

Tailoring Antimicrobial Polypropylene with Dual-Metal Oxide Systems: Hydrothermal Versus Commercial Approaches Against Key Bloodstream Pathogens

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Abstract

The persistent challenge of microbial colonization and biofilm formation on medical device surfaces continues to compromise patient safety, particularly in the context of rising antibiotic resistance. Nanostructured materials offer a promising avenue for the development of inherently antimicrobial biomaterials. In this study, polypropylene composites embedded with dual-metal oxide systems, comprising commercial CuO–TiO₂ and Cu–TiO₂ synthesized via hydrothermal processing, were investigated. This work pioneers the integration of elemental copper and titanium dioxide nanoparticles into a single matrix, leveraging their combined antimicrobial and photocatalytic properties to disrupt microbial colonization. The antimicrobial efficacy of the composites was evaluated against *Candida albicans* and *Staphylococcus epidermidis* using a modified microbial adhesion assay. Cu–TiO₂-PP (3 wt%) demonstrated enhanced antifungal activity against *C. albicans*, attributable to the bioactivity of elemental copper and its increased amorphous character, which likely facilitates water uptake and ion release. In contrast, both composites exhibited limited antibacterial activity against *S. epidermidis* unless higher concentrations of nanoparticles were embedded. Structural analysis indicated that the reduced crystallinity of Cu–TiO₂-PP may contribute to improved antimicrobial performance. These findings support the potential of copper-based nanocomposites as antimicrobial coatings for medical devices, with implications for reducing device-associated bloodstream infections.

Introduction

Over the past two decades, there has been a significant increase in bacterial and fungal infections, particularly among immunocompromised patients [1, 2, 3]. Such infections present a major challenge in clinical settings, especially when associated with medical devices that come into direct contact with patients, as these devices serve as potential vectors for cross-contamination and subsequent morbidity. Bloodstream infections (BSIs) are estimated to affect approximately 4–5 per 1000 patients receiving peripheral or central intravenous catheters [4, 5]. The predominant cause of device-associated infections is bacterial adhesion and subsequent colonization on the device surface [6]. Consequently, it is widely recognized that antimicrobial coatings on medical devices can inhibit bacterial adherence and biofilm formation, thereby reducing infection risk [7]. Several preventive strategies have been developed to mitigate catheter-related bloodstream infections (CRBSIs), including aseptic insertion techniques, rigorous post-insertion care protocols, optimized implantation methods, and the use of antibiotic-impregnated materials [8]. However, these approaches often fall short of fully eliminating bacterial colonization, showing the need for alternative antimicrobial solutions.

Nanotechnology offers a promising avenue to address CRBSIs by leveraging the unique physicochemical properties of metal oxide nanoparticles (NPs) [9]. The antimicrobial efficacy of these NPs depends on their morphology, size, structural stability, and concentration. Specific interactions between nanoparticles and microbial cell walls can disrupt colonization processes, inhibiting biofilm formation in NP-amended environments [10, 11]. Coating medical devices with antimicrobial nanomaterials at contamination-prone sites could enhance patient safety by minimizing cross-contamination. Historically, copper and its alloys, such as brass and bronze, have demonstrated antimicrobial properties and have been utilized in hospital environments, for example, in doorknobs, to reduce microbial transmission [12, 13, 14]. Recently, copper has regained interest as an affordable antimicrobial agent in potable water systems, especially in resource-limited settings [15]. In addition to copper, nanomaterials such as silver, zinc oxide, and titanium dioxide (TiO₂) have been widely incorporated into various consumer and biomedical products due to their broad-spectrum antimicrobial activity [16, 17, 18].

In this study, we investigate copper-based nanocomposites embedded within polypropylene (PP) matrices, focusing on Cu–TiO₂-PP and CuO–TiO₂-PP composites. Preliminary evidence suggests that Cu–TiO₂-PP exhibits superior antimicrobial activity compared to CuO–TiO₂-PP, potentially due to greater release of copper ions (Cu²⁺) from the composite material [19]. However, microbial survival on copper surfaces varies depending on the copper species, particle size, and the microorganism involved [20, 21]. Elemental copper (Cu) and copper oxide (CuO) are well established for their bactericidal activity against bloodstream pathogens [22]. However, the influence of their physicochemical properties, including surface morphology, hydrophobicity, and porous variation, particularly in nanoparticulate form and in combination with TiO₂ nanoparticles within a polypropylene (PP) matrix, remains insufficiently explored [23].

Therefore, the primary objective of this work is to synthesize and characterize Cu–TiO₂-PP and CuO–TiO₂-PP nanocomposites with 3 wt% loading and evaluate their antimicrobial efficacy against *Staphylococcus epidermidis* and *Candida albicans*. This study aims to

elucidate the relationship between nanoparticle composition, structure, and antimicrobial activity. The outcome provides crucial insights into the rational design of advanced antimicrobial coatings for infection-prone medical devices such as IV catheters and dialysis ports.

