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CONTENTS

МАЗМҰНЫ

СОДЕРЖАНИЕ

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY
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SYNTHESIS OF SILVER NANOPARTICLES TO IMPART ANTIMICROBIAL PROPERTIES TO BIODEGRADABLE PACKAGING MATERIALS

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Abstract. The study is aimed at addressing two global challenges of our time: reducing environmental burden caused by the accumulation of synthetic polymer waste and improving the microbiological safety of food products. In this regard, the development of biodegradable packaging materials with antimicrobial properties represents a relevant scientific and technological direction. To develop a scientifically grounded approach to the synthesis of silver nanoparticles and to create, on their basis, an antimicrobial coating for biodegradable packaging materials that ensures a combination of environmental safety and bactericidal activity. Silver nanoparticles were synthesized using a "green" chemical reduction method, in which silver nitrate was reduced by glucose in the presence of polyvinyl alcohol acting as a stabilizer to prevent particle aggregation. A comprehensive study was carried out to evaluate the influence of reactant concentrations and synthesis conditions on the formation kinetics, morphology, size distribution, and optical properties of the nanoparticles. The optical characteristics of the hydrosols were analyzed by spectrophotometry in the 300–700 nm range based on the position and intensity of the surface plasmon resonance band. The morphology and particle size were examined using scanning electron microscopy and atomic force microscopy, while the elemental composition was confirmed by energy-dispersive analysis. The biodegradable polylactic acid food film was modified by spraying a colloidal solution of silver nanoparticles onto its surface. It was established that the size of the synthesized silver nanoparticles ranged from 1 to 80 nm and could be controlled by adjusting the concentrations of silver nitrate and the reducing agent. An increase in silver nitrate concentration led to a growth in the average particle size and enhanced aggregation processes. It was demonstrated that, when applied by spraying, the nanoparticles were uniformly distributed and stably fixed within the porous structure of the polylactic acid film without altering its physicochemical and morphological characteristics. The resulting nanocomposite material combines biodegradability with pronounced bactericidal properties. The proposed technology is characterized by simplicity of implementation, reproducibility, and cost-effectiveness. The developed material is promising for industrial application in the production of next-generation active biodegradable packaging for the food industry, ensuring extended shelf life and improved microbiological safety of products while simultaneously reducing environmental impact.

Keywords: silver nanoparticles, biodegradable packaging materials, polyvinyl alcohol, glucose (reducing agent)

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БИОЫДЫРАЙТЫН ОРАМА МАТЕРИАЛДАРЫНА АНТИМИКРОБТЫҚ ҚАСИЕТ БЕРУ ҮШІН КҮМІС НАНОБӨЛШЕКТЕРІН СИНТЕЗДЕУ

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Аннотация. Зерттеу қазіргі заманның екі жаһандық мәселесін шешуге бағытталған: синтетикалық полимер қалдықтарының жиналуынан туындайтын экологиялық жүктемені азайту және тағам өнімдерінің микробиологиялық қауіпсіздігін арттыру. Осыған байланысты антимикробтық қасиеттері бар биоыдырайтын қаптама материалдарын әзірлеу өзекті ғылыми-технологиялық бағыт болып табылады. Күміс нанобөлшектерін синтездеудің ғылыми негізделген тәсілін әзірлеу және олардың негізінде экологиялық қауіпсіздік пен бактерицидтік белсенділікті үйлестіретін биоыдырайтын қаптама материалдары үшін антимикробтық жабын жасау. Күміс нанобөлшектері күміс нитратын глюкозамен «жасыл» химиялық тотықсыздандыру әдісі арқылы, бөлшектердің агрегациясын болдырмайтын тұрақтандырғыш қызметін атқаратын поливинил спиртінің қатысуымен алынды. Бастапқы реагенттердің концентрациясы мен синтез жағдайларының нанобөлшектердің түзілу кинетикасына, морфологиясына, өлшемдік таралуына және оптикалық қасиеттеріне әсері кешенді түрде зерттелді. Гидрозольдердің оптикалық сипаттамалары 300–700 нм диапазонында беттік плазмондық резонанс жолағының орны мен қарқындылығы бойынша спектрофотометрия әдісімен анықталды. Бөлшектердің морфологиясы мен өлшемдері сканерлеуші электрондық және атомдық-күштік микроскопия әдістерімен зерттелді, ал элементтік құрамы энергодисперсиялық талдау арқылы расталды. Полилактидті тағамдық үлдірді модификациялау күміс нанобөлшектерінің коллоидтық ерітіндісін бүрку әдісімен жүзеге асырылды. Синтезделген күміс нанобөлшектерінің өлшемдері 1–80 нм аралығында өзгеретіні және олардың мөлшері күміс нитраты мен тотықсыздандырғыш концентрациясына байланысты реттелетіні анықталды. Күміс нитраты концентрациясының артуы бөлшектердің орташа өлшемінің ұлғаюына және агрегация үдерістерінің күшеюіне алып келетіні көрсетілді. Бүрку әдісімен енгізілген нанобөлшектердің полилактидті үлдірдің кеуекті құрылымында біркелкі таралып, оның физика-химиялық және морфологиялық сипаттамаларын бұзбай тұрақты бекітілетіні дәлелденді. Алынған нанокомпозиттік материал биоыдырағыштық қасиет пен айқын бактерицидтік белсенділікті үйлестіреді. Ұсынылған технология жүзеге асырудың қарапайымдылығымен, қайта өндірілу мүмкіндігімен және экономикалық тиімділігімен ерекшеленеді. Әзірленген материал тағам өнеркәсібінде өнімнің сақтау мерзімін ұлғайтуға және микробиологиялық қауіпсіздігін арттыруға мүмкіндік беретін, экологиялық жүктемені төмендететін жаңа буын белсенді биоыдырайтын қаптаманы өнеркәсіптік деңгейде енгізуге перспективалы болып табылады.

