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Silver and Titanium Dioxide Nanoparticle-Loaded Low-Density Polyethylene Films for Antimicrobial Medical-Device Surfaces

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ABSTRACT: Healthcare-associated infections remain a persistent challenge because frequently handled medical-device surfaces can support microbial attachment, persistence and cross-transmission. Low-density polyethylene (LDPE) is widely used in healthcare products because of its processability, chemical resistance and favourable mechanical properties, but it lacks intrinsic antimicrobial activity. This study prepared LDPE films loaded with silver (Ag) and titanium dioxide (TiO_2) nanoparticles, two fillers with complementary bactericidal mechanisms, and evaluated their morphology and antibacterial activity. Films were produced by solvent-assisted dispersion and melt blending of LDPE pellets with Ag nanoparticles formed *in situ* by $NaBH_4$ reduction of $AgNO_3$ and with anatase TiO_2 nanoparticles. Film morphology was examined by scanning electron microscopy (SEM), and antibacterial performance against *Escherichia coli* and *Staphylococcus aureus* was determined by colony-forming unit (CFU) enumeration after 24 h exposure. SEM showed a comparatively smooth surface for unmodified LDPE, whereas Ag/TiO_2-loaded films displayed particulate domains distributed on and within the polymer surface, with minor agglomeration at higher filler loading. The composite film reduced *E. coli* from 1.0×10^6 to 1.2×10^3 CFU/mL (99.88%; ≈2.92-$\log_{10}$ reduction) and *S. aureus* from 1.0×10^6 to 8.5×10^2 CFU/mL (99.91%; ≈3.07-$\log_{10}$ reduction). Ag/TiO_2-loaded LDPE films therefore showed strong antibacterial activity against both Gram-negative and Gram-positive bacteria while retaining a processable film format, supporting their further development as antimicrobial surfaces for healthcare plastic components. Compositional confirmation, replicate antimicrobial testing, durability, silver-release and cytocompatibility studies are required before application.

1. INTRODUCTION

Polyethylene-based materials are widely used in biomedical and healthcare products because they are lightweight, chemically stable, easily processed and generally compatible with several device-manufacturing routes [1]. Despite these advantages, unmodified polyethylene is biologically passive rather than antimicrobial. When used in high-touch or semi-critical environments, polymer surfaces can become contaminated by bacteria, support early adhesion events and contribute to the formation of biofilm-like residues unless cleaning and disinfection are consistently effective [2,3].

The development of antimicrobial polymer nanocomposites is therefore an important materials-engineering route for reducing microbial burden on healthcare-associated surfaces. Metal and metal-oxide nanoparticles are attractive for this purpose because they can be incorporated into a polymer matrix without fundamentally changing the base polymer and because their

antimicrobial mechanisms differ from those of conventional antibiotics [3,13]. Silver nanoparticles are especially relevant because they exhibit broad-spectrum antibacterial activity through oxidative dissolution, Ag^+ release, disruption of bacterial membranes, interactions with sulfur-containing proteins and interference with DNA-associated cellular processes [4,5].

Titanium dioxide (TiO_2) provides a complementary mechanism. Under suitable light exposure, TiO_2 can generate reactive oxygen species such as hydroxyl radicals and superoxide species that damage lipids, proteins and nucleic acids. Photocatalytic TiO_2-containing polymer coatings have previously shown antimicrobial effects on surfaces [6,7]. Ag/TiO_2 combinations are often more effective than TiO_2 alone because Ag can improve charge separation, extend photo-response and add an intrinsic ion-mediated antimicrobial pathway [8,9].

Previous polyethylene-based nanocomposites containing Ag, TiO_2 or Ag/TiO_2 have shown improved antibacterial performance in packaging or surface-coating applications [10,11]. However, translation toward medical-device films requires additional attention to nanoparticle dispersion, polymer processability, mechanical integrity, biocompatibility, sterilization compatibility, ion release and durability during handling [12]. LDPE is particularly suitable for film applications because it is flexible and readily processed, but the antimicrobial filler must be dispersed in a way that maintains film function and minimizes excessive particle agglomeration.

