Original Scientific Paper https://doi.org/10.24867/GRID-2026-p76

Bio-Based Antibacterial Paper Coatings Enabled by Surface-Modified Silver Nanoparticles

Emine Arman Kandirmaz
Arif Ozcan

Marmara University,
Faculty of Applied Sciences,
Printing Technologies,
Istanbul, Turkey

ABSTRACT

The increasing demand for safer food products and the growing concern over microbial contamination have accelerated the development of sustainable active packaging materials capable of extending shelf life and improving food safety. In this study, bio-based antibacterial paper coatings were developed using a starch matrix reinforced with surface-modified silver nanoparticles (m-AgNPs). The coating formulations were prepared with varying nanoparticle loadings (0, 1, 2.5, and 5 wt%) to investigate the influence of m-AgNP concentration on antibacterial performance and coating functionality. Prior to application, the rheological behavior of the coating dispersions was evaluated to ensure their suitability for coating processes. The formulations were subsequently applied onto paper substrates using an automatic laboratory-scale film applicator under controlled conditions. After drying, the coated papers were characterized in terms of coating deposition and antibacterial activity. The antimicrobial performance of the developed coatings was assessed against the Gram-negative bacterium Escherichia coli and the Gram-positive bacterium Staphylococcus aureus using the disk diffusion method. The results demonstrated that the incorporation of surface-modified silver nanoparticles significantly enhanced the antibacterial performance of the starch-based coatings. Increasing nanoparticle concentration resulted in progressively larger inhibition zones, indicating a concentration-dependent antimicrobial effect. Among the investigated formulations, the coating containing 5 wt% m-AgNP exhibited the highest antibacterial activity against both bacterial strains. The surface modification of silver nanoparticles improved their dispersion stability within the starch matrix, promoting more effective nanoparticle–polymer interactions and contributing to the formation of highly functional antimicrobial surfaces. The findings highlight the potential of starch/m-AgNP composite coatings as environmentally friendly and high-value alternatives to conventional petroleum-based active packaging materials. The developed system provides an effective strategy for integrating renewable biopolymers and nanotechnology to produce next-generation antibacterial paper packaging with enhanced food protection capabilities.

KEY WORDS
Active food packaging, starch coating, surface-modified silver nanoparticles, antibacterial paper, sustainable packaging, bio-based materials, nanotechnology

1. Introduction

Packaging protects the product it contains from unwanted effects, moisture loss or spoilage, damage that may occur due to external factors, and biological degradation. However, these basic functions are becoming insufficient to meet the new needs of today's increasingly consumption-oriented lifestyle and the habits that accompany it.

Consumers now want access to both fresh, high-quality, and safe food (Upadhyay et al., 2024). At this point, the selection, design, and facilitation of packaging materials suitable for the structural characteristics of the food product are extremely important for the preservation and maintenance of quality (Yue et al., 2024).

Various chemical substances can be added to paper during production to give it different properties depending on its intended end use. Paper has a rough surface and does not exhibit the same properties at every point. Therefore, certain chemical substances are added to the paper to fill the voids and create a smoother structure. Surface coating makes the paper physically and chemically more resistant (Ozcan et al., 2021). Some of the substances used in paper surface coating are fillers, binders, optical brighteners, anti-foaming agents, pH balancers, and preservatives. Some existing chemical substances used in paper surface coating or pulp may have negative effects on the environment and human health. This is of serious importance in the production of papers to be used in food packaging (Kunam et al., 2024).

Applications involving coating the surfaces of packaging products, which fall into the active packaging category, with antioxidant natural biopolymer materials to make them suitable for food contact are gaining increasing importance. Environmentally friendly, renewable, and biodegradable natural pigments and dyes are being developed to replace the synthetic pigments currently used to coat food-contact packaging papers. Recent studies have shown that coating paper surfaces with natural dyes and pigments known for their antibacterial and antioxidant properties can provide protection against external factors when in contact with food (Aloui et al., 2011; Rudra et al., 2013).

Antimicrobial agents are defined as substances that inhibit or limit the growth of microorganisms such as bacteria, fungi, and single-celled organisms. Antimicrobial chemicals are essentially divided into two categories: antimicrobial products used industrially to control microorganisms, and chemicals designed to inhibit the growth of pathogens in the environment and on external surfaces. Antimicrobials used in the control of microorganisms are chemicals used in food, textile and paper products, cooling towers, and ventilation systems. Chemicals designed to inhibit pathogens on external surfaces include sterilizers, disinfectants, sanitizing products, and antiseptics (Fahmy et al., 2020).

