Nanostructured Surface Engineering of Titanium Implants Using Gadolinium Quantum Dots

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**Abstract:**The aim of this study is to evaluate the potential of titanium substrates coated with gadolinium quantum dots (GdQDs) for implant applications. Specifically, the objective is to synthesize gadolinium quantum dots and integrate them onto commercially pure titanium (Cp-Ti) surfaces to enhance their functional properties. Structural and chemical characterizations were performed using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR).Gadolinium (0.5 g) was dissolved in distilled water and stirred for 15 minutes to form a homogeneous solution. Commercially pure titanium (Cp-Ti) samples were mechanically polished using silicon carbide (SiC) abrasive papers up to 1000 grit to achieve a smooth surface finish. The polished titanium substrates were then ultrasonically cleaned using acetone and distilled water to remove surface contaminants. The prepared gadolinium solution was subsequently used to coat the cleaned Cp-Ti substrates, which were then subjected to thermal treatment at 60°C for 2 hours to promote adhesion and surface modification. The coated samples were characterized using SEM to assess surface morphology and FTIR to identify functional groups and confirm chemical bonding.SEM analysis revealed that the surface morphology of the gadolinium-coated titanium displayed well-defined diamond-shaped nanostructures, indicative of successful GdQD deposition. FTIR spectra showed distinct absorption peaks corresponding to functional groups associated with gadolinium quantum dots, confirming their presence on the titanium surface. Preliminary biocompatibility assessment demonstrated favorable cell viability, suggesting the modified surface supports cellular activity.Gadolinium quantum dots present a promising multifunctional coating for titanium implants. Their unique optical and magnetic properties not only enhance visibility through fluorescence and MRI-based imaging but also enable potential real-time monitoring of implant integration and performance. The successful integration of GdQDs onto titanium surfaces highlights their potential for next-generation theranostic implants that combine structural functionality with diagnostic capability.

**Keywords:** Titanium; Peri-implantitis; Gadolinium; Quantum dots

# Introduction

Peri-implantitis is a chronic inflammatory condition that affects the soft and hard tissues surrounding dental implants, ultimately leading to the progressive loss of supporting alveolar bone. This pathological condition often arises silently, with many cases being detected only during routine follow-up examinations due to signs such as bleeding on probing, increased pocket depth, and radiographic bone loss [(Assery et al., 2023)](https://paperpile.com/c/8x5UFx/D2Hp)[(Labh et al., 2021)](https://paperpile.com/c/8x5UFx/jmvc). Clinical manifestations, when present, may include suppuration, mucosal edema, recession, and the presence of sinus tracts[(G. & Ganapathy, 2022; Kumar & Ramesh, 2021)](https://paperpile.com/c/8x5UFx/Ou2wf+jXxoa)). If left undiagnosed or untreated, peri-implantitis can result in the complete failure of osseointegration and subsequent loss of the dental implant[(Pranati et al., 2021; Sakthi & Department of Public Health Dentistry, 2021)](https://paperpile.com/c/8x5UFx/LGXBV+rxYEt). The reported prevalence of peri-implantitis ranges from 12% to 43% of implant sites and affects approximately 28% to 56% of individuals with dental implants, posing a significant public health and clinical burden [(Prathapachandran & Suresh, 2012)](https://paperpile.com/c/8x5UFx/wwuk). While several factors contribute to its onset including poor oral hygiene, history of periodontitis, smoking, and improper implant placement the primary etiological factor is bacterial infection[(Keerthana & Ramesh, 2021; Murugesan, 2021; Tiwari & Jain, 2021)](https://paperpile.com/c/8x5UFx/We0fi+63NRa+2gxob)[(Keerthana & Ramesh, 2021; Murugesan, 2021; Subramanian et al., 2021; Tiwari & Jain, 2021)](https://paperpile.com/c/8x5UFx/We0fi+63NRa+2gxob+wDaDz). A healthy peri-implant mucosa serves as a crucial biological barrier that inhibits microbial invasion; disruption of this barrier facilitates the rapid spread of bacterial contaminants to the underlying bone, accelerating bone resorption and inflammation [(Mehta et al., 2023)](https://paperpile.com/c/8x5UFx/ajlc).Titanium and its alloys are widely regarded as the gold standard materials for dental and orthopedic implants due to their excellent mechanical properties, including high tensile strength, corrosion resistance, low elastic modulus, and biocompatibility [(Marin & Lanzutti, 2023)](https://paperpile.com/c/8x5UFx/cH5h) [(Shruthilaya, A., Gosala, R. & Ramadoss, R, 2025)](https://paperpile.com/c/8x5UFx/go53). Additionally, titanium can undergo surface modifications such as anodization, plasma spraying, grit blasting, and calcium phosphate coating, which have been shown to significantly enhance bone-to-implant contact and osseointegration. Nevertheless, titanium implants are not immune to complications[(Kasabwala et al., 2021; Rajeshkumar & Lakshmi, 2021; Varghese et al., 2023)](https://paperpile.com/c/8x5UFx/zXtDr+zq95o+VKYAt). Bacterial colonization on the implant surface can lead to biofilm formation, persistent infection, and peri-implant tissue breakdown[(Ramakrishnan et al., 2023; Shenoy & Maiti, 2023; J. S. Sindhu et al., 2023)](https://paperpile.com/c/8x5UFx/iamxS+FQzYJ+Rm1Vc). Moreover, recent research has identified that titanium ion and particle release due to wear or galvanic corrosion when paired with dissimilar metals may exacerbate inflammatory responses in peri-implant tissues, contributing further to implant failure. These limitations highlight the need for innovative strategies that can enhance the biological performance of titanium implants, particularly in preventing infection and supporting tissue regeneration [(Kligman et al., 2021)](https://paperpile.com/c/8x5UFx/tBaB).Recent advances in material science have suggested that incorporating gadolinium (Gd) into implant coatings may confer multiple functional benefits[(Rajaraman et al., 2021)](https://paperpile.com/c/8x5UFx/xybm). Gadolinium, a rare earth element primarily known for its use in magnetic resonance imaging (MRI), possesses favorable optical and magnetic properties that can be harnessed for real-time, non-invasive imaging of implants[(Dharman et al., 2023; S. Sindhu et al., 2023; Sreenivasagan et al., 2023)](https://paperpile.com/c/8x5UFx/fIllK+KPnG6+9MfIB). Additionally, gadolinium-based materials have demonstrated anti-inflammatory, antibacterial, and osteogenic properties, making them attractive candidates for multifunctional implant coatings. Functionalized Gd complexes have shown promise in improving bone density, enhancing corrosion resistance, and promoting wound healing in bone tissue engineering applications [(Elschot et al., 2021; Venkatachalam, 2024)](https://paperpile.com/c/8x5UFx/mnrv+MjO8).Quantum dots (QDs) are fluorescent semiconductor nanocrystals with unique physicochemical properties, including size-tunable light emission, high quantum yield, and exceptional photostability. Their nanoscale dimensions and robust optical characteristics enable precise imaging and targeted therapeutic delivery, making them highly attractive in biomedical applications. Gadolinium-based quantum dots (GdQDs) represent a novel class of nanomaterials that combine the imaging functionality of QDs with the magnetic and biological benefits of gadolinium. Despite their potential, challenges such as poor biointegration and the risk of infection have limited the long-term success of implantable devices. However, the integration of GdQDs onto titanium surfaces offers a promising strategy to mitigate these concerns by providing enhanced antibacterial activity, improved tissue compatibility, and theranostic (therapeutic + diagnostic) functionality [(Nabil & Megahed, 2024)](https://paperpile.com/c/8x5UFx/U0g9) .Given the rising incidence of implant-related complications and the limitations of current materials, there is a compelling need for advanced multifunctional coatings that not only promote osseointegration but also prevent bacterial infection and enable real-time monitoring. Therefore, the objective of the present study is to investigate the use of gadolinium quantum dots in combination with titanium substrates for potential implant applications. Through material characterization techniques such as Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR), this study aims to assess the surface morphology and chemical composition of GdQD-coated titanium, thereby contributing to the development of next-generation bioactive and imageable implant systems.