Түйін сөздер: күміс нанобөлшектері, биологиялық ыдырайтын орама материалдар, поливинил спирті, глюкоза (тотықсыздандырғыш)

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СИНТЕЗ НАНОЧАСТИЦ СЕРЕБРА ДЛЯ ПРИДАНИЯ АНТИМИКРОБНЫХ СВОЙСТВ БИОРАЗЛАГАЕМЫМ УПАКОВОЧНЫМ МАТЕРИАЛАМ

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Аннотация. Исследование направлено на решение двух актуальных задач: снижение экологической нагрузки, обусловленной накоплением синтетических полимерных отходов, и повышение микробиологической безопасности пищевой продукции. В этой связи разработка биоразлагаемых упаковочных материалов с антимикробными свойствами является актуальным научно-технологическим направлением. Целью работы является разработка научно обоснованного подхода к синтезу наночастиц серебра и созданию на их основе антимикробного покрытия для биоразлагаемых упаковочных материалов, обеспечивающего сочетание экологической безопасности и бактерицидной активности. Наночастицы серебра получены методом «зелёного» химического восстановления нитрата серебра глюкозой в присутствии поливинилового спирта, выполняющего функцию стабилизатора и предотвращающего агрегацию частиц. Проведено комплексное исследование влияния концентраций исходных реагентов и условий синтеза на кинетику образования, морфологию, размерное распределение и оптические свойства наночастиц. Оптические характеристики гидрозолей изучены методом спектрофотометрии в диапазоне 300–700 нм по полосе поверхностного плазмонного резонанса. Морфология и размеры частиц исследованы методами сканирующей электронной и атомно-силовой микроскопии, а элементный состав подтверждён энергодисперсионным анализом. Модификацию полилактидной пищевой плёнки проводили методом распыления коллоидного раствора наночастиц серебра. Установлено, что размеры синтезированных наночастиц варьируются в пределах 1–80 нм и регулируются концентрациями нитрата серебра и восстановителя. Повышение концентрации нитрата серебра приводит к увеличению среднего размера частиц и усилению процессов агрегации. Показано, что при нанесении методом распыления наночастицы равномерно распределяются и устойчиво фиксируются в пористой структуре полилактидной плёнки, не нарушая её физико-химические и морфологические характеристики. Полученный нанокомпозитный материал сочетает биоразлагаемость с выраженными бактерицидными свойствами. Разработанная технология отличается простотой реализации, воспроизводимостью и экономической эффективностью. Полученный материал перспективен для промышленного внедрения при создании активной биоразлагаемой упаковки нового поколения для пищевой промышленности, обеспечивающей увеличение срока хранения и повышение микробиологической безопасности продукции при одновременном снижении экологической нагрузки.

Ключевые слова: наночастицы серебра, биоразлагаемые упаковочные материалы, полилактидная плёнка, поливиниловый спирт, глюкоза, зелёный синтез, антимикробное покрытие

Introduction. Mankind's need for polymer products has been growing at an incredible rate over the past centuries. This is primarily due to their high mechanical strength, durability, heat resistance, chemical stability, light weight, and cost-effectiveness in various industrial and consumer applications. Polymers have become indispensable in construction, medicine, electronics, transportation, and especially in the food packaging sector. The versatility of polymeric materials allows manufacturers to design packaging systems with tailored barrier, mechanical, and optical properties suitable for specific food products.

However, despite their technological advantages, the environmental impact of polymers, particularly packaging materials, remains a serious global concern. Polymer packaging typically has a very short service life and goes out of circulation almost immediately after the goods have fallen into the hands of the buyer. As a result, massive quantities of plastic waste accumulate annually. Neither landfill disposal nor incineration nor even recycling fully resolves the environmental burden. While recycling technologies are being improved, they remain energy-intensive and economically limited in many regions. Consequently, long-term persistence of synthetic polymers in the environment leads to soil and water contamination, formation of microplastics, and disruption of ecological systems.