Due to its strong antibacterial effect and non-toxicity, silver and silver compounds are frequently used in daily life by coating the surfaces of many materials (textiles, ceramics, metals, plastics, glass, paints, etc.) where various microorganisms are frequently found during or after production. Materials containing silver are durable and retain silver ions on their surfaces for a long time (Kawashita et al., 2000). Today, we can see the use of nanotechnology in many fields. It is possible to encounter nano properties even in many ordinary products we use in daily life. Nanotechnological studies are being conducted to control individual atoms or molecules in order to design or create new products (Mohammad et al., 2012; Cerqueira et al., 2018). This technology has a wide range of applications in the food industry in different areas such as increasing product safety, nutrition, reducing agricultural inputs, and new manufacturing methods. For many years, most of the food products we consume have contained nano-components in their structure (Sekhon, 2010; Schnettler et al., 2014; del Rosario Herrera-Rivera et al., 2024).

In this study, bio-based antibacterial paper coatings were developed using a starch matrix reinforced with surface-modified silver nanoparticles (m-AgNPs). The coating formulations were prepared with varying nanoparticle loadings (0, 1, 2.5, and 5 wt%) to investigate the influence of m-AgNP concentration on antibacterial performance and coating functionality. The antimicrobial performance of the developed coatings was assessed against the Escherichia coli and Staphylococcus aureus using the disk diffusion method.

2. Materials and methods

2.1. Materials

In this study, natural starch was used as the coating matrix. Silver nitrate (AgNO3, ≥99.9% purity), sodium borohydride (NaBH4, ≥98% purity), polyvinylpyrrolidone (PVP, mean molecular weight ≈40,000 g/mol), nitric acid (HNO3, 65% w/w), and glycerol were obtained from Sigma-Aldrich and used without any further purification. Deionized water was used in the preparation of all solutions. 80 g/m2 UPM commercial paper was preferred as the coating substrate.

2.2. Methods

2.2.1. Synthesis and surface modification of silver nanoparticles

Surface-modified silver nanoparticles (m-AgNP) were synthesized under laboratory conditions using a chemical reduction method. For this purpose, 0.01 M NaBH4 and 0.01 M PVP solutions were mixed in a 1:1 volume ratio and homogenized on a magnetic stirrer at 1000 rpm for 1 hour. Then, a reduction reaction was carried out by adding a 0.1 M AgNO3 solution dropwise to the reaction medium. The change in the color of the solution from colorless to light yellow during the reaction was considered the first visual indication of the formation of silver nanoparticles (El Hotaby et al.,

2017). After the reaction was completed, the synthesized nanoparticles were filtered, washed with deionized water, and dried under controlled conditions.

The obtained silver nanoparticles were surface modified with nitric acid (65%, w/w) to improve their surface properties and increase their dispersion stability within the polymer matrix (Lestari et al., 2025). For this purpose, the dried nanoparticles were re-dispersed in deionized water, and surface activation was performed by adding a certain amount of HNO3. The prepared suspension was treated in an ultrasonic bath for 6 hours to reduce particle agglomeration and ensure homogeneous surface modification. Following the modification process, the nanoparticles were washed several times with deionized water to remove acid and reaction byproducts, then dried and stored for use in characterization and preparation of coating formulations.

2.2.2. Preparation and application of starch-based antibacterial coating formulations

Coating formulations were prepared using a 10% by weight (w/v) starch solution. For this purpose, the required amount of starch was dispersed in deionized water and heated to 97 °C under continuous magnetic stirring to ensure complete gelatinization. After obtaining a homogeneous dispersion, the system was cooled to room temperature (25 ± 2 °C). Glycerol was added to the cooled starch dispersion as a plasticizer at a ratio of 1.5 mL/100 mL and magnetic stirring was applied for 15 minutes (El-Lakany et al., 2026). Then, silver nanoparticles, synthesized in the laboratory and surface-modified, were added to the dispersion at ratios of 1%, 2.5%, and 5% by weight, based on the amount of dry starch. The formulations were mechanically mixed to ensure homogeneous distribution of the nanoparticles within the starch matrix. A starch dispersion without nanoparticles was also prepared using the same steps and used as a control group. Before coating application, the flow behavior of all prepared formulations was evaluated by rheological analysis.

The prepared coating dispersions were applied to 80 g/m2 base paper surfaces using an automated laboratory-type coating device with a No. 4 K-bar (Mayer rod). The coating process was carried out under constant application conditions to obtain a homogeneous wet film thickness in all samples. The coated samples were dried under controlled laboratory conditions and conditioned before analysis (Kansal et al., 2020).

The coating amount was determined gravimetrically based on the mass difference per unit area of the papers before and after coating, and the results were expressed in g/m2. All measurements were performed in triplicate.

2.2.3. Characterization

Changes in the chemical structure of synthesized and surface-modified silver nanoparticles were investigated using Fourier Transform Infrared Spectroscopy (ATR-FTIR). Analyses were performed using a PerkinElmer Spectrum 100 ATR-FTIR spectrophotometer (PerkinElmer Inc., Waltham, MA, USA) in the wavenumber range of 400–4000 cm^{-1} and with a spectral resolution of 2 cm^{-1}. The obtained spectra were evaluated to determine the changes occurring in the functional groups after surface modification.

