Innovation of High-Performance Nano Titanium Dioxide-Coated Wallpaper with Light-Diffusing Properties for Enhanced Brightness and Bacterial Reduction in Dental Room

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Abstract

Dental clinics require a clean environment with adequate illumination to support dental procedures and reduce the risk of bacterial contamination in both the air and on wall surfaces.
This study aimed to develop high-performance titanium dioxide (TiO_2) nanoparticle-coated wallpaper capable of enhancing light diffusion and reducing bacterial accumulation in dental clinics.
TiO_2 nanoparticles were synthesized using the sol-gel method and mixed with acrylic resin before being coated onto wallpaper by the doctor blade coating technique. Four TiO_2 concentrations (0, 1, 3, and 5 wt%) were investigated. The performance of the coated wallpaper was evaluated in three aspects: (1) photocatalytic activity using methylene blue as an indicator of organic degradation, (2) antibacterial performance by determining the number of airborne bacterial colonies cultured on agar plates inside a simulated chamber, and (3) light diffusion performance by measuring the increase in illumination using a lux meter. The results showed that the wallpaper coated with 3 wt% TiO_2 exhibited the highest photocatalytic activity, achieving the greatest degradation of organic compounds, and significantly reduced the number of bacterial colonies. In addition, it improved light diffusion and increased the illumination level inside the simulated chamber compared with uncoated wallpaper without requiring additional electrical energy. Furthermore, this project supports several United Nations Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Therefore, TiO_2 nanoparticle-coated wallpaper has strong potential as an interior wall material for dental clinics to promote hygiene, improve lighting efficiency, and support the sustainable use of resources.

Keywords: TiO_2 nanoparticle-coated wallpaper; photocatalysis; light diffusion; antibacterial activity; dental clinic

Introduction

Dental clinics require a clean and well-lit environment to ensure accurate treatment and minimize the risk of cross-infection. Dental procedures generate aerosols through high-speed hand-pieces and air–water syringes, facilitating the spread of airborne microorganisms. Previous studies identified seven major bacterial genera in dental clinics, including *Pseudomonas stutzeri, Staphylococcus* spp., *Streptococcus* spp., *Micrococcus* spp., *Enterobacter* spp., *Escherichia coli*, and *Bacillus* spp., with *Bacillus* spp. accounting for 24% of all isolates. The average airborne bacterial concentration also exceeded the WHO indoor air quality guideline of 500 CFU/m³, emphasizing the need for improved infection control. Adequate illumination is equally important for clinical accuracy and visual comfort. Thai standards recommend a minimum illuminance of 2,400 lux in dental treatment areas, which is commonly achieved using LED or fluorescent lamps with a correlated color temperature of 4,000–5,000 K, leading to substantial electricity consumption. Although wallpaper is widely used to improve the indoor atmosphere, conventional wallpaper provides neither antibacterial activity nor enhanced light distribution. Consequently, frequent disinfection with alcohols, glutaraldehyde, or hydrogen peroxide is required, which may release volatile organic compounds (VOCs) in enclosed spaces. Titanium dioxide (TiO_2) is a promising n-type semiconductor widely recognised for its photocatalytic activity, enabling the degradation of organic pollutants and the inactivation of microorganisms under light irradiation. In addition, its high refractive index (approximately 2.5) enhances visible light scattering and reflection, making TiO_2 suitable for improving indoor illumination without increasing electrical energy consumption. Therefore, this study aims to develop a TiO_2 nanoparticle-coated wallpaper capable of simultaneously enhancing light diffusion and reducing bacterial accumulation in dental clinics. The proposed material is expected to improve hygiene, reduce electricity consumption, and decrease the use of chemical disinfectants, contributing to a safer and more sustainable healthcare environment.

