Antibacterial Performance of Biodegradable Polymer and Hazelnut Husk Flour Antibacterial Biofilm with Silver Nanoparticles

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The antibacterial performance of biocomposite films prepared from lignocellulosic waste (hazelnut husk or hazelnut leafy green cover) modified with silver nanoparticles and polylactic acid (PLA) was determined. The amount of hazelnut husk in the PLA matrix ranged from 10 to 40% by weight in 10% increments. The composite pellets were produced using a twin-screw extruder. Biocomposite films of 0.6 mm x 40 mm x 200 mm were produced from the pellets in a laboratory hydraulic hot press. The surfaces of the modified hazelnut husk and biocomposite specimens were analyzed by scanning electron microscopy (SEM) and inductively coupled plasma optical emission spectrometry (ICP-OES). The antibacterial activity of the biocomposite films against *Staphylococcus aureus* bacteria was determined using the ASTM E 2149 (2020) method. The antibacterial activity of the biocomposite films increased noticeably with the addition of hazelnut husk modified with the silver nanoparticles. Compared to the pure PLA film, the biocomposite films with 10 wt% modified husk flour showed the lowest antibacterial activity (31.3%) against *S. aureus* over 24-h while the films with 40 wt% showed the highest antibacterial activity (99.9%). The biocomposite films made of hazelnut husk flour with silver nanoparticles and PLA matrix could be considered for food packaging applications.

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INTRODUCTION

The use of renewable resources is increasing continually and is an important factor in reducing environmental problems. To this end, the effective utilisation of agricultural waste is of great importance. Multiple problems, such as increasing environmental pollution, uncertainty of fossil fuel reserves, changing raw material costs, and fossil energy crises between countries, have led to research activities for alternatives to fossil fuels (Mohite *et al.* 2022). Lignocellulosic materials stand out among the abundant, easily accessible, renewable, and inexpensive biological resources found in nature that are the subject of much research today.

Agricultural residues come mainly from crop residues, such as straw and processing residues such as husks and cobs. They are usually destroyed or used as animal feed. These wastes should be considered as a large potential source for biomass utilisation. Effective utilisation of agricultural wastes is important to prevent environmental pollution, to produce different raw materials (starch, cellulose, lignin, *etc.*), value-added products such as biocomposites, and biomass for energy production (Özgüven *et al.* 2020). Hazelnut (*Corylus avellana* L.) is a popular nut worldwide due to its unique properties, such as its ability to consolidate soil and minimise erosion, as well as the quality of its hard-shelled fruits (Poșta *et al.* 2022). After almonds, hazelnuts are the most widely grown hard-shelled fruit in the world (TUIK 2023). Based on the data obtained from the FAO (Food and Agriculture Organization of the United Nations), world hazelnut (in shell) production, has been increasing since 1961 and is expected to reach 1,196,000 tonnes in 2022 (FaoStat 2024). Türkiye, with around 70% by weight, is the country with the largest share of hazelnut production in Asia, followed by Italy, USA, and Azerbaijan. Hazelnut (in shell) production, in Türkiye will be 765,000 tonnes in 2021, with a projected increase of around 29% in 2022 (FaoStat 2024). The north-east of Türkiye (Black Sea coast) is a natural habitat for hazelnut cultivation due to its humid temperate climate and annual rainfall variations. In addition to the Black Sea region, hazelnut cultivation is also practiced in the Eastern Marmara sub-region of Türkiye (An *et al.* 2020).

Table 1. Lignocellulosic Components of Hazelnut Husk (Guney 2013)

Component	Content (% weight)
Holocellulose	55.1
α-cellulose	34.5
Lignin	35.1
Ash	8.22

After harvesting hazelnuts, the shell, husk (hazelnut leafy green cover), and leaves are obtained by roasting, crushing, and peeling (Shahidi *et al.* 2007). As shown in Fig. 1, hazelnut husk, a by-product of hazelnut husk processing, is removed from hazelnuts shortly after harvest and has no economical value. It is composted and used as fertiliser for hazelnut trees or burned (Alasalvar *et al.* 2006). After harvesting, 1 kg of fresh hazelnuts yields 1/3 of dry shelled hazelnuts and 1/5 of hazelnut husk (Ekbic *et al.* 2022). In this case, 215,000 tons of hazelnut husk waste were generated worldwide in 2021 alone, with 137,000 tons in Türkiye (FAO 2021). Converting this waste into high value-added composite materials, such as sustainable filler for biocomposite films, is of great importance to meet the growing demand for renewable resources. The lignocellulosic components of the hazelnut husk are given in Table 1. It has a higher content lignin in comparison to wood.

Fig. 1. The appearance of hazelnut husk (hazelnut leafy green cover).

Growing environmental concerns, rising fossil fuel prices, dwindling fossil fuel supplies, and problems with production processes have led to the widespread use of biopolymers in developing technologies. Among bioplastics, poly(lactic acid) (PLA) has recently become the most widely used bioplastic because it can be biologically produced from the fermented starch of organic renewable resources such as corn and sugar cane (Özdemir *et al.* 2022). PLA is environmentally friendly and has good tensile properties (Yurttas *et al.* 2023). Biocomposites made with a PLA matrix and lignocellulosic fibres offer environmental benefits in terms of sustainability. The lignocellulosic fibres increase the stiffness of PLA and reduce its price (Siakeng *et al.* 2018).

Packaging of foods is a key factor in protecting them from external influences and ensuring food safety. However, conventional non-biodegradable packaging materials are made from petroleum polymers, which are responsible for serious environmental pollution (Kraśniewska *et al.* 2020). The food industry uses a variety of packaging materials such as plastic and cardboard. Plastics used for food packaging make up a large proportion of plastic waste, causing environmental pollution with devastating effects on humans and aquatic animals.

Food coatings offer many packaging benefits when used in the food industry. Biodegradable materials are designed not only to protect the food from the hazards to which it is exposed. The impact of packaging on the environment and the product, which is necessary to store products under different conditions, is of great importance (Ncube *et al.* 2020). In addition, in food processing and preparation facilities, the material surfaces of food packaging are ideal for attachment of *Staphylococcus aureus* and many other bacteria, as well as for colonisation by biofilm-forming strains. The widespread presence of *S. aureus* in food and food service establishments, food production, hospital staff, and hospital environments is an important public health issue. *S. aureus* is the most important pathogenic bacterium. It can cause a wide range of infections in both humans and animals. It is extremely resistant to environmental conditions and is often found in environmental sources that grow in food and can cause food poisoning with the toxins they produce.

Virulence characteristics, such as the ability to form biofilms and develop resistance to antibiotics and disinfectants, make *S. aureus* a priority pathogen (Sudağıdan and Aydın 2013; Erkmen 2021; Narayanan *et al.* 2021).

Silver has been one of the preferred alternative treatments for various ailments for centuries. Silver is a broad-spectrum antibiotic. After treatment, the bacteria remain weak and do not show aclimation to silver. Altaş *et al.* (2012) studied the shelf life of sardine fillets packed with food pads containing silver fibres. Due to its unique properties and broad spectrum of effects, such as antibacterial, antifungal, and antiviral effects, silver is of particular interest as an antimicrobial agent. Because of the increasing ineffectiveness of conventional antibiotics, silver nanoparticles (AgNPs) have recently received increasing attention for their potential antimicrobial effects and applications (Sudhakar *et al.* 2015; Can *et al.* 2019; Nwabor *et al.* 2020, 2021a, 2021b). Turalija *et al.* (2016) observed an increase in hydrophilicity and a notable enhancement in the antimicrobial properties of PLA-based films with silver. Additionally, PLA/30 wt% flax fibre composites with different additives, such as kraft lignin, have been the subject of investigation. According to the findings of the investigation by Khan *et al.* (2016), the antibacterial activity of the PLA filled with hemp hurd was found to be significantly enhanced, with a notable reduction in bacterial growth observed at silver nanoparticle concentrations of 0.025 wt % and 0.05 wt %. The antibacterial efficacy was evidenced by a 85% and 89% decline in bacterial growth, respectively. Yurttas *et al.* (2023) reported that PLA composites containing wood flour modified with silver nanoparticles showed antibacterial activity against *E. coli* (99.61%) and *S. aureus* (99.97). They concluded that the obtained biocomposites could be considered for biomedical and food industry applications.

Several mechanisms have been proposed for the antibacterial effects of silver nanoparticles. Positively charged Ag^+ can easily interact with negatively charged cell membranes, enhancing antibacterial properties (Al-Tayyar *et al.* 2020). Silver ions interact with proteins in thiol groups (-SH), inactivating them and replacing them with hydrogen cations, thereby reducing membrane permeability (deactivation). In a bacterial cell exposed to silver, a gap develops between the cell membrane and the cytoplasm, causing the cell to die. In the micromolar range, silver ions disrupt the electron transport system during oxidative phosphorylation by impairing membrane permeability to protons and phosphates or by inactivating enzymes in the respiratory chain. Silver nanoparticles disrupt the bacterial membrane, increase intracellular potassium loss, and reduce adenosine triphosphate (ATP), resulting in loss of cell viability (Feng *et al.* 2000; Durán *et al.* 2010).

Based on an extensive review of the literature review, the mechanical and thermal properties of the PLA composite films filled with hazelnut husk flour were investigated by Özdemir *et al.* (2022). They reported that the thermal stability of the PLA composite films was enhanced with increasing content of the hazelnut husk flour while the tensile strength decreased. The incorporation of the compatibilizers into the composition may improve the tensile properties of the biocomposite films. In the present study, to impart an antibacterial effect to the biocomposite film, the surface of the hazelnut husk flour was modified with silver nanoparticles. Gram-positive *Staphylococcus aureus* (*S. aureus*) (ATCC 6538) was selected as the bacterial strain. It is an important foodborne pathogen. Foods that are not produced and stored under hygienic conditions and that are left unpackaged in the open air pose a potential risk of staphylococcal poisoning. To preserve the nutritional value and shelf life of these products, antimicrobial films and coatings are offered as an alternative method of protecting the quality of the products. The antibacterial performance of the biocomposite films was investigated under laboratory conditions. The use of the hazelnut husk flour in the PLA film could play an important role in the use of hazelnut husk in high-value added biocomposites.

EXPERIMENTAL

Preparation of Hazelnut Husk Flour

Hazelnuts were collected in Temelli village, Maçka district, Trabzon city, Türkiye. During the hazelnut harvest, the hazelnut husk covering the hazelnut was manually removed from the hazelnuts after harvesting. The collected hazelnut husk was subjected to natural drying in the sun at 20 to 25 °C for 3 days to prevent rotting and other decomposition during storage. After drying in the sun, the hazelnut husk turns brown and begins to crumble easily. It was pre-dried in a drying oven (model: Binder ED 720, Binder GmbH, Tuttlingen, Germany) at 80 °C for 2 to 3 h to reduce the moisture content to below 3%. The dried particles of hazelnut husk were ground into flour using a hammer mill (Model: LB-160, Mertest company, Eskişehir city, Türkiye). The flour was sieved with a vibrating sieve (model: AEK30S, Akyol Company, İstanbul, Türkiye) for 10 min. The hazelnut husk flour passing through a sieve with openings of 100 microns was dried in a oven with fan at 90 °C until the moisture content of the flour was reduced to 1%.

The melting point, density, and melt flow index of the matrix component PLA polymer (code: Ingeo 2003D, Resinex™ Company, Slovenia) were 146 to 160 ºC, 124 g/cm^3, and 6 (10 min/216 kg), respectively. Silver nitrate ($AgNO_3$) specimen (ACS activation > 990%) was obtained from Sigma-Aldrich® in St. Louis, MO, USA.

Preparation of Hazelnut Husk Flour

The modification process of the hazelnut husk flour is illustrated in Fig. 2.

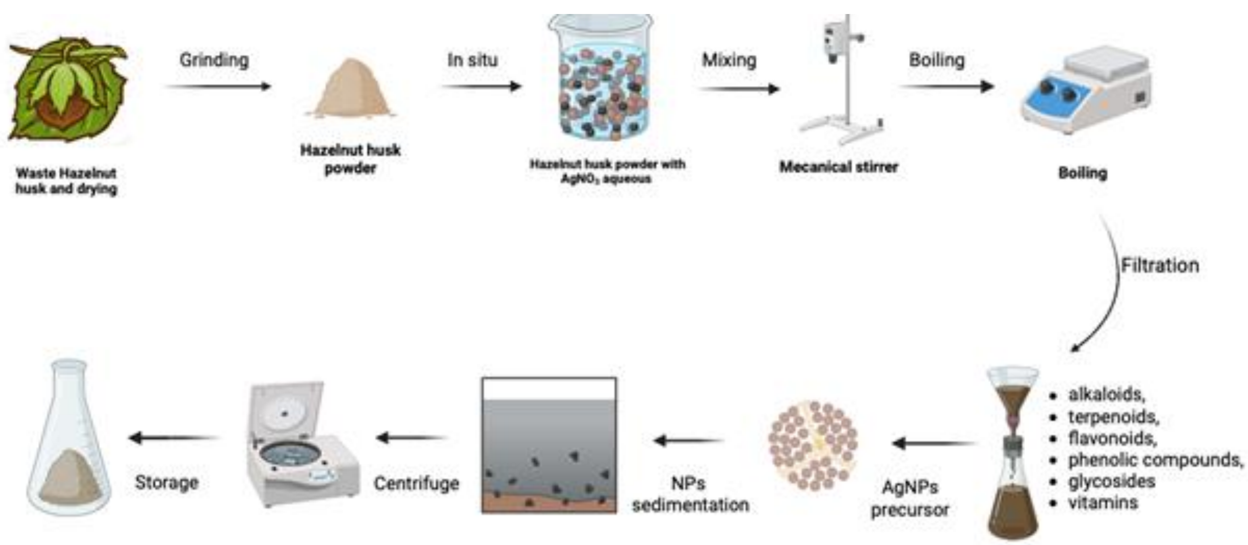
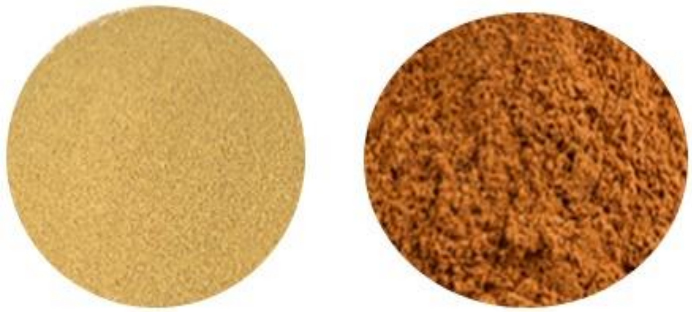


Fig. 2. The modification process of hazelnut husk flour with silver nanoparticles (AgNPs)

Aqueous $AgNO_3$ solution was prepared at a concentration of 5 mM. Exactly 0.4246 g of $AgNO_3$ salt was dissolved in 500 mL of deionized water to prepare a 1 molar solution. Hazelnut husk flour was immersed in concentrated solution in a beaker and mixed with a magnetic stirrer at 80 °C and 500 rpm for 24-h. The hazelnut husk were then centrifuged several times with deionized water. This thoroughly removed any remaining silver nanoparticles (10000 rpm, 20 min). After centrifugation, the flour was dried for 24-h at 80 °C. The dried and lumpy flour was re-ground and sifted. The hazelnut husk flour was dried at 90 °C to reduce its moisture content to less than 1%. The appearance of the unmodified and modified hazelnut shells is shown in Fig. 3.



a. **b.**

Fig. 3. a: Unmodified hazelnut husk flour; b: Modified hazelnut husk flour

Production of Extruded Compounds and Biocomposite Films

The manufacturing compositions of the PLA/modified hazelnut husk flour biocomposite films are shown in Table 2. First, the composite pellets were prepared from the premixed PLA and hazelnut husk flour using a 20-mm co-rotating twin-screw laboratory scale extruder (model; Microlab Twin-Screw Rondol Company, Staffordshire, UK). The temperature between the extruder sections was 125 to 140 °C, the pressure was 45 bar, and the screw speed was 60 rpm. The average residence time of the compound in the extruder was 3 min. The filaments exiting the extruder die were air cooled and then the pellets were obtained using a pelletiser.

Table 2. Experimental Design

Specimen Code	Raw Materials in Biocomposite Film	
	Modified Hazelnut Husk (wt%)	PLA (% Weight)
PLA	-	100
MHH-10	10	90
MHH-20	20	80
MHH-30	30	70
MHH-40	40	60

Biocomposite films with dimensions of 0.6 mm x 40 mm x 200 mm were produced in a hydraulic laboratory hot press (model: RTX-Px, Kökbir company, Kirklareli, Türkiye) with water cooling. The pellets were put in the mould (by weight %) prepared from the Teflon tape were preheated at 180 °C for 75 min in the hot press. The pellets were then subjected to the main pressure of 10 MPa for 10 min. After hot pressing, the cooling process was carried out for 15 min with a cold water system to ensure homogeneous cooling of the material surface. The produced biocomposite film specimens had the dimensions of 0.6 mm (thickness) × 40 mm × 200 mm. The resulting biocomposite films were conditioned at 20 °C and 50% relative humidity until they reached constant weight as defined in ISO 291 (2008).

ICP-OES Analysis of Modified Hazelnut Husk

The biocomposite films were cut into small specimens of approximately 1 g and then placed in another tube. The specimens were microwaved and analysed by ICP-OES (inductively coupled plasma optical emission spectroscopy) (Model: Optima 2100 DV, Perkin Elmer Inc, MA, USA). The 1 g of specimens were digested using HNO_3/HCl in the microwave apparatus. A total of 3 mL of 65% HNO_3 and 1 mL of HCl at a concentration of 30% were added to the system. After microwave digestion, the solutions were made up to 50 mL with deionised water and applied to the ICP-OES instrument. Formulation and % silver ion calculations were determined with the results of the ICP-OES instrument according to the following Eq. 1:

$$Metal\ oxide(\%) = \frac{Measured\ value\ (ppm) \times Conversion\ factor}{Amount\ weighed\ (g)} \tag{1}$$

Determination of Antibacterial Activity of Composite Films

The level of antibacterial activity was quantitatively determined by the number of microorganisms living in the solution according to the antibacterial test method ASTM E 2149 (2020). The extent of change in bacterial counts after 24-h in specimens inoculated with the same number of bacteria was calculated as a percentage. This shaking method is a quantitative test method for a non-releasing antibiotic in a bacterial suspension under dynamic contact conditions. The method is often used to determine the antibacterial activity of porous or nonporous materials.

The specimens to be tested and the antibacterial untreated control specimen (PLA) were weighed 1 g and placed in 50 mL of sterile ASTM buffer test solution. *S. aureus* bacterial solution was then prepared at 25 x 10^5 cfu/mL (25 colonies in 10^5 dilution) and 0.5 mL of bacteria was incorporated to each buffer and incubated with shaking at 37 °C for 24-h. When the incubation was completed, 1 mL of each buffer was diluted (Fig. 4), and 0.1 mL spread was plated on the TSA (Tryptone Soy Agar Neogen® Culture Media) surface and incubated for 24-h at 37 °C. After thin-cubation which was the process of keeping microorganisms at a temperature and time that allows them to reproduce, the bacterial colonies were counted immediately after the inoculation which was the time after the microbial concentration obtained from the bacterial suspension added to 50 mL ASTM buffer jars. Then this jar was left for the incubation for 24-h, the number of bacteria was checked during the incubation period. The bacterial reduction (or the logarithmic reduction) between two values was calculated using the following Eq. 2 as per ASTM E2149 (2020).

$$Antibacterial\ activity\ (\%) = [(A - B) / A] \times 100 \tag{2}$$

In Eq. 2, *A* is the 0 number of bacteria from test specimens at the time of contact and *B* is the number of bacteria (colony count) from 24-h incubated test specimens.

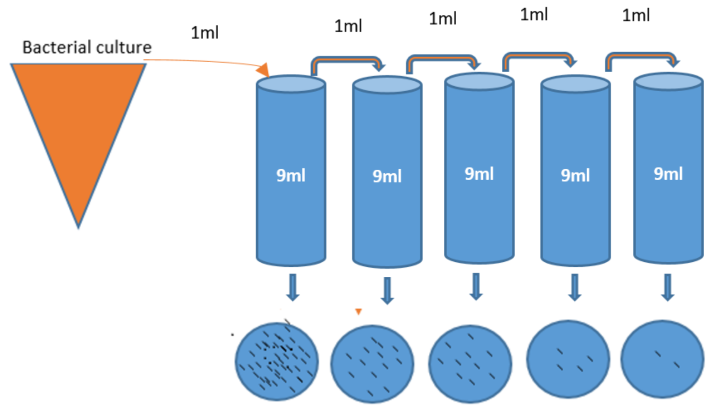


Fig. 4. Dilution of the bacterial concentration done with the physiological saline solution

Morphological Analysis

Scanning electron microscopy (SEM) micrographs of the gold-coated biocomposite film specimens were observed to understand the distribution of modified hazelnut husk in the PLA matrix. The SEM micrographs were taken using a JEOL JCM-5000 NeoScope. The SEM with an accelerating voltage of 10 kV Fractured surfaces were created on the specimens to obtain better images.

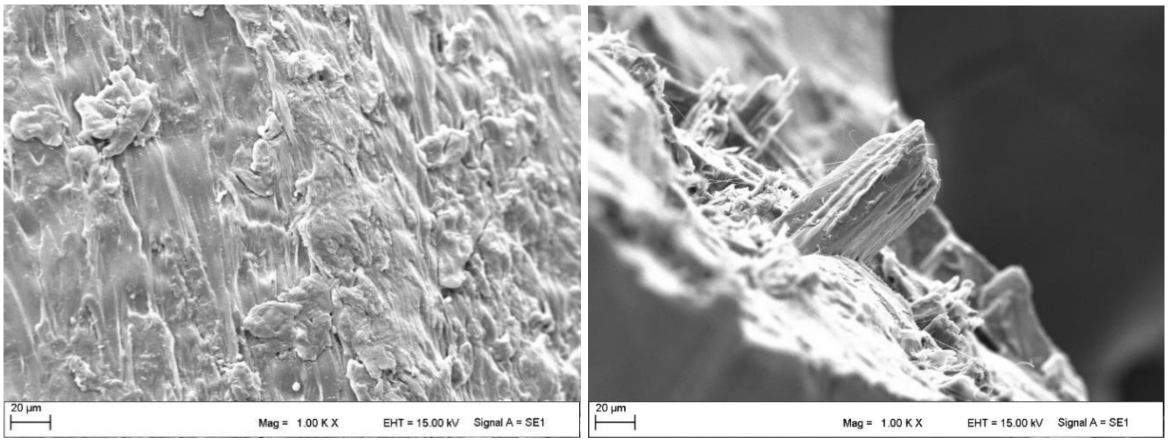
RESULTS AND DISCUSSION

ICP-OES Analysis of Modified Hazelnut Husk Flour

Hazelnut husk flour showed a clear colour change due to the aqueous silver nitrate solution (Fig. 3b). According to the results of the ICP-OES analysis, the concentration of the silver nanoparticles was 3716.7 mg/kg. This result showed that the hazelnut shell particles have the potential to absorb the silver ions. The reason can be partly attributed to the chemical and phenolic structure of the hazelnut husk. Guney (2013) reported that hazelnut husk is a good source of total phenolics because the phenolic contents ranged from 2.5 to 30.5 g/kg. Hazelnut husk, a by-product of harvesting hazelnuts, are a potential source of natural antioxidants (Oliveira *et al.* 2007; Guney 2013). In a previous study, it was reported that 551% of silver ions were bound to hydroxyl groups in the amorphous region of hemicellulose and cellulose, especially holocellulose (Cai *et al.* 2009).

A total of 11 phenolic substances have been identified in hazelnut husk and grouped into five main classes by Cabo *et al.* (2021): benzoic acids (gallic acid, vanillic acid, and protocatechuic acid), ellagitannin (ellagic acid), flavonols (kaempferol-O-[acetic acid]-3-hydroxymethyl), (kaempferol-3-O-[6-acetylglucoside]-7-O-rhamnoside, kaempferol-3,7-O-diglucoside, kaempferol-3-O-[6-acetylglucoside]-7-O-glucoside, and quercetin-3-O-rutinoside), flavan-3-ol (epicatechin), and flavone (luteolin-7-O-rutinoside). Guo *et al.* (2008) reported that the adsorption behaviour of metal ions on phenolic sites was observed in a reasonable manner, indicating that phenolic sites have an affinity for metal ions.

The binding of metal ions to cellulose fibres is usually weak due to interactions between the electrostatic van der Waals attractions between metal ions and the dipole moments of the cell wall of the cellulose (de Santa Maria *et al.* 2009; Cabo *et al.* 2021). The weak interaction results in low efficiency and low dispersion of the metal particles on the cellulose fibers (Ifuku *et al.* 2009). A strong bond between silver nanoparticles and hazelnut husk particles is important to prevent leaching of silver nanoparticles through the hazelnut husk network, thereby minimising the potential toxicity of silver nanoparticles. This makes it suitable for use as medical and food packaging (Wu *et al.* 2014). A typical comparison of the neat PLA film and the PLA composite film with 10 wt% modified hazelnut husk flour is presented in Fig. 5. The hazelnut husk particles can be seen in the fracture surfaces of the fractured PLA composite film specimens in Fig. 5-b.



a. b.

Fig. 5. A typical SEM micrographs of the specimens. (a) the neat PLA film. (b) the PLA composite film with 10 wt% modified hazelnut husk flour

Antibacterial Activity of Biocomposite Films

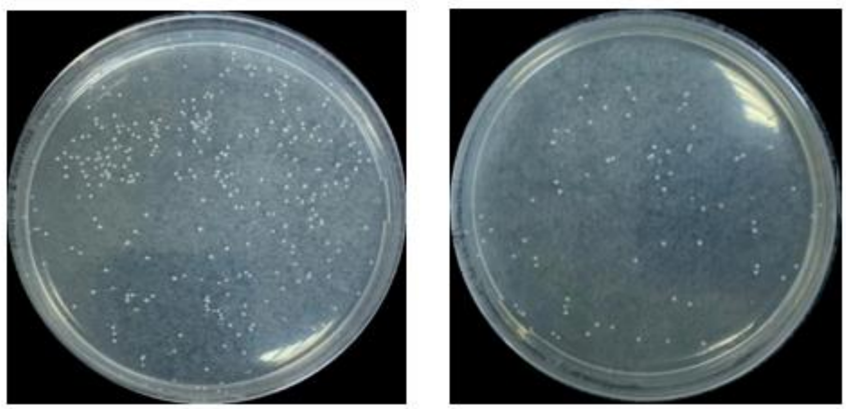
The results of the antibacterial tests of the biocomposite specimens with silver nanoparticles are shown in Table 3.

Table 3. Antibacterial Activity Results of Biocomposite Films

Specimen Code	**Number of Bacteria**	Log (Logarithm of the number of bacteria)	**Antibacterial Activity (%)**
PLA	3.00×10^5	5.48	-
MHH-10	2.06×10^5	5.31	31.33
MHH-20	1.42×10^5	5.15	52.67
MHH-30	8.50×10^4	4.93	71.67
MHH-40	3.60×10^2	2.56	99.88

The PLA control group without silver showed growth in 10^5 dilutions while 10^2 dilutions of the biocomposite specimens containing 40 wt% hazelnut husk with silver nanoparticles showed bacterial growth. When the bacteria grow heavily, dilution is important for counting colonies and colonies are counted at larger dilutions. Therefore, the dilution factor varies according to the density of the bacteria. Compared to the control group, the specimens containing 40 wt% hazelnut husk with silver nanoparticles showed a decrease in the number of bacteria by log 2.56 after 24-h (99.88% antibacterial activity). For the biocomposite specimens containing 30% hazelnut husk with silver nanoparticles, the antibacterial activity was 71.67%. As shown in Table 3, when the amount of modified hazelnut husk in the PLA biocomposite specimens was increased, the antibacterial activity increased in proportion. This is because the silver content increased as the hazelnut husk content increased. Silver ions target cytoplasmic membranes and nucleic acids, suppressing respiratory chain enzymes and altering membrane permeability (Kalwar and Shan 2018; Swolana and Wojtyczka 2022). The silver nanoparticles penetrate into the bacterial cell and alter the different metabolic pathways of the bacteria. It influences DNA replication and protein synthesis; ROS generation occurs due to the oxidative stress. Moreover, eventually, it leads to the cell death (Ferdous and Nemmar 2020; More *et al.* 2023).

Based on the ASTM E2149-20 (2020) standard, a typical comparison of the control PLA film and PLA biocomposite with 40 wt% husk flour against *S. aureus* (ATCC 6538) bacteria in 10^2 dilution petri dish. 10^2 dilution was used as the basis for calculation, as shown in Fig. 6. When the control specimen was counted at 10^5 dilution, no bacterial colonies were observed in the antibacterial specimen when compared at the same dilution. To get accurate results, it is necessary to compare with the lowest dilution at which bacteria can be counted. This approach makes it possible to assess the antibacterial effect more clearly. When the number of bacteria is low, the colonies can be counted at a lower dilution. In the control specimens, there was no antibacterial agent, so the number of bacteria present at time zero increased after incubation; these bacterial colonies can be counted at higher dilutions. In the specimens with antibacterial properties, bacterial growth was reduced by the antibacterial agents so that the number of bacteria was low enough to be counted at lower dilutions.



a. **b.**

Fig. 6. a: *S. aureus* bacteria growing on the PLA 10^3 dilution petri dish. b: *S. aureus* bacteria growing in 10^2 dilution petri dish of biocomposite containing 40 wt% husk flour.

The bacterial cell wall, which contains a broad layer of peptidoglycan compounds, is damaged by silver nanoparticles interacting with these compounds (Hedge *et al.* 2010). In a previous study, it was reported that the antifungal activity of the silver nanoparticles against *C. albanicans* was explained by disrupting the structure of the cell membrane through disrupting the membrane integrity, thereby preventing the budding process (Kim *et al.* 2009). A similar effect was observed for *S. aureus* in the present study. The antibacterial activity was improved by the interaction of the silver nanoparticles with clinical pathogens and the presence of effective functional groups in the nanocomposites. All the biocomposites with silver nanoparticles showed antibacterial activity in both quantitative and qualitative tests. It is known that nucleophilic amino acid residues in proteins attached to sulphhydryl, amino, imidazole, phosphate, and carbonyl groups of membrane or enzyme proteins can react with silver ions (Wangchuk *et al.* 2017; Yurttas *et al.* 2023).

The activity of micro-organisms that contaminate food is affected by antibacterial food packaging (Sung *et al.* 2013). The food-borne pathogens that are a threat to consumer health can be eliminated through improved food safety and a food packaging system that contains biocompatible antimicrobials. Antibacterial packaging inhibits the growth of microbes by prolonging the lag phase, as well it also reduces the number of bacteria by reducing their growth rate. After a certain period of time, it continuously dissolves from the packaging material, resulting in a long shelf life (Malhotra *et al.* 2015). Sağlam and Özüsağlam (2023) investigated the antibacterial activity of methanol-extracted hazelnut husk against Gram-positive *S. aureus* and Gram-negative *Escherichia coli* bacteria. According to their results, hazelnut husk extract showed antibacterial activity against these bacteria. They also stated that hazelnuts with high antibacterial activity and their waste products could be natural antibacterial alternatives to chemicals. Similar antibacterial results have also been observed for extracts of various plants in previous studies (Bahtiyari and Yilmaz 2018; Yılmaz 2020, 2021, 2023; Yılmaz and Bahtiyari 2020).

CONCLUSIONS

1. The poly(lactic acid) (PLA) matrix filled with hazelnut husk particles modified with the silver nanoparticles had good antibacterial performance compared to the unfilled PLA film. When the amount of the modified hazelnut husk flour was increased from 10 to 40 wt% in the PLA matrix, the antibacterial activity increased from 31.3 to 99.9%.
2. The use of the hazelnut husk biomass, which is mostly used as waste/fertilizer, will play an important role as an alternative raw material to expensive natural fibres for biocomposite films. Partial replacement of the relatively expensive PLA polymer with hazelnut husk flour can reduce the production cost of the composite film.
3. The biocomposite films produced could be a good green material for use in areas such as food packaging and biomedical applications. The results of this study contribute to future studies on the conversion of agricultural wastes into value-added products that could enable the production of alternative and environmentally friendly materials.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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