The morphology and particle sizes of the synthesized silver nanoparticles were examined using scanning electron microscopy (SEM). SEM analyzes were carried out with a Philips XL30 SEM device. Before analysis, dried nanoparticle samples were placed on the SEM carrier and coated with a thin layer of platinum to increase electron conductivity. Using the obtained micrographs, the morphology, particle size and possible agglomeration state of the nanoparticles were evaluated.

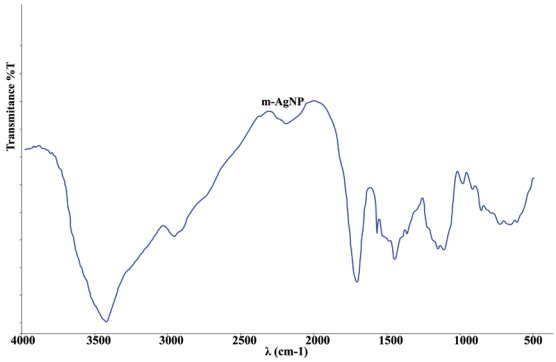
Hydrodynamic particle size, polydispersity index (PDI) and zeta potential values of nanoparticles were determined using the Malvern Zetasizer Nano ZS90 (Malvern Instruments Ltd., Worcestershire, United Kingdom) device, which works on the dynamic light scattering (DLS) principle. The obtained data were used to evaluate the colloidal stability of the synthesized nanoparticles and the effect of surface modification on their dispersion properties.

The antibacterial efficacy of the prepared coating formulations was evaluated using the disk diffusion method. Gram-negative and Gram-positive were selected as test microorganisms. Bacterial cultures were activated by incubating them in Tryptic Soy Broth (TSB) medium at 37 °C for 24 hours prior to the experiment. After the activated cultures were spread homogeneously on the surface of solid medium under sterile conditions, 6 mm diameter disks prepared from uncoated base paper, paper coated only with starch, and coated paper containing different concentrations of surface-modified silver nanoparticles were aseptically placed on the medium. After incubating the Petri dishes at 37 °C for 24 hours, the diameters of the inhibition zones formed around the samples were measured using a digital caliper and evaluated as an indicator of antibacterial activity. All experiments were performed in triplicate, and the results are reported as mean ± standard deviation.

3. Results and discussion

The ATR-FTIR spectra of surface-modified silver nanoparticles are given in Figure 1. The characteristic bands observed in the spectra allowed for the evaluation of

the surface chemistry of the synthesized nanoparticles and the functional group changes that occurred after the modification process. The absorption band determined in the range of 1695–1615 cm^{-1} in pure AgNP samples was associated with the stretching vibrations of amide carbonyl (C=O) in the PVP structure. Similarly, the bands observed at 1462 cm^{-1} and 1423 cm^{-1} originated from the vibrations of the tertiary nitrogen groups in the PVP chains, while the bands at 2953 cm^{-1} and 2874 cm^{-1} corresponded to the asymmetric and symmetric stretching vibrations of the aliphatic –CH2 groups, respectively. The broad absorption band observed at approximately 3447 cm^{-1} was associated with the stretching vibrations of the hydroxyl groups (–OH) and the water molecules adsorbed on the surface. These characteristic bands demonstrate that PVP successfully functions as a coating and stabilizing agent on the synthesized silver nanoparticles. This results in line with literature (Pasieczna-Patkowska, Cichy & Flieger, 2025).

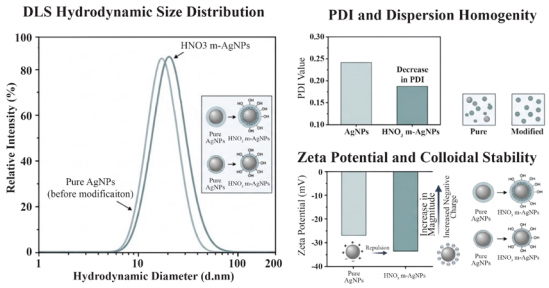


» **Figure 1:** *ATR-FTIR spectrum of m-AgNPs*

Significant changes were observed in the ATR-FTIR spectrum after surface modification with HNO3 (65%, w/w) followed by a 6-hour ultrasonic dispersion treatment. In particular, the intensity of the broad –OH stretching band in the 3420–3455 cm^{-1} range increased by approximately 35–40% compared to pure AgNP samples. In addition, the band associated with hydroxyl groups and adsorbed water molecules on the surface became more prominent around 1630 cm^{-1}, indicating an increase in oxygen-containing functional groups on the surface. These changes reveal that nitric acid treatment increased hydroxylation on the nanoparticle surface and resulted in a more hydrophilic surface structure (Mohammadi, Ishak & Sultan, 2024).