Methodology

Synthesis and Characterization of TiO_2 Nanoparticles

TiO_2 nanoparticles were synthesized using the sol–gel method in a controlled chamber maintained at 26°C and 40% relative humidity to ensure uniform particle formation. First, 40 mL of titanium isopropoxide (TTIP, $Ti[OCH(CH_3)_2]_4$) was diluted in 240 mL of isopropanol (C_3H_8O) under continuous magnetic stirring. The precursor solution was then added dropwise at approximately 50 drops min^{-1} into 640 mL of deionized water containing 1.5 mL of 1 M nitric acid (65% HNO_3), producing a white TiO_2 precipitate. The suspension was stirred at 100°C for 3 h and centrifuged at 7,000 rpm for 15 min to collect the precipitate. The obtained powder was annealed at 150°C overnight to remove residual organic compounds and improve crystallinity, followed by calcination at 500°C for 1 h in air. The resulting white powder was ground into TiO_2 nanoparticles. The synthesized TiO_2 nanoparticles were characterized using X-ray diffraction (XRD) to determine their crystal phase and UV–Vis–NIR spectrophotometry to evaluate their optical properties and estimate the band gap.

Coating of TiO_2 Nanoparticles onto Wallpaper and Plastic Substrates

Wallpaper and transparent plastic sheets (30 × 30 cm) were divided into four experimental groups (A–D), corresponding to TiO_2 concentrations of 0, 1, 3, and 5 wt%, respectively. TiO_2 nanoparticles were mixed with acrylic resin using a ball mill for 30 min to ensure homogeneous dispersion, followed by ultrasonication for 5 min to reduce particle agglomeration. The suspension was then ball-milled for an additional 30 min. Before coating, the wallpaper surface was cleaned with alcohol. The prepared coating suspension was subsequently applied to the wallpaper and plastic substrates using a doctor blade coater.

Evaluation of Photocatalytic Activity

The photocatalytic activity of TiO_2-coated samples was evaluated using methylene blue (MB, 2 mg L^{-1}, 50 mL) as the model pollutant. Transparent plastic substrates coated with 0, 1, 3, and 5 wt% TiO_2 were prepared, with the uncoated sample (0 wt%) serving as the control. Each experiment was performed in triplicate. Samples (1 × 2 cm) were immersed in the MB solution and kept in the dark for 30 min to establish adsorption–desorption equilibrium. The suspensions were then irradiated with a fluorescent lamp under fixed conditions. Aliquots (3.5 mL) were collected at 0 and 60 min, filtered through a 0.45 µm syringe filter, and analyzed using a UV–Vis spectrophotometer at λmax = 664 nm. The percentage of MB degradation was calculated to compare the photocatalytic performance of the different TiO_2 coatings.

Evaluation of Antibacterial Activity and Light Enhancement Performance

The experimental chamber was disinfected with 70% ethanol before each trial. Uncoated wallpaper was used as the control, while TiO_2-coated wallpaper served as the treatment. Wallpaper samples (A–D) were installed in their corresponding chambers, and Petri dishes were placed at two predetermined positions. The chamber was opened to allow airborne bacteria to settle onto the agar surfaces, after which the light source was switched on and the chamber was sealed for 48 h. Bacterial colonies from both sampling positions were counted, and the average colony number and percentage of bacterial colonies relative to the initial condition were determined. Subsequently, illuminance inside each chamber was measured using a lux meter in triplicate, and the average illuminance was calculated for each treatment.

Result and Discussion

Characterization of Titanium Dioxide (TiO_2) Nanoparticles

1) Crystal Phase Analysis of Titanium Dioxide Nanoparticles by X-ray Diffraction (XRD)

The crystal structure of the titanium dioxide (TiO_2) nanoparticles was analyzed using X-ray diffraction (XRD). The obtained XRD pattern exhibited characteristic diffraction peaks corresponding to TiO_2 nanoparticles, as shown in Figure 1.1.

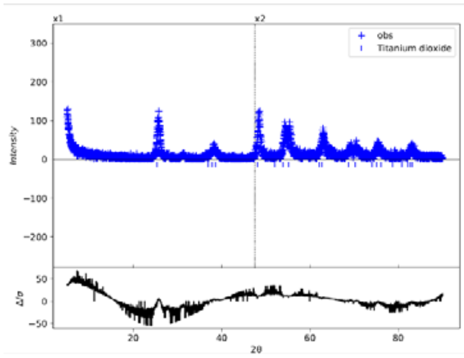


Figure 1.1 X-ray diffraction (XRD) pattern of titanium dioxide (TiO_2) nanoparticles.