Although until recently the durability of synthetic polymers was considered their main advantage, according to modern concepts it is associated with significant environmental problems and, in the long term, poses a serious threat to ecosystems and human health. The accumulation of plastic waste in marine and terrestrial environments has become one of the most pressing ecological challenges of the 21st century (Geyer et al., 2017; Andrady, 2011).

In this context, the development of sustainable packaging materials that combine environmental safety and functional performance has become an urgent scientific and technological task. One of the promising approaches is the creation of biodegradable polymer materials with enhanced functional properties, including antimicrobial activity.

Thus, the aim of this work is to impart antibacterial properties to biodegradable packaging materials by impregnation with a silver nanoparticle solution. This study focuses on the green synthesis of silver nanoparticles using polyvinyl alcohol as a stabilizing matrix and investigates their physicochemical characteristics, morphological features, and antibacterial effectiveness. The development of such materials contributes to solving two critical challenges simultaneously: reducing environmental pollution caused by synthetic polymers and enhancing microbiological safety of food packaging systems.

Literary review. Conventional polymer packaging may contribute to microbial contamination. Pathogenic microorganisms can actively develop in polymer-based packaging under favorable storage conditions, especially in high-moisture environments (Marsh et al., 2007). Microbial growth not only reduces shelf life but also poses potential risks to consumer health.

Various technologies have been introduced to improve food safety, including thermal treatment, irradiation, modified atmosphere packaging, and advanced sterilization methods. Although effective, these methods are often energy-intensive, require expensive equipment, and may negatively affect the organoleptic properties of food products. Therefore, the development of innovative packaging solutions remains a priority (Vanderroost et al., 2014; Siracusa, 2012; Tausarova, 2017).

In this regard, active packaging technologies have attracted significant attention. Nanotechnology plays an important role in this field, offering new approaches such as antimicrobial and smart packaging systems, improved barrier properties, and enhanced food preservation capabilities. The incorporation of nanoscale materials into polymer matrices enables modification of mechanical strength, gas permeability, UV resistance, and antimicrobial properties without significantly altering bulk characteristics.

Among nanomaterials, metal nanoparticles are of particular interest due to their strong antimicrobial activity. Silver nanoparticles, in particular, have been extensively studied and demonstrate broad-spectrum effectiveness against Gram-positive and Gram-negative bacteria, fungi, and some viruses (Duncan, 2011; Ruparelia et al., 2008; Ahmed et al., 2016). Their antimicrobial mechanism involves disruption of cell membranes, generation of reactive oxygen species, and interaction with microbial DNA and proteins.

In response to environmental concerns, significant research efforts have been directed toward the development of biodegradable polymers with antibacterial properties. Biopolymers derived from renewable resources such as cellulose, starch, wood, and polylactide are considered promising alternatives to conventional plastics. However, most biodegradable polymers lack inherent antimicrobial activity, limiting their application in food packaging. To address this limitation, nanoparticles of metals such as silver, copper, and zinc are incorporated into polymer matrices to impart antibacterial functionality (Niaounakis, 2013; Cushen et al., 2014).

Polyvinyl alcohol (PVA) is widely used in biomedical, pharmaceutical, and packaging applications due to its biocompatibility, film-forming ability, water solubility, and chemical stability. Unlike most polymers obtained through direct polymerization, PVA is produced by hydrolysis of polyvinyl acetate, which distinguishes it from other polymeric materials (Gudikandula et al., 2016; Khodashenas et al., 2019).

In recent years, increasing attention has been given to environmentally friendly ("green") synthesis methods of nanoparticles. These approaches employ mild reaction conditions and non-toxic reducing and stabilizing agents, making them suitable for food-related applications. For instance, glucose can be used as a reducing agent, while polyvinyl alcohol serves as a stabilizer to form stable silver nanoparticle colloids under controlled conditions.

Materials and methods. The objects of the study are: biodegradable packaging material, chemical compounds - silver nitrate, glucose, polyvinyl alcohol.

Silver nitrate was used as the main reagent. Silver nitrate is used in medicine for cauterizing and sterilizing wounds. The therapeutic effect of silver nitrate is to inhibit the vital activity of microorganisms; in small concentrations it acts as an anti-inflammatory and astringent, and concentrated solutions, like $AgNO_3$ crystals, cauterize living tissues.

Glucose served as the reducing agent and polyvinyl alcohol (PVA) as the stabilizer. Chemical reduction is a multifactorial process. It depends on the oxidant-reductant pair, their concentrations and conditions of the process realization.

Glucose is a colorless crystalline substance of sweet taste, soluble in water, soluble in Schweitzer's reagent (ammonia solution of copper hydroxide $Cu(NH_3)_4(OH)_2$), in concentrated zinc chloride solution and concentrated sulfuric acid solution.

