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Promising Methods of Antibacterial Finishing of Textile Materials

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Abstract—A review article, containing information on the options, possibilities, and prospects for the development of antibacterial finishing of textile materials, is presented. A wide range of products designed to impart antibacterial, antimicrobial, and antiviral properties to textile materials is considered. The main factors determining the appropriate decision on the technological and functional choice of the protective composition are presented, including the nature of the fiber-forming polymer, the tasks that the resulting material is designed to solve, and its application options. Compositions providing the required effect of destruction of the pathogenic flora and their application technologies are described. Special attention is paid to antimicrobial agents based on silver nanoparticles. Nanoparticles of this metal have a detrimental effect on antibiotic-resistant strains of bacteria; their effectiveness is higher as compared to a number of well-known antibiotics, for example, penicillin and its analogues. Silver nanoparticles are harmless to the human body. Acting as an inhibitor, they limit the activity of the enzyme responsible for oxygen consumption by single-cell bacteria, viruses, and fungi. In this case, silver ions bind to the outer and inner proteins of the bacterial cell membranes, blocking cellular respiration and reproduction. Various options to apply microencapsulation methods for the implementation of antibacterial finishing are considered, including: phase separation, suspension crosslinking, simple and complex coacervation, spray drying, crystallization from the melt, evaporation of the solvent, co-extrusion, layering, fluidized bed spraying, deposition, emulsion and interphase polymerization, layer-by-layer electrostatic self-assembly etc. All presented technologies are at various development stages—from the laboratory stage to production tests, they all have certain advantages and disadvantages. The accelerated development and implementation of the described methods in production of textile materials is relevant and is related to the existing complex epidemiological situation in the world.

Keywords: antibacteriality, nanoparticles, silver ions, microencapsulation, polyelectrolytes

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The Current Situation and Development Prospects for Antibacterial Finishing of Textile Materials

Textile materials with an ability to resist malignant and putrefactive bacteria, providing protection against viruses and microorganisms have long gained a strong position in the global market. At the same time, there are two interrelated, but fundamentally different development directions in the fight against microorganisms: the first is to protect the materials themselves from their destructive action and the second is to protect humans from the pathogenic microflora [1]. The second direction is gaining particular importance in connection with the global pandemic caused by the SARS-CoV-2 coronavirus. There is a necessity to create brand new antibacterial and antifungal fibrous materials and products, necessary not only for application in everyday life, but also for medical purposes. This article presents data on the options, possibilities, and prospects for the development of antibacterial finishing of textile materials.

Fibrous materials of any chemical nature, both chemical and natural, are susceptible to the action of microorganisms. They can both be used by bacteria and fungi for nutrition—this phenomenon is called

assimilation—and be damaged (destructured) by the action of the metabolites of microorganisms.

At the same time, due to their hydrophilicity, natural fibers are less resistant to the action of microorganisms [2]. The fibrillar structure, the amorphous-crystalline structure, and the presence of hydrated moisture in amorphous regions contribute to the spread of microbes, whose enzymes cause the hydrolysis of polymer bonds in fiber-forming polymers. In this regard, products made of wool and cotton fibers are the most vulnerable to the attacks of putrefactive bacteria. Due to their peculiar structure and the presence of impurities, silk, linen, jute, and kenaf are to some extent more stable; however, their protective properties cannot be compared with the security of the synthetic fiber. The development of the vital activity of organisms on fibers, formed from chemical raw materials, is hindered by the density and orientation of polymer components, the high degree of the fiber crystallinity, and the absence of hydrated and capillary-bound moisture. As a result, the growth of microbes on synthetic materials sharply slows down [3].

The manifestation of bio-damage on fibrous substrates is accompanied by a number of changes, the majority of which are easily noted visually and organoleptically. Such changes include the presence of multicolored spots, the coloristic parameters of which will depend on the type and color of the fungi-produced pigment, and a specific smell. Apparent destruction of the fiber is possible, which is especially characteristic of woolen materials. Changes in strength characteristics can be recorded instrumentally, including: reduced tensile strength, tensile elongation, and abrasion resistance. In some cases, there is a mass change.

The interaction of pathogenic bacteria with fiber-forming polymers proceeds in several stages:

1. Attachment of the microorganism to the fiber;

2. The microorganism's growth and reproduction; and

3. The fiber damage.

At some point, the second stage triggers the third, and they take place simultaneously.

The efficiency of microorganisms' fixation on the fiber and their reproduction rate depends on the nature of the fiber-forming substrate, its chemical composition, physicochemical and structural characteristics, hydrophobicity, and external factors such as the atmospheric humidity, temperature, and the time of the pathogen's contact with the fiber.

This leads to the conclusion that textile materials are not only a nutrient medium for microorganisms, but they can be active carriers of viruses and bacteria as well. There are data that pathogenic organisms persist on bed linen, clothing, bandages, and personal belongings for up to 24 hours. Moreover, for all the insusceptibility of synthetic fibers to reproduction of microorganisms, they persist longer on synthetics than on cotton, linen, or wool. After washing of textile materials in cold water, viruses retain their activity and are found practically intact in rinse waters. Conventional surfactants wash them off the fabric, but do not destroy them. Cold washing does not ensure complete removal of the pathogen from the fiber; in addition, there is a possibility to transfer it to an uninfected material. Cross exchange of viruses and bacteria is possible when washing bed linen in hospitals, sanatoriums, and nursing homes and can lead to nosocomial epidemics and other negative processes [4].