The XRD pattern showed several diffraction peaks at different 2θ positions. The major diffraction peak appeared at approximately 25.3°, corresponding to the (101) crystal plane of the anatase phase. Another prominent peak was observed at approximately 27.4°, corresponding to the (110) crystal plane of the rutile phase. Comparison with the standard reference data from the Joint Committee on Powder Diffraction Standards (JCPDS) confirmed that the synthesized TiO_2 nanoparticles consisted of a mixed crystalline phase of anatase and rutile.

2) Optical Properties and Band Gap Analysis of Titanium Dioxide (TiO_2) Nanoparticles by UV–Vis–NIR Spectrophotometry

The optical properties of the TiO_2 nanoparticles were investigated by measuring their diffuse reflectance spectra (% Reflectance) over the wavelength range of 200–1000 nm. The reflectance decreased rapidly in the ultraviolet region. In addition, an absorption edge was observed at approximately 380–400 nm, indicating the onset of optical absorption. The reflectance spectrum is shown in Figure 1.2

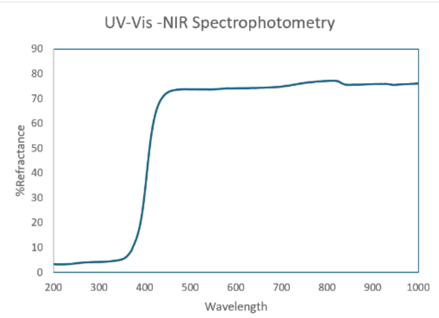


Figure 1.2 Diffuse reflectance spectrum of titanium dioxide (TiO_2) nanoparticles.

The Tauc plot of the titanium dioxide (TiO_2) nanoparticles was constructed by converting the diffuse reflectance data using the Kubelka–Munk function. The relationship between $[F(R)h\nu]^{1/2}$ and the photon energy ($h\nu$) was then plotted. The resulting graph showed an increase in $[F(R)h\nu]^{1/2}$ with increasing photon energy, indicating an indirect allowed electronic transition. The Tauc plot is presented in Figure 1.3.

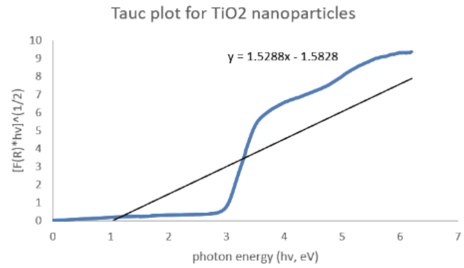


Figure 1.3 Tauc plot of titanium dioxide (TiO_2) nanoparticles.

Figure 1.4 shows the enlarged linear region of the Tauc plot used for determining the optical band gap energy. A linear fit was applied to the linear portion of the curve, and the intercept with the photon energy (**$h\nu$**) axis was used to estimate the band gap energy. Based on the fitted linear equation, the optical band gap of the titanium dioxide (TiO_2) nanoparticles was estimated to be approximately 2.95 eV.

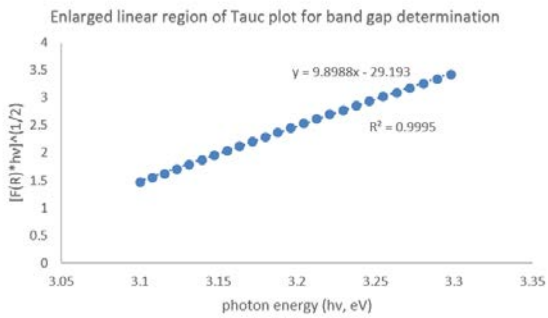


Figure 1.4 Enlarged linear region of the Tauc plot used for determining the optical band gap of titanium dioxide (TiO_2) nanoparticles.