The literature reports that surface activation with nitric acid promotes the formation of oxygen-containing functional groups on metal nanoparticles, thereby increasing the strength of hydroxyl bands. Furthermore, this chemical transformation on the surface is said to increase the colloidal stability of the nanoparticles, reduce agglomeration, and ensure more homogeneous distribution within polymer matrices. The ATR-FTIR results obtained in this study are consistent with these findings, confirming that the applied surface modification was successful and that hydrophilic functional groups capable of enhancing interaction with the starch matrix were effectively formed on the nanoparticle surface. (Li & Li, 2019; Huang et al., 2019).

The hydrodynamic dimensions, polydispersity index (PDI), and zeta potential values of pure and surface-modified silver nanoparticles are given in Figure 2. Dynamic light scattering (DLS) analyses revealed that the average hydrodynamic diameter of AgNPs before modification was in the range of 35.5–49.3 nm. In contrast, after surface modification with HNO_3, the hydrodynamic dimension was observed to increase to the range of 37.8–51.5 nm. This limited increase in size can be attributed to the hydration layer and changes in surface chemistry due to the formation of hydroxyl-rich functional groups on the nanoparticle surface. Considering that the DLS technique determines the hydrodynamic diameter in the dispersion medium, not the dry particle diameter, the observed increase is considered a natural consequence of surface modification.



» **Figure 2:** *DLS and Zeta potential of AgNPs and m-AgNPs*

While the polydispersity index was measured in the range of 0.25–0.29 in AgNPs before modification, it decreased to the range of 0.18–0.22 after surface modification. This decrease in PDI values indicates that the nanoparticles have a narrower size distribution and the dispersion homogeneity increases. In general, PDI values < 0.30 are considered to be indicative of acceptable monodispersity and good dispersion properties in nanoparticle dispersions. Therefore, the results obtained reveal that the surface modification performed with HNO_3 not only changes the surface chemistry but also improves the dispersion behavior of the particles (Badawy et al., 2010).

Zeta potential, a key indicator of colloidal stability, was determined to be −27.10 mV in AgNPs before modification, while it increased to −33.80 mV after surface modification. An absolute value exceeding 30 mV indicates an increase in electrostatic repulsive forces between nanoparticles, resulting in a significant reduction in

agglomeration tendency. This finding supports the idea that oxygen-containing surface functional groups, identified in ATR-FTIR analyses, create additional negative charges on the nanoparticle surface, enhancing dispersion stability. Similarly, the literature reports that acid-activated silver nanoparticles exhibit higher absolute zeta potential values, supporting the formation of more stable colloidal systems. (Gontijo et al., 2020)

When the effect of surface modification on the dispersion behavior within the starch matrix was evaluated, heterogeneous dispersion regions and an initial tendency towards agglomeration were observed in systems containing unmodified AgNPs. This can be attributed to the limited interfacial interactions between the nanoparticle surface and the hydrophilic starch matrix. In contrast, formulations using m-AgNPs showed a more homogeneous dispersion at all nanoparticle concentrations. The hydrophilic functional groups formed as a result of HNO3 modification strengthened hydrogen bonding and other secondary interactions with the starch chains, enabling more effective dispersion of nanoparticles within the polymer matrix. Furthermore, the high viscosity and steric hindrance of the starch matrix limited particle mobility, suppressing re-agglomeration and contributing to the maintenance of dispersion stability. The observed limited local heterogeneities are considered to be due to the natural structural organization of the starch chains rather than nanoparticle aggregation (Abreu et al., 2015; Srikhao et al., 2023).

When all the obtained results are evaluated together, it is concluded that surface modification with HNO_3 not only changes the surface chemistry of the nanoparticles but also increases colloidal stability, improves particle size distribution, and strengthens interface compatibility with the starch matrix, thus significantly contributing to the achievement of more homogeneous composite coatings.

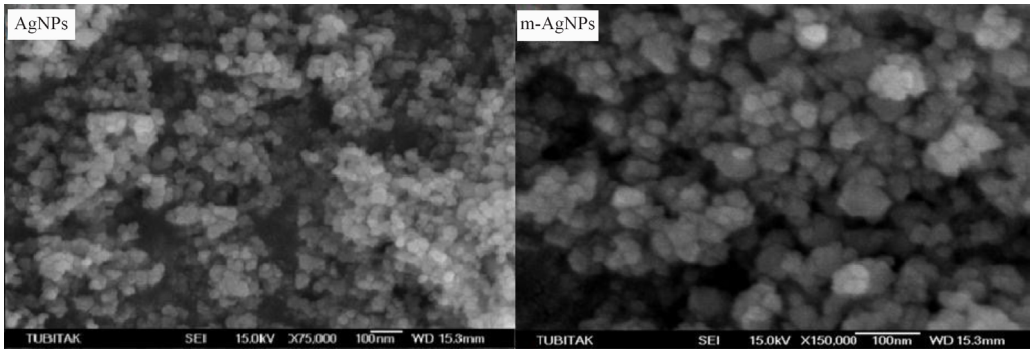
Figure 3 presents SEM images of synthesized pure AgNPs and surface-modified AgNPs. SEM analyses allowed for the evaluation of the morphology, size distribution, and agglomeration tendency of the nanoparticles. In both samples, it was determined that the particles generally exhibited a homogeneous distribution and no significant agglomeration formation was observed.