One of the side effects of bacterial reproduction that are the easiest for humans to notice is the appearance of an unpleasant odor. This phenomenon is caused by the release of such specifically smelling substances as the carboxylic acid, various amines, and aldehydes during processing of skin impurities and sweat by the bacteria. An example is the gram-positive Staphylococcus aureus, which produces 3-methyl-2-hexanoic acid during reproduction, causing a characteristic body odor.

The specific smell of baby diapers appears when the gram-negative Proteusvulgaris bacteria interacts with urea, which results in the formation of ammonia.

The negative effect can be eliminated by using appropriate preparations that can slow down or completely stop the growth of the bacteria. The effectiveness of such products depends on a great number of factors, and primarily on their effect on the external cell wall of microorganisms: microbes, bacteria, or fungi. Antimicrobial and antiviral drugs are divided into two classes according to their effect on the microbial cells integrity:

—bactericidal, destroying microorganisms;

—bacteriostatic, inhibiting the growth of microorganisms' cells [5, 6].

Regardless of its action option, antimicrobial finishing of textile materials should not reduce their strength characteristics and shape stability, degrade the handle of the fabric; it should maintain its effectiveness for a long

time during operation and should be environmentally safe [7].

The methods of imparting antiviral, antimicrobial, and antibacterial properties to fibrous materials are divided into physical, physicochemical, and chemical. At the same time, the chemical methods are conventionally more frequently applied and are considered the most effective.

It is commonly believed that the greatest protection against pathogenic flora is provided by antimicrobial preparations, fixed to the fiber by rather weak bonds: ionic, coordination, or labile covalent. If the bond is stronger (covalent), the antimicrobial effect decreases or disappears altogether [8].

One of the conventional options to create materials with the protection against viruses and bacteria is the introduction of an active substance into the structure of the fiber-forming polymer at the fiber formation stage. The undoubted advantage of this method is the resistance of the resulting effect to external influences. The main disadvantage is the complexity and the high production cost of such fiber, as well as the impossibility to apply this method to fabrics made of natural fibers [9].

Therefore, under production conditions, a more frequently applied method to obtain materials with antimicrobial properties is to apply protective agents to the fabric or fiber by impregnation. This option can be put in practice at various stages of textile finishing production, but it is implemented in the most successful manner in the final finishing process [10]. This method is technologically simple and less expensive than the previous technique; however, the stability of such finish is quite low.

Among the physical methods for production of antibacterial materials, metallization of the surface of textile materials has recently been gaining increasing popularity. The advantage of this process is the absence of wastewater; however, it is time-consuming and requires complex and expensive equipment [11, 12].

Preparations Imparting Antibacterial Properties to Textile Materials

Currently, there is a wide range of products designed to impart antibacterial, antimicrobial, and antiviral properties to textile materials. The choice of the composition is determined by the nature of the fiber-forming polymer, the tasks that the finished material has to solve, and its operation options [13].

In this respect, the most important requirements to the finishing compositions are as follows:

—lethal effect of the active substance even in minimal concentrations on the majority of pathogenic microorganisms;

—long-term efficiency preservation in the course of operation;

—absence of harmful effects on the human body; and

—preservation of the textile material quality indicators (strength, hygroscopicity, softness etc.) after finishing [14].

Depending on the structure and the chemical nature of biocidal agents, it is possible to distinguish the mechanisms of their influence on the pathogenic flora. It can be the inhibition of the microorganisms' metabolic processes or the termination of the synthesis of nucleic acids and proteins, which will not allow them to multiply. The effect at the cellular level is also possible, including the damage or inhibition of the cell wall synthesis, the inhibition of functions of the cell membrane, redistributing the intracellular and extracellular flow of substances [15, 16]. Alkyltrimethylammonium bromide (quaternary ammonium salt), which damages the microorganisms' cell membranes and inhibits the DNA production, is applied for bactericidal treatment of materials made of wool, cotton, polyester, and nylon. Due to the positive charge on the nitrogen cation, the compound is active and gets fixed on the negatively charged fiber by ionic bonds [17].

To protect a fiber from a number of gram-negative and gram-positive bacteria, as well as viruses and some fungi, the fiber is treated with linear alkylammonium compounds, containing alkyl chains of 12–18 carbon atoms. The presence of the perfluorinated group in the molecules, the number of ammonium groups, and the length of the alkyl chain affect the effectiveness of the preparation during operation [18]. As an example, such compositions as BioGuard (produced by AEGIS Microshield), as well as Sanigard KC and Sanitized (released by LN ChemicalIndustries) can be presented. The main disadvantage of using these compounds for finishing is their low resistance to wet treatments.

Another group of antimicrobial agents is based on 2,4,4′-trichloro-2'hydroxydiphenyl ether (metronidozole as the trade name). This substance exhibits an antibacterial activity against all types of bacteria, as well as some viruses and fungi [19, 20]. The mechanism of its action is to destructure the cell membranes by blocking

biosynthesis of phospholipids, lipopolysaccharides, and lipoproteins [21].

A number of products (BIOFRESH (USA), Irgaguard by BASF etc.) for treatment of synthetic and artificial fibers have been released on its basis. The compositions are applied both for introduction into the fiber at the fiber-formation stage and for impregnation of the fabrics [22].