# Materials and methods

## Gadolinium quantum dots synthesis

Rapid coalescence with microwave assistance was used to make the Gd carbon dots. 1.5 g of citric acid was added after 0.57 g of Gd had been dissolved in agitated deionized water of 10 ml. The solution was heated in the microwave for 4 minutes after being subjected to ultrasonication for 10 minutes. Following the response, the end product was then allowed to naturally cool to ambient temperature. Before being thoroughly dissolved in deionized water of 10 ml, continue stirring to bring out brown solution. In order to eliminate the contaminant, centrifugation was done at 9000 rpm for 10 minutes before being filtered. The developed solution has been extracted using ethyl acetate and then stored for subsequent use in a refrigerator at or below 4°C [(Molaei, 2022)](https://paperpile.com/c/8x5UFx/iMe7).

## Preparation of Gd-coated titanium

From Ti Anode Fabricators Pvt. Chennai, commercially pure (Cp-Ti) was purchased.The sample dimension was 2cm x 2cm x 1mm thickness. The sheets were polished using paper (SIC) till grade of 1000 and acetone and water was used for cleaning. Then the sample was dried at room temperature. After the above prepared solution is used to coat the CP-Ti metal and heated with 60 degrees for 2hr [(Sur et al., 2020)](https://paperpile.com/c/8x5UFx/P3Fo).

## SEM Studies

SEM is an effective imaging method used to view the surface of objects at extremely high magnifications. It gives specific details regarding the shape, texture, and composition of materials.The surface morphology structure carried by using (Field Emission Scanning Electron Microscope)with a JEOL (Energy Dispersive X-ray Spectrometer) model (JSM -IT800 NANO SEM) was utilized for assessing the prepared Ti-Gd morphology.

## FT-IR studies

Based on their infrared absorption patterns, functional groups in a sample can be recognized and quantified using an analytical technique that is widely utilized in chemistry and materials research.From the functional group identification of the coated sample was examined by the Alpha II Bruker model spectrometer executed from the wavenumber range of 4000 to 500 cm-1, confirming the functional group.

## Lysozyme protein adsorption study