Polyvinyl alcohol (PVA) is an artificial solid white (less often light yellow or creamy) polymer in the form of powder, flakes or grits. The crystalline component of the substance can be up to 68%. The chemical formula of polyvinyl alcohol is as follows: [- CH_2 - CH(OH)-] n, where n is the degree of polymerization. The value of n can reach 5000, that is, a molecule of polyvinyl alcohol can have in its composition up to 5000 identical links.

Pure polyvinyl alcohol is odorless, tasteless and non-toxic. Its only solvent is water. Polyvinyl alcohol is not soluble in any organic solvent. It is particularly resistant to any oils, gasoline, kerosene and other hydrocarbons, as well as diluted alkalis and acids.

Silver nanoparticles were synthesized by reducing aqueous silver nitrate solution. In this synthesis technique, the same volume of reducing agent solution (0.001 M - 0.05 M) was added to silver nitrate solution of a certain concentration (0.0001 M - 0.0005 M) and the solutions were stabilized with 25% polyvinyl alcohol. Distilled water and reagents of qualification “CP” (chemically pure) were used for the synthesis.

Optical absorption spectra of Ag hydrosols were recorded at room temperature in the region of 300-700 nm on an Analytik Jena spectrophotometer in a quartz cuvette, the length of the optical layer was 1 cm. Concentration, size, aggregative state of nanoparticles in solutions were determined by the position and intensity of surface plasmon resonance bands. Sedimentation stability of sols was also evaluated visually (Matusiak J., et.al. 2017).

The microscopic study was carried out using JSM-6510LA electron scanning microscopy. The biopackages were examined using scanning electron microscopy (SEM). The content of carbon, oxygen and silver nanoparticles was determined in the studied samples using energy dispersive analysis.

Results. When glucose ($C(AgNO_3) = 0.001$ M; $C(C_6H_{12}O_6) = 0.05$ M was used as a reducing agent, relatively stable colloidal solutions with a characteristic yellow coloration were formed. The optical spectra show a pronounced absorption maximum in the range of $\lambda = 410–420$ nm. The presence of this band indicates the formation of silver nanoparticles. The plasmonic band is relatively narrow and symmetrical, indicating a fairly uniform particle size distribution and a limited degree of aggregation in the studied system.

When studying the influence of the initial $AgNO_3$ solution concentration in the range of 0.001–0.005 M (at a constant glucose concentration of $C(C_6H_{12}O_6) = 0.05$ M), it was found that the intensity of the absorption maximum at 420 nm increases proportionally with increasing silver nitrate concentration (Figure 1).

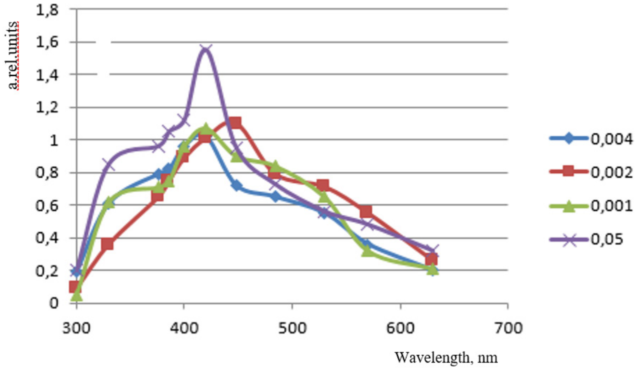


Figure 1 — Effect of initial silver nitrate concentration on optical absorption spectra of silver sols formed: 1 - 0.004M; 2 - 0.002M; 3 - 0.001M; 4 - 0.05M

At the same time, a noticeable change in the color of the solution from light yellow to dark yellow and further to brown was observed (Figure 2).

In addition to the increase in peak intensity at 420 nm, an increase in optical density at wavelengths above 500 nm was recorded with increasing silver salt concentration. In some cases, a "shoulder" appeared in the spectra within the 500–550 nm range.

A broadening of the absorption band and its shift to longer wavelengths (batochromic shift) was also noted at elevated silver concentrations.

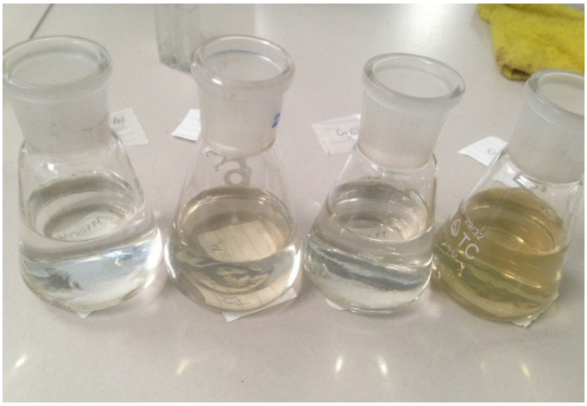


Figure 2 — Coloring of the obtained solutions

Under the influence of the reducing agent concentration — glucose — a noticeable increase in the intensity of the absorption band maximum (Figure 3) was observed as the glucose concentration increased within the range of 0.001–0.005 M (the typical silver ion concentration in the experiments was 0.0001 M).