However, in case of metronidazole, there is a number of problems, one of which results from its frequent use in toothpastes, creams, deodorants, and medicines. Such a wide distribution of the substance and the consumers' constant contact with it contributes to the emergence of metronidazole-resistant bacterial strains [23]. Another important disadvantage of this compound is its photochemical transformation in aqueous solutions into the toxic 2,8-dichlorodibenzo-*n*-dioxin [24, 25].

In some cases, polyelectrolytes, both natural and synthetic, are applied to impart antibacterial properties to textile materials. Most often chitosan and polyguanidine are used. Chitosan is a natural polymer, extracted from the exoskeleton of the crustaceans by chitin deacetylation. Chitosan possesses hydrophilic properties, is nontoxic and biocompatible; therefore, it is successfully used in finishing of fabrics made of cotton, wool, and polyester [26–28]. Positively charged primary amino groups of chitosan interact with negative charges on the microbes' surface. In this case, the antibacterial effectiveness is determined by the degree of polymerization and deacetylation of the polymer, its molecular weight, and the medium pH. With an increase in the positive charge density in the chitosan polymer chain during complexation with the ions of divalent metals—copper, zinc, and iron, it is possible to obtain a highly biocidal composition for textile finishing [28, 29]. The main disadvantage, restraining the use of chitosan in the finishing processes, is its exact requirements to the environment and the temperature regime, as its viscosity and molecular weight can change with an increase in the temperature, and its antibacterial effectiveness is preserved in an extremely narrow pH range of 6.3–6.5.

Polyhexamethylene guanidine (PHMG) belongs to polycationic amines (polyalkylene guanidines). In general, these polyelectrolytes are applied as a biocidal disinfectant, mainly, in the form of its salts of phosphoric or hydrochloric acids. Their disinfecting effect is based on the leakage of cytoplasmic materials during the destruction of the microbial cell membranes [30, 31]. A number of works by foreign researchers are devoted to the development of PHMG-based finishing agents [30]. The factor, restraining a wide application of this compound, is the selectivity of its action on certain types of microorganisms, and its tolerance to other classes of pathogens [32].

When used for textile materials finishing, n-galamines make a biocidal effect on a wide range of microorganisms. These substances are heterocyclic organic compounds, containing one or two covalent bonds between nitrogen and halogen in their composition. The halogen in this situation can be chlorine, bromine, or iodine [33, 34]. The destruction of microorganisms in this case is associated with the interaction of the chlorine cations with the microorganisms' acceptor parts, occurring in an aqueous medium during the electrophilic substitution of hydrogen atoms for halogen atoms [33, 17]. The disadvantage of using these chemicals is a possible decrease in the strength characteristics of the treated materials and a sharp smell, resulting from the excessive amount of chlorine on the fiber [33, 34].

Unlike synthetic agents, natural preparations obtained from herbs and plants are devoid of such disadvantages. They include substances based on terpinoids [35, 36], lectins, and polypeptides [37, 38], flavonoids [39–41], quinones [42, 43], tannins [44, 45], and coumarins [46–48]. They are safe, readily available, non-toxic when used by humans, and have no negative impact on the environment. Amino acids and peptides can also be referred to as natural compounds with protective properties [49, 50]. There is a number of theories [46, 49–53], explaining the mechanism of action of natural substances as antimicrobial agents; however, all of them are currently hypothetical.

Such substances have been studied as antimicrobial peptides, exhibiting a high bacterial activity against gram-positive microorganisms, as plectazine, [49, 50, 54], or, for example, L-cysteine, applied for antibacterial finishing of woolen fibrous materials [55].

The biocidal activity of metals: copper, silver, cobalt, zinc, their oxides, and salts has been studied. The oxidative stress under the influence of metals and their compounds causes damage to the cellular proteins, lipids, and DNA of pathogenic microorganisms. In addition, metal ions can bind to some donor ligands (O, N, and S) and replace the source metals in biomolecules, which leads to the cell death [56, 57].

Conventionally, silver-based agents are used for antibacterial finishing. Textile materials, treated with the application of silver-containing compositions, are

successfully used to prevent nosocomial infections. Silver has specific properties, which positively affect the immune defense of the human body. Products with such a finish are hypoallergenic and can have a beneficial effect on people suffering from skin diseases.

For bactericidal finishing of cellulose-containing fabrics, Russian enterprises most frequently use a "line" of products under the Sanitized trademark: Sanitized T99-19 based on a quaternary silicon compound, Sanitized T25-25 based on silver chloride, and Sanitized T96-21 based on triclosan. Sanitized T99-19 possesses the best protective properties and has a destructive effect on the cellular structure of pathogenic microorganisms. This product forms a strong chemical (covalent) bond with cellulose molecules, forming a mesh structure that prevents the human-hostile microflora from penetration on the fiber surface [58].

In addition to Sanitized, under the finishing production conditions, compositions by the RUDOLF GROUP Company under such tradenames as RUCO-BAC CID, RUCO-BAC MED are used. They are based on chemicals based on trialzol, silver salts, a mixture of quaternary ammonium compounds, and diphenylalkane derivatives.

It should be noted that at present, Russian enterprises mainly use products of foreign manufacturers for bactericidal finishing. The main disadvantage of such agents is their high cost.

