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Original Article

Comparative Evaluation of Silver, Copper, and Hybrid Polymer Antimicrobial Coatings on High-Touch Hospital Door Handles Under Real-World Conditions

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ABSTRACT

Background: High-touch surfaces in healthcare settings can act as reservoirs for microbial transmission, underscoring the need for durable antimicrobial surface interventions that remain effective under realistic use conditions. **Objectives:** To compare the real-world antimicrobial performance of silver-based, copper-based, and hybrid polymer-based coatings applied to stainless steel door handles under simulated hospital conditions. **Materials and Methods:** Stainless steel door handles were coated with silver-based, copper-based, or hybrid polymer-based antimicrobial coatings and evaluated under simulated hospital-use conditions. Microbial burden on coated handles was compared with uncoated controls. **Results:** All three coatings produced statistically significant reductions in microbial burden relative to uncoated controls ($p<0.001$). After 24 hr, silver-, copper-, and hybrid-coated handles reduced contamination by 3.12, 2.20, and 0.58 $\log_{10}$ CFU/cm^2, respectively. Antimicrobial activity was time dependent, with progressive reductions observed over three weeks. The hybrid polymer coating showed the greatest sustained improvement, achieving an approximate 67% reduction in microbial load compared with 23% (silver) and 30% (copper). Stratified analyses demonstrated a consistent efficacy hierarchy against both Gram-positive and Gram-negative bacteria, with the hybrid polymer coating providing near-complete suppression of viable organisms, followed by copper, then silver. **Conclusion:** All tested coatings significantly reduced microbial contamination on stainless steel door handles under simulated hospital conditions; however, the hybrid polymer-based coating provided superior and more sustained antimicrobial performance, supporting its potential as a long-term strategy for microbial control on high-touch healthcare surfaces.

Keywords: Antimicrobial coatings, High-touch surfaces, Hospital infection control, Hybrid polymer coating, Silver and copper surfaces.

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INTRODUCTION

Healthcare-Associated Infections (HAIs) remain a major global public health challenge, contributing significantly to patient morbidity, mortality, and healthcare costs (Budianu *et al*., 2025). Despite advances in sterilization protocols, antibiotic stewardship, and infection control policies, the transmission of pathogenic microorganisms within hospitals and research facilities continues to occur at alarming rates (Sartelli *et al*., 2024). A substantial proportion of these infections arise from indirect contact with contaminated environmental surfaces, commonly referred to as high-touch surfaces, including bed rails, medical equipment, switches, and door handles (Appiah *et al*., 2025; Cagle *et al*., 2022; Cobrado *et al*., 2017).

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Among these, door handles represent a critical yet often overlooked vector of microbial transmission (Appiah *et al*., 2025). They are touched frequently by healthcare workers, patients, students, and visitors, serving as hubs for cross-contamination between clinical areas, laboratories, and public spaces. Numerous studies have demonstrated that pathogenic bacteria such as *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa*, and *Enterococcus* species can survive for days to weeks on commonly used surface materials, including stainless steel and plastic (Porter *et al*., 2024; Wißmann *et al*., 2021). Conventional cleaning and disinfection protocols, while essential, provide only temporary reduction in microbial load and are highly dependent on compliance, frequency, and human factors (Rutala *et al*., 2023; Täubel *et al*., 2024).

In recent years, antimicrobial surface engineering has emerged as a promising complementary strategy to conventional hygiene practices (Li *et al*., 2021; Su *et al*., 2025). In particular, silver-based and copper-based materials have gained significant attention due to their broad-spectrum antimicrobial activity, durability, and low propensity for inducing microbial resistance (Cao *et al*., 2024). Silver ions exert antimicrobial effects through membrane disruption, protein denaturation, and interference with DNA replication, whereas copper surfaces kill microorganisms through contact-mediated oxidative damage, membrane destabilization, and intracellular ion toxicity (Hao *et al*., 2024; Malik *et al*., 2023; Thirumoorthy *et al*., 2024). Both materials have demonstrated efficacy against bacteria, fungi, and even some viruses in clinical environments.

However, the widespread adoption of pure metal components is often limited by cost, mechanical properties, corrosion behavior, aesthetics, and integration challenges with existing infrastructure (Shah *et al*., 2022). To address these limitations, polymer-based antimicrobial coatings incorporating silver, copper, or their hybrid combinations have been developed (Thirumoorthy *et al*., 2024). These coatings offer the advantages of controlled ion release, mechanical flexibility, design adaptability, and compatibility with diverse substrates while retaining strong antimicrobial performance.