SEM micrographs of pure AgNPs show that the nanoparticles have a largely spherical morphology and their particle sizes range from approximately 35–48 nm. The narrow size distribution indicates that the nucleation and growth steps occur in a controlled manner during chemical reduction. This can be explained by the rapid reduction capacity of NaBH4, which is due to the controlled particle growth and the limitation of secondary agglomeration (Polte et al., 2012).

It was determined that the morphological integrity of the nanoparticles was preserved after surface modification, but the particle size increased slightly to the range of 38–53 nm. However, it was observed that the m-AgNPs exhibited a more regular size distribution and the distance between particles was more homogeneous. The limited increase in size is thought to be related to the oxygen-containing functional groups formed on the nanoparticle surface after HNO3 treatment and the resulting surface hydration. Nevertheless, the preservation of particle morphology indicates that the applied surface modification did not compromise the structural integrity of the nanoparticles.

SEM results were found to be consistent with DLS and zeta potential analyses. The limited increase in hydrodynamic diameter and decrease in PDI values in the m-AgNPs in DLS analyses support the more homogeneous particle distribution observed in the SEM images. Similarly, the increase in zeta potential from −27.10 mV to −33.80 mV reveals an increase in electrostatic repulsive forces between particles and a decrease in agglomeration tendency. Considering these findings together, it is concluded that surface modification with HNO3 not only alters the surface chemistry but also improves the morphological homogeneity and colloidal stability of the nanoparticles (Danaei et al., 2018).

The obtained results are consistent with the spherical morphology and particle sizes in the range of 20–60 nm reported in the literature for silver nanoparticles synthe-

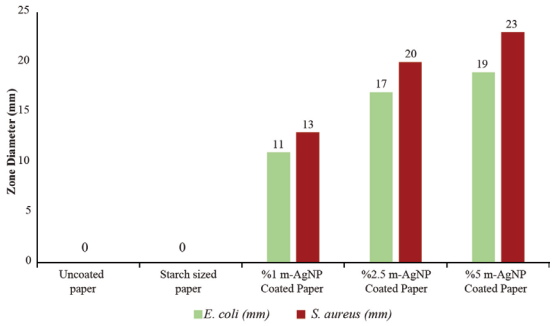


» **Figure 3:** *SEM images of AgNPs and m-AgNPs*

sized by chemical reduction methods. Furthermore, they support the literature findings that surface activation with acid improves dispersion quality and provides a more homogeneous distribution within polymer matrices without significantly altering the morphology of the nanoparticles (Agnihotri, Mukherji & Mukherji, 2013).

All four different coating formulations (control, 1% m-AgNP, 2.5% m-AgNP, and 5% m-AgNP) were successfully obtained without any visible phase separation or precipitation. A slight increase in the viscosity of the dispersions was observed with increasing nanoparticle concentration, and in the formulation containing 5% m-AgNP, it was necessary to extend the mixing time compared to the other formulations to ensure that the nanoparticles were completely homogeneously distributed within the starch matrix. However, it was determined that after additional mixing, the dispersion acquired a homogeneous appearance and maintained suitable flow properties for coating application.

All prepared formulations were successfully applied to the base paper surfaces using a No. 4 K-bar (Mayer rod) in a laboratory-type automated coating device. During the coating process, no streaking, irregular film formation, flow, or coating defects were observed on the surface; a continuous and homogeneous coating layer was obtained in all samples. As a result of gravimetric analyses, the average coating weight was determined as 8.0 g/m2 in all formulations, and no statistically significant difference was found between the samples ($p > 0.05$). This indicates that the change in nanoparticle concentration did not affect the amount of coating applied and that all samples were prepared under comparable coating conditions.



» **Figure 4:** *Antibacterial activity of coatings against E. coli and S. aureus*

The antibacterial activity of starch-based coatings containing varying concentrations of surface-modified silver nanoparticles (m-AgNP) was evaluated against Escherichia coli and Staphylococcus aureus bacteria using the disk diffusion method, and the results are presented in Figure 4. It was determined that no inhibition zones were formed against either bacterial species in the uncoated base paper and control samples coated only with starch. This finding reveals that starch alone does not exhibit antibacterial activity and that the observed antimicrobial activity is entirely due to the surface-modified silver nanoparticles added to the coating formulation (Boukraâ & Amara, 2008).

Significant inhibition zones were formed in all coating formulations containing m-AgNP, and it was observed that antibacterial activity increased steadily with increasing nanoparticle concentration. In coatings containing 1% m-AgNP, inhibition zones of 11 mm and 13 mm were obtained for E. coli and S. aureus, respectively, while these values increased to 17 mm and 20 mm with an increase in nanoparticle concentration to 2.5%. The highest antibacterial activity was determined in coatings containing 5% m-AgNP, with inhibition zones of 19 mm for E. coli and 23 mm for S. aureus. The results demonstrate a significant dose-response relationship between the concentration of surface-modified silver nanoparticles and antibacterial performance (De Plano et al., 2025).