Experimental procedures

Materials Selection and Preparation Protocol

In this section, two dual-metal oxides were prepared to assess their physicochemical and antimicrobial properties: Cu-doped TiO₂ (Cu-TiO₂) synthesized via a hydrothermal method, and a commercially obtained CuO-TiO₂ blend. The CuO-TiO₂ composite was synthesized by manually mixing 1 wt% copper oxide (5 µm, Sigma Aldrich) and 0.1 wt% titanium dioxide nanoparticles (25 nm, Sigma Aldrich) in isopropanol using an agate mortar to ensure uniform dispersion. The resulting mixture was then dried in an oven at 100°C. Cu-TiO₂ nanoparticles were synthesized by adding titanium tetraisopropoxide solution dropwise into deionized water containing 2-propanol under stirring, with simultaneous introduction of copper (II) nitrate pentahydrate solution. The mixture underwent hydrothermal treatment in a Teflon-lined autoclave at 150°C for 6 h, followed by washing and drying at 100°C to yield the nanopowders. PP (density 907 kg/m³, MFR 10 g/10 min at 230°C) was melt-compounded with 3 wt% of each dual-metal oxide and 3 wt% PP-g-MAH using a Haake internal mixer at 175°C, 50 rpm for 10 min. The resulting composites (CuO-TiO₂-PP and Cu-TiO₂-PP) were pelletized and compression molded into rectangular sheets (150 × 120 × 1 mm³) by preheating at 175°C for 6 minutes, compressing at 1000 psi for 3 minutes, and cooling under pressure for 3 minutes. Final samples were die-cut into dumbbell shapes and punched into 12.7 mm diameter discs for subsequent antimicrobial testing.

Physicochemical characterization

Microstructure observation

The microstructure and architecture of the dual-metal oxide polypropylene composites (CuO-TiO₂-PP and Cu-TiO₂-PP), along with the dispersion of metal oxide particles within the polymer matrix, were investigated using scanning electron microscopy (SEM). Prior to imaging, the samples were cryogenically cleaved and sputter-coated with a thin gold layer to improve surface conductivity. SEM observations were conducted using a field emission scanning electron microscope (FESEM, SUPRA 35VP, ZEISS). Furthermore, transmission electron microscopy (TEM) was utilized to analyze the morphology and particle size of the synthesized Cu-TiO₂ nanoparticles.

Thermal analysis test

Differential Scanning Calorimetry (DSC; Perkin Elmer) was employed to investigate the crystallization and melting behavior of the dual-metal oxide polypropylene composites (CuO-TiO₂-PP and Cu-TiO₂-PP). Samples weighing approximately 10–15 mg were subjected to heating from ambient temperature to 200°C with a ramp rate of 20°C per minute under a continuous nitrogen (N₂) flow of 50 mL/min to maintain an inert atmosphere. The melting temperature (T_m) and enthalpy of fusion (ΔH) of the composites were determined. The relative crystallinity was evaluated by applying Eq. 1, which relates the measured enthalpy values to the theoretical enthalpy of fusion for completely crystalline polypropylene [24].

$$(1 - \lambda) \% = \frac{\Delta H_f}{\Delta H_{f100\%}^{\circ} \cdot w} \times 100 \text{ Eq. 1}$$

w = Blends' weight percentage of filler or matrix

ΔH_f = The filler's or matrix's absolute melting enthalpy

ΔH_{f100%}^o = 209 J/g is the enthalpy of fusion for 100% crystalline polypropylene, used as a reference

Mechanical testing

Tensile properties of the composites were measured at room temperature following **ASTM D638-08** [25, 26] using an Instron Model 3366 universal testing machine. Dog-bone shaped tensile specimens were securely clamped and subjected to loading at a constant crosshead speed of 5 mm/min until failure. The tensile modulus, strength under tension and elongation at rupture were calculated as the average of five replicates. Prior to testing, the cross-sectional area (6.4 mm²) and average thickness, measured at three points along each specimen, were recorded.

Antimicrobial characterization

A single colony was inoculated into five milliliters of autoclaved broth to create the bacterial solution, which was then grown for sixteen to eighteen hours at 150 rpm and 37°C. 10 ml of autoclaved distilled water was used to dilute 100 µl of a broth containing microbes. Using the 0.5 McFarland Standard, the turbidity of the diluted bacterial solution was adjusted [27].

