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Long-Term Antimicrobial Durability of Visible-Light Photocatalytic Coatings for Indoor Environmental Surfaces

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Abstract

Microbial contamination of indoor environmental surfaces contributes to the transmission of infectious diseases and poses ongoing challenges for maintaining hygienic indoor environments. Conventional disinfectants typically provide only temporary antimicrobial effects and require repeated application, while some technologies such as ultraviolet irradiation may introduce safety or operational limitations. Therefore, durable antimicrobial surface technologies capable of continuous microbial inactivation under indoor lighting conditions are highly desirable. In this study, a visible-light responsive photocatalytic coating was developed for long-term antimicrobial protection of indoor surfaces. The coating formulation consists of a photocatalyst, a photosensitizer, and a functional binder designed to sustain photocatalytic activity under typical indoor illumination. The dispersion exhibited a particle size of 196.2 nm, zeta potential of 10.9 mV, surface tension of 33.20 mN m^{-1}, and low viscosity suitable for coating applications. The prepared sample was spraying coating on the wall of a salon. Long-term field monitoring using ATP bioluminescence measurements showed that coated surfaces maintained relative light unit (RLU) values well below the hygiene benchmark of 1500 over a period of up to 48 months. These results demonstrate the potential of visible-light photocatalytic coatings as durable antimicrobial solutions for improving indoor environmental hygiene.

Keywords : Visible light active-Photocatalyst, long-term antimicrobial coating, spray coating, indoor environment

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1.0 INTRODUCTION

Indoor environmental hygiene has become an increasingly important public health concern as people spend the majority of their time in enclosed spaces such as homes, offices, hospitals, schools, and public transportation facilities (Leech et al., 2002). Microbial contamination of indoor surfaces can facilitate the transmission of pathogens through direct contact or indirect transfer via fomites, contributing to the spread of infectious diseases (Boone & Gerba, 2007). In high-traffic environments, contaminated surfaces can act as reservoirs for bacteria and viruses, posing risks to occupants and complicating infection control strategies (Appiah et al., 2025).

Conventional surface disinfection practices typically rely on chemical disinfectants such as alcohol-based solutions, chlorine compounds, and quaternary ammonium compounds. While these agents are effective in rapidly inactivating microorganisms upon application, their antimicrobial activity is generally short-lived due to evaporation, degradation, or removal from surfaces (Artasensi et al., 2021; Gallandat et al., 2021). Consequently, maintaining hygienic indoor environments requires frequent reapplication, increasing operational costs and raising concerns regarding chemical exposure and environmental impact (Salonen et al., 2024).

Various alternative technologies have been explored to provide continuous antimicrobial protection. Ultraviolet (UV) irradiation such as UVC 254 nm is widely used for microbial inactivation due to its ability to damage nucleic acids and inhibit microbial replication. However, continuous UV exposure in occupied indoor environments presents safety concerns, including potential harm to human skin and eyes, and may contribute to the formation of undesirable secondary pollutants such as ozone under certain conditions (Park et al., 2022). In recent years, far-UVC radiation at 222 nm has been reported to be safe for use in occupied indoor environments. However, subsequent studies have indicated that its application may necessitate enhanced ventilation and air filtration to mitigate ozone accumulation. Furthermore, wavelengths around 230 nm have been shown to pose potential health risks to humans. (Park & Rim, 2024).

Photocatalytic materials have emerged as a promising strategy for developing self-disinfecting surfaces. Upon light irradiation, photocatalysts generate reactive oxygen species (ROS), including hydroxyl radicals (•OH), superoxide radicals (O_2•$^-$), and singlet oxygen ($^1O_2$), which can oxidatively damage microbial cell membranes, proteins, and nucleic acids (Koh et al., 2017; Leong et al., 2023). This mechanism enables continuous antimicrobial activity as long as light is available, offering advantages over conventional disinfectants.

Among various photocatalysts, titanium dioxide (TiO_2) has been extensively studied due to its chemical stability, strong oxidative capability, low toxicity, and cost-effectiveness (Abdelfattah & El-Shamy, 2024). Numerous studies have demonstrated its antibacterial and antiviral properties under ultraviolet illumination. However, the wide bandgap of TiO_2 (~3.2 eV) limits its activation primarily to UV light, which is scarce in typical indoor environments, thereby restricting its practical application (Sari et al., 2024).