In all formulations, the inhibition zones obtained against S. aureus were found to be higher than those obtained against E. coli. This difference stems from fundamental differences in the cell wall structures of Gram-positive and Gram-negative bacteria. Gram-negative bacteria have an outer membrane containing lipopolysaccharide (LPS) in addition to a thin peptidoglycan layer, which can partially restrict the diffusion of nanoparticles and Ag^+ ions into the cell. In contrast, Gram-positive bacteria lack an outer membrane, and their thick peptidoglycan layer allows for direct interaction with silver nanoparticles. The higher S. aureus inhibition observed in our study suggests that the surface chemistry and dispersion properties of the m-AgNPs used interact more effectively with the Gram-positive cell surface (Tripathi & Goshisht, 2022).

The increase in antibacterial performance is consistent with previous characterization results. ATR-FTIR analyses revealed an increase in surface hydroxyl groups after HNO_3 modification, while DLS analyses showed lower PDI values and higher absolute zeta potential. These findings indicate that the m-AgNPs are more homogeneously distributed within the starch matrix and exhibit a reduced tendency towards agglomeration. Homogeneous distribution increased the active nanoparticle surface area, enhancing the likelihood of contact with microorganisms and thus contributing to improved antibacterial efficacy.

The antimicrobial effect of silver nanoparticles is explained by complementary mechanisms such as disruption of cell membrane permeability, triggering of reactive oxygen species (ROS) formation, inactivation of intracellular proteins and enzymes, suppression of DNA replication, and controlled release of Ag^+ ions. Increasing the nanoparticle concentration increased the

active contact surface area and the amount of released Ag^+ ions, promoting the growth of inhibition zones.

The results obtained are consistent with the concentration-dependent antibacterial behavior reported in the literature for silver nanoparticles used in starch and other polysaccharide matrices. Previous studies have also reported that surface-functionalized AgNPs, in particular, enhance antibacterial efficacy by providing higher colloidal stability and more homogeneous dispersion compared to unmodified nanoparticles. The starch/m-AgNP coating system developed in this study demonstrated effective antibacterial activity even at low nanoparticle loadings, and the formulation containing 5% m-AgNP exhibited the highest performance against both bacterial species, revealing it as a promising alternative for environmentally friendly active coating systems that can be used in food packaging (Yoksan & Chirachanchai, 2010; Rhim, Park & Ha, 2013).

4. Conclusions

In this study, starch-based antibacterial coatings enhanced with surface-modified silver nanoparticles were successfully developed and homogeneously applied to paper-based packaging surfaces. Surface modification significantly increased antibacterial efficacy by improving the colloidal stability and dispersion of nanoparticles within the starch matrix. In particular, the coating containing 5% m-AgNP showed the highest inhibition performance against both Escherichia coli and Staphylococcus aureus. The findings demonstrate that the developed bio-based coating system is a promising alternative for active food packaging due to its potential to reduce microbial contamination. With its simple production method, use of renewable raw materials, and scalable structure, this approach offers a significant alternative that can contribute to the development of sustainable and high-performance next-generation active packaging technologies.

5. Acknowledgments

This study was supported by Marmara University, Commission of Scientific Research Project (M.U. BAPKO) under project FBA-2025-11702.

6. References

Abreu, A.S., Oliveira, M., de Sá, A., Rodrigues, R.M., Cerqueira, M.A., Vicente, A.A. and Machado, A.V. (2015) 'Antimicrobial nanostructured starch based films for packaging', *Carbohydrate Polymers*, 129, pp. 127–134. DOI: 10.1016/j.carbpol.2015.04.021

Agnihotri, S., Mukherji, S. and Mukherji, S. (2013) 'Size-controlled silver nanoparticles synthesized over the range 5–100 nm using the same protocol and their antibacterial efficacy', *RSC Advances*, 4(8), pp. 3974–3983. DOI: 10.1039/c3ra44507k

Aloui, H., Khwaldia, K., Slama, M.B. and Hamdi, M. (2011) 'Effect of glycerol and coating weight on functional properties of biopolymer-coated paper', *Carbohydrate Polymers*, 86(2), pp. 1063–1072. DOI: 10.1016/j.carbpol.2011.06.026

Badawy, A.M.E., Luxton, T.P., Silva, R.G., Scheckel, K.G., Suidan, M.T. and Tolaymat, T.M. (2010) 'Impact of environmental conditions (pH, ionic strength, and electrolyte type) on the surface charge and aggregation of silver nanoparticles suspensions', *Environmental Science & Technology*, 44(4), pp. 1260–1266. DOI: 10.1021/es902240k

Boukraâ, L. and Amara, K. (2008) 'Synergistic effect of starch on the antibacterial activity of honey', *Journal of Medicinal Food*, 11(1), pp. 195–198. DOI: 10.1089/jmf.2007.502