Overall antimicrobial experiment view

Antimicrobial activities of synthesized Cu-TiO₂-PP (Copper-Titanium dioxide-Polypropylene) and CuO-TiO₂-PP (Copper oxide-Titanium dioxide-Polypropylene) were determined using *Candida albicans* (ATCC 10231) and *Staphylococcus epidermidis* (ATCC 12228) (Sigma Aldrich) strains. PP served as the experiment's control. Mueller-Hinton broth (Merck) was used to culture the bacteria in an incubator for eighteen hours at 37°C and 100 rpm. Each 24 well plate received 1.5 ml of sterile media and 2 µl of microbial culture (tuned to 0.5 McFarland Standard 10⁸ CFU/mL). Test discs with a diameter of 1/2 inch were sterilized and positioned in an aseptic 24-well plate to evaluate the antimicrobial activities. For 24, 36, 72, and 96 hours, respectively, prepared 24-well plates carrying the antibacterial test disc sample with impregnated strain were maintained in an incubator at 37°C and 100 rpm. Following the corresponding incubation period, 100 µl of media from 24-well plate was aliquot and serially diluted (10⁶) in sterile 1X Phosphate Buffered Saline (PBS). Then 100 µl of 1X PBS is aliquot from the diluted well and spread onto the prepared plates (Mueller Hinton and Potato Dextrose Agar, Merck). Antibacterial test discs were aseptically removed from 24-well plates using sterile forceps and subsequently washed three times with 1X PBS. The antibacterial test disc samples were aseptically inserted into a fresh 24-well plate that had been sterilized (1.5 ml of PBS), and they were incubated at 37°C and 400 rpm for 40 minutes to guarantee the elimination of the non-adherent cells. Subsequent to incubation, 100 µl of solution was taken from each well, serially diluted (10⁶) and plated onto prepared agar (Mueller Hinton and Potato Dextrose Agar, Merck) for recovery of undamaged microbes. Following a 24-hour incubation period at 37°C, the CFU/mL was measured on the plates. For every material tested, three duplicate plates were used. Figure 1 depicts the overall layout of the antimicrobial activity experiment.

Phase 1:

After the respective incubation time, 100 µl of media from 24-well plate was aliquot and serially diluted (10⁶) in sterile PBS. Then 100 µl of PBS is aliquot from the diluted well and plated on prepared media. Figure 2 illustrates the experimental layout for Phase 1 of the antimicrobial activity investigation.

Phase 2:

Afterwards, sterile forceps were used to remove the test discs (control, sample A, and sample B) from the 24-well plates, and they were thoroughly cleaned 3 times using PBS solution. The antibacterial test disc samples were put in the fresh, aseptic 24-well plate to guarantee that the non-adherent cells were eliminated. In each test disc's plate well, 1.5 ml PBS solution was pipetted on. Cell culture plates containing antibacterial test disc samples immersed in PBS were incubated at 37°C with orbital shaking at 400 rpm for 40 minutes. Figure 3 presents the layout of the antimicrobial activity experiment for Phase 2 of the investigation.

Statistical analysis

Statistical computations were carried out using SPSS Statistics 20 software. Descriptive statistics are presented as mean ± standard deviation. Within-group differences were analyzed with paired samples t-tests, and significance was set at $p < 0.05$, adhering to the protocol described by Sahgal et al. (2009).

Results and discussion

Microstructural analysis of Cu-TiO₂-PP and CuO-TiO₂-PP composites

The Cu-TiO₂ nanoparticles exhibited an elliptical form, with sizes around 20 nm across and 35 nm in length [28]. SEM analysis of the commercial powders showed that TiO₂ particles were spherical and agglomerated, averaging 25 nm, while CuO particles appeared flaky with a size of about 5 μm [29]. SEM morphology of the CuO-TiO₂-PP composites containing 3 wt% CuO-TiO₂ revealed a uniform dispersion and good encapsulation of particles within the polypropylene matrix [29]. In contrast, the Cu-TiO₂-PP composites at 3 wt% loading exhibited slight nanoparticle agglomeration and a brittle fracture surface [28]. Notably, the hydrothermally synthesized Cu-TiO₂ nanoparticles were smaller than the commercial CuO-TiO₂ particles, a characteristic likely contributing to enhanced antibacterial activity. These microstructural observations align with findings reported in our previous studies [28, 29].

Mechanical properties of Cu-TiO₂-PP and CuO-TiO₂-PP composites

The average strength under tension, modulus young, and tensile strain of the dual-metal oxide polypropylene (PP) composites containing 3 wt% PP-g-MAH are summarized in Table 1. Notably, the incorporation of up to 3 wt% of the dual-metal oxide filler agent did not adversely affect the inherent mechanical properties of pure PP. Typically, higher loadings of antimicrobial agents in the PP matrix lead to weakened structures due to factors such as increased porosity, agglomeration of particles, poor interfacial adhesion, and inadequate encapsulation, all of which contribute to mechanical deterioration. However, in this study, the addition of 3 wt% PP-g-MAH compatibilizer effectively mitigated these issues by promoting a more homogeneous dispersion of the antimicrobial agent within the PP matrix, thereby preserving the composite’s mechanical integrity.