To overcome this limitation, significant research efforts have focused on developing visible-light responsive photocatalysts. Strategies such as metal and non-metal doping, heterojunction construction, and photosensitization have been explored to extend light absorption into the visible spectrum (Mao et al., 2024; Yu et al., 2025). Among these, photosensitizer-modified systems are particularly attractive due to their ability to efficiently harvest indoor light and enhance photocatalytic performance under low-intensity illumination conditions (Hamza et al., 2023).

Despite these advancements, most studies have focused on short-term antimicrobial performance under controlled laboratory conditions. The long-term durability and stability of photocatalytic coatings under real environmental conditions remain insufficiently investigated. In practical applications, coatings are subjected to environmental stressors such as dust accumulation, mechanical wear, and routine cleaning, all of which can significantly affect performance over time. Therefore, evaluating long-term antimicrobial durability is essential for assessing real-world applicability.

In this study, a visible-light responsive photocatalytic coating was developed for long-term antimicrobial protection of indoor environmental surfaces. the long-term durability was assessed through field monitoring using ATP bioluminescence measurements over a period of up to 18 months. This study aims to bridge the gap between laboratory-scale evaluation and real-world application by demonstrating both rapid antimicrobial efficacy and extended durability of visible-light photocatalytic coatings.

2.0 MATERIALS AND METHODS

2.1 Materials

The photocatalytic coating formulation was developed in-house using a proprietary composition. The formulation consists of a titanium dioxide (TiO_2)-based photocatalyst, a visible-light responsive photosensitizer, and a polymeric binder. The detailed composition and ratios of the components are confidential for intellectual property protection. All chemicals were used as received without further purification. Deionized water was used as the dispersion medium for all formulations.

2.2 Physical Characterization

A series of physicochemical characterizations were performed to determine the intrinsic properties of prepared photocatalyst. The pH was measured using a calibrated pH meter (Mettler Toledo). Density was determined using a microbalance (Vibra, AJ-620E) in combination with a micropipette (DragonLab). Particle size distribution and zeta potential were analyzed with a Malvern Zetasizer (Nano ZS, ZEN3600). Surface tension was measured using a surface tension analyzer (SEO, DCA-200). and viscosity was further evaluated using a rotational viscometer (Anton Paar, ViscoQC-300).

2.3 Third-Party Laboratory Tests

2.3.1. Antiviral Activity

The antiviral activity of the prepared photocatalyst was evaluated in accordance with the quantitative suspension test method for virucidal activity, based on EN 14476:2013+A2:2019 (E), under 100% concentration and clean conditions (0.30 g L^{-1} bovine albumin solution).Human coronavirus strain 229E (ATCC VR-740) was used as the model virus. The photocatalyst sample, in liquid form, was directly mixed with a standardized viral suspension and incubated under controlled conditions for 5 minutes. Following contact time, the reaction was neutralized, and the remaining infectious viral particles were quantified using the tissue culture infectious dose ($TCID_{50}$) method. The antiviral efficacy was expressed as the reduction in viral infectivity relative to an untreated control sample.

2.3.2. Antibacterial Activity

Antibacterial activity of photocatalyst sample was assessed according to EN 1276:2019 (E) using *E. hirae (ATCC 10541)*, *S. aureus* (ATCC 6538), *E. coli* (ATCC 10536) and *P. aeruginosa* (ATCC 15442). The photocatalyst sample was tested at 100% concentration for 5 minutes, at 20 ℃ and under clean condition. Afterwards, an appropriate neutralization step was performed to quench the antimicrobial activity of the photocatalyst.The number of surviving bacteria was then determined using standard plate counting methods, and the results were expressed as colony-forming units (CFU). Antibacterial efficacy was calculated as the reduction in viable bacterial counts compared to an untreated control sample. Log reduction values ($\log_{10}$ reduction) were also determined to quantify antimicrobial performance.

2.4 Preparation of Photocatalytic Coating and Durability Study

The photocatalytic coating was used as received without further dilution, as it was pre-homogenized in an aqueous medium. Prior to application, the formulation was gently shaken to ensure uniform dispersion. The coating was applied directly onto target surfaces using an electrostatic spraying system (Victory Innovations backpack sprayer) equipped with a medium nozzle (80 μm). The flow rate was maintained at approximately 150 mL min^{-1} to ensure consistent deposition.