Antimicrobial Agents Based on Silver Nanoparticles and Their Application Technologies

The current trend in production of textile materials with antibacterial finishing is the use of silver hydrosols [59, 60]. Nanoparticles of this metal have a detrimental effect on antibiotic-resistant strains of bacteria; the effectiveness of their application is higher as compared to a number of well-known antibiotics, for example, penicillin and its analogues [61]. Silver exhibits a significant fungicidal effect even at minimal (0.1 mg/L) concentrations. Other things being equal, it is superior to chemicals based on strong oxidizing agents and, first of all, chlorine compounds (lime chloride, sodium hypochloride etc.) [62]. Thus, silver nanocomposites have major advantages over other antibacterial and antimicrobial agents.

In works of Russian and foreign researchers, much attention is paid to the creation of nanoscale antimicrobial products based on silver nanoparticles (NP_{Ag}) and the development of technologies for biocidal finishing of textile materials with their application [63–67].

At the moment, the effectiveness of nanosilver in the fight against pathogenic microorganisms is beyond doubt. Silver nanoparticles are harmless to the human body. Acting as an inhibitor, they limit the activity of the enzyme responsible for oxygen consumption by unicellular bacteria, viruses, and fungi. At the same time, silver ions bind to the outer and inner proteins of the bacterial cell membranes, blocking cellular respiration and reproduction [68].

The authors of work [69] have demonstrated a possibility of NP_{Ag} synthesis through the reduction of its salts in bast fiber extracts.

Based on the study of the impact of the quantitative yield of impurities in the extract on the efficiency of formation of nanoparticles 4–50 nm in size, the Nanotex product has been developed.

The synthesized silver sols can be successfully applied to impart an antimicrobial activity to materials of various types (non-woven and woven) made of both natural and synthetic fibers. The antimicrobial activity of materials is recorded even at the minimum content of nanoparticles in them (0.07 wt %); moreover, the resistance to microbiological destruction reaching up to 90–96 % is preserved after a prolonged (10–14 days) contact of the nanocomposites with soil microflora. The developed method includes several stages and is environmentally safe.

In production of sets of uniforms and professional clothing and footwear made of natural materials (leather) for employees of the military-industrial and oil and gas complexes, compositions with silver nanoparticles stabilized with oleic acid are used as a biocidal agent. These preparations exhibit a well-pronounced microbicidal effect against the colonies of the Escherichiacoli and Bacillussubtilis bacteria [70].

Another option to stabilize NP_{Ag}-based nanocomposites are cationic polyelectrolytes, which differ in the polymerization degree and the charge density along the length of the polymer chain. It is believed that they contribute to an increase in the antibacterial activity of silver-containing products. In any case, the use of cationic polyelectrolytes in a certain concentration [69] increases the affinity of the composition to the cellulose fiber, which strengthens the antibacterial effect and makes it more durable.

When implementing bactericidal finishing of synthetic materials, it is an effective solution to combine nanomodification with plasma treatment, due to which the fabrics do not only become biocidal, but also hydrophilic, which is important for such materials [71].

For cellulose-containing materials, a method to give them antibacterial properties using silver hydrosol (C = 0.0185 %), stabilized with gelatin, has been developed. In order to make the finish highly resistant to wet treatments, after application of the silver-containing composition, the fabric is treated with a solution of quebracho vegetable tannins in a concentration of 1.5 %. After such a treatment, the ready material retains the required biocidal activity after 2 washes and the biostatical characteristics—after 5 washes [72].

There is a known option to create a dressing material in the form of a microfiber matrix with embedded aluminum oxyhydroxide particles, on which colloidal silver is adsorbed [73]. In this case, the concentration of colloidal silver is ~ 0.7 mg/cm^2, which ensures high antibacterial characteristics of the dressing and its high sorption capacity.

The ultrasound can also be successfully applied in the practice of medical materials development. The ultrasonic treatment of a textile material pre-impregnated with a solution containing silver nitrate, ethylene glycol, and ammonium hydroxide contributes to the formation of nanoscale (80 nm) silver particles [74]. The method is quite simple and eco-friendly; however, it creates a well-pronounced color on the fiber.

All the presented technologies are at various development stages, varying from the laboratory stage to production tests, and all of them have certain advantages and disadvantages. The technology to produce an antibacterial composition and apply it to obtain hosiery with an antibacterial effect, presented in work [69], has been introduced into production.

Microencapsulation as a Promising Method to Create Antibacterial Agents

In recent years, the method of encapsulating bactericidal agents into a shell and creating the so-called micro- or nanocapsules has been increasingly used. The microencapsulation technologies make it possible to obtain long-acting products, which are safe for humans, applying minimal concentrations of active substances and constantly monitoring the release of the active agents from the capsules [75].

Table 1. Microencapsulation methods according to classification proposed in 2011 [80]

Method	Application
Suspension polymerization	Textile
Emulsion polymerization	Pharmaceuticals
Dispersion method	Biological sciences
Interphase method	Plant protection, catalysis, pharmaceuticals
Suspension stitching	Pharmaceuticals
Extraction	
Spray drying	
Coacervation	
Condensation of vapors	Pharmaceuticals, food industry
Crystallization from melts	Food industry
Deposition	Food industry
Co - extrusion	Biological sciences
Fluidized bed coating	Biomedicine
Freezing	Biological sciences
Disk rotation	Pharmaceuticals
Impregnation method	Pharmaceuticals

Microencapsulation is used in various industrial sectors. Thanks to the application of the innovative approach, efficient technologies have been developed and unique original products have been manufactured to be successfully used in various spheres of the human life: from agriculture (microencapsulated insecticides, vitamin supplements) to medicine and cosmetology (microcapsules with medications, essential and fatty oils, probiotics etc.).