Table 1
Tensile properties of Cu-TiO₂-PP and CuO-TiO₂-PP composites

No.	Sample	Strength under tension, σ (MPa)	Modulus young, E (MPa)	Maximal strain, ε (%)
1	Pure PP	28 ± 2.10	956 ± 49.7	8.63 ± 2.50
2	Cu-TiO ₂ -PP 3wt%	27 ± 0.53	1154 ± 22.9	10.2 ± 0.42
3	CuO-TiO ₂ -PP 3wt%	28 ± 0.50	923 ± 63.0	10.6 ± 0.80

Thermal transitions and crystallization dynamics of CuO-TiO₂-PP and Cu-TiO₂-PP composites

Differential scanning calorimetry (DSC) analysis was conducted on pure polypropylene (PP) and the dual-metal oxide composites CuO-TiO₂-PP and Cu-TiO₂-PP, each containing 3 wt% compatibilizer. The results are summarized in Table 2 reveal differences in melting behavior and crystallinity upon incorporation of the dual-metal oxide fillers.

Table 2
DSC characterization of dual-metal oxide CuO-TiO₂-PP and Cu-TiO₂-PP composite materials

No.	Sample	T _m (°C)	ΔH _f (J/g)	Crystallinity (%)
1	Pure PP	163.15	69.55	33.28
2	CuO-TiO ₂ -PP 3wt%	164.65	52.87	27.06
3	Cu-TiO ₂ -PP 3wt%	163.87	40.32	20.63

The melting temperature of pure PP was recorded at 163.15°C, consistent with literature values for isotactic PP. Upon incorporation of the dual-metal oxide fillers, a slight increase in T_m was observed for both nanocomposites, particularly for CuO-TiO₂-PP (164.65°C) and to a lesser extent for Cu-TiO₂-PP (163.87°C). This modest elevation suggests a possible nucleating effect from the embedded metal oxide particles, which may marginally influence the packing order of PP chains, thereby requiring more thermal energy to initiate melting. However, the overall impact on T_m is minimal, indicating that the crystalline phase remains largely dominated by the PP matrix, and the nanofillers primarily affect the degree of crystallinity rather than the crystalline phase structure itself [30].

A clear downward trend is observed in the enthalpy of fusion and corresponding crystallinity as fillers are introduced whereby pure PP exhibits the highest ΔH_f (69.55 J/g) and crystallinity (33.28%). CuO-TiO₂-PP reduces crystallinity to 27.06%, with ΔH_f dropping to 52.87 J/g while Cu-TiO₂-PP shows the most pronounced reduction, with ΔH_f of 40.32 J/g and crystallinity of just 20.63%. This reduction in crystallinity upon nanoparticle incorporation can be explained by several interrelated factors. The incorporation of metal oxide nanoparticles disrupts the regular packing of PP chains [31]. These nanoparticles tend to occupy interlamellar or interspherulitic regions, physically hindering the growth of crystalline lamellae during cooling. The more agglomerated or poorly dispersed the particles, the more pronounced this effect becomes. As for the CuO-TiO₂-PP, the commercial CuO used here exists in micrometer-scale flakes (~ 5 μ m), while TiO₂ is in nano-range. The size mismatch and less uniform dispersion may cause moderate disruption to crystal formation, explaining the partial reduction in crystallinity. For Cu-TiO₂-PP, this composite uses hydrothermally synthesized nanoparticles with nanoscale size (~ 20–35 nm) and more uniform dispersion, leading to greater interfacial interaction with the polymer chains. Their higher accessible surface area enhances physical hindrance and restricts polymer chain mobility more effectively during crystallization, thus reducing crystallinity more significantly [32].

Besides, the nature of the copper species plays a crucial role. Elemental Cu (in Cu-TiO₂-PP) is more reactive, and its surface can interact more strongly with the PP matrix, especially in the presence of the maleated PP-g-MAH compatibilizer. This results in enhanced interfacial adhesion, which, while mechanically beneficial, further inhibits chain folding and alignment, contributing to lower crystallinity. CuO (in CuO-TiO₂-PP), being more stable and oxidized, exhibits lower surface reactivity and less interfacial bonding with PP chains. As a result, it interferes less with chain crystallization compared to elemental Cu.

The significant decrease in crystallinity, especially for Cu-TiO₂-PP, indicates a higher proportion of amorphous regions, which are generally more permeable and hydrophilic than crystalline zones. This structural feature is particularly relevant to antimicrobial performance, as it facilitates greater water uptake and enhances ion mobility and diffusion from the embedded nanoparticles. It improves the release profile of Cu²⁺ ions, contributing to the superior antifungal activity observed in Cu-TiO₂-PP.

Antimicrobial activity of Cu-TiO₂-PP and CuO-TiO₂-PP composites

The bactericidal assessment of PP, Cu-TiO₂-PP and CuO-TiO₂-PP were carried out against *C. albicans* and *S. epidermidis*. Table 3 presented the growth of microbes from the well for control, Cu-TiO₂-PP and CuO-TiO₂-PP. Supplementary Figs. 1 and 2 display the number of colonies counts the pellets for tested microbes after the 40 min of washing with PBS.

