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EFFECT OF ZNO NANOPARTICLES SYNTHESIZED BY THE IMPROVED METHOD ON THE ANTIBACTERIAL PROPERTIES OF COTTON TEXTILE MATERIALS

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The object of this study is imparting antimicrobial properties to textile materials made from natural fibers and their blends.

The study is aimed at solving the problem of ensuring a prolonged antimicrobial effect of cotton-containing fabrics.

The use of ZnO nanoparticles, synthesized by the simple resource-saving method, as part of polymer-colloidal finishing compositions for the fabrics finishing is proposed. The effectiveness of using synthesized ZnO to impart prolonged antibacterial properties to cotton fabrics was assessed by studying the morphology, chemical composition, and bactericidal activity of nanoparticles.

ZnO nanoparticles were synthesized by direct precipitation method at low temperatures in a short time in an aqueous solution using zinc acetate dihydrate and sodium hydroxide as precursors. The average crystallite size calculated using the Scherrer method is 28 nm. The degree of crystallinity according to X-ray diffraction pattern is 93 %.

Using scanning electron microscopy, the formation of nanoparticles of uniform size in the form of short rods was established and the successfully synthesized ZnO phase in the hexagonal wurtzite structure was confirmed. The chemical purity of the crystalline material was confirmed using energy dispersive analysis. The atomic percentages of the elements are 47.6 % and 52.4 % for Zn and O, respectively. Study of the inhibition zone around fabric disks treated with ZnO showed their high bactericidal activity against air microflora and the gram-negative bacterium P. aeruginosa. It has been established that the use of ZnO as part of a polymer-colloidal system based on the acrylic polymer ensures the resistance of bactericidal treatment to washing.

The reported scientific results are of practical importance for improving the standard technological process for finishing cotton textile materials

Keywords: ZnO nanoparticles, precipitation method, morphological structure, EDX, antibacterial activity

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1. Introduction

Textile materials capable of counteracting disease-causing bacteria, microbes, and viruses have gained a stable position in the world market. The widespread use of textile materials with bactericidal activity is due to the spread of pathogenic microorganisms, which causes serious harm not only to human health but also negatively affects the economic situation in the world. The pandemic caused by the SARS-CoV-2 coronavirus has led to an increase in demand for antimicrobial textiles for both medical and household purposes. In this connection, there was a need to design new antibacterial fibrous materials and products from them.

Antibacterial treatment of textile materials is aimed at protecting the human body from the effects of pathogenic microflora in contact with textile products and should also protect the fabric from the action of pathogenic microorganisms. This direction is caused by the fact that the textile materials themselves are a nutrient medium for the development of bacteria, molds, and yeasts, which live and develop in the presence of moisture and the appropriate temperature. In this regard, textile materials can be active carriers of viruses and bacteria.

The effectiveness of the fixation of microorganisms on the fiber and the speed of their reproduction primarily depend on the nature and chemical composition of the fiber-forming substrate, its physicochemical and structural characteristics. Materials of any chemical nature can undergo microbiological damage. However, the development of the vital activity of microorganisms on synthetic materials is significantly slowed down due to the density, high degree of crystallinity and hydrophobicity of the fibers. Natural fibers are characterized by less resistance to biodamage. The presence of capillary-bound moisture due to the fibrillar structure of the fiber, as well as the presence of hydrated moisture in the amorphous zones of the fiber-forming polymer, contribute to the spread of pathogens whose enzymes cause hydrolysis of polymer bonds. The most prone to biodamage are materials made of wool and cotton fibers, in contrast to silk, linen, jute, and kenaf, which have relatively greater resistance due to their special structure and the presence of impurities [1]. Manifestations of excessive growth of microorganisms on textile products are diverse and extremely undesirable. In addition to the formation of odors, the appearance of mold stains and discoloration, microbiological damage can lead to the loss of functional properties of the material, for example, its elasticity or tensile strength.

It is possible to prevent the negative impact of microorganisms on textile materials by chemically or physically incorporating appropriate antibacterial drugs capable of delaying or completely stopping the growth of pathogenic microbes. However, biocides that are not chemically bound to the fibers can enter the wastewater during the washing process and affect the biological system, creating potential environmental problems [2]. In addition, some antibacterial agents, which include quaternary ammonium salts, can be harmful to human health when the textile material is in close contact with the skin. In order to prevent the above-mentioned problems, there is a trend in the world to use non-toxic substances as bactericidal agents that are safe for human health and the environment [3].

Currently, textile materials with antimicrobial properties are not produced in Ukraine. Fabrics intended for clothing that comes into contact with the skin (sports goods, socks, stockings), fabrics for sewing mattresses, blankets, and pillows, as well as textile materials for medical institutions are purchased abroad. The lack of production of such fabrics by Ukrainian enterprises is caused by the lack of scientifically based technologies for equipping the appropriate assortment.