The objective of this work was to prepare Ag/TiO_2-loaded LDPE films by a solvent-assisted melt-blending approach and to evaluate their morphology and antibacterial performance against *E. coli* and *S. aureus* as representative Gram-negative and Gram-positive organisms. SEM was used to assess film morphology and particle distribution, while definitive confirmation of elemental composition and crystal phase by energy-dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD) is identified as a priority for subsequent work.

2. MATERIALS AND METHODS

2.1 Materials

Low-density polyethylene (LDPE) pellets were obtained from SABIC, Saudi Arabia. The polymer had a reported melting point of approximately 115 °C and a density of approximately 0.92 g/cm³. Anatase TiO_2 powder was obtained from Sigma-Aldrich. Methanol (98%) was obtained from Merck and used during solvent-assisted dispersion. Silver nitrate ($AgNO_3$) was used as the Ag precursor, and sodium borohydride ($NaBH_4$) was used as the reducing agent for Ag nanoparticle formation (Figure 1).

2.2 Preparation of Ag/TiO_2-loaded LDPE films

The Ag/TiO_2-LDPE composite films were prepared through a solvent-assisted dispersion and melt-blending route (Figure 1). LDPE pellets were first wetted/dispersed in methanol for approximately 1 h to enhance contact with the nanoparticle-containing suspension. Ag nanoparticles were formed by chemical reduction of $AgNO_3$ using $NaBH_4$. The Ag-containing dispersion was dried for approximately 2 h and mixed with TiO_2 nanoparticles before thermal blending with LDPE at approximately 104 °C for 1 h, close to the LDPE processing range.

The formulation was designed to maintain LDPE as the continuous polymer matrix while introducing Ag and TiO_2 as antimicrobial fillers. The experimental design allowed Ag loading in the range of approximately 1–5 wt.% and TiO_2 loading in the range of approximately 1–10 wt.%, with the antimicrobial particle-containing surface layer in the micrometre range. Because antimicrobial performance and agglomeration are sensitive to filler loading, the results are interpreted in relation to dispersion quality and the observed bacterial reductions rather than as a fully optimized formulation study. The prepared film is shown in Figure 2.

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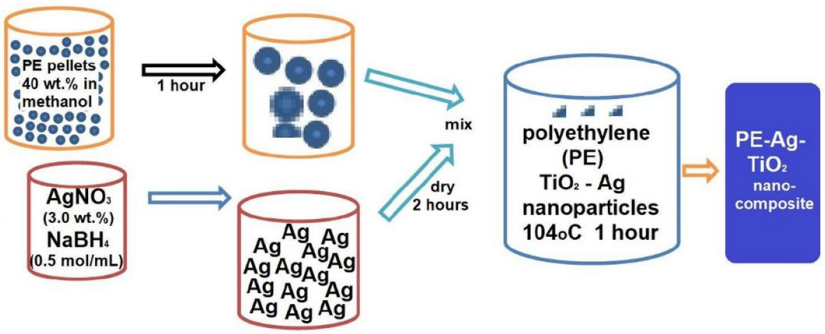


Figure 1. Schematic representation of the solvent-assisted reduction, drying, mixing and melt-blending process used to prepare Ag/TiO_2-loaded LDPE nanocomposite films.



Figure 2. Photograph of the prepared Ag/TiO_2-loaded LDPE film showing the macroscopic film morphology after processing.

2.3 Film morphology and SEM characterization

Film morphology was evaluated by scanning electron microscopy. Samples were mounted and sputter-coated with gold to improve conductivity before imaging. SEM images were used to compare the surface appearance of unmodified LDPE with Ag/TiO_2-loaded LDPE and to assess whether particulate regions were distributed across the polymer surface. SEM was treated as a morphological method only, as it cannot by itself confirm elemental identity or crystal phase.