Candida albicans

Cu-TiO₂-PP and CuO-TiO₂-PP composites are more effective on antimicrobial activity against *C. albicans* (Supplementary Fig. 1). A notable decline in the attachment and colonization of *C. albicans* was seen, with a *p*-value less than 0.05. This demonstrated the effectiveness of the antimicrobial agents derived from Cu-TiO₂-PP and CuO-TiO₂-PP in preventing *C. albicans* from growing. In this finding, the Cu-TiO₂-PP displays prominent antimicrobial effectiveness for *C. albicans*, compared to CuO-TiO₂-PP. Under normal conditions *C. albicans* exist as single yeast cells which reproduce through budding while under physical stress conditions it may develop to pseudohyphae form [33, 34]. One of the main opportunistic fungal *C. albicans*, may alter its morphology from a spherical to a filamentous state in response to environmental stimuli [33]. The PP matrix which is hydrophobic is a suitable support for the attachment of this yeast like dimorphic fungus. According to previous studies, hydrophobicity of the cell surface affects the pathogenesis of *C. albicans* [35]. As a result, the PP matrix has many colonies attached to it. However, on day 1 there was no colony count on Cu-TiO₂-PP and CuO-TiO₂-PP (Supplementary Fig. 1). This may be due to the hydrophilic characteristic of Cu-TiO₂-PP and CuO-TiO₂-PP. It was also reported that the hydrophilic proteins related to the adhesion on the surface vary during the growth of *C. albicans* [35]. As a result, on day 2, there are more colonies in Cu-TiO₂-PP and CuO-TiO₂-PP than in the control. This indicated

the possibility that *C. albicans* might have carried out alteration on hydrophilic fibrillar protein components [35]. The samples showed signs of cell attachment after 24 h. Nevertheless, on day 3 the count decreased extremely. This may be due to the significant effect of antibacterial agents from Cu-TiO₂-PP and CuO-TiO₂-PP. As per Sahgal et al., report, *C. albicans* will form a mucus-like material to protect itself from any antimicrobial agent and will be killed for continuous exposure of antimicrobial agent [36]. *C. albicans* attached to the surface, secreted substance to protect the cells, then finally the antimicrobial agent could inhibit the growth may be through disrupt the cell wall and/or DNA. Earlier findings showed that Cu and TiO₂ in PP matrix has more than 90% efficiency in short time exposure against *C. albicans* [37]. These reports support strongly our findings that Cu-TiO₂-PP and CuO-TiO₂-PP have significant growth inhibitory and/or killing effects on *C. albicans*.

Table 3. Average colony forming counts for four days on tested microbes directly from 24 well-plates

		<i>S. epidermidis</i>						<i>C. albicans</i>					
		Control		Sample A		Sample B		Control		Sample A		Sample B	
		mean x10 ⁶	sd	mean x10 ⁶	sd	mean x10 ⁶	sd	mean x10 ⁶	sd	mean x10 ⁶	sd	mean x10 ⁶	sd
Day 1	lawn	-	-	lawn	-	lawn	-	lawn	-	lawn	-	lawn	-
Day 2	lawn	-	-	lawn	-	lawn	-	lawn	-	lawn	-	lawn	-
Day 3	lawn	-	-	lawn	-	lawn	-	lawn	-	lawn	-	lawn	-
Day 4	lawn	-	-	lawn	-	lawn	-	lawn	-	1.33	0.57	-	-

Note: sample A: Cu-TiO₂-PP and sample B: CuO-TiO₂-PP, while PP served as the experiment's control

Staphylococcus epidermidis

Supplementary Fig. 2 shows the antimicrobial activity of Cu-TiO₂-PP and CuO-TiO₂-PP against *S. epidermidis*. Cu-TiO₂-PP and CuO-TiO₂-PP are not promisingly inhibiting the growth or attachment of *S. epidermidis*. It has been proved that the PP matrix alone was not conducive to the attachment and growth of *S. epidermidis*. PP is characterized as hydrophobic (Supplementary Fig. 2) matrix while *S. epidermidis* prefers hydrophilic condition for propagation [38]. Thus, on the 1st day a high number of colony counts were observed but the trend did not continue for following treatment days. Thus, *S. epidermidis* cannot proliferate or attach itself to PP matrix alone. However, attachments of microbes were detected for samples Cu-TiO₂-PP and CuO-TiO₂-PP on day 2 and this was decreased on day 3 and day 4. This could be due to the hydrophilic component, TiO₂, which was present in the samples (Supplementary Fig. 2). The colony counts increased for Cu-TiO₂-PP and CuO-TiO₂-PP may be due to insufficient antimicrobial agent in the pellet to react with the attached *S. epidermidis*. Thus, the microbes were able to repropagate gradually. For Cu-TiO₂-PP the number of colonies have decreased on the 2nd day while for CuO-TiO₂-PP it happened on the 3rd day compared to that on the 2nd day. In the case of CuO-TiO₂-PP, *S. epidermidis* attached on the 1st day and it continued the propagation on the 2nd day while the effect of antimicrobial agent was started only on the 3rd day. This phenomenon arises from the thick peptidoglycan layer that characterizes the Gram-positive bacterial cell wall [39]. The number of colonies increased for Cu-TiO₂-PP on day 3 and day 4 while for CuO-TiO₂-PP it has increased on day 4. This indicated that the amount of Cu²⁺ as antimicrobial agent was depleted on day 4. Thus, there was an increase in attachment or growth for *S. epidermidis*. The results indicate that higher concentrations of dual biocidal agents (i.e., Cu-TiO₂ and CuO-TiO₂) within the polypropylene matrix are required to effectively inhibit *S. epidermidis* colonization; thus, further investigations are needed to optimize their antimicrobial efficacy.