Considering the above, research aimed at finding effective antimicrobial drugs and developing innovative environmentally friendly resource-saving technologies for processing textile materials to protect against common pathogenic microorganisms is relevant. Devising a scientifically based approach to the development of polymer-colloid composite compositions taking into account the purpose of fabrics could solve the problem of providing durable antimicrobial properties to textile materials of various raw materials for household and special purposes.

2. Literature review and problem statement

Bacterial infections pose a serious threat to human life due to the growing number of strains of pathogens resistant to antibiotics.

Research aimed at finding effective antimicrobial drugs, in particular for use in the field of textile materials, has been intensively developed. Antimicrobial agents for textile processing are characterized by different chemical structure, economic efficiency, processing methods, and safety of use. Particularly important and significant requirements for modern biocides are the absence of harmful effects on the human body and the environment, high activity against harmful bio factors, availability, and low cost.

One of the modern directions is the use of "green technologies", namely the study of biologically active additives capable of influencing pathogenic microflora. There are known advancements in the design of antimicrobial textiles using natural plant extracts of neem, pomegranate, aloe vera, turmeric, cloves, etc. [4]. The main problem is the stable fixation of the applied antibacterial reagent on the surface of the textile material. Chitosan, a substance obtained from the shells of crustaceans, is used to form a polymer coating on textiles, which enables the immobilization of functional substances to provide antimicrobial properties to synthetic [5] and cotton [3] fabrics. Disadvantages of chitosan are the need to use it in high concentrations, which impairs the hygienic properties of textile materials and increases their stiffness, as well as insufficient resistance to washing.

A promising direction of imparting antibacterial properties to textile materials is the use of preparations based on nanoforms of metals and metal oxides. Nanoparticles have a more pronounced biocidal effect against gram-positive and gram-negative bacteria, viruses, fungi, and protozoa than ionic forms. In addition, compared to organic antibacterial agents, nanocrystalline inorganic agents are characterized by greater durability, lower toxicity, better selectivity, and heat resistance, and also make it possible to avoid the development of resistance of microorganisms. For the modification of textile fibers and materials of various structures, nanoparticles of metal oxides are most often used [7]: Ag_2O, CuO, ZnO, TiO_2, Fe_3O_4, MnO_2. Multicomponent nanocomposites, including those doped with various metals or non-metals, such as Ag, Ce, Cr, Mn, Nd, Co, Sn, Fe, N, F, etc., are characterized by increased efficiency. The most common antimicrobial agents are Ag-based nano preparations. However, the use of nanoparticles of argentum oxides and a number of other metals to create antibacterial textiles leads to the acquisition of a pronounced gray color of the modified material, which limits the production of biocidal textile materials of light shades.

The interest of scientists in the field of creating antibacterial textile materials is aroused by the study of ZnO nanoparticles, which are a multifunctional, economical, and environmentally friendly material. The advantages of using ZnO as an antibacterial agent are its significant effectiveness against resistant strains of microbial pathogens, low toxicity, and heat resistance. The high photocatalytic activity of ZnO significantly enhances the interaction of the nanomaterial with bacteria. Unlike TiO_2 nanoparticles, the activity of ZnO is preserved even in the absence of UV-irradiation.

It was established that the bacteriostatic effect of ZnO is related to the surface properties of the particles, which play a crucial role in the generation of reactive oxygen species (ROS), which is the most developed paradigm of nanoparticle toxicity. The contribution of ZnO polar faces to biochemical activity has been suggested, i.e., more polar surfaces have more oxygen vacancies. It is known that oxygen vacancies increase the generation of ROS and therefore affect the bactericidal activity of ZnO [8]. It is noted that the genotoxicity of ZnO nanoparticles at low exposure doses can be caused primarily by the shape and size of the particles [9]. As the particle size decreases, the specific surface area increases, which improves the efficiency of the interaction of nanoparticles with the cell surface. Thus, the antibacterial properties of ZnO nanoparticles are directly correlated with the size and shape of the crystal structure, which depend on the synthesis conditions.

The main methods of nanoscale ZnO synthesis include the mechanochemical process, controlled deposition, sol-gel method, condensation from the gas phase, solvothermal and hydrothermal methods, methods using emulsion and microemulsion media, etc. [10]. Modern "green methods" of synthesis of ZnO nanoparticles using plant extracts are becoming widespread [11]. The vast majority of technologies for obtaining ZnO nanoparticles are based on the wet chemical method, in which the synthesis conditions are regulated. The growing interest in nano preparations based on ZnO entails the need to increase the yield of nanoparticles and reduce the cost of their production. From a technological point of view, this problem can be solved by using the most effective methods of synthesis in terms of reducing process time, removing or minimizing stabilizing additives and technical means.