2.4 Antibacterial testing

Antibacterial activity was evaluated against *Escherichia coli* and *Staphylococcus aureus* as representative Gram-negative and Gram-positive bacteria. Bacterial suspensions with an initial concentration of 1.0×10^6 CFU/mL were exposed to the Ag/TiO_2-LDPE nanocomposite films for 24 h. Surviving bacteria were quantified as CFU/mL, and percentage reduction was calculated relative to the initial bacterial count using Equation (1):

$$\text{Reduction (\%)} = [(\text{initial CFU/mL} - \text{CFU/mL after exposure}) / \text{initial CFU/mL}] \times 100 \qquad (1)$$

2.5 Data analysis

Log reduction was calculated as $\log_{10}$(initial CFU/mL / CFU/mL after exposure). Percentage and log reductions were derived from summary CFU counts and are presented descriptively; inferential statistical testing was not performed.

3. RESULTS AND DISCUSSION

3.1 Morphological observations

The unmodified LDPE film showed a relatively smooth polymer surface, consistent with a non-filled thermoplastic film. After incorporation of Ag/TiO_2 nanoparticles, SEM images showed particulate domains distributed across the film surface (Figures 3 and 4). The observed surface morphology indicates that the preparation route enabled incorporation or surface deposition of

inorganic particles within/on the LDPE matrix. Minor agglomeration was visible, particularly in particulate-rich areas, which is expected when metal/metal-oxide nanoparticles are processed in a hydrophobic polyolefin matrix.

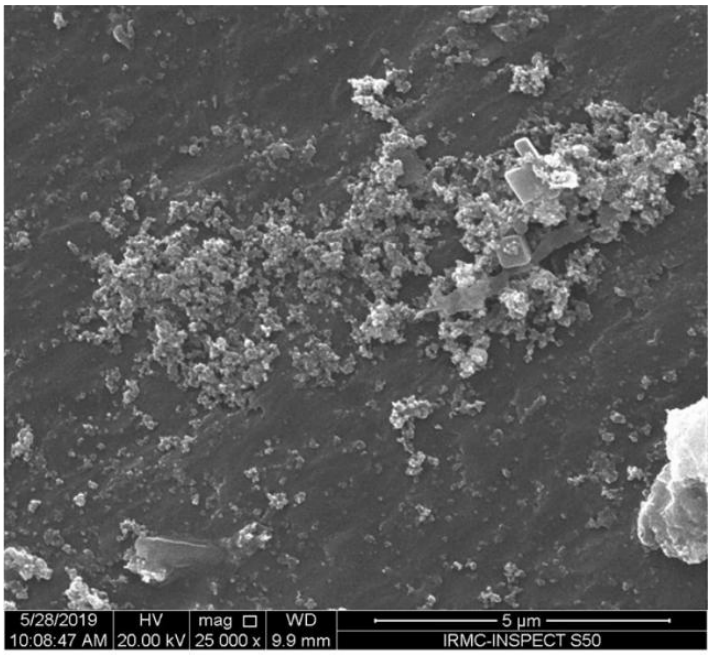


Figure 3. Representative SEM micrograph of Ag/TiO_2-loaded LDPE showing particulate regions distributed on the polymer surface and local agglomeration at the micrometre scale.