Application was carried out to cover the entire interior surface area, including walls, floors, furniture, and high-touch surfaces such as door handles and chair armrests. A two-layer coating strategy was employed to achieve uniform coverage. The first layer was applied in a horizontal spraying pattern, followed by drying under ambient conditions. After the first layer was completely dried, a second layer was applied in a vertical spraying pattern to enhance coating uniformity and surface coverage.

The coated surfaces were allowed to dry under ambient conditions prior to subsequent testing and field evaluation using a Kikkoman Lumitester and A3 swabs. The salon wall was irradiated 8 hours a day by a standard ceiling-mounted visible LED light tube (6500 K). The illuminance measured at the wall surface was approximately 600 lux. A 10 × 10 cm area of the wall was swabbed before and after coating, and monitoring was conducted continuously for up to 18 months.

3.0 RESULTS AND DISCUSSION

3.1 pH and Density

The prepared photocatalytic formulation exhibited a density of 1.032 g cm^{-3} and a near-neutral pH of 6.48, indicating good compatibility with common indoor surface materials and a low risk of corrosion or substrate damage. It is well established that the colloidal stability of TiO_2 nanoparticles is strongly dependent on pH, with stable dispersions typically achieved under highly acidic or alkaline conditions. For instance, TiO_2 particles can remain well dispersed in strongly acidic environments (pH < 3) (Kaneko, 2019). The isoelectric point (IEP) of TiO_2 is generally reported in the range of pH 5–6, where the net surface charge approaches zero and particle aggregation is favored (Galletti et al., 2016). Consequently, stable dispersions are typically obtained at pH values far from the IEP, either under acidic or alkaline conditions.

However, such extreme pH conditions are not suitable for practical coating applications due to concerns related to material compatibility, user safety, and potential surface degradation. Therefore, achieving stable TiO_2-based photocatalytic coatings under near-neutral conditions remains a significant formulation challenge. In the present system, slight aggregation was observed after prolonged standing, which is consistent with the moderate zeta potential of the dispersion. Nevertheless, the formulation can be readily redispersed through mild agitation prior to application, restoring a homogeneous suspension suitable for coating processes. This reversible aggregation behavior indicates that the system maintains adequate practical stability for real-world use.

3.2 Particle Size Distribution and Zeta Potential

The particle size distribution exhibits a multimodal profile, with a dominant peak in the range of approximately 100–200 nm, secondary populations between 300–1200 nm, and a tail extending to around 5500 nm. The average hydrodynamic particle size was measured to be 196 nm. As DLS measures hydrodynamic diameter, the reported size includes contributions from particle aggregation and interactions with the binder matrix, which are commonly observed in practical coating formulations.

The presence of a dominant 100-200 nm particles size population indicates that a significant fraction of the photocatalyst particles is well dispersed within the aqueous medium. However, the existence of secondary peaks and larger aggregates suggests partial aggregation within the system, which is consistent with the moderate zeta potential of 10.9 mV observed.

Such multimodal distributions are frequently seen in TiO_2-based dispersions, particularly in formulated systems containing binders or additives for stabilization. Importantly, particles in the range of 100–200 nm remain advantageous for photocatalytic applications due to the improved distribution of TiO_2 particle, which enhanced photocatalytic acitivity (Greco et al., 2025), while limited aggregation may contribute to improved coating integrity and adhesion (Faure et al., 2013).