Comparative Antimicrobial Mechanisms of Cu-TiO₂-PP and CuO-TiO₂-PP Composites

Cu-TiO₂-PP composites exhibit stronger antimicrobial efficacy compared to CuO-TiO₂-PP, largely due to differences in copper speciation, particle size, and surface properties. In Cu-TiO₂-PP, copper exists primarily in a more elemental or reduced state, facilitating a controlled and sustained release of copper ions (Cu²⁺), which are known to disrupt bacterial cell walls and inactivate essential enzymes, leading to cell death. This controlled ion release maintains effective antimicrobial activity over time while

minimizing environmental toxicity and resistance development. Conversely, CuO-TiO₂-PP releases copper ions more slowly or less efficiently due to the stable oxide form of copper, resulting in a potentially prolonged but less immediate antimicrobial effect. Furthermore, the synergistic photocatalytic activity between copper and TiO₂ in Cu-TiO₂-PP may be enhanced compared to CuO-TiO₂-PP. Under light exposure, this interaction can generate reactive oxygen species (ROS), which are potent microbial killers. The elemental copper state in Cu-TiO₂-PP likely improves this photocatalytic efficiency, contributing to superior antimicrobial effects.

Particle size is a critical determinant of antimicrobial potency. The Cu-TiO₂-PP composite consists of nanoscale particles, ensuring homogenous dispersion within the polypropylene matrix and enabling enhanced penetration and disruption of microbial cells and biofilms. In contrast, CuO-TiO₂-PP contains micron-sized CuO particles alongside nanoscale TiO₂, resulting in heterogeneous distribution and diminished antimicrobial activity [10, 40]. Given that bacterial cells measure micrometers with nanometer-sized pores in their membranes, nanoparticle-sized antimicrobial agents can more effectively interact with and penetrate bacterial structures [10]. Lastly, environmental factors such as pH, temperature, and organic matter can modulate copper ion release and antimicrobial efficacy. The physicochemical stability and reactivity of Cu-TiO₂-PP likely confer broader applicability and effectiveness across varied conditions compared to CuO-TiO₂-PP.

In summary, the enhanced antimicrobial activity of Cu-TiO₂-PP arises from its elemental copper state, nanoscale particle size, improved hydrophilicity, optimized copper ion release, and potential for photocatalytic ROS generation, all contributing to superior inhibition of microbial colonization relative to CuO-TiO₂-PP.

Conclusion

This study successfully developed and characterized a novel polypropylene-based nanocomposite Cu-TiO₂-PP that integrates elemental copper and titanium dioxide nanoparticles through a hydrothermal synthesis route. The composite demonstrated strong antifungal activity against *Candida albicans*, primarily due to the homogeneous nanoparticle dispersion, increased amorphous content in the polymer matrix, and the sustained release of biocidal Cu²⁺ ions. These findings highlight the effectiveness of the dual-metal oxide system in disrupting fungal colonization, underscoring its potential as an inherently antimicrobial material for infection-prone surfaces. In contrast, the composite exhibited limited antibacterial activity against *Staphylococcus epidermidis*, a result likely tied to the Gram-positive cell wall structure and insufficient release of active copper species at the current loading. This suggests that optimization of filler concentration and surface chemistry may be necessary to broaden the antimicrobial spectrum, particularly against bacteria with thicker peptidoglycan layers. Importantly, the composite retained its mechanical integrity at 3 wt% loading, affirming its suitability for structural applications in medical devices. The observed reduction in crystallinity further supports its potential to enhance antimicrobial ion diffusion while maintaining functional properties. This work marks a significant step toward non-antibiotic-based infection control strategies, particularly in the context of rising antibiotic resistance. The use of a dual-metal oxide system within a thermoplastic matrix offers a scalable, cost-effective, and biocompatible solution for next-generation antimicrobial coatings. Potential applications include intravenous catheters, ports, dialysis tubing, and other indwelling medical devices where biofilm prevention is critical.