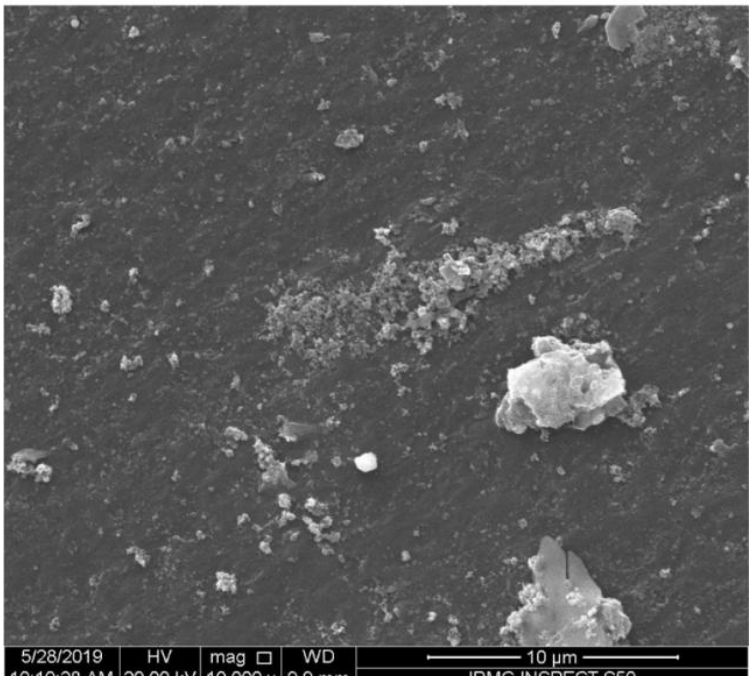


Figure 4. Additional SEM micrograph showing surface-deposited particulate domains within the LDPE matrix.

The observed agglomeration is important because antimicrobial efficiency depends not only on the total nanoparticle loading but also on the accessible surface area, particle exposure at the film surface and the ability of reactive species or ions to interact with microbial cells. Excessive agglomeration can reduce active surface area and may compromise reproducibility. Therefore,

dispersion optimization, compatibilization and controlled filler loading should be considered in subsequent formulation development.

3.2 Antibacterial activity

The Ag/TiO_2-LDPE films demonstrated high antibacterial activity after 24 h exposure against both tested bacteria (Table 1; Figure 5). *E. coli* decreased from 1.0×10^6 to 1.2×10^3 CFU/mL, representing a 99.88% reduction and an approximate 2.92-log_{10} reduction. *S. aureus* decreased from 1.0×10^6 to 8.5×10^2 CFU/mL, representing a 99.91% reduction and an approximate 3.07-log_{10} reduction. These reductions indicate activity against both Gram-negative and Gram-positive bacterial models.

Table 1. Antibacterial efficiency of Ag/TiO_2-loaded LDPE nanocomposite films after 24 h exposure

Bacterial strain	Initial count (CFU/mL)	After 24 h (CFU/mL)	Reduction (%)	Log_{10} reduction
E. coli	1.0×10^6	1.2×10^3	99.88	2.92
S. aureus	1.0×10^6	8.5×10^2	99.91	3.07

Note: Log_{10} reduction was calculated from summary CFU values; statistical significance testing was not performed.



Figure 5. Representative microbiological assay image showing bacterial exposure to the Ag/TiO_2-loaded LDPE film. The visual assay supports the CFU-based antibacterial evaluation; quantitative interpretation relies on enumerated colony counts.

3.3 Discussion

The findings indicate that Ag/TiO_2 nanoparticles can be incorporated into an LDPE film format and that the resulting composite film has strong antibacterial activity against *E. coli* and *S. aureus*. The approximately 3-log_{10} reductions observed for both organisms are consistent with the expected antimicrobial contribution of Ag-containing polymer nanocomposites and TiO_2-based photocatalytic or oxidative mechanisms [3–9].

The likely antibacterial mechanism is multi-factorial. Ag nanoparticles can undergo oxidative dissolution and release Ag^+, which interacts with bacterial membranes, thiol-containing enzymes and DNA-associated cellular processes, leading to impaired respiration and cell death [4,5]. TiO_2 can generate reactive oxygen species under appropriate light exposure, causing oxidative

damage to cell-wall components, proteins and nucleic acids [6,7]. When Ag and TiO_2 are combined, Ag may also facilitate charge separation and improve photocatalytic efficiency, while providing an additional ion-mediated antimicrobial pathway [8].