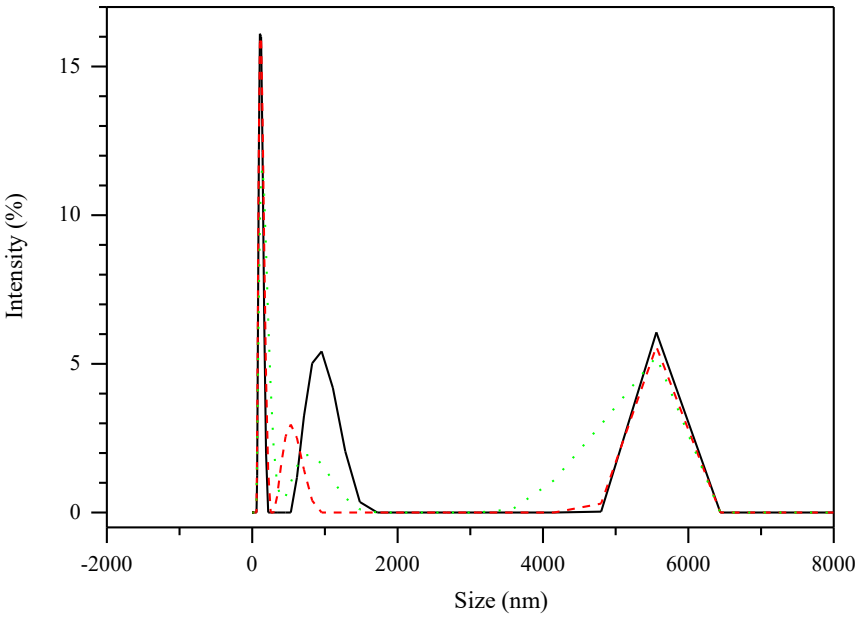


Figure 1: Hydrodynamic Particle Size Distribution of Photocatalyst

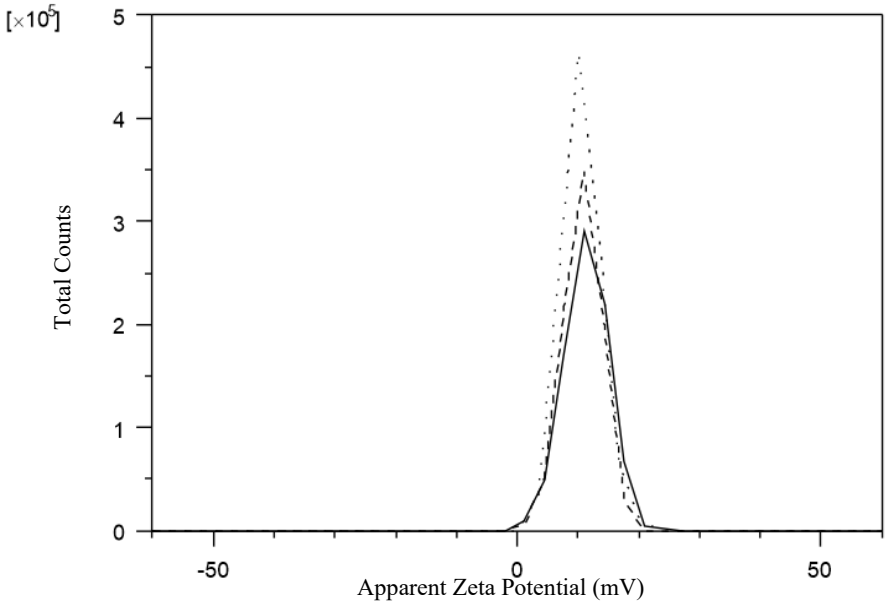


Figure 2 : Zeta Potential of Photocatalyst

3.3 Viscosity

The viscosity of the photocatalytic coating ranged from 11.08 to 15.90 cP over a rotational speed of 50–150 rpm. Although a slight increase in viscosity with increasing shear rate was observed, the variation was relatively small, indicating that the formulation exhibits near-Newtonian behavior within the tested shear range as supported by rheology study (Figure 3). The particle–particle interactions are minimal and the rheological behavior is primarily governed by the continuous aqueous phase. Similar near-Newtonian behavior has been widely reported for dilute colloidal dispersions (Tao et al., 2012).