Microencapsulation is a process of enclosing the functional substance into a shell, protecting it from evaporation, contamination, and the effect of other environmental impacts and allowing the substance to release in a prolonged manner [76, 77].

The intensity of the active material release from the microcapsule core depends both on the thickness and the material of the shell, and on the external conditions of the temperature, pH, biodegradation etc. [78, 79].

The currently applied microencapsulation methods can be divided into 3 types (Table 1):

—chemical;

—physical [80]; and

—physicochemical [81, 82].

In each specific case, the choice of the method is determined by a whole number of factors, the main of which are the properties of the substance to be encapsulated, the material costs of the process, and the required characteristics of the final product.

The physical microencapsulation techniques include methods in which the capsules are formed without any chemical interaction: phase separation, suspension crosslinking, simple and complex coacervation, spray drying, crystallization from the melt, evaporation of the solvent, co-extrusion, layering, fluidized-bed spraying, deposition etc. [83–85].

Microencapsulation by emulsion or interphase polymerization, by the dispersed and interphase methods is referred to as a chemical way to produce encapsulated preparations [86]. In this case, the shells of the microcapsules are formed during polymerization of monomers or during intra- and inter-macromolecular reactions of polymers and oligomers, whose functional groups participate in chain growth or crosslinking reactions.

The formation of polyelectrolyte capsules by the electrostatic self-assembly technique, called "layer-by-layer," is a chemical method as well. It was developed by researchers of the Max Planck Institute in 1998 [87, 88] and was first used to create ultrathin monolayer polymer films on a macroscopic substrate. In 1966, the authors of work [89] proposed to apply alternate adsorption for the assembly of films. In 1991, Decher and co-authors considered a method to produce polyelectrolyte films, involving alternating adsorption of polycations and polyanions on a substrate [90]. The method is based on the selection of a certain solid micro-core (template), which can be represented by polystyrene, silicon dioxide [91], calcium carbonate [92], cadmium carbonate particles etc., on which the oppositely charged polyelectrolytes are sequentially applied, forming a multilayer coating. Subsequently, this core is dissolved and removed.

The capsule core is most frequently removed by dissolution. The material, forming the micro-core, influences such characteristics of the capsule as the shape, the shell permeability, the morphology and the rate of the core extraction from the capsule. When encapsulating medications, it is most convenient to use calcium carbonate as the core, as it has a porous structure and, as a result, a large sorption capacity, which makes it possible to apply it to encapsulate a wide range of drugs. In addition, it possesses biocompatibility and a possibility to be removed by biodegradation [93]. It should be noted that calcium carbonate templates are most frequently used in encapsulation processes. The application of silicon dioxide is limited by complications associated with its dissolution, as the process requires hydrofluoric acid. Polystyrene and melamine formaldehyde also have difficulties dissolving.

The capsule shells around the template are formed using synthetic (polystyrene sulfonate, polyacrylic acid, polydialyl dimethylammonium chloride etc.) and biocompatible polyelectrolytes (hyaluronic acid, sodium alginate, chitosan, L-lysine etc.). Their formation is accompanied by electrostatic interaction, and the presence of hydrogen forces and hydrophobic interactions is also possible [94–96]. The oppositely charged macromolecules of the polyelectrolyte alternately form layers around the capsule core and thus a shell of any thickness can be formed [97–99].

In case of applying melamine-formaldehyde latex particles and tetrahydrofuran as templates [98–100], organic solvents are used.

Modifications of microcapsules can be carried out in three ways: by synthesis of nanoparticles in the polyelectrolyte shell, for example, gold nanoparticles [101–104], by incorporation into the core or by adsorption of the stabilized nanoparticles in the polyelectrolyte shell [105, 106].

A technology to synthesize microcapsules by sequential adsorption of chitosan and xanthan gum polyelectrolytes on calcium carbonate templates has been developed. Silver nanoparticles are included into the capsule shell and a biologically active agent is found in the core. Immobilization of multilayer microcapsules on the fibrous material is provided by the system of polyelectrolytes: the positively charged chitosan and the negatively charged xanthan gum. The developed method makes it possible to impart antibacterial and antimycotic properties to textile materials [106].

The described methods of giving antimicrobial properties to textile materials are currently rapidly developing, which is due to the complex epidemiological situation in the world.