Declarations

Authors Contributions

G Ambarasan Govindasamy: Conceptualization; Data curation; Investigation; Methodology; Writing - Original draft.

Srimala Sreekantan: Funding acquisition; Resources; Administration; Supervision; Validation; Writing - Review & Editing.

Geethaa Sahgal: Investigation; Writing.

Khairul Arifah Saharudin: Investigation.

Ming Thong Ong: Investigation.

Priscilla Jayanthi Thavamany: Investigation.

Tan Aik Aun: Project administration; Funding acquisition.

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Data Availability

Not applicable.

Code Availability

Not applicable.

Ethical Approval

Not applicable.

Consent for Publication

As the authors of this manuscript, we hereby consent to the publication of this work in this journal.

Conflict of Interest

The authors declare no competing interests.

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Figures

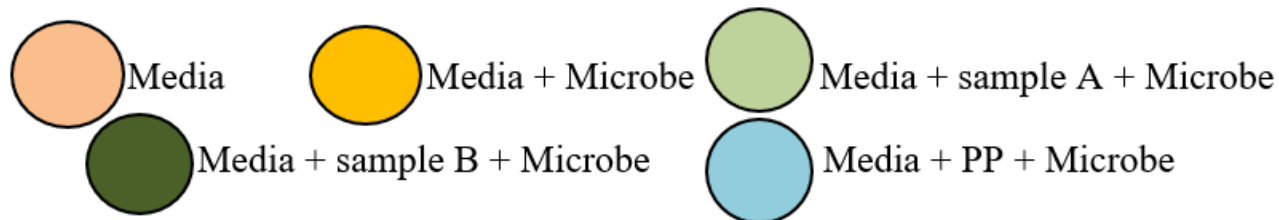
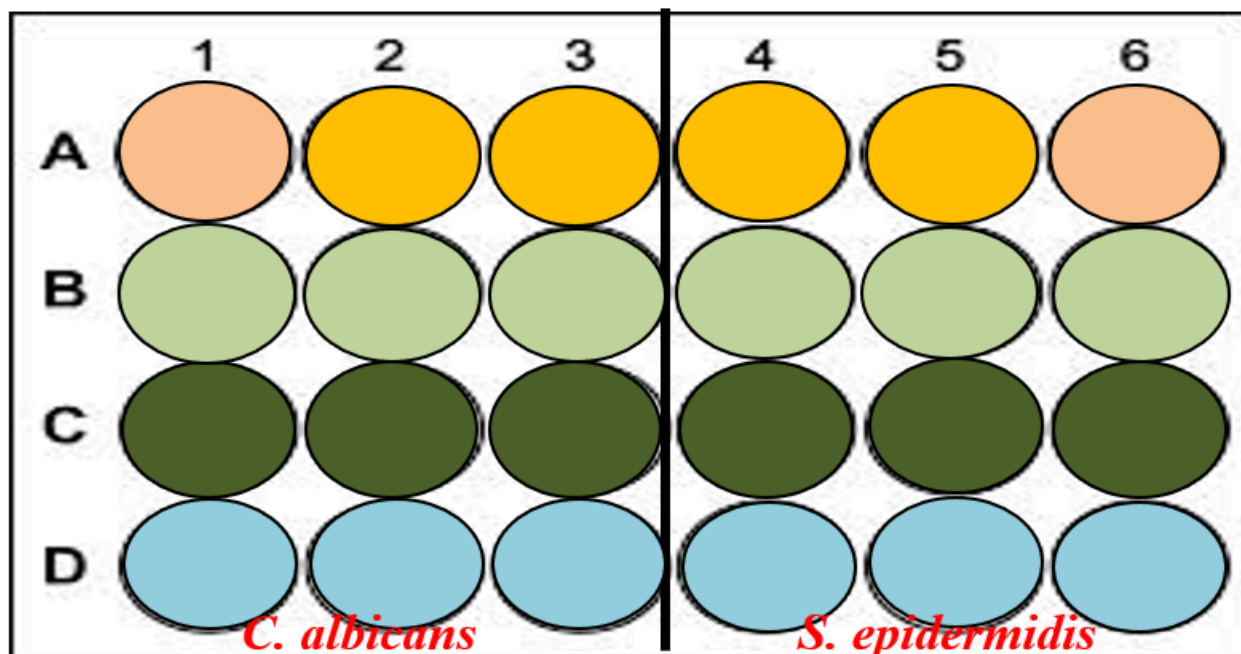


Figure 1

The overall antimicrobial activity experiment layout. Note: sample A: $\text{Cu-TiO}_2\text{-PP}$ and sample B: $\text{CuO-TiO}_2\text{-PP}$