Modification of textile materials in order to give them antibacterial properties can be carried out at the stage of processing the fiber-forming polymer into a textile fiber, as well as at the stage of processing the finished textile fiber, cloth, or product. It should be noted that the provision of antibacterial properties at the stage of synthesis and formation of the fiber-forming polymer is used only for synthetic textile materials and is fundamentally impossible for the modification of natural fibers. In the case of cellulosic textile materials, it is proposed to synthesize metal nano preparations directly on the fabric [12, 13], which may cause difficulties in the implementation of the indicated technologies in production. The most rational is the method of applying an antibacterial drug at the stage of final tissue treatment, as it requires changes in the technological process only at the last stage. However, the significant price of imported nano preparations holds back the introduction of this technology at Ukrainian enterprises.

Therefore, our review of the literature [7–11] reveals unresolved issues regarding the development of economically feasible technologies for equipping cotton fabrics with the use of nano-sized systems to provide effective antibacterial protection without deterioration of the physical and mechanical characteristics of the material. The search for the optimal method of synthesis of ZnO nanostructures with high biocidal activity for the creation of antibacterial preparations will allow solving important practical problems, such as ensuring a prolonged bactericidal effect while simultaneously reducing the number of compounds used.

3. The aim and objectives of the study

The purpose of our study is to determine the effectiveness of ZnO nanoparticles synthesized by a simple direct deposition method to provide antibacterial properties to cotton fabrics. This will make it possible to create ecologically safe composite formulations for the design of resource-saving technologies for furnishing textile materials.

To achieve the goal, the following tasks were set:

– to synthesize ZnO nanoparticles and characterize their morphological structure;

– to determine the chemical purity of the synthesized crystalline material;

– to evaluate the bacteriostatic effect of treating textile materials with synthesized ZnO nanoparticles.

4. The study materials and methods

The object of research is the processes of imparting antimicrobial properties to textile materials made of natural fibers and their mixtures.

The subject of the study is the regularities of the formation of polymer-colloidal systems with ZnO nanoparticles for the creation of antibacterial coatings on textile materials made of natural fibers and their mixtures.

The main hypothesis of the study assumes the ability of ZnO nanoparticles in colloidal form or as part of a polymer coating to have a bactericidal effect.

The synthesis of ZnO nanoparticles was carried out by the method of direct deposition in an aqueous solution using zinc acetate ($Zn(CH_3COO)_2{\cdot}2H_2O$) and sodium hydroxide (NaOH). Both precursors were qualified chemically pure and were used without further purification. In the process of synthesis, the NaOH solution was introduced dropwise into the $Zn(CH_3COO)_2{\cdot}2H_2O$ solution with intensive stirring. Nanoparticles grew at 70 °C for 2 hours. The resulting suspension was separated by centrifugation, and the resulting precipitate was washed with distilled water and ethanol. The washed crystalline material was dried at 60 °C followed by heat treatment at 300 °C for 2 h and ZnO powder was obtained.

The study of the morphological structure of ZnO nanoparticles and elemental analysis of the synthesized sample was carried out using scanning electron microscopy (SEM) on a MIRA 3 FE-SEM microscope (TESCAN, Czech Republic) equipped with an energy dispersive X-ray detector (EDX) (Oxford Instruments, Great Britain). The sample was placed on an electrically conductive non-porous carbon tape. To eliminate the effects of the charge, the sample was covered with a thin conductive layer of gold 3 nm thick. Magnifications of 50,000x and 100,000x were used for SEM micrographs.

The study of the antibacterial activity of the synthesized ZnO nanoparticles was carried out on samples of cotton (100 %) and cotton-polyester fabrics (53 % cotton/47 % PEF).

Fabric treatment was carried out by impregnation with cleaning solutions at a temperature of 20–25 °C with double immersion/spinning and subsequent drying. Synthesized nanoparticles in a concentration of 1 % were pre-dispersed in an aqueous solution using ultrasonic treatment for 10 min. Neoprint NPO acrylic polymer was used as a film former capable of immobilizing nanoparticles on the surface of textile fibers.

Determination of the antimicrobial activity of treated tissue samples was performed by analyzing the diffusion of tissue discs on seeded LB agar medium of the following composition (g/l): peptone – 10.0; yeast extract – 5.0; NaCl – 5.0; agar-agar – 14.0; pH – 7.0±0.2.

Inoculation of agar with microorganisms from the microflora of the air took place in an open space in the room for 15 minutes, after which fabric samples were placed on the surface and closed Petri dishes were kept in a thermostat at a temperature of 38 °C for 72 h for incubating crops.