The activity against both *E. coli* and *S. aureus* is relevant because the two organisms differ in cell-envelope structure. Gram-negative *E. coli* has an outer membrane that can influence nanoparticle–cell interactions, while Gram-positive *S. aureus* has a thicker peptidoglycan layer. The similar magnitude of reduction in both organisms suggests that the composite film has broad-spectrum potential. This observation aligns with previous reports of Ag-containing and TiO_2-containing polymer systems that inhibited multiple bacterial strains [6,8–11,14].

Morphology is a critical performance determinant. The SEM images demonstrated visible particulate domains on the LDPE film surface, but also showed local agglomeration. Agglomeration may reduce the effective surface area of the active fillers and create batch-to-batch variability. This limitation can be addressed by optimizing mixing energy, processing temperature, filler loading, particle surface treatment or compatibilizer selection [15]. For medical-device applications, future formulations should aim to maximize exposed antimicrobial surface while minimizing loosely bound particles and uncontrolled ion release.

SEM provides morphological evidence of particle incorporation but cannot establish elemental composition or crystal structure. Crystalline phase identification requires XRD or selected-area electron diffraction, and elemental confirmation requires EDS, XPS or equivalent techniques. The conclusions of the present study are therefore restricted to film morphology and antibacterial performance.

3.4 Limitations and future perspectives

For practical translation, antimicrobial performance must be balanced against safety and durability. Ag release can be beneficial for antimicrobial action, but excessive release may raise cytotoxicity or environmental concerns. TiO_2 photocatalysis depends on light conditions and may vary between clinical environments. Therefore, future work should include Ag release kinetics, cytocompatibility assays using relevant mammalian cells, hemocompatibility where appropriate, surface durability after wiping and sterilization, mechanical testing, and antimicrobial testing under realistic light and soiling conditions.

The current study provides promising preliminary evidence but is limited by the absence of replicate-level antimicrobial data, the absence of untreated LDPE and single-filler controls in the antibacterial assay, and the lack of compositional confirmation by EDS/XPS/XRD. These limitations do not invalidate the observed antibacterial reductions, but they mean that the findings should be regarded as proof-of-concept rather than final device validation. A strengthened follow-up design would include LDPE, TiO_2-LDPE and Ag-LDPE controls, Ag/TiO_2-LDPE at multiple loadings, dark/light exposure arms, triplicate experiments and statistical analysis.

4. CONCLUSION

Ag/TiO_2-loaded LDPE nanocomposite films were successfully prepared using a solvent-assisted reduction, drying and melt-blending approach. SEM showed particulate domains distributed on/within the LDPE surface, with some local agglomeration. The films demonstrated strong antibacterial activity after 24 h, reducing *E. coli* by 99.88% and *S. aureus* by 99.91%, equivalent to approximately 2.92-$\log_{10}$ and 3.07-$\log_{10}$ reductions, respectively. These findings support the potential use of Ag/TiO_2-LDPE films as antimicrobial polymer surfaces for healthcare-associated plastic components. Before clinical or commercial application, further validation is required, including compositional analysis, standardized replicate antimicrobial testing, durability assessment, biocompatibility testing and evaluation of silver release under simulated use conditions.

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AUTHOR CONTRIBUTIONS

Khaled F. Salama: Conceptualization, Methodology, Project Administration, Supervision, Writing—Original Draft, Writing—Review & Editing.

Arwa Althumairi: Conceptualization, Methodology, Project Administration, Supervision, Writing—Original Draft, Writing—Review & Editing.

Both authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest. For transparency, the authors note that the antimicrobial film technology described in this study is related to United States Patent No. US 11,850,312 B2, issued on 26 December 2023.

ETHICS STATEMENT

This study involved polymer-film preparation and *in vitro* antibacterial testing only; no human participants or animals were involved. The related research project was approved by the Institutional Review Board of Imam Abdulrahman Bin Faisal University (approval No. IRB-03-589, dated 26 August 2024).

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are included in this article. Additional raw data are available from the corresponding author upon reasonable request.

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