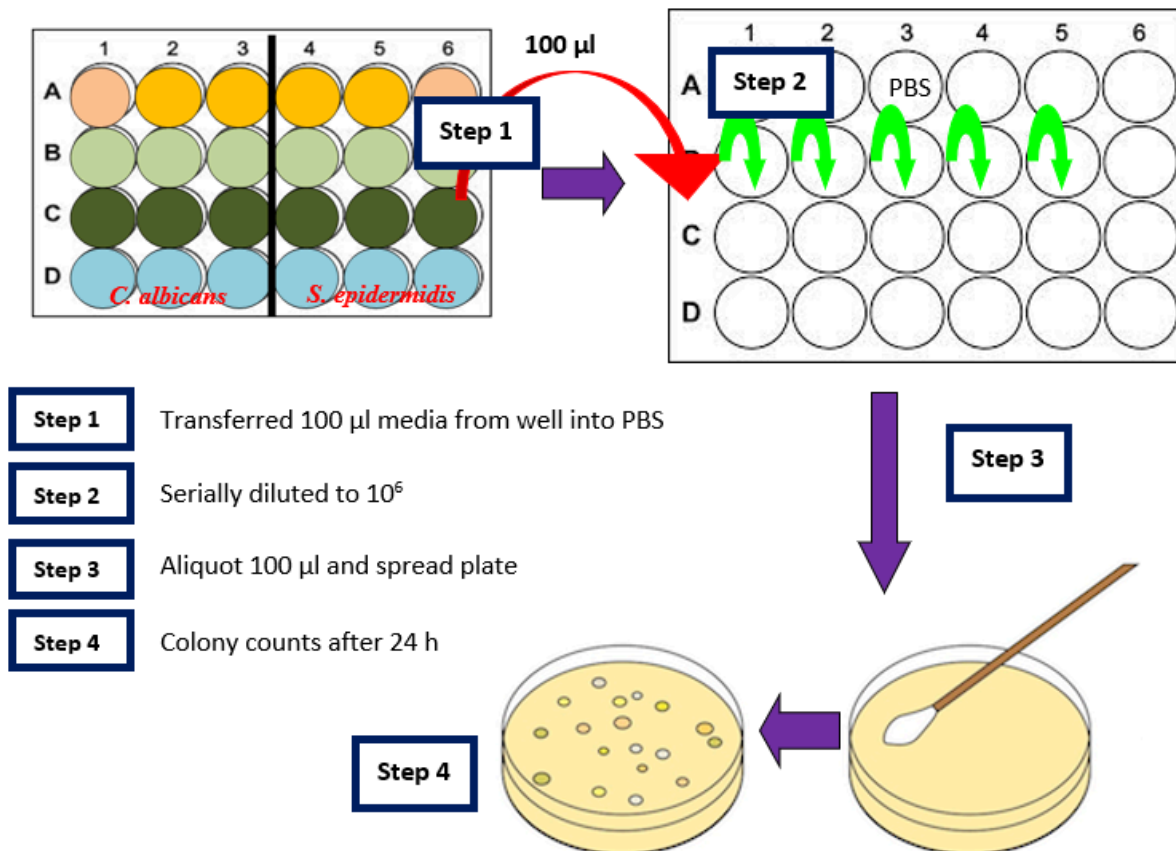
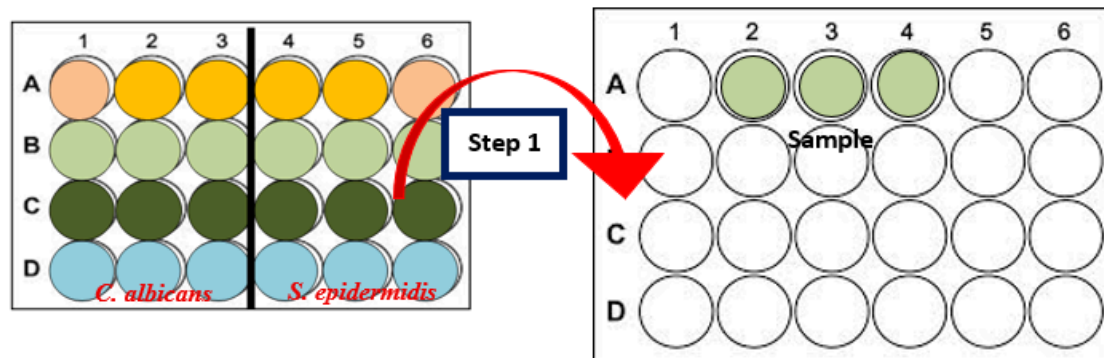


Figure 2

Phase 1 investigation layout for antimicrobial activity



- Step 1** Transferred the pellets from well into PBS well
- Step 2** Incubate for washing process at 400 rpm, 37 °C for 40min
- Step 3** Serially diluted to 10^6
- Step 4** Aliquot 100 μ l and spread
- Step 5** Colony counts after 24 h

Figure 3

Phase 2 investigation's antimicrobial activity layout

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