To study the effectiveness of antimicrobial treatment of fabric in relation to the gram-negative bacterium *Pseudomonas aeruginosa* B-907 from the Ukrainian collection of microorganisms, the test culture was cultivated at 37 °C for 24 hours. After that, a suspension was prepared on the basis of a physiological solution and aliquots were applied to the LB agar medium. The bacteriostatic effect was evaluated after the incubation of the crops by the size of the growth retardation zone around the fabric discs.

5. Results of investigating the characteristics of the synthesized ZnO nanoparticles

5. 1. Synthesis and morphological analysis

In this study, the synthesis of ZnO was carried out by the method of direct precipitation from an aqueous solution according to the following reactions:

$$Zn(CH_3COO)_2{\cdot}2H_2O+2NaOH\rightarrow$$
$$\rightarrow Zn(OH)_2+2CH_3COONa+2H_2O,$$

$$\mathrm{Zn(OH)_2 + 2H_2O \rightarrow Zn(OH)_4^{2-} + 2H^+},$$

$$\mathrm{Zn(OH)_4^{2-} \rightarrow ZnO + H_2O + 2OH^-}.$$

The formation of the ZnO phase was confirmed by X-ray diffraction analysis (Fig. 1) [14].

The results of X-ray diffraction analysis (Fig. 1) show that ZnO nanoparticles are formed in a hexagonal wurtzite structure with an average crystallite size of 28 nm [14]. The calculated structural parameters of the synthesized ZnO nanoparticles are in good agreement with the standard data (JCPDS 36-1451).

The surface morphology of the investigated nanomaterial was characterized using the scanning electron microscopy (SEM) method. Photomicrographs of the synthesized ZnO sample at different magnifications are shown in Fig. 2.

The obtained SEM images (Fig. 2) indicate the uniform growth of high-density ZnO nanostructures with a small degree of agglomeration. The crystalline material consists of nanoparticles of uniform size, mainly in the form of short rods, which is a typical morphology of ZnO particles.

5. 2. Determining elemental composition

The results of studying the elemental composition of the synthesized ZnO nanoparticles by energy dispersive X-ray spectroscopy (EDX) are shown in Fig. 3.

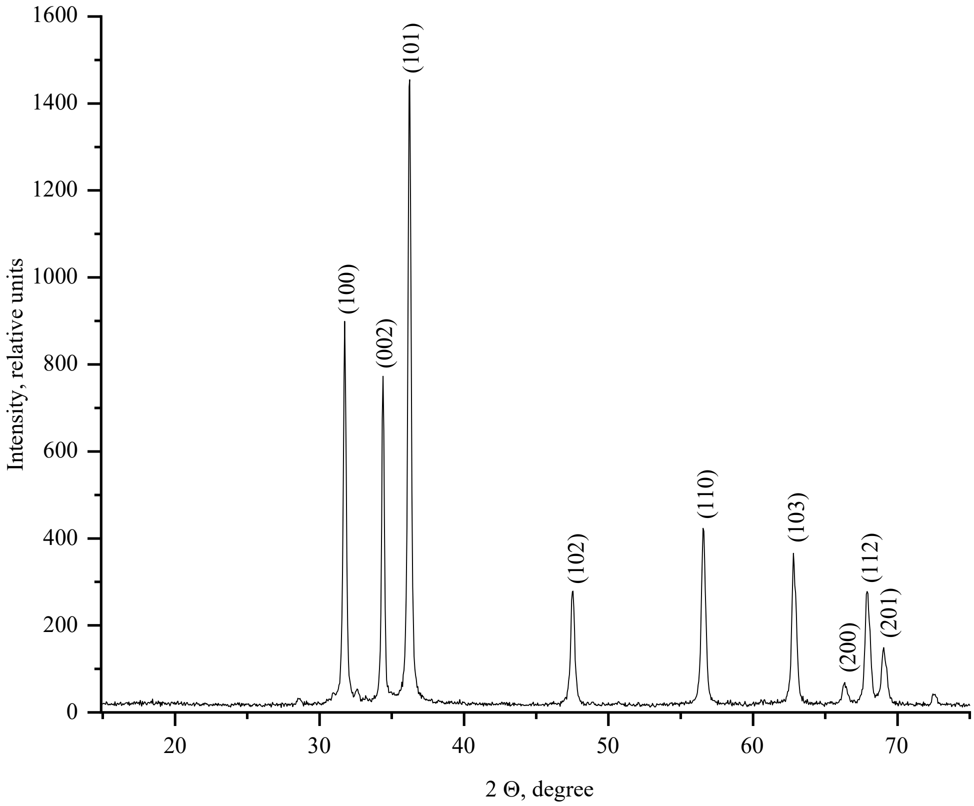
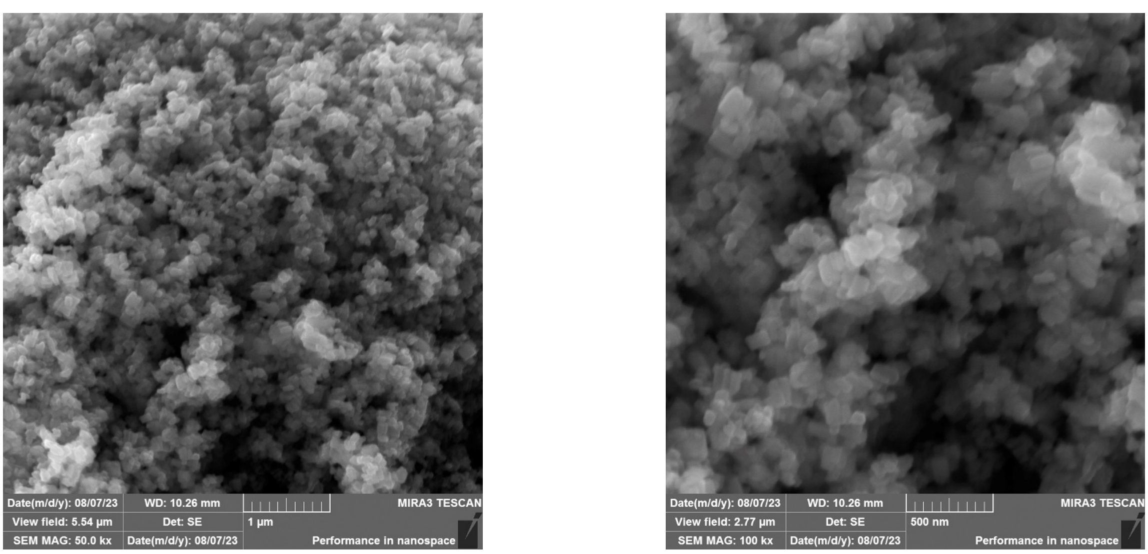


