechanical properties of the films produced, as well as the use of organic dyes, both as separate components of the culture composite substance and as part of monosaccharides (e.g. replacing glucose with fructose derived from a fruit substance with organic dyes in its composition).

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