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CONFLICT OF INTEREST

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REFERENCES

1. Bukina, Yu.A. and Sergeeva, E.A., *Vest. Kaz. Tekh. Univ.*, 2012, no. 14, pp. 170–172.
2. Gao, Y. and Cranston, R., *Tex. Res. J.*, 2008, vol. 78, no. 1, pp. 60–72.
3. Gutarowska, B. and Michalski, A., *Woven Fabrics*, 2012, pp. 267–296.
4. Shahidi, S. and Wiener, J., *Antibact. Agents*, 2012, pp. 387–406.
5. Khaliullina, M.K. and Gadel'shina, E.A., *Vest. Kaz. Tekh. Univ.*, 2014, vol. 17, no. 8, pp. 87–91.
6. Rahman, M.A., Ahsan, T., and Islam, S., *Bang. J. Pharm.*, 2010, vol. 5, no. 1, pp. 41–44.
7. Windler, L., Height, M., and Nowack, B., *Environ. Int.*, 2013, vol. 53, pp. 62–73.
8. Kalontarov, I.Ya. and Liverant, V.L., *Pridanie tekstil'nym materialam biotsidnykh svoistv i ustoichivosti k mikroorganizmam* (Giving Textile Materials Biocidal Properties and Resistance to Microorganisms), Dushanbe: Doshish,1981.
9. Bshena, O., *Future Med. Chem.*, 2011, vol. 3, no. 14, pp. 1821–1847.
10. Szostak-Kot, J., Błyskal, B., and Sygula-Cholewinska, J., *Beijing: China Agriculture Press*, 2004, pp. 197–201.
11. Grebenkin, A.A., Grebenkin, A.N., Zverlin, S.V., and Makarov, A.E., *Vest. SPb Gos. Univ. Tekh. i Diz., Ser. 1: Estestv. i Tekh. Nauki*, 2010, no. 3, pp. 40–42.
12. Gorberg, B.L., *Heat and Sound Insulation and Tech. Conf.*, 2013, p. 6.
13. Kiseleva, A.Yu., Shushina, I.A., Kozlova, O.V., and Telegin, F.Yu., *Izv. Vyssh. Ucheb. Zaved.*, 2011, vol. 12, no. 2, pp. 110–112.
14. Szostak-Kot, J., *Fibers and Nonwovens, Microbiology of Materials*, Technical University of Lodz Publ., 2005, pp. 89–136.
15. Glazer, A.N. and Nikaido, H., *Microbial Biotechnology: Fundamentals of Applied Microbiology*, Cambridge University Press, 2007.
16. Russell, A.D., Furr, J.R, and Maillard, J.Y., *ASM News-American Society for Microbiology*, 1997, vol. 63, no. 9, pp. 481–487.
17. Simoncic, B. and Tomsic, B., *Textile Res. J.*, 2010, vol. 80, no. 16, pp. 1721–1737.
18. Kegley, S.E., *PAN Pesticide Database, Pesticide Action Network*, North America, San Francisco, CA, 2009.
19. Orhan, M., Kut, D., and Gunesoglu, C., *Indian J. Fiber Tex. Res.*, 2007, vol. 32, pp. 114–118.
20. Jones, R.D., *Am. J. Infect. Control*, 2000, vol. 28, no. 2, pp. 184–196.
21. Yazdankhah, S.P., *Microbial Drug Res.*, 2006, vol. 12, no. 2, pp. 83–90.
22. Mansfield, R.G., *Textile World*, 2002, vol. 152, no. 2, p. 42.
23. Russell, A.D., *J. Hospital Infection*, 2004, vol. 57, no. 2, pp. 97–104.
24. Latch, D.E., *J. Photochem. Photobiol., A: Chemistry*, 2003, vol. 158, no. 1, pp. 63–66.
25. Buth, J.M., *Environ. Sci. Technol.*, 2010, vol. 44, no. 12, pp. 4545–4551.
26. Bartels, V., *Handbook of Medical Textiles*, Elsevier, 2011.
27. Badawy, M.E.I. and Rabea, E.I., *Int. J. Carbohydrate Chem.*, 2011.
28. Wang, X., *Polymer Bull.*, 2005, vol. 55, nos. 1–2, pp. 105–113.
29. Kong, M., *Front. Mater. Sci. in China*, 2008, vol. 2, no. 2, pp. 214–220.
30. Varesano, A., *Sci. Microbial Pathogens: Commun. Current Res. Technol. Adv.*, 2011, vol. 3, pp. 99–110.
31. Chadeau, E., *J. Food Safety, 2012*, vol. 32, no. 2, pp. 141–151.
32. Vointseva, I.I. and Gembitskii, P.A., *Poliguanidiny – dezinfektsionnye sredstva i polifunktsional'nye dobavki v kompozitsionnye materialy* (Polyguanidines – Disinfectants and Multifunctional Additives in Composite Materials), Moscow: LKM-Press, 2011.
33. Zanoaga, M. and Tanasa, F., *Chem. J. Moldova*, 2014, vol. 9, no. 1, pp. 14–32.
34. Hui, F., *Biomacromol.*, 2013, vol. 14, no. 3, pp. 585–601.
35. Bach, S.M., *Nat. Product Commun.*, 2011, vol. 6, no. 2, pp. 163–166.
36. Mathabe, M.C., *J. Ethnopharmacol.*, 2008, vol. 116, no. 1, pp. 194–197.
37. Petnual, P., Sangvanich, P., and Karnchanatat, A., *Food Sci. Biotechnol.*, 2010, vol. 19, no. 4, pp. 907–916.
38. Kheeree, N., *Appl. Biochem. Biotechnol.*, 2010, vol. 162, no. 3, pp. 912–925.
39. Orhan, D.D., *Microbiol. Res.*, 2010, vol. 165, no. 6, pp. 496–504.
40. Rattanachaikunsopon, P. and Phumkhachorn, P., *J. Med. Plants Res.*, 2010, vol. 4, no. 5, pp. 393–396.