Fig. 1. X-ray of the synthesized ZnO sample



a *b*

Fig. 2. SEM image of the synthesized ZnO sample: *a* – magnification 50000x; *b* – magnification 100,000x

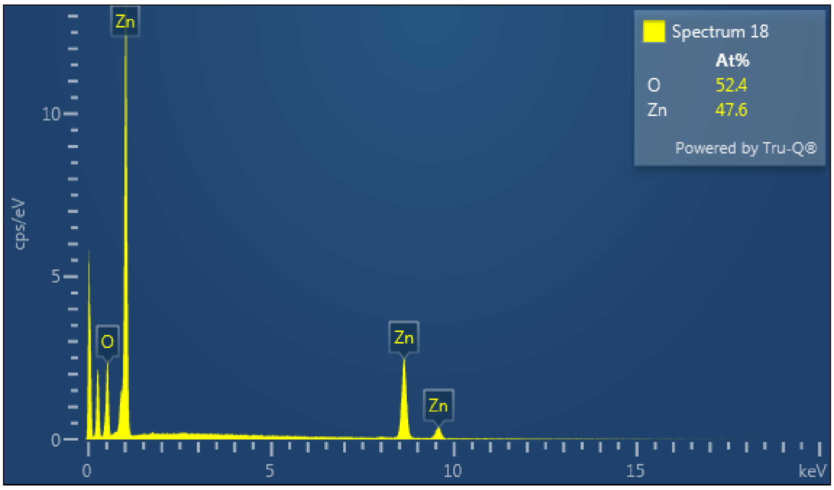


Fig. 3. EDX spectrum of synthesized ZnO nanoparticles

Strong peaks observed in the EDX spectrum (Fig. 3) refer to zinc and oxygen. It was established that the atomic percentages of elements in the studied ZnO nanostructure are 47.6 % and 52.4 % for Zn and O, respectively. The absence of any other characteristic peaks in the given EDX spectrum indicates the chemical purity of the synthesized product.

5. 3. Antibacterial activity of synthesized ZnO on textile materials

The study of the biocidal activity of the synthesized ZnO nanoparticles to suppress the bacterial contamination of air microflora was determined by means of the diffusion analysis of discs from treated cotton fabric. The results are shown in Fig. 4.

Fig. 4. The influence of synthesized ZnO nanoparticles on the development of bacterial contamination of air microflora of cotton fabric samples: 1 — without treatment; 2 — treated with synthesized nano-ZnO; 3 — processed after 5 washing cycles

The original fabric (Fig. 4, sample 1) is characterized by high bacterial contamination, the absence of an inhibition zone around the sample, and a significant development of various microflora seeded from the air. Treatment with synthesized ZnO nanoparticles (Fig. 4, sample 2) demonstrates a significant zone of growth retardation of pathogenic microflora around fabric discs within 10 mm and suppression of its development at a longer distance. After the fifth wash (Fig. 4, sample 3), the quality of the antimicrobial treatment decreases, but still, at a distance of 1–2 mm around the sample, the maximum amount of microflora is suppressed.