The relatively low viscosity range (11–16 cP) indicates that the formulation remains a low-viscosity fluid, which is advantageous for spray coating applications. Low-viscosity systems facilitate atomization, improve surface wetting, and enable uniform film formation during application

Table 1: Viscosity of photocatalyst

Viscosity (using ViscoQC)	50 rpm, 11.08cP, 1.03%
	100 rpm 13.63cP, 3.02%
	150 rpm, 15.90cP, 5.6%

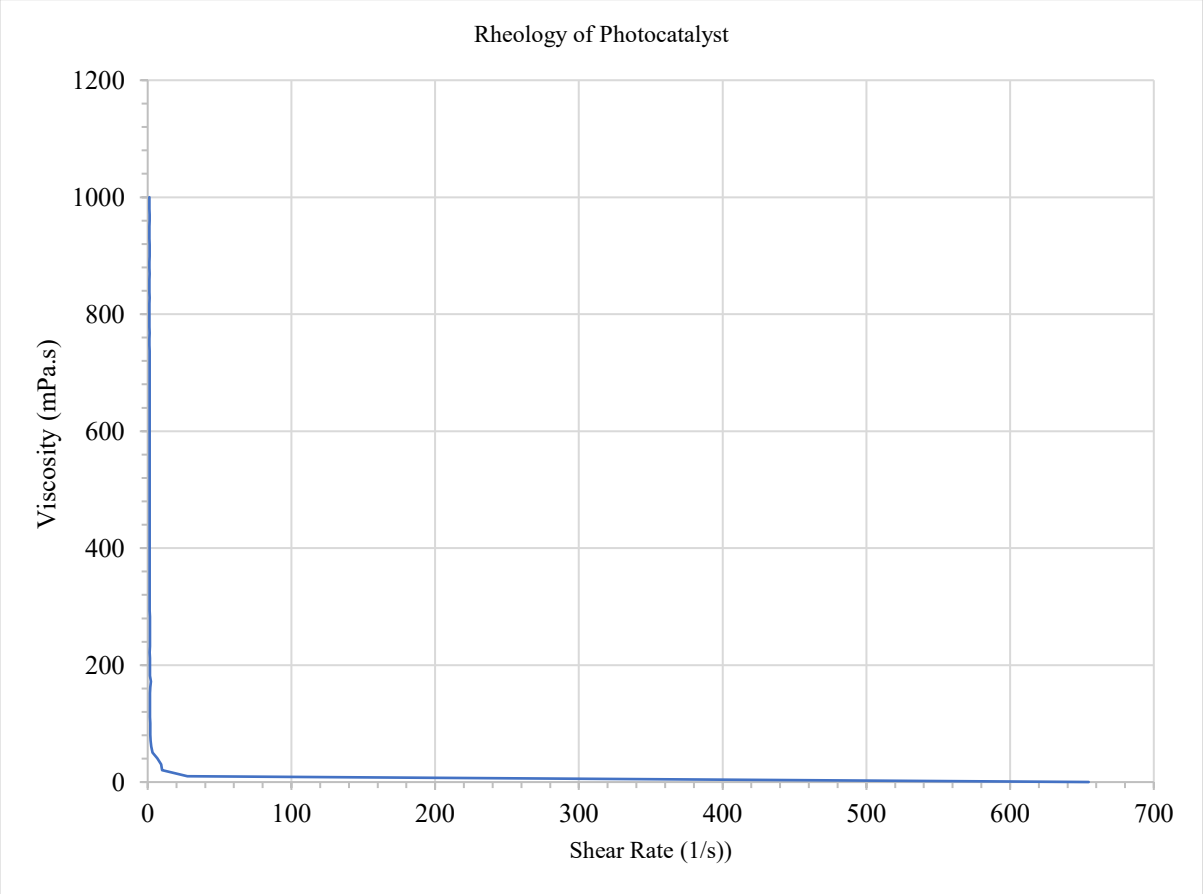


Figure 3 : Rheology behaviour of sample

3.4 Antiviral and Antibacterial Performance

The antimicrobial efficacy of the photocatalytic formulation was evaluated using quantitative suspension tests against a range of microorganisms, including one virus and four bacterial strains. The results are summarized in Table 2.

The photocatalyst demonstrated excellent broad-spectrum antimicrobial activity, achieving log reductions greater than 5.0 within 5 minutes for all tested organisms. Specifically, a log reduction of ≥ 5.32 ± 0.32 was observed against Human Coronavirus 229E, indicating highly effective antiviral activity. Similarly, strong antibacterial performance was recorded against

both Gram-positive and Gram-negative bacteria, including *Staphylococcus aureus* (≥ 5.33 ± 0.05), *Enterococcus hirae* (≥ 5.16 ± 0.05), *Escherichia coli* (≥ 5.38 ± 0.05), and *Pseudomonas aeruginosa* (≥ 5.16 ± 0.09).