41. Özçelik, B., *Tropical J. Pharm. Res.*, 2008, vol. 7, no. 4, pp. 1151–1157.
42. Ignacimuthu, S., *Asian J. Traditi. Med*., 2009, vol. 4, no. 1, pp. 36–40.
43. Singh, D.N., *Bioorg. Med. Chem. Lett.*, 2006, vol. 16, no. 17, pp. 4512–4514.
44. Engels, C., *J. Agricult. Food Chem.*, 2009, vol. 57, no. 17, pp. 7712–7718.
45. Scalbert, A., *Phytochem.*, 1991, vol. 30, no. 12, pp. 3875–3883.
46. Cowan, M.M., *Clin. Microbiol. Rev.*, 1999, vol. 12, no. 4, pp. 564–582.
47. Venugopala, K.N., Rashmi, V., and Odhav, B., *BioMed Res. Int.*, 2013, vol. 2013.
48. Saleem, M., *Natural Product Rep.*, 2010, vol. 27, no. 2, pp. 238–254.
49. Sobczak, M., *Molecules*, 2013, vol. 18, no. 11, pp. 14122–14137.
50. Gouveia, I.C., *FORMATEX Microbiol. Ser. 2*, 2010, vol. 2, pp. 407–414.
51. Rokitskaya, T.I., *Biomembran.*, 2011, vol. 1808, no. 1, pp. 91–97.
52. Upadhyay, A., *BioMed Res. Int.*, 2014, vol. 2014.
53. Savoia, D., *Future Microbiol.*, 2012, vol. 7, no. 8, pp. 979–990.
54. Breidenstein, E.B.M., Courvalin, P., and Meziane-Cherif, D., *Microbial Drug Res.*, 2015, vol. 21, no. 4, pp. 373–379.
55. Kyung, K.H. and Lee, C., *Food Rev. Int.*, 2001, vol. 17, no. 2, pp. 183–198.
56. Xu, F.F. and Imlay, J.A., *Appl. Environ. Microbiol*., 2012, vol. 78, no. 10, pp. 3614–3621.
57. Palza, H., *Int. J. Mol. Sci.*, 2015, vol. 16, no. 1, pp. 2099–2116.
58. Razuvaev, A.V., *Izv. Vyssh. Uch. Zaved., Ser.: Khim. Khim. Tekhnol.*, 2010, vol. 53, no. 8, pp. 3–7.
59. Petrova, L.S., Lipina, A.A., Zaitseva, A.O., and Odintsova, O.I., *Izv. Vuzov: Tekhnol. Tekstil. Prom–ti*, 2018, no. 6, pp. 81–85.
60. Dmitrieva, A.D., Kuz'menko, V.A., Odintsova, L.S., and Odintsova, O.I., *Izv. Vuzov: Khim. Khim. Tekhnol.*, 2015, p. 58.
61. Gubin, S.P., Yurkov, G.Yu., and Kataeva, N.A., *Nanochastitsy blagorodnykh metallov* (Nanoparticles of Precious Metals), Moscow: IONKH RAN, 2006.
62. Ivanov, V.N., Larionov, G.M., Kulish, N.I., and Luttseva, M.A., *Serebro Med., Biol., Tekhn., Sib. Otd. RAMN*, 1995, no. 4, pp. 53–62.
63. Dastjerdi, R. and Montazer, M., *Colloid. Surfac. B: Biointerfaces*, 2010, vol. 79, no. 1, pp. 5–18.
64. Dymnikova, N.S. and Erokhina, N.S., *Sb. Materialov Mezhdunarod. Nauch. i Tekh. Konf. INNOVATIONS-2016* (Collection of Materials, International Scientific and Technical Conference INNOVATIONS-2016), Moscow: FGBOUVO MGUDT, 2016, pp. 107–110.
65. Dubas, S.T., Kumlangdudsana, P., and Potiyaraj, P., *Colloids Surfac. A: Physicochem. Eng. Aspects*, 2006, vol. 289, nos. 1–3, pp. 105–109.
66. Yun, G., *Adv. Healthcare Mater.*, 2018, vol. 7, no. 5, p. 1700934.
67. Perkas, N., Perelshtein, I., and Gedanken, A., *Probl. Ekspluatats.*, 2018, vol. 4, pp. 15–26.
68. Achwal, W.B., *Colourage*, 2003, vol. 50, no. 1, pp. 58–59.
69. Dymnikova, N.S., Erokhina, E.V., Kuznetsov, O. Yu., and Moryganov, A.P., *Ross. Khim. Zh*., 2017, vol. 61, no. 2, pp. 3–12.
70. Kulevtsov, G.N., Stepin, S.N., Nikolaenko, G.R., and Shestov, A.V., *Vest. Kazan. Tekhn. Univ.*, 2013, vol. 16, no. 8, pp. 86–88.
71. Baranova, O.N. and Zolina, L.I., Abstracts of Papers, *International Scientific and Practical Conference and School of Young Scientists MED-TEKSTIL'-2012*, Moscow, 2012, p. 29.
72. Khorobraya, E.G., Bakina, O.V., Serova, A.N., and Tikhonova, I.N., Abstracts of Papers, *International Scientific and Practical Conference and School of Young Scientists MED-TEKSTIL'-2012*, Moscow, 2012, p. 35.
73. Abaev, Yu.K., *Khirurgicheskaya povyazka* (Surgical Dressing), Minsk: Belarus', 2005.
74. Serova, A.N., Pekhen'ko, V.G., Tikhonova, I.N., Glazkova, E.A., Bakina, O.V., Lerner, M.I., and Psakh'e, S.G., *Sib. Med. Zh.*, 2012, vol. 27, no. 3, pp. 137–141.
75. Valdés, A., *Curr. Org. Chem.*, 2018, vol. 22, no. 12, pp. 1237–1248.
76. Ghost, S.K., *Functional Coatings by Polymer Microencapsulation*, Willey-VCHVerlagGmbh&CoKGaA: Weinheim, 2006.
77. Krolevets, A.A., Tyrsin, Yu.A., and Bykovskaya, E.E., *Vest. Ross. Akad. Est. Nauk*, 2013, no. 1, pp. 77–84.
78. Cheng, S.Y., Yuen, C.W.M., Kan, C.W., and Cheuk, K.K.L., *Res. J. Textile Apparel*, 2008, vol. 12, no. 4, pp. 41–51.
79. Sarma, S.J., Pakshirajan, K., and Mahanty, B., *J. Chem. Technol. Biotechnol.*, 2011, vol. 2, pp. 266–272.
80. Pavan, K.B., Sarath, C.I., and Bhavya, B., *Indian J. Pharm. Sci. Res.*, 2011, vol. 1, pp. 19–37.