The results of investigating the effect of synthesized ZnO nanoparticles on the inhibition of *P. aeruginosa* B-907 culture are given in Table 1. Taking into account that textile materials during operation are exposed to various physical and chemical influences, in particular washing, acrylic polymer was additionally introduced into the finishing composition as a film former capable of immobilizing various substances on the surface of textile fibers.

Our data (Table 1) showed that in the control untreated sample of cotton-polyester fabric, a high growth of microorganisms is observed, which is expressed in the absence of a zone of retardation of the growth of bacterial microflora around the fabric disc. Treatment of fabric with synthesized ZnO nanoparticles leads to inhibition of the growth of *P. aeruginosa* B-907 culture within 19 mm. The application of ZnO nanoparticles in the form of a composition with an acrylic binder slightly reduces the zone of inhibition around the treated fabric to 15 mm, in contrast to individual application. However, it should be noted that in samples with a polymer nanocomposite coating, the growth retardation zone of the tested pathogen is observed even after 5 washing cycles and is about 7 mm.

Table 1

Effect of synthesized ZnO nanoparticles on *P. aeruginosa* B–907 culture growth retardation

Sample of cotton-polyester fabric	Zone of growth retardation, mm
Raw	0
Nano-ZnO	19.7±2.5
Nano-ZnO+Neoprint NPO	15.1±3.2
Nano-ZnO+Neoprint NPO after 5 washing cycles	7.6±3.3

6. Discussion of results of investigating the effectiveness of the use of synthesized ZnO nanoparticles for antibacterial treatment of fabrics

Under modern conditions, it is economically expedient to devise technologies that allow reducing the costs of chemical materials and energy resources. Thus, a simple method of synthesis of ZnO nanoparticles with good crystallinity at low temperatures in a short time is of interest.

Since the properties of ZnO nanoparticles, including antibacterial activity, depend on their size and shape [15], it is necessary to control the structural characteristics of the crystalline material during the synthesis process.

In a previously conducted study [14], the crystalline phase and structural parameters of ZnO nanoparticles synthesized by the proposed deposition method were determined. The powder X-ray pattern of the obtained ZnO sample (Fig. 1) shows diffraction peaks (100), (002), (101), (102), (110), (103), (200), (112), and (201), characteristic for ZnO with a hexagonal wurtzite structure. Comparison of the data of the obtained X-ray pattern (Fig. 1) with the standard (JCPDS 36-1451) shows that for the studied sample, the displacements of the positions of the diffraction peaks are very small. The intensity of the diffraction peaks indicates the high crystallinity of the particles. The presence of only characteristic diffraction peaks of ZnO in the X-ray pattern of the synthesized sample may indicate the absence of impurities in it.

Based on the obtained X-ray structural analysis data (Fig. 1), the average size of the crystallites of the synthesized ZnO sample was calculated using the Scherrer method, which is 28 nm [14]. The obtained value can be considered as a lower limit of the size of nanoparticles since the particles are often agglomerations of a large number of crystallites.

Thus, it was established that the proposed method of synthesis by carrying out precipitation reactions at a temperature of 70 °C for 2 h followed by roasting the dried powder at 300 °C for 2 h allows obtaining ZnO nanoparticles with an average crystallite size of 28 nm [14]. For comparison, in [16] the characteristics of the crystalline structure of ZnO nanoparticles synthesized from $Zn(NO_3)_2{\cdot}4H_2O$ by a similar method of direct deposition at different temperatures (60 °C, 80 °C, 100 °C) for 2 h are given, and it is shown that that the smallest crystallite size of 44 nm is formed at 80 °C with calcination at 500 °C for 5 h. The advantages of the synthesis method proposed in this paper are the possibility to obtain nanoparticles of smaller size at lower temperatures in a shorter time. This can be explained by the effect of the selected precursor $Zn(CH_3COO)_2{\cdot}2H_2O$ on the parameters of the formed crystal structure, which confirms the results of study [14].

It is assumed that the size of the crystallite is the size of the coherently diffracting domain and does not necessarily coincide with the size of the particles. In order to fully assess the quality of the nanocrystalline material, it is necessary to conduct a further study of the morphological structure of the synthesized ZnO.

The morphological characteristics of the obtained ZnO nanoparticles were investigated using SEM. The results of the analysis of SEM images (Fig. 2) confirm the formation under the conditions of the proposed synthesis method of ZnO nanoparticles of a rod-like shape with a diameter of up to 50 nm, which is in good agreement with the data calculated according to Scherrer's formula [14]. The aggregation observed in the micrographs of the synthesized ZnO probably occurs during the drying of the powder and is due to the large specific surface area and high surface energy of the particles.