Cerqueira, M.A., Vicente, A.A. and Pastrana, L.M. (2018) 'Nanotechnology in food packaging: opportunities and challenges', *Nanomaterials for Food Packaging*, pp. 1–11. DOI: 10.1016/B978-0-323-51271-8.00001-2

Danaei, M., Dehghankhold, M., Ataei, S., Hasanzadeh Davarani, F., Javanmard, R., Dokhani, A., Khorasani, S. and Mozafari, M.R. (2018) 'Impact of particle size and polydispersity index on the clinical applications of lipidic nanocarrier systems', *Pharmaceutics*, 10(2), 57. DOI: 10.3390/pharmaceutics10020057

De Plano, L.M., Morganti, D., Nicotra, G., Calorenni, P., Sciuto, E.L., Oddo, S. and Conoci, S. (2025) 'Engineered phage-silver nanoparticle complexes as a new tool for targeted therapies', *Scientific Reports*, 15(1), 36135. DOI: 10.1038/s41598-025-05069-y

del Rosario Herrera-Rivera, M., Torres-Arellanes, S.P., Cortés-Martínez, C.I., Navarro-Ibarra, D.C., Hernández-Sánchez, L., Solis-Pomar, F., Pérez-Tijerina, E. and Román-Doval, R. (2024) '*Nanotechnology in food packaging materials: role and application of nanoparticles*', RSC Advances, 14(30), pp. 21832–21858. DOI: 10.1039/D4RA03711A

El Hotaby, W., Sherif, H., Hemdan, B., Khalil, W. and Khalil, S. (2017) 'Assessment of in situ-prepared polyvinylpyrrolidone-silver nanocomposite for antimicrobial applications', *Acta Physica Polonica A*, 131(6), pp. 1554–1560. DOI: 10.12693/APhysPolA.131.1554

El-Lakany, S.A., Elgindy, N.A., Kamoun, E.A., Masanga, P.M., El-Moslamy, S.H., Abu-Serie, M., Aly, R.G. and Abo Aasy, N.K. (2026) 'Phyto-assisted synthesized CuO NPs embedded in crosslinked zein/alginate composite films for hastening wound healing and tissue regeneration in rats bio-template', *Drug Delivery and Translational Research*, 16(5), pp. 1388–1405. DOI: 10.1007/s13346-025-01948-z

Fahmy, H.M., Salah Eldin, R.E., Abu Serea, E.S., Gomaa, N.M., AboElmagd, G.M., Salem, S.A., Elsayed, Z.A., Edrees, A., Shams-Eldin, E. and Shalan, A.E. (2020) '*Advances in nanotechnology and antibacterial properties of biodegradable food packaging materials*', RSC Advances, 10(35), pp. 20467–20484. DOI: 10.1039/D0RA02922J

Gontijo, L.A.P., Raphael, E., Ferrari, D.P.S., Ferrari, J.L., Lyon, J.P. and Schiavon, M.A. (2020) 'pH effect on the synthesis of different size silver nanoparticles evaluated by DLS and their size-dependent antimicrobial activity', *Matéria (Rio de Janeiro)*, 25(04), e-12845. DOI: 10.1590/S1517-707620200004.1145

Huang, B., Liu, G., Wang, P., Zhao, X. and Xu, H. (2019) 'Effect of nitric acid modification on characteristics and adsorption properties of lignite', *Processes*, 7(3), 167. DOI: 10.3390/pr7030167

Kansal, D., Hamdani, S.S., Ping, R., Sirinakbumrung, N. and Rabnawaz, M. (2020) 'Food-safe chitosan–zein dual-layer coating for water-and oil-repellent paper substrates', *ACS Sustainable Chemistry & Engineering*, 8(17), pp. 6887–6897. DOI: 10.1021/acssuschemeng.0c02216

Kawashita, M., Tsuneyama, S., Miyaji, F., Kokubo, T., Kozuka, H. and Yamamoto, K. (2000) 'Antibacterial silver-containing silica glass prepared by sol–gel method', *Biomaterials*, 21(4), pp. 393–398. DOI: 10.1016/S0142-9612(99)00201-X

Kunam, P.K., Ramakanth, D., Akhila, K. and Gaikwad, K.K. (2024) 'Bio-based materials for barrier coatings on paper packaging', *Biomass Conversion and Biorefinery*, 14(12), pp. 12637–12652. DOI: 10.1007/s13399-022-03241-2

Lestari, D.Y., Syoufian, A., Hariani, P.L., Saviola, A.J., Oh, W.-C., Amin, A.K., Pratika, R.A. and Wijaya, K. (2025) 'Facile green synthesis of silver nanoparticles decorated on sulfonated graphene oxide by rambutan (Nephelium lappaceum) leaf extract and application as a catalyst for converting benzene into nitrobenzene', *Results in Engineering*, 25, 104321. DOI: 10.1016/j.rineng.2025.104321