In addition to the increase in absorption intensity, a slight shift (approximately 20 nm) of the plasmon absorption maximum toward the short-wavelength region was observed with increasing glucose concentration. A narrowing of the plasmon resonance band was also noted at higher reducing agent concentrations.

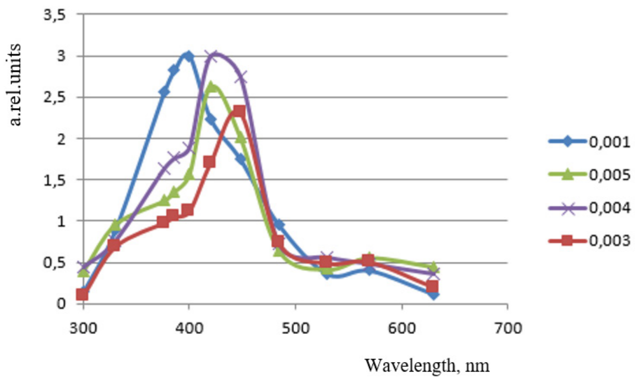


Figure 3 — Effect of glucose concentration on the optical absorption spectra of the formed silver sols: 1 - 0.001M; 2 - 0.005M; 3 - 0.004M; 4 - 0.003M

Under our determined optimal synthesis conditions ($C(AgNO_3)$ = 0.0001M; $C(C_6H_{12}O_6)$ = 0.05M; a few drops of 25% polyvinyl alcohol), silver nanoparticle solutions were prepared and examined by atomic force microscopy (Figure 4).

The developed nanocomposite composition was applied to the surface of bio-packaging using a spraying method.

The processed bio-packaging samples were then examined using scanning electron microscopy (SEM) and subjected to microbiological analysis.

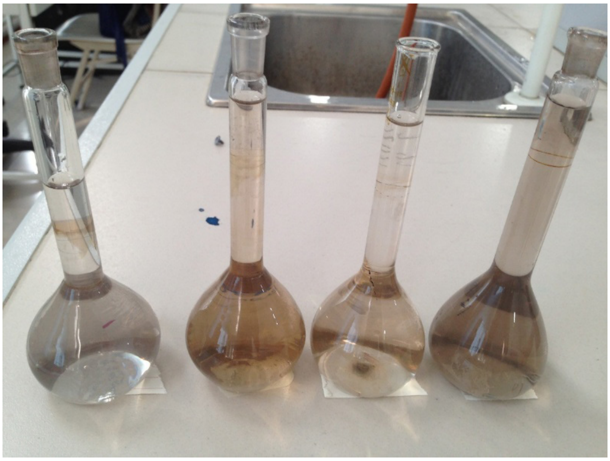
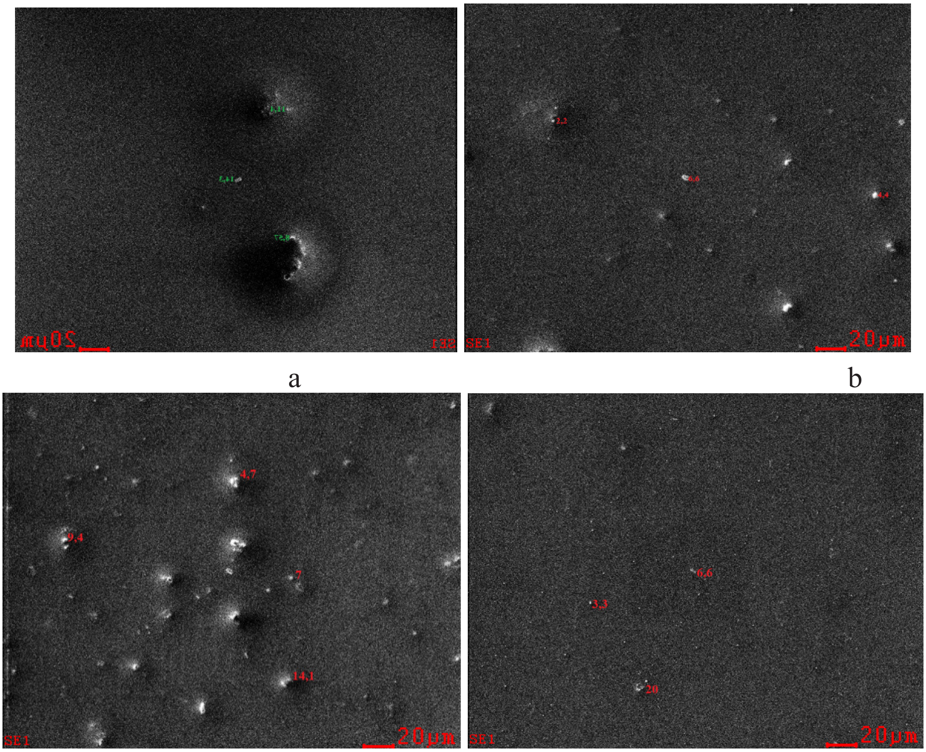


Figure 4 — Silver nanoparticle solutions with concentration: 0.0001M; 0.0002M; 0.003M; 0.005 M.