The study of the morphology of ZnO, synthesized by a simple method of direct deposition, showed that the uniform growth of nanoparticles in shape and size is ensured by the optimal molar ratio of Zn^{2+} to OH^-, the selected type and concentration of the precursor, and the synthesis conditions. In contrast to [16], in which the result is achieved thanks to the additional introduction of a stabilizer – pectin – into the solution. At the same time, the synthesized nanoparticles have a spherical shape. A similar influence of the stabilizer on the change in the morphology of ZnO nanoparticles is shown in [17], in which the shape of the nanoparticles changes from rod-like to spherical as the concentration of glycerol increases. Since the share of polar planes on the surface of ZnO directly affects the photocatalytic activity of nanoparticles and, accordingly, their cytotoxic effect, the shape of rods has advantages compared to spheres.

The elemental analysis of the investigated nanoparticles (Fig. 3) additionally confirmed the purity of the synthesized ZnO, which consists only of Zn and O with an atomic percentage close to the stoichiometric ratio of 1:1. The obtained result is in good agreement with the analysis of the diffraction peaks of the powder X-ray pattern of ZnO (Fig. 1).

Given that textile materials are used in everyday life, transport, and other public places, determining the effectiveness of antimicrobial treatment to suppress bacterial contamination of air microflora is of great importance. Analysis of the degree of diffusion of cotton fabric discs treated with the studied ZnO testifies to the bactericidal activity of the synthesized nanoparticles against a significant number of airborne pathogens.

The main problem in the technologies of antibacterial treatment of fabrics is obtaining textile materials with sustainable properties. This is due to the low adhesion of biocides to textile fibers and their washing out from the surface of textile materials during the operation of the products.

It is possible to ensure stable fixation of the antibacterial reagent on the surface of the textile material by creating composite polymer coatings, which will make it possible to preserve the properties obtained by the material after modification with a biocide.

In this regard, at the next stage of the work, the effectiveness of the antimicrobial effect of the synthesized ZnO as part of the nanocomposite coating based on the acrylic polymer Neoprint NPO was investigated. The pronounced zone of inhibition around the fabric samples after the incubation process confirms the antibacterial activity of textile materials treated with synthesized ZnO nanoparticles against *P. aeruginosa* B–907 (Table 1).

In [18], ZnO nanoparticles were applied to cotton fabric as part of printing ink. A similar bactericidal effect of the composite coating formed on the textile material in relation to *P. aeruginosa* is expressed by the growth retardation zone of the culture with a size of 12–15 mm. It has been shown that ZnO increases color intensity and has a positive effect on color fastness of printed fabrics. However, there are no studies of the resistance of the antibacterial effect to physicochemical influences in this work. In addition, the size of the nanoparticles synthesized by the authors using a similar direct deposition method is within 200–300 nm, which may be related to the short reaction time (30 min.) and the higher calcination temperature (400 °C).

The results of the study (Table 1) show that the use of a polymer binder slightly reduces the bacteriostatic effect of ZnO compared to treatment with individual nanoparticles but makes it possible to ensure the resistance of the antibacterial treatment to washing.

Although the biocidal activity of ZnO is well studied, the exact mechanism of antimicrobial action is not completely defined and is controversial. Among the main possible mechanisms discussed in the literature [11], the following processes can be cited. First, direct contact of ZnO nanoparticles with cell walls, which leads to destruction of membrane integrity. Secondly, the formation of reactive oxygen species (ROS) on the surface of nanoparticles. Third, the release of Zn^{2+} ions into the cytoplasm and cell organelles, which causes excessive generation of intracellular ROS and eventually leads to cell death. It is also possible that the antibacterial effect of ZnO nanoparticles is a cumulative effect of the above pathways.

The studied microorganisms *P. aeruginosa* belong to the group of gram-negative bacteria, which are characterized by greater resistance to external influences than gram-positive ones due to the presence of an additional outer layer of the cell wall. It is believed that an electromagnetic attraction occurs between negatively charged bacteria and positively charged ZnO nanoparticles, which leads to the formation of bonds between them. ZnO nanoparticles interact with membrane lipids and thiol – SH groups of enzymes and proteins important for bacterial respiration, as well as transmembrane and intracellular transport. In addition, ZnO nanoparticles can release Zn^{2+} ions inside the bacterial cell and damage membranes, proteins, and DNA as a result of the oxidative action of the generated ROS [19].