Li, B. and Li, K. (2019) 'Effect of nitric acid pre-oxidation concentration on pore structure and nitrogen/oxygen active decoration sites of ethylenediamine-modified biochar for mercury (II) adsorption and the possible mechanism', *Chemosphere*, 220, pp. 28–39. DOI: 10.1016/j.chemosphere.2018.12.099

Mohammad, A.W., Lau, C.H., Zaharim, A. and Omar, M.Z. (2012) 'Elements of nanotechnology education in engineering curriculum worldwide', *Procedia-Social and Behavioral Sciences*, 60, pp. 405–412. DOI: 10.1016/j.sbspro.2012.09.398

Mohammadi, M., Ishak, M.R. and Sultan, M.T.H. (2024) 'Exploring chemical and physical advancements in surface modification techniques of natural fiber reinforced composite: a comprehensive review', *Journal of Natural Fibers*, 21(1), 2408633. DOI: 10.1080/15440478.2024.2408633

Ozcan, A., Tozluoglu, A., Arman Kandirmaz, E., Tutus, A. and Fidan, H. (2021) 'Printability of variative nanocellulose derived papers', *Cellulose*, 28(8), pp. 5019–5031. DOI: 10.1007/s10570-021-03861-3

Pasieczna-Patkowska, S., Cichy, M. and Flieger, J. (2025) 'Application of Fourier transform infrared (FTIR) spectroscopy in characterization of green synthesized nanoparticles', *Molecules*, 30(3), 684. DOI: 10.3390/molecules30030684

Polte, J., Tuaev, X., Wuithschick, M., Fischer, A., Thuenemann, A.F., Rademann, K., Kraehnert, R. and Emmerling, F. (2012) 'Formation mechanism of colloidal silver nanoparticles: analogies and differences to the growth of gold nanoparticles', *ACS Nano*, 6(7), pp. 5791–5802. DOI: 10.1021/nn301724z

Rhim, J.W., Park, H.M. and Ha, C.S. (2013) 'Bio-nanocomposites for food packaging applications', *Progress in Polymer Science*, 38(10–11), pp. 1629–1652. DOI: 10.1016/j.progpolymsci.2013.05.008

Rudra, S.G., Singh, V., Jyoti, S.D. and Shivhare, U.S. (2013) 'Mechanical properties and antimicrobial efficacy of active wrapping paper for primary packaging of fruits', *Food Bioscience*, 3, pp. 49–58. DOI: 10.1016/j.fbio.2013.07.002

Schnettler, B., Crisóstomo, G., Mora, M., Lobos, G., Miranda, H. and Grunert, K.G. (2014) 'Acceptance of nanotechnology applications and satisfaction with food-related life in southern Chile', *Food Science and Technology*, 34, pp. 157–163. DOI: 10.1590/S0101-20612014005000001

Sekhon, B.S. (2010) 'Food nanotechnology–an overview', *Nanotechnology, Science and Applications*, pp. 1–15. DOI: 10.2147/nsa.s12187498

Srikhao, N., Ounkaew, A., Srichiangsa, N., Phanthanawiboon, S., Boonmars, T., Artchayasawat, A., Theerakulpisut, S., Okhawilai, M. and Kasemsiri, P. (2023) 'Green-synthesized silver nanoparticle coating on paper for antibacterial and antiviral applications', *Polymer Bulletin*, 80(9), pp. 9651–9668. DOI: 10.1007/s00289-022-04530-6

Tripathi, N. and Goshisht, M.K. (2022) 'Recent advances and mechanistic insights into antibacterial activity, antibiofilm activity, and cytotoxicity of silver nanoparticles', *ACS Applied Bio Materials*, 5(4), pp. 1391–1463. DOI: 10.1021/acsabm.2c00014

Upadhyay, A., Agbesi, P., Arafat, K.M.Y., Urdaneta, F., Dey, M., Basak, M., Hong, S., Umeileka, C. and Argyropoulos, D. (2024) 'Bio-based smart packaging: Fundamentals and functions in sustainable food systems', *Trends in Food Science & Technology*, 145, 104369. DOI: 10.1016/j.tifs.2024.104369

Yoksan, R. and Chirachanchai, S. (2010) 'Silver nanoparticle-loaded chitosan–starch based films: Fabrication and evaluation of tensile, barrier and antimicrobial properties', *Materials Science and Engineering: C*, 30(6), pp. 891–897. DOI: 10.1016/j.msec.2010.04.004

Yue, C., Wang, M., Zhou, Z., You, Y., Wang, G. and Wu, D. (2024) 'Cellulose-based intelligent packaging films with antibacterial, UV-blocking, and biodegradable properties for shrimp freshness monitoring', *Chemical Engineering Journal*, 488, 150975. DOI: 10.1016/j.cej.2024.150975



© 2026 Authors. Published by the University of Novi Sad, Faculty of Technical Sciences, Department of Graphic Engineering and Design. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license 4.0 Serbia (http://creativecommons.org/licenses/by/4.0/rs/).