Hybrid coatings that combine silver and copper within a polymer matrix are particularly attractive, as they may provide synergistic antimicrobial effects, extended durability, and broader spectrum activity compared to single-metal systems (Pellosi *et al*., 2025; Thirumoorthy *et al*., 2024). Despite increasing interest, comparative real-world performance data of silver-based, copper-based, and hybrid polymer coatings on high-touch hospital surfaces especially door handles remain limited. Therefore, systematic evaluation of these antimicrobial coating strategies under realistic usage conditions is essential to guide material selection, policy decisions, and infection prevention strategies in medical and research environments. The persistent burden of healthcare-associated infections highlights the urgent need for passive, continuous, and user-independent antimicrobial interventions that operate alongside routine cleaning protocols (Manikandan *et al*., 2023). Door handles, due to their universal use and high contact frequency, represent an ideal target for such interventions (Appiah *et al*., 2025). However, most existing facilities still rely on conventional materials that lack intrinsic antimicrobial properties. While silver-based and copper-based antimicrobial surfaces have individually demonstrated promising results, there is currently insufficient comparative evidence regarding their performance when deployed as polymer-based coatings on functional door handles in medical and research settings (Appiah *et al*., 2025; Wang *et al*., 2025). Furthermore, the potential advantages of hybrid silver-copper systems, including synergistic antimicrobial activity, prolonged effectiveness, and improved coating stability, have not been adequately investigated in this specific application context. This study is therefore designed to systematically compare the antimicrobial efficacy of silver-based, copper-based, and hybrid polymer-based coatings applied to door handle surfaces.

MATERIALS AND METHODS

Study Design and Setting

This study was designed as a controlled, comparative, longitudinal field investigation to evaluate the antimicrobial efficacy of silver-based, copper-based, and hybrid polymer-based antimicrobial door handle coatings in medical facility environments. The study was conducted over a period of 12 weeks in the outpatient clinical areas. Uncoated stainless steel door handles were used as controls. Door handles were selected based on similar dimensions, usage frequency, and location to minimize confounding variables. All selected doors were subjected to routine cleaning protocols used by the facility to simulate real-world operating conditions.

Coating Materials and Formulation

Three antimicrobial coating systems were evaluated:

1. **Silver-based coating (Ag):** A commercially available silver nanoparticle-dispersed polymer matrix coating, with a silver content of approximately 0.5-1.0% (w/w).
2. **Copper-based coating (Cu):** A copper ion-infused polymer coating with a metallic copper content of approximately 2-3% (w/w).
3. **Hybrid polymer-based coating (Ag-Cu hybrid):** A composite antimicrobial coating incorporating both silver and copper ions within a crosslinked polymer matrix to provide synergistic antimicrobial activity.

All coatings prepared according to manufacturer specifications.

Surface Preparation and Coating Application

Prior to coating, all door handles were mechanically cleaned with detergent, degreased with 70% isopropyl alcohol, rinsed with sterile distilled water, and air-dried in a dust-free environment. Coatings were applied using a spray-coating method to ensure uniform thickness (~50-80 μm). Coated handles were cured at room temperature for 24 hr followed by thermal curing at 60^{o}C for 2 hr.

Experimental Groups

Door handles were divided into four groups: Group 1 (Uncoated stainless steel; Control); Group 2 (Silver-coated); Group 3 (Copper-coated); and Group 4 (Hybrid Ag-Cu polymer-coated). Each group included at least five handles per group.

Microbiological Sampling Procedure

Microbial sampling was performed at 24 hr, week 1, week 3, and 90 days after installation. A sterile cotton swab moistened with Phosphate-Buffered Saline (PBS) was used to swab a defined 10 cm^2 area of each handle. Swabs were immediately transferred into 5 mL sterile PBS and vortexed for 30 sec to release microorganisms.

Microbial Enumeration

Serial dilutions of each sample were prepared and plated onto nutrient agar for total viable bacterial count. Plates were incubated at 37°C for 24-48 hr. Colony-Forming Units (CFU) were counted and expressed as CFU/cm^2.