A log reduction of ≥5 corresponds to a ≥99.999% reduction in microbial population, which is widely regarded as a high level of antimicrobial efficacy in disinfection standards ("EN 1276:2019- Chemical disinfectants and antiseptics- Quantitative suspension test for the evaluation of bactericidal activity of chemical disinfectants and antiseptics used in food, industrial, domestic and institutional areas- Test method and requirements (phase 2, step 1)," ; "EN 14476: 2013+A2:2019 - Chemical disinfectants and antiseptics - Quantitative suspension test for the evaluation of virucidal activity in the medical area - Test method and requirements (Phase 2/Step 1),"). The consistent performance across different microbial species suggests that the photocatalytic system exhibits broad-spectrum activity, independent of cell wall structure or microbial classification.

The rapid inactivation observed within a short contact time (5 min) indicates that the antimicrobial mechanism is highly efficient. This performance can be attributed to the generation of reactive oxygen species (ROS), such as hydroxyl radicals (•OH) and superoxide radicals (O_2•$^-$), which are known to induce oxidative damage to microbial cell membranes, proteins, and nucleic acids (Lazić et al., 2025). For viruses, particularly enveloped viruses such as Human Coronavirus 229E, ROS can disrupt the lipid envelope and denature viral proteins, leading to loss of infectivity (Ryosuke Matsuura, 2021).

Notably, the comparable log reduction values observed for both Gram-positive (*S. aureus*, *E. hirae*) and Gram-negative (*E. coli*, *P. aeruginosa*) bacteria suggest that the photocatalytic mechanism is non-selective and effective against different cell envelope structures. This aligns with previous studies reporting that photocatalytic disinfection is not limited by microbial resistance mechanisms, as oxidative damage affects multiple cellular targets simultaneously (Foster et al., 2011).

Table 2: Antiviral and antibacterial performance of prepared photocatalyst

Test Strain	Test Concentration (%) / min	Log reduction
Human Coronavirus ATCC VR-740	100%* / 5 min	≥ 5.32 ± 0.32
E. hirae ATCC 10541	100%* / 5 min	≥ 5.16 ± 0.05
E. coli ATCC 10536	100%* / 5 min	≥ 5.38 ± 0.05
P. aeruginosa ATCC 15442	100%* / 5 min	≥ 5.16 ± 0.09
S. aureus ATCC 6538	100%* / 5 min	≥ 5.33 ± 0.05

*The product can only be tested at 80% concentration or less, as some dilution always occurs when test organisms and interfering substance are added

3.5 Durability of Coating

The long-term antimicrobial performance of the photocatalytic coating was evaluated using ATP bioluminescence measurements, expressed as relative light units (RLU), as shown in Figure 4 and Figure 5. ATP measurement is widely used as a rapid and quantitative indicator of biological contamination on surfaces, where lower RLU values correspond to lower levels of microbial or organic residues (Bakke et al., 2019). ATP bioluminescence results are typically interpreted using application-dependent thresholds. In general hygiene monitoring, RLU values below approximately 1000–1500 are commonly considered indicative of acceptable surface cleanliness, although specific limits may vary depending on the monitoring system, surface type, and application context.

Prior to coating application, the surface exhibited a high RLU value of approximately 5400, indicating significant biological contamination. Following application of the photocatalytic coating, the RLU value decreased sharply to approximately 600, representing a substantial immediate reduction in surface contamination. Over the subsequent monitoring period, the RLU values further decreased to below 100 within the first month, and remained consistently low throughout the duration of the study. From month 1 to month 18, the RLU values were generally maintained below 500, which is well below the commonly accepted hygiene threshold for textured, indirect-contact surfaces.

A slight increase in RLU values was observed at later time points (6–18 months), which may be attributed to environmental exposure, surface wear, or accumulation of organic residues over time. However, the RLU values remained significantly lower than the pre-treatment level, indicating sustained antimicrobial effectiveness of the coating.

The rapid reduction in RLU immediately after application suggests effective initial antimicrobial activity, which can be attributed to the generation of reactive oxygen species (ROS) by the photocatalyst under ambient light conditions. These ROS are known to oxidatively degrade organic matter and inactivate microorganisms on surfaces (Leong et al., 2023).

Importantly, the ability of the coating to maintain low RLU values over an extended period demonstrates its long-term durability, which is a critical requirement for practical antimicrobial coatings. Many conventional disinfectants exhibit only short-term activity and require frequent reapplication, whereas photocatalytic systems can provide continuous antimicrobial effects under light irradiation.

Overall, the results demonstrate that the developed photocatalytic coating provides both rapid antimicrobial action and long-term durability, making it a promising solution for maintaining hygienic indoor surfaces.

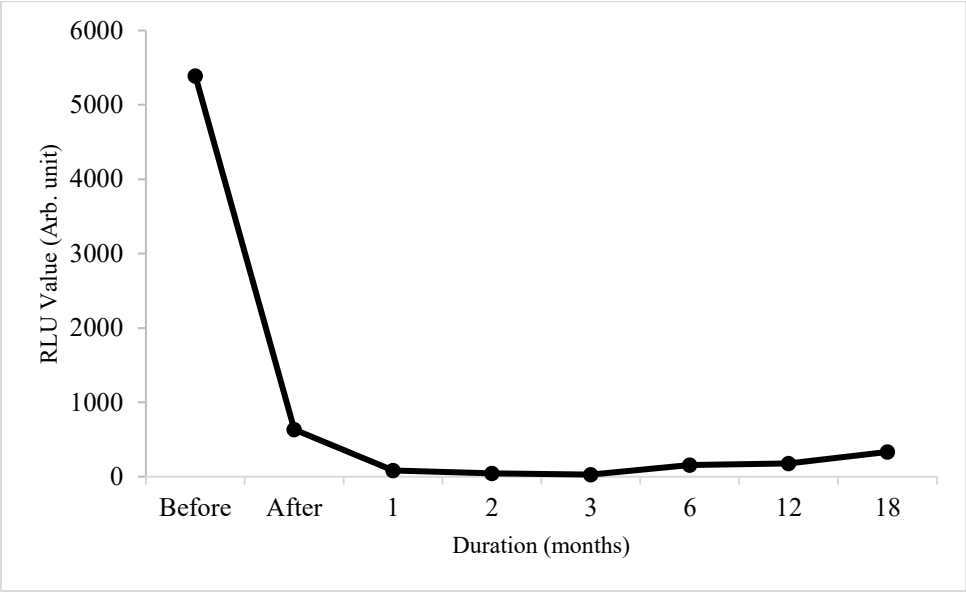


Figure 4: Long-term antimicrobial performance of the photocatalytic coating evaluated using ATP bioluminescence (RLU)



Figure 5: Images show the corresponding RLU values measured using a lumitester

4.0 CONCLUSION

A visible-light responsive photocatalytic coating was successfully developed for antimicrobial applications on indoor environmental surfaces. The formulation, consisting of a TiO_2-based photocatalyst, photosensitizer, and binder, exhibited suitable physicochemical properties for coating applications, including near-neutral pH, low viscosity, and stable dispersion behavior. The particle 100-200 size range distribution, together with moderate colloidal stability, enabled practical applicability while maintaining adequate performance. The photocatalytic formulation demonstrated excellent broad-spectrum antimicrobial activity, achieving ≥5 log reduction (>99.999%) against Human Coronavirus 229E and multiple bacterial strains within 5 minutes under suspension test conditions. This rapid inactivation highlights the intrinsic antimicrobial potency of the system, which is attributed to the generation of reactive oxygen species under light irradiation. In addition to its rapid antimicrobial efficacy, the

coating exhibited remarkable long-term durability in real environmental conditions. ATP bioluminescence monitoring showed sustained low contamination levels over an extended period, indicating continuous antimicrobial performance without the need for frequent reapplication. This addresses a key limitation of conventional disinfectants, which typically provide only short-term activity. Importantly, the formulation was designed to operate under near-neutral pH conditions, overcoming the common challenge of TiO_2 dispersion instability that typically requires strongly acidic or alkaline environments. This feature enhances material compatibility, user safety, and practical applicability for indoor use. Overall, the developed photocatalytic coating provides a combination of rapid antimicrobial action and long-term durability, demonstrating strong potential as a practical and sustainable solution for improving indoor environmental hygiene.

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