As follows from the electron microscopic study of the samples shown in Figure 5, the samples contain a fairly large number of silver nanoparticles with sizes ranging from 1-30nm.



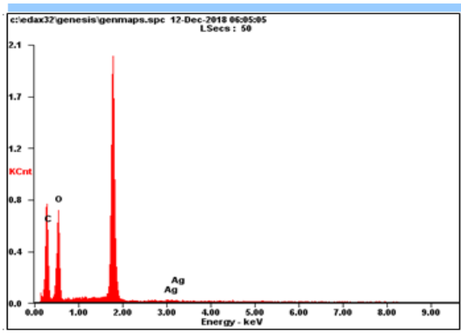
a b

c d

Figure 5 — Photographs of nanoparticles obtained by SEM with different concentrations: a - 0.0001M; b - 0.0002M; c - 0.0003M; d - 0.0005M

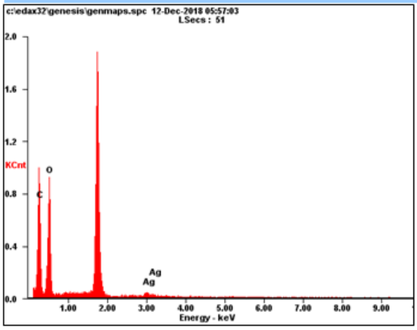
Energy dispersive analysis (EDA) of the studied samples revealed the presence of carbon, oxygen, and silver nanoparticles in their composition (in elemental and atomic percentages) (Figure 6). The spectra revealed characteristic silver peaks in the corresponding energy range, confirming its presence in the samples. The relative intensity of the Ag peaks increased with increasing initial silver concentration.

The consistent detection of silver in the analyzed regions indicates its distribution and fixation within the structure of the biodegradable packaging material.



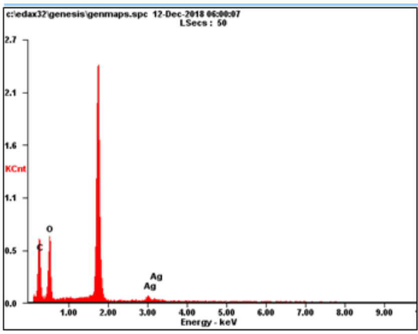
Element	Wt%	At%
C	50.83	59.95
O	44.53	39.44
Ag	4.64	0.61

a



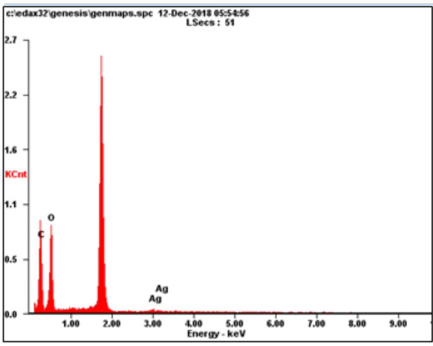
Element	Wt%	At%
C	47.65	58.34
O	44.11	40.54
Ag	8.24	1.12

b



Element	Wt%	At%
C	42.80	55.72
O	43.23	42.26
Ag	13.97	2.03

c



Element	Wt%	At%
C	48.14	58.09
O	45.30	41.03
Ag	6.56	0.88

d

Figure 6 — Results of energy dispersive analysis of the studied samples (with silver concentration a - 0.0001M; b - 0.0002M; c - 0.0003M; d - 0.0005M)

The SEM result of the investigated sample (Fig.7) treated with a solution with silver concentration of 0.0001M contains silver nanoparticles with sizes ranging from 1-35nm; 1-50nm (concentration of 0.0002M); 1-70nm (concentration of 0.003M); 1-80nm (concentration of 0.0005M).

Thus, with an increase in the concentration of silver, an expansion of the size range of nanoparticles is observed.