81. Borodina, T.N., *Candidate Sci. (Chem.) Dissertation*, Moscow, 2008.
82. Anal, A.K. and Singh, H., *Trends Food Sci. Technol.*, 2007, vol. 18, pp. 240–251.
83. Sanjoy, D., *Int. J. Pharm. Sci. Technol.*, 2011, vol. 6, no. 2, pp. 1–23.
84. Silva, P.T., *Ciência Rural*, 2014, vol. 44, no. 7, pp. 1304–1311.
85. Salaün, F., *Microencapsulation Technology for Smart Textile Coatings, Active Coatings for Smart Textiles*, Woodhead Publishing, 2016, pp. 179–220.
86. Patel, K.R., Mukesh, R., and Tarak, Mehta J., *Int. J. Pharm. Technol.*, 2011, vol. 3, pp. 894–911.
87. Donath, E., *Angewandte Chemie Int. Ed.*, 1998, vol. 37, no. 16, pp. 2201–2205.
88. Sukhorukov, G.B., *Colloid. Surfac. A: Physicochem. Eng. Aspects*, 1998, vol. 137, nos. 1–3, pp. 253–266.
89. Iler, R.K., *J. Colloid Interface Sci.*, 1966, vol. 21, no. 6, pp. 569–594.
90. Decher, G. and Hong, J.D., *Macromol. Chem. Macromol. Symp*., 1991, vol. 46, pp. 321–327.
91. Schuetz, P. and Caruso, F., *Adv. Funct. Mater.*, 2003, vol. 13, no. 12, pp. 929–937.
92. Volodkin, D.V., *Langmuir*, 2004, vol. 20, no. 8, pp. 3398–3406.
93. Combes, C., Bareille, R., and Rey, C., *J. Biomed. Mater. Res., Part A*, 2006, vol. 79, no. 2, pp. 318–328.
94. Kozlovskaya, V., *Responsive Microcapsule Reactors Based on Hydrogen-Bonded Tannic Acid Layer-by-Layer Assemblies*, 2010, vol. 6, no. 15, pp. 3596–3608.
95. Lee, D., Rubner, M.F., and Cohen, R.E., *Chem. Mater.*, 2005, vol. 17, no. 5, pp. 1099–1105.
96. Such, G.K., Johnston, A.P.R., and Caruso, F., *Chem. Soc. Rev.*, 2010, vol. 40, no. 1, pp. 19–29.
97. Aisina, R.B. and Kazanskaya, N.F., *Itogi Nauki i Tekhniki: Ser. Bioteknol*., Moscow: VINITI, 1986, vol. 6, pp. 6–52.
98. Lameiro, M.H., *Int. J. Pharmaceutics*, 2006, vol. 312, nos. 1–2, pp. 119–130.
99. Grenha, A., Seijo, B., and Remunán-López, C., *Eur. J. Pharm. Sci.*, 2005, vol. 25, nos. 4–5, pp. 427–437.
100. Lambert, G., Fattal, E., and Couvreur, P., *Adv. Drug Delivery Rev.*, 2001, vol. 47, no. 1, pp. 99–112.
101. Parakhonskii, B.V., *J. Phys. Chem. C*, 2010, vol. 114, no. 5, pp. 1996–2002.
102. Antipov, A.A., Fabrication of a Novel Type of Metallized Colloids and Hollow Capsules, Langmuir, 2002, vol. 18, no. 17, pp. 6687–6693.
103. De Geest, B.G., *Macromol. Rapid Commun.*, 2007, vol. 28, no. 1, pp. 88–95.
104. Bagaria, H.G., Kadali, S.B., and Wong, M.S., *Chem. Mater.*, 2010, vol. 23, no. 2, pp. 301–308.
105. Yuan, W., Lu, Z., and Li, C.M., *J. Mater. Chem.*, 2011, vol. 21, no. 13, pp. 5148–5155.
106. Odintsova, O.I., Petrova, L.S., and Kozlova, O.V., *Izv. Vuzov: Tekhnol. Tekstil. Prom–ti*, 2018, no. 4, pp. 85–89.