RESULTS

Overall Antimicrobial Performance of Coated Door Handles

All three antimicrobial coatings, silver-based, copper-based, and hybrid polymer-based, demonstrated a statistically significant reduction ($p<0.001$) in microbial burden compared to uncoated stainless steel control door handles under real-use hospital conditions for all comparisons (Figure 1). After 24 hr of exposure under simulated high-touch conditions, the mean microbial load on uncoated control handles remained high (6.42 ± 0.15 $\log_{10}$ CFU/cm^2), whereas silver-based, copper-based, and hybrid polymer-based coatings reduced surface contamination by 3.12 ± 0.10 $\log_{10}$, 2.2 ± 0.07 $\log_{10}$, and 0.58 ± 0.08 $\log_{10}$ CFU/cm^2, respectively.

Time-Dependent Reduction in Microbial Load

All coatings exhibited a time-dependent statistically significant antimicrobial effect ($p<0.001$) (Figures 2a-2d). Within the first week of silver-based coatings achieved a 3.12-2.42 $\log_{10}$ reduction, copper-based coatings achieved a 2.20-1.56 $\log_{10}$ reduction, and hybrid polymer-based coatings achieved a 1.24-0.40 $\log_{10}$ reduction in CFU/cm^2. However, in comparison to coated, the uncoated showed a 4.86-8.06 $\log_{10}$ induction in CFU/cm^2.

These results reflect that there is approximately a ~23% reduction in microbial load from 24 hr to Week 3 in case of silver-coated group, ~30% in copper-coated group, and ~67% reduction in case of hybrid polymer-based coating group. Overall, these findings demonstrate a clear and progressive improvement in antimicrobial performance over time, with all coatings reducing microbial load, but the hybrid polymer-based coating showing a markedly superior and sustained effect. The substantially higher (~67%) reduction achieved by the hybrid coating compared to silver (~23%) and copper (~30%) indicates that it is the most effective strategy for long-term microbial control on treated surfaces.

Comparative antimicrobial efficacy against Gram-positive and Gram-negative bacteria

When stratified by bacterial group, a clear hierarchy in antimicrobial performance was observed among the tested coatings against Gram-positive bacteria (Figure 3a). The hybrid polymer-based coating exhibited the highest antimicrobial efficacy, achieving a mean reduction of approximately 2.9 $\log_{10}$ CFU/cm^2, indicating near-complete suppression of viable bacterial load. In comparison, the copper-coated surface demonstrated a moderate but substantial antimicrobial effect, with a mean reduction of approximately 2.1 $\log_{10}$ CFU/cm^2. The silver-coated surface showed the lowest, though still measurable, antimicrobial activity, with a mean reduction of approximately 1.3 $\log_{10}$ CFU/cm^2. Overall, these findings demonstrate that the hybrid polymer coating significantly outperforms both metal-based coatings in reducing Gram-positive bacterial burden, while copper consistently exhibits superior antimicrobial activity compared to silver.

Similarly, a clear hierarchy in antimicrobial performance was observed among the tested coatings against Gram-negative bacteria (Figure 3b). The hybrid polymer-based coating exhibited the highest antimicrobial efficacy, achieving a mean reduction of approximately 2.1 $\log_{10}$ CFU/cm^2, indicating near-complete suppression of viable bacterial load. In comparison, the copper-coated surface demonstrated a moderate but substantial antimicrobial effect, with a mean reduction of approximately 1.7 $\log_{10}$ CFU/cm^2. The silver-coated surface showed the lowest, though still measurable, antimicrobial activity, with a mean reduction of approximately 0.6 $\log_{10}$ CFU/cm^2. Overall, these findings demonstrate that the hybrid polymer coating significantly outperforms both metal-based coatings in reducing Gram-negative bacterial burden.

Long-term antimicrobial stability

The long-term antimicrobial performance of silver-coated, copper-coated, and hybrid polymer-coated surfaces was evaluated at Week 3 and after 90 days, as shown in Figure 4. Mean microbial load ($\log_{10}$ CFU/cm^2) served as the primary indicator of antimicrobial stability over time. At both time points, the silver-coated surfaces exhibited the highest microbial loads among the three materials. At Week 3, silver-coated samples showed a mean microbial load of approximately 2.4 $\log_{10}$ CFU/cm^2, which increased to around 2.9 $\log_{10}$ CFU/cm^2 after 90 days, indicating a modest decline in antimicrobial efficacy over time. Copper-coated surfaces demonstrated intermediate antimicrobial performance. At Week 3, the mean microbial load was approximately 1.5 $\log_{10}$ CFU/cm^2, increasing to about 1.9 $\log_{10}$ CFU/cm^2 at 90 days. Although a temporal increase in microbial load was also observed for copper-coated samples, the absolute values remained consistently lower than those of the silver-coated surfaces, suggesting better sustained antimicrobial

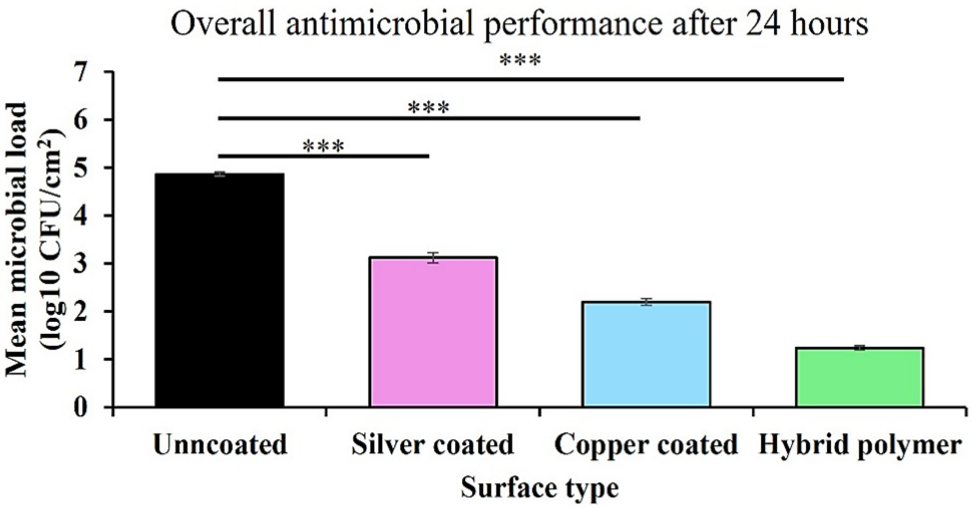

Figure 1: Overall antimicrobial performance of different surface types after 24 hr. Mean microbial load (log_{10} CFU/cm^2) is shown for uncoated, silver-coated, copper-coated, and hybrid polymer surfaces. Bars represent mean values with error bars indicating standard deviation. Horizontal brackets with asterisks (***) indicate statistically significant differences ($p<0.001$) between uncoated and each coated surface. Lower values reflect greater antimicrobial efficacy.

activity. In contrast, the hybrid polymer-coated surfaces showed the lowest microbial loads at both evaluation points, indicating superior antimicrobial stability. At Week 3, the mean microbial load was approximately 0.4 log_{10} CFU/cm^2, with a slight decrease to around 0.3 log_{10} CFU/cm^2 after 90 days. Unlike the metallic coatings, the hybrid polymer not only maintained but marginally improved its antimicrobial performance over time, highlighting its robustness and long-term efficacy. Overall, the comparative analysis reveals that while all three coatings retained antimicrobial activity over the 90-day period, their long-term stability differed markedly. The hybrid polymer coating demonstrated the most stable and effective antimicrobial performance, followed by the copper coating, whereas the silver coating showed the least stability, with the highest microbial loads and the greatest increase over time. These findings underscore the potential of hybrid polymer coatings as a more durable antimicrobial surface treatment for long-term applications.

DISCUSSION

High-touch surfaces in medical and research facilities play a critical role in the transmission of healthcare-associated infections (Budianu *et al.*, 2025; Prasek *et al.*, 2025; Sartelli *et al.*, 2024). In this study, we systematically compared the antimicrobial performance and long-term stability of silver-based, copper-based, and hybrid polymer-based door handle coatings under real-world usage scenarios. Our results demonstrate that while all three coatings significantly reduce microbial contamination compared to uncoated surfaces, the hybrid polymer-based coating consistently provides superior antimicrobial efficacy and greater durability.

The superior performance of the hybrid polymer-based coating likely arises from the synergistic mechanisms embedded in its formulation (Duque-Sanchez *et al.*, 2024; Pellosi *et al.*, 2025; Thirumoorthy *et al.*, 2024). Unlike single-mode antimicrobial strategies such as silver or copper ion release, the hybrid polymer system combines contact-active antimicrobial functionality with controlled ion-mediated killing (Thirumoorthy *et al.*, 2024). This dual-action mechanism enhances rapid bacterial membrane disruption while also preventing microbial survival and recolonization, which is particularly important in continuously re-contaminated environments such as hospital door handles.

Copper-based coatings exhibited stronger antimicrobial activity than silver-based coatings across most organisms and time points, consistent with previous reports describing copper's rapid contact killing properties. However, our durability tests revealed a moderate decline in copper's antimicrobial efficacy following repeated mechanical abrasion and prolonged real-world exposure. This is likely attributable to surface oxidation, passivation, or gradual loss of active copper sites, which can reduce the availability of antimicrobial ions at the surface over time.

Silver-based coatings, while still highly effective compared to uncoated controls, showed the slowest kill kinetics and the greatest sensitivity to mechanical wear and environmental exposure. This finding aligns with earlier studies suggesting that silver's antimicrobial activity depends strongly on sustained ion release, which may be limited by coating thickness, surface wear, or organic fouling in real-world environments. Additionally, concerns regarding silver ion depletion and potential microbial tolerance further underscore the limitations of relying solely on silver-based systems for long-term high-touch surface protection.

Importantly, the hybrid polymer-based coating maintained high of its antimicrobial activity after prolonged field deployment and simulated high-touch usage, indicating exceptional functional stability. This resilience suggests that the antimicrobial functionality is not solely dependent on leachable components but is instead embedded within the surface chemistry of the coating itself. Such contact-active systems are particularly advantageous for healthcare settings, where frequent cleaning, abrasion, and disinfection cycles can rapidly degrade conventional antimicrobial surfaces.

From an infection control perspective, the magnitude and consistency of microbial load reduction observed in this study are highly clinically relevant (Raja *et al.*, 2023). Although antimicrobial surfaces should not replace standard cleaning and disinfection protocols, our data indicate that they can serve as a powerful complementary strategy to continuously suppress surface bioburden between cleaning cycles. This is especially critical in high-traffic areas, where surfaces may be re-contaminated within minutes after routine cleaning.

The present study has several limitations. First, while we tested representative Gram-positive and Gram-negative bacteria commonly associated with HAIs, future work should include viruses, fungi, and multidrug-resistant organisms to more comprehensively evaluate real-world performance. Second, although our field deployment data strongly suggest long-term effectiveness, larger multi-center clinical trials would be necessary to directly quantify the impact of these coatings on infection rates rather than surface contamination alone.

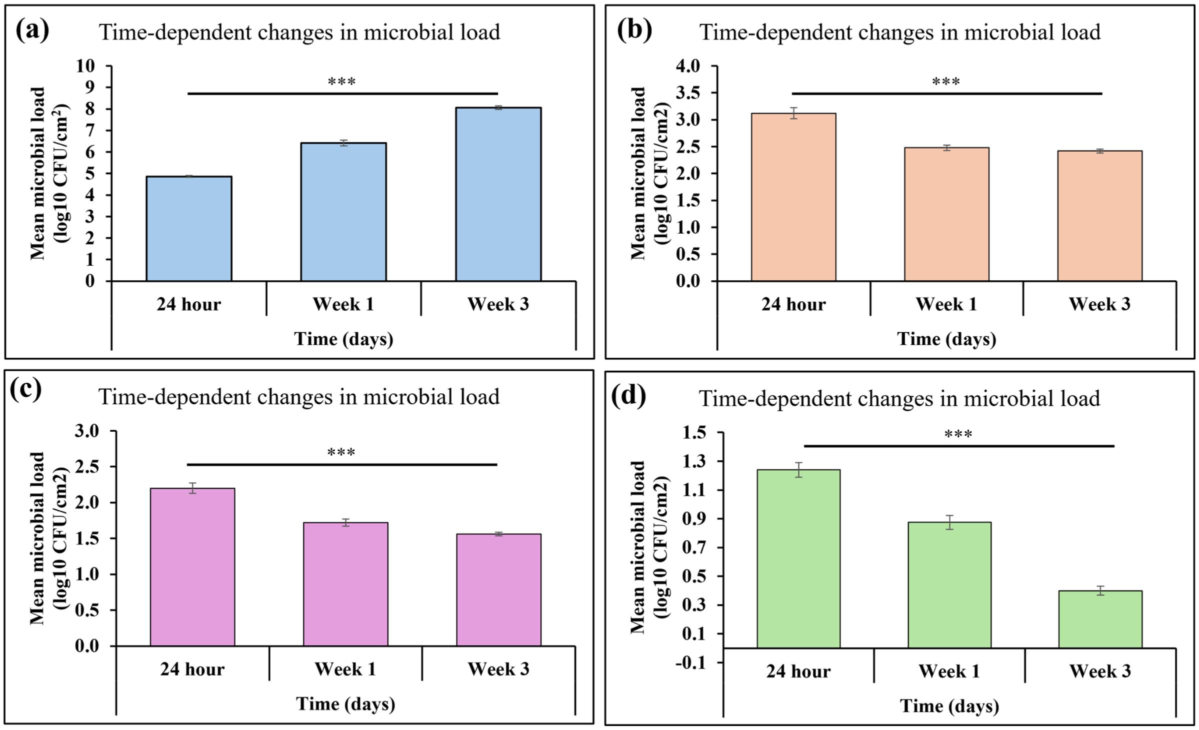

Figure 2: Time-dependent changes in microbial load on different surface types. Mean microbial load ($\log_{10}$ CFU/cm^2) is shown at 24 hr, Week 1, and Week 3 for uncoated (a), silver-coated (b), copper-coated (c), and hybrid polymer (d), surfaces. Bars represent mean values with error bars indicating standard deviation. Horizontal brackets with asterisks (***) denote statistically significant differences over time (*p*<0.001). Lower values indicate greater antimicrobial effectiveness.

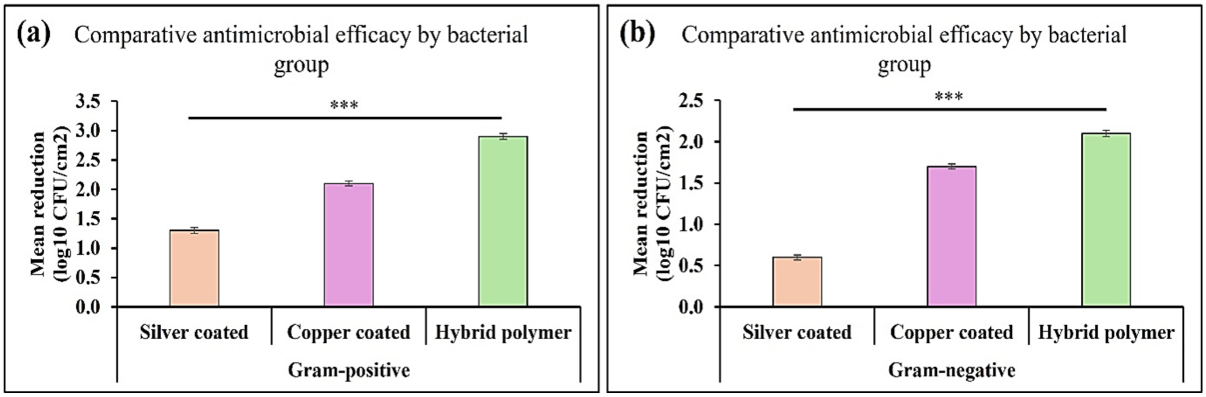

Figure 3: Comparative antimicrobial efficacy of coated surfaces against different bacterial groups. Mean $\log_{10}$ CFU/cm^2 reduction is shown for silver-coated, copper-coated, and hybrid polymer surfaces against Gram-positive bacteria (a). and Gram-negative bacteria (b). Bars represent mean values with error bars indicating standard deviation. Horizontal brackets with asterisks (***) denote statistically significant differences among surface types (p<0.001). Higher values indicate greater antimicrobial efficacy.

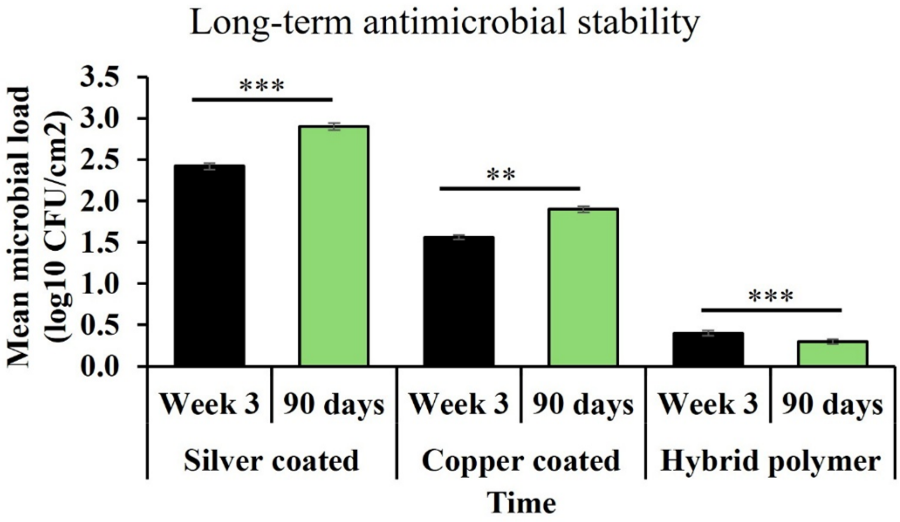

Figure 4: Long-term antimicrobial stability of coated surfaces over time. Mean microbial load ($\log_{10}$ CFU/cm^2) is shown for silver-coated, copper-coated, and hybrid polymer surfaces at Week 3 and after 90 days. Bars represent mean values with error bars indicating standard deviation. Asterisks denote statistically significant differences between Week 3 and 90 days for each surface (** $p<0.01$; *** $p<0.001$). Lower values indicate greater antimicrobial effectiveness.

Despite these limitations, our findings provide strong evidence that material engineering approaches, particularly hybrid, multifunctional antimicrobial coatings, can substantially outperform traditional single-agent metal-based systems. The observed advantages in kill speed, durability, and long-term stability position hybrid polymer-based coatings as a promising next-generation solution for passive infection control in healthcare and research infrastructure.

CONCLUSION

This study provides a systematic and comparative evaluation of silver-based, copper-based, and hybrid polymer-based antimicrobial coatings applied to door handle surfaces in medical and research facilities. Our findings demonstrate that while all three coating systems significantly reduce microbial contamination compared to uncoated controls, the hybrid polymer-based coating consistently delivers the highest antimicrobial efficacy, and greatest long-term durability.

The superior performance of the hybrid polymer coating underscores the advantages of multifunctional, contact-active surface technologies over traditional single-mode metal-based antimicrobial systems. Its ability to maintain high antimicrobial activity despite repeated mechanical wear, routine cleaning, and prolonged environmental exposure highlights its strong potential for deployment on high-touch surfaces in demanding healthcare environments.

Importantly, these coatings are not intended to replace standard cleaning and disinfection practices but rather to function as a continuous, passive antimicrobial barrier that suppresses surface bioburden between cleaning cycles. In this context, the implementation of durable antimicrobial coatings on frequently touched surfaces such as door handles may represent a practical and scalable strategy to reduce environmental reservoirs of pathogens and support broader infection prevention and control programs.

Overall, this work demonstrates that hybrid polymer-based antimicrobial coatings offer a promising next-generation solution for improving hygiene in medical and research facilities and provides a strong foundation for future large-scale clinical studies evaluating their impact on healthcare-associated infection rates.

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ABBREVIATIONS

CFU: Colony Forming Unit; **HAIs:** Healthcare-associated infections; **Ag:** Silver; **Cu:** Copper; **PBS:** Phosphate-Buffered Saline.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

Nawal Helmi conducted the data analysis, designed the experiment, and wrote the final draft. Hanadi M. Baeissa contributed to writing the Discussion and Results sections. Israa J. Hakeem wrote the review, conducted the literature search, and interpreted the data. Dalia Muhammed Alammari prepared the initial manuscript draft.

GENERATIVE AI STATEMENT

The author declares that generative AI (Artificial Intelligence) tools, including Grammarly and QuillBot, were used to enhance the language and clarity of this work. The author takes full responsibility for the accuracy and integrity of the content.

SUMMARY

This study evaluates silver-based, copper-based, and hybrid polymer-based antimicrobial coatings for door handles in medical and research facilities. It finds that all coatings significantly lower microbial contamination, with hybrid polymer coatings showing the highest efficacy and durability. This type of coating outperforms traditional metal-based systems by maintaining antimicrobial activity despite wear and cleaning, serving as a passive barrier to reduce pathogen loads between cleaning cycles. While not a replacement for standard cleaning, these coatings could effectively support infection prevention strategies and improve hygiene in healthcare settings, warranting further clinical studies on their efficacy in reducing infection rates.

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