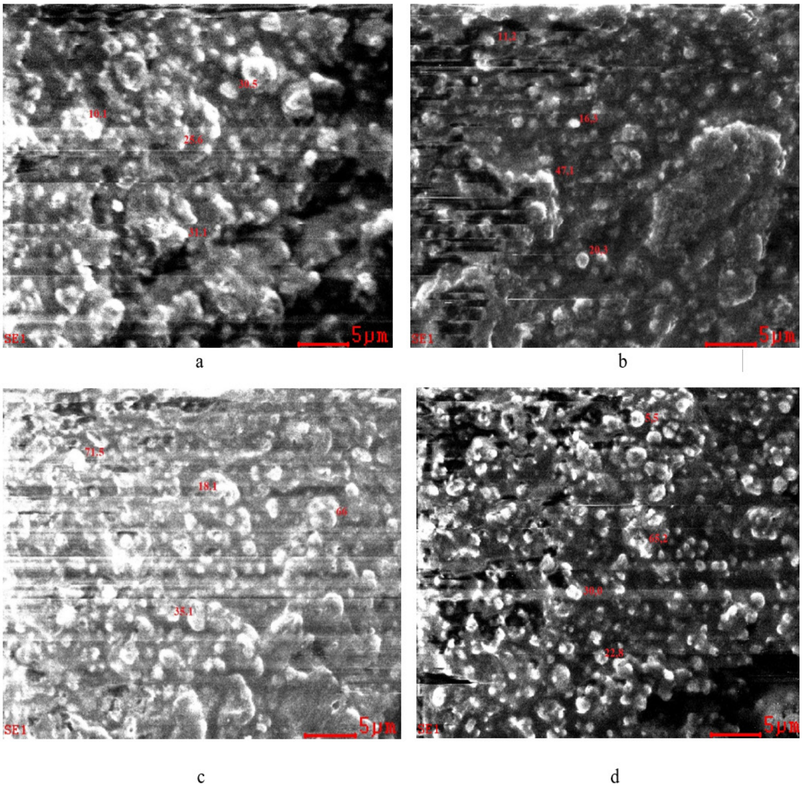


Figure 7 – Photograph of nanoparticles on the surface of the biopackage obtained by SEM (with silver concentration a - 0.0001M; b - 0.0002M; c - 0.0003M; d - 0.0005M)

Transmission electron microscopy data revealed that the resulting nanoparticles are predominantly spherical. The majority of particles are characterized by diameters of 1–10 nm, with some particles up to 80 nm in size being recorded. The spherical shape of the nanoparticles is indicated by the yellow coloration of the solution. The particles formed are stable, do not precipitate and do not change color for several weeks. When reconstituted with glucose, the solutions changed coloration from light gray to black, indicating larger silver particles (particle association). Energy dispersive analysis showed that the studied samples show an increase in the size of silver nanoparticles with increasing concentration from 0.0001M to 0.0005M.

Discussion. The appearance of a yellow color is characteristic of silver nanoparticle hydrosols and is associated with surface plasmon resonance (SPR). The absorption maximum in the 410–420 nm range confirms the formation of predominantly spherical silver nanoparticles, which is consistent with literature data for nanosized particles dispersed in an aqueous medium and stabilized by a polymer matrix.

The relative narrowness and symmetry of the plasmon resonance peak indicate a fairly uniform particle size distribution and a limited degree of aggregation under the selected synthesis conditions. The stability of the colloidal system can be explained by the combined effect of the reduction kinetics of glucose and the steric stabilization provided by polyvinyl alcohol, which prevents rapid particle growth and agglomeration.

An increase in the peak intensity at 420 nm indicates an increase in the concentration of formed nanoparticles in the colloidal system. As the amount of precursor ions increases, the number of nucleation centers rises, resulting in a greater overall nanoparticle yield.

Such a color transition is typically associated with an increase in nanoparticle concentration and possible changes in their size distribution. The darker coloration may indicate the formation of larger particles or the occurrence of partial aggregation processes at higher precursor concentrations.

The increase in optical density in the region $\lambda > 500$ nm and the appearance of a spectral "shoulder" in the 500–550 nm range may be due to interparticle plasmonic interactions that arise as the interparticle distance decreases. These features are also characteristic of systems with partial aggregation or the formation of nonspherical (spheroidal or anisotropic) particles.

Broadening of the absorption band and its shift toward longer wavelengths (red shift) at higher silver concentrations may also indicate an increase in the average particle size. According to Mie theory, the position and width of the plasmon resonance band are sensitive to particle size, shape, and the dielectric properties of the surrounding medium. Therefore, the observed spectral changes reflect modifications in the balance between nucleation and growth processes during synthesis. At higher precursor concentrations, the reduction rate may locally increase, promoting particle growth and increasing the probability of collision and aggregation.

The increase in peak intensity indicates a higher yield of silver nanoparticles formed in the colloidal system under enhanced reducing conditions. Since the concentration of silver ions remained constant, the observed spectral changes can be directly attributed to modifications in the reduction kinetics caused by varying glucose content.

The shift of the absorption maximum to the short-wavelength region indicates a decrease in the average particle size. The shift toward shorter wavelengths is consistent with theoretical and experimental data showing that smaller silver nanoparticles exhibit plasmon resonance maxima at lower wavelengths due to quantum size effects and changes in the oscillation behavior of conduction electrons.

The narrowing of the plasmonic band confirms the formation of a narrower particle size distribution. The increased rate of recovery at high glucose concentrations promotes the rapid formation of a large number of nuclei and suppresses secondary growth and aggregation processes due to the rapid consumption of silver ions.

Polyvinyl alcohol provides additional stabilization of the system, creating steric repulsion between particles and preventing their coalescence.

Thus, increasing the reducing agent concentration shifts the balance of processes toward intense nucleation with limited particle growth. At low glucose concentrations, reduction proceeds more slowly, facilitating the formation of larger particles, whereas at high concentrations, supersaturation is quickly reached, mass nucleation is initiated, and smaller nanoparticles are formed.

The selection of optimal synthesis conditions made it possible to obtain a stable dispersed system of silver nanoparticles suitable for practical use as a functional coating. The spraying method was chosen because it is technologically simple and ensures uniform distribution of nanoparticles across the surface of the material. The use of bio-packaging as a base is driven by its environmental safety, hygiene, and ability to rapidly biodegrade, which is important for sustainable waste management.

The use of a set of analytical methods (AFM, SEM and microbiological studies) made it possible to evaluate both the morphological characteristics of the coating and its potential antimicrobial properties, which confirms the feasibility of using the developed system for the creation of functional packaging materials.

The detection of carbon and oxygen is mainly associated with the polymer matrix of the biodegradable film, as well as with the presence of polyvinyl alcohol used as a stabilizer during nanoparticle synthesis. The presence of characteristic silver peaks confirms the successful incorporation and fixation of silver nanoparticles within the material structure.

The relative intensity of silver peaks in the spectra increased with increasing initial silver concentration, indicating a higher content of metallic nanoparticles in the analyzed areas. The characteristic Ag peaks observed in the corresponding energy range provide direct evidence of the formation of metallic silver rather than ionic forms. This confirms the effectiveness of the reduction process under the selected synthesis conditions.

It should be noted that the obtained results are predominantly qualitative rather than strictly quantitative. During scanning electron microscopy combined with energy dispersive analysis, the samples were exposed to a focused electron beam, which may cause local heating or partial damage to polymer materials. In some cases, prolonged irradiation may lead to partial degradation or “burning” of organic components, affecting the measured elemental ratios. In addition, energy dispersive spectroscopy does not allow detection of hydrogen due to its low atomic number; therefore, the complete elemental composition of the polymer matrix cannot be fully determined.

Despite these limitations, energy dispersive analysis reliably confirms the presence and distribution of silver nanoparticles in the studied samples. The consistent detection of silver depending on the initial precursor concentration indicates successful deposition and fixation of nanoparticles on the surface of the biodegradable packaging material.

The expansion of the particle size range with increasing silver concentration indicates a shift in the balance of nucleation and growth processes toward more intense particle growth. Higher precursor content promotes the formation of larger nanoparticles and increases the likelihood of their coalescence.

The spherical shape of the particles is consistent with optical spectroscopy data, particularly the characteristic yellow color of the solution due to surface plasmon resonance, typical of spherical silver nanoparticles.

The stability of the colloidal solutions for several weeks indicates effective stabilization of the particles, likely due to the presence of the polymer matrix and stabilizing agent.

The change in the color of the solutions upon interaction with glucose, from light gray to black, may indicate the formation of larger particles or their association, which is associated with enhanced aggregation processes.

Thus, the combined results of SEM, TEM, and EDX confirm the dependence of silver nanoparticle size on the initial precursor concentration and reflect the kinetics of their formation in the studied system.

Conclusion. Thus, as a result of this study, an effective and reproducible method for the synthesis of silver nanoparticles by chemical reduction using glucose as a reducing agent and polyvinyl alcohol as a stabilizer has been developed. The proposed approach ensures the formation of stable colloidal systems under mild reaction conditions. The key parameters governing silver nanoparticle synthesis — primarily the concentrations of silver nitrate and glucose — were identified and optimized, allowing controlled regulation of nanoparticle size and optical properties.

Silver nanoparticles obtained via reduction of silver nitrate solution with glucose were successfully synthesized. The size of the nanoparticles was found to range from 1 to 80 nm and was directly dependent on the concentration of the reagents used during synthesis. Comprehensive characterization of the synthesized nanoparticles was performed using scanning electron microscopy (SEM), atomic force microscopy (AFM), and energy dispersive analysis (EDA), confirming their morphology, size distribution, and elemental composition.

A novel method for imparting antibacterial properties to biodegradable packaging materials, specifically polylactide-based food film, has been developed. The silver nanoparticles deposited onto the polylactide film were uniformly and stably immobilized within the porous surface structure of the material. Microscopic analysis demonstrated that the incorporation of nanoparticles does not disrupt or degrade the structural integrity of the polylactide matrix at the microlevel.

The developed nanocomposite system combines environmental compatibility with antimicrobial functionality, addressing both ecological and food safety challenges. The proposed approach can be recommended for practical application in the production of biodegradable packaging materials with antimicrobial properties, particularly in the food industry. Its environmental safety, technological simplicity, cost-effectiveness, and scalability make it a promising solution for sustainable packaging technologies.

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