The analysis of the results of investigating the antimicrobial properties of the treated textile materials in relation to the air microflora and *P. aeruginosa* bacteria shows that the proposed synthesis method allowed us to ensure high bacteriostatic activity of ZnO nanoparticles. Moreover, the effectiveness of the synthesized nanoparticles has been confirmed both when used individually and as part of a polymer-colloidal system. It has been proven that the immobilization of ZnO nanoparticles in an acrylic polymer coating provides a high level of bactericidal activity of the treated textile material, which is preserved after washing. This became possible due to the formation of sufficiently small nanoparticles with a large specific surface area for active interaction with the cell walls of microorganisms. Also important is the rod-like shape of nanocrystals, which contributes to the increased generation of ROS due to the presence of a larger number of polar planes. Better antimicrobial activity of rod-shaped ZnO nanoparticles compared to spherical and lamellar ones against five types of bacteria (*S. aureus, B. subtilis, P. aeruginosa, E. coli* and *S. Typhi*) and fungi (*C. albicans*) is also shown in [15].

Thus, as a result of our research, a method of solving the problem of providing sustainable antimicrobial properties to cotton-containing textile materials is proposed. This method consists in the use of ZnO nanoparticles, synthesized by the precipitation method from an aqueous solution without additional stabilizers in a short time at low temperature, as part of a polymer composite coating. The obtained dependences of the antibacterial effect of ZnO on the structural and morphological characteristics of the synthesized nanoparticles will be useful in devising a scientifically based approach to the development of polymer-colloid dressing compositions.

The results of investigating the stability of the bactericidal action of the nanocomposite coating under operating conditions indicate the prospects of using the obtained ZnO nanoparticles in the technologies of furnishing cotton textile materials with the aim of providing prolonged antibacterial properties. The proposed synthesis method creates the possibility of small-scale production of nano dispersed ZnO for the needs of the textile industry instead of using imported commercial nano preparations.

It should be noted that a significant limitation when using nanoparticles in multicomponent water systems is their ability to aggregate due to the presence of high uncompensated surface energy. Since the uniform distribution of the nanofiller determines the properties of the polymer nanocomposite and, therefore, the quality of the functional coating, an important condition is controlling the dispersion of nanoparticles in the polymer matrix.

The main characteristics of dispersions are agglomeration and surface charge. The aggregative stability of aqueous dispersions of ZnO nanoparticles is determined by the ion-electrostatic factor. During the dispersion of nanoparticles in aqueous solutions, surface ionization and adsorption of cations or anions leads to the formation of a surface charge and the formation of an electric potential between the surface of the particles and the volume of the dispersion medium. According to the classical theory of stability of dispersed systems, an increase in the surface charge of particles can increase the electrostatic force of repulsion and prevent agglomeration. If the surface charge is represented by the zeta potential, then to achieve a stable dispersion, its value should be in the range of -30 mV$<\zeta<$30 mV. Effective regulation of dispersion properties is carried out by changing the pH of the medium. Thus, the formation of a stable polymer-colloidal system is possible at the pH value of the aqueous dispersion of the selected film-former, which is in the range favorable for dispersing the investigated nanoparticles.

Taking into account the above, a necessary condition for the successful use of nanosized drugs is taking into account the kinetic parameters of the stability of the dressing compositions. In this regard, further research will be aimed at determining the optimal composition of the polymer-colloidal system with ZnO nanoparticles to ensure prolonged antimicrobial activity of cotton textile materials. Considerable attention will be paid to determining the impact of the formed polymer nanocomposite coatings on the physical and mechanical characteristics of the furnished fabrics.

7. Conclusions

1. ZnO nanoparticles in the hexagonal structure of wurtzite were successfully synthesized by an improved method of direct deposition from an aqueous solution using precursors $Zn(CH_3COO)_2{\cdot}2H_2O$ and NaOH by conducting reactions at a temperature of 70 °C for 2 h followed by roasting the dried sediment at 300 °C for 2 h. According to the results of X-ray structural analysis, it was established that the proposed synthesis method allows obtaining ZnO nanoparticles with a high degree of crystallinity (93 %) and an average crystallite size of 28 nm. As a result of studying the morphological structure of the synthesized crystalline material using SEM, it was established that the synthesized ZnO nanoparticles are uniform in size and have the form of short rods, which is characterized by a high cytotoxic effect.

2. As a result of the elemental analysis of the synthesized ZnO, the absence of extraneous impurities in the crystalline material was revealed, which correlates with the previously obtained results of X-ray structural analysis. The atomic percentage of Zn and O is about 1:1.

3. The results of evaluating the bacteriostatic effect of the synthesized ZnO nanoparticles on cotton-containing fabrics by the disk diffusion method show their high bactericidal activity against air microflora and the gram-negative bacterium *P. aeruginosa*. It was established that the use of ZnO nanoparticles as part of a polymer-colloidal system based on the acrylic polymer Neoprint NPO increases the resistance of the antimicrobial treatment of fabrics to washing. Thus, ZnO nanoparticles, synthesized by a simple resource-saving method, have prospects for use in creating durable antibacterial coatings on textile materials.

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 and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

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

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