The crystal structure of the synthesized titanium dioxide (TiO_2) nanoparticles was characterized using X-ray diffraction (XRD). The results indicated that the synthesized material consisted of a mixed crystalline phase of anatase and rutile. The presence of this mixed-phase structure is consistent with previous reports indicating that TiO_2 nanoparticles can undergo partial phase transformation from the anatase phase to the rutile phase, depending on the synthesis conditions and heat treatment (Ba-Abbad et al., 2013).

Photocatalytic Performance of TiO_2-Coated Wallpaper

The photocatalytic activity of TiO_2-coated wallpaper was evaluated by monitoring the degradation of methylene blue (MB) under different TiO_2 concentrations (Blank, Control, 1%, 3%, and 5%). After reaching adsorption–desorption equilibrium, the absorbance of MB was measured at 664 nm using a UV–Vis spectrophotometer before irradiation and after 30 min of photocatalytic reaction. The initial absorbance values were 0.115, 0.203, 0.202, 0.184, and 0.155, which decreased to 0.113, 0.088, 0.081, 0.050, and 0.046, respectively (Figure 1.5).

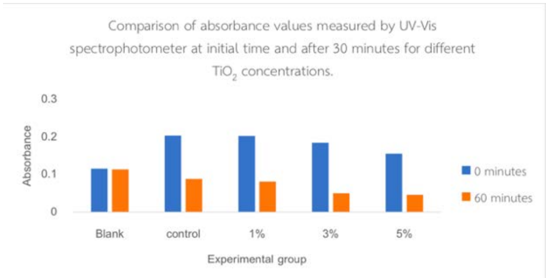


Figure 1.5 Comparison of methylene blue solution absorbance at the initial time and after 30 min of photocatalytic reaction.

Based on these measurements, the corresponding MB degradation efficiencies were 1.7%, 57%, 60%, 73%, and 70%, respectively (Figure 1.6).

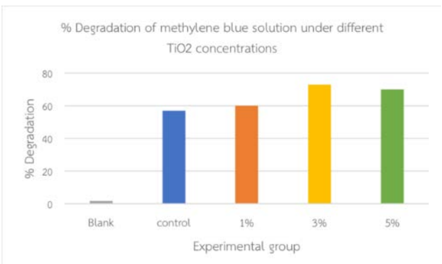
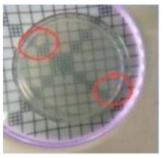


Figure 1.6 Comparison of the percentage degradation of methylene blue (MB) solution among different experimental groups.

The reduction in absorbance indicates the photocatalytic degradation of MB, consistent with the Beer–Lambert law, in which absorbance is directly proportional to dye concentration. One-way ANOVA revealed that TiO_2-coated samples (1%, 3%, and 5%) exhibited significantly greater MB degradation than the blank and control groups ($p < 0.05$), confirming the photocatalytic activity of TiO_2 (Fujishima et al., 2008). Among the tested concentrations, 3 wt% TiO_2 achieved the highest degradation efficiency (73%). Although the 5 wt% coating also showed high photocatalytic activity, its performance was not significantly different from that of the 3 wt% coating. This result is likely due to nanoparticle agglomeration at higher TiO_2 loadings, which reduces the effective surface area and increases light scattering, thereby limiting light penetration and the generation of electron–hole pairs (e^-/h^+) required for photocatalysis (Carp et al., 2004; Herrmann, 2010). Consequently, increasing the TiO_2 concentration beyond 3 wt% did not further improve photocatalytic efficiency.

Antibacterial Performance Against Airborne Bacteria

Figures 1.7–1.10 present the antibacterial performance of wallpaper coated with different TiO_2 concentrations (0%, 1%, 3%, and 5%) against airborne bacteria. The 0% TiO_2 (control) group showed numerous distinct bacterial colonies on the nutrient agar plates. In the 1% TiO_2 group, the number and density of bacterial colonies were noticeably reduced compared with the control. In contrast, 3% and 5% TiO_2 coatings showed no visible bacterial colonies, indicating a markedly enhanced antibacterial effect with increasing TiO_2 concentration.



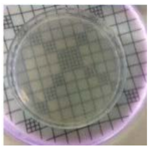
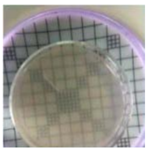


Figure 1.7 control (0%) Figure 1.8 (1%)



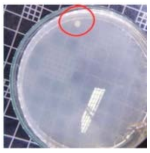


Figure 1.9 (3%) Figure 1.10 (5%)

Figures 1.7–1.10 show the antibacterial performance of wallpaper coated with different TiO_2 concentrations against airborne bacteria. The 0 wt% TiO_2 (control) sample exhibited numerous bacterial colonies, indicating that uncoated wallpaper has no inherent antibacterial activity (Fujishima et al., 2008). The 1 wt% TiO_2 coating reduced the number of bacterial colonies, demonstrating the antibacterial effect of photocatalytically generated reactive oxygen species. However, some colonies remained, suggesting that 1 wt% TiO_2 was insufficient for complete antibacterial coverage (Hajkova et al., 2007). In contrast, 3 wt% and 5 wt% TiO_2 showed no visible bacterial colonies and similar antibacterial performance, indicating that increasing the TiO_2 concentration beyond 3 wt% provides no additional benefit, likely due to surface saturation and nanoparticle dispersion limits (Carp et al., 2004). Therefore, 3 wt% TiO_2 was identified as the optimum concentration for inhibiting airborne bacteria.

Evaluation of Brightness Enhancement Performance Using a Small-Scale Simulated Model

The brightness enhancement performance of wallpapers coated with titanium dioxide (TiO_2) nanoparticles at different concentrations (0%, 1%, 3%, and 5%) was evaluated inside a small-scale simulated model. The brightness was measured using a lux meter, with three measurements performed for each experimental condition. The results showed that the brightness values varied depending on the concentration of TiO_2 nanoparticles.

In the first measurement, the wallpapers with TiO_2 concentrations of 0%, 1%, 3%, and 5% exhibited brightness values of 326, 364, 355, and 409 lux, respectively. In the second measurement, the brightness values were 350, 408, 409, and 375 lux, respectively. In the third measurement, the measured brightness values were 343, 394, 404, and 372 lux, respectively.

The average brightness values calculated from the three measurements were 340, 387, 389, and 358 lux for the 0%, 1%, 3%, and 5% TiO_2 concentrations, respectively. The results are presented in Figure 1.11.

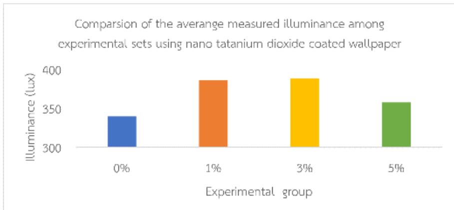


Figure 4.11 Bar chart comparing the average illuminance values of TiO_2-coated wallpaper samples at different concentrations.

The results of the illuminance measurements for each experimental condition using TiO_2 nanoparticle-coated wallpapers at different concentrations (0%, 1%, 3%, and 5%) showed that the average illuminance values of the TiO_2-coated groups tended to be higher than those of the uncoated group.

Conclusions

The synthesized TiO_2 nanoparticles exhibited a mixed anatase–rutile crystalline phase and an optical band gap of approximately 2.95 eV, indicating favorable optical properties for visible-light photocatalytic applications. TiO_2-coated wallpaper significantly enhanced methylene blue degradation, antibacterial activity against airborne bacteria, and indoor illuminance compared with the uncoated control. Among the tested concentrations, the 3 wt% TiO_2 coating demonstrated the best overall performance, achieving 73% methylene blue degradation within 30 min, complete inhibition of airborne bacterial colonies comparable to the 5 wt% coating, and the highest illuminance. Increasing the TiO_2 concentration to 5 wt% did not provide further improvements, likely due to nanoparticle agglomeration, reduced effective surface area, and increased light scattering. These findings indicate that a 3 wt% TiO_2 coating provides the optimum balance between photocatalytic efficiency, antibacterial performance, and light enhancement, highlighting its potential for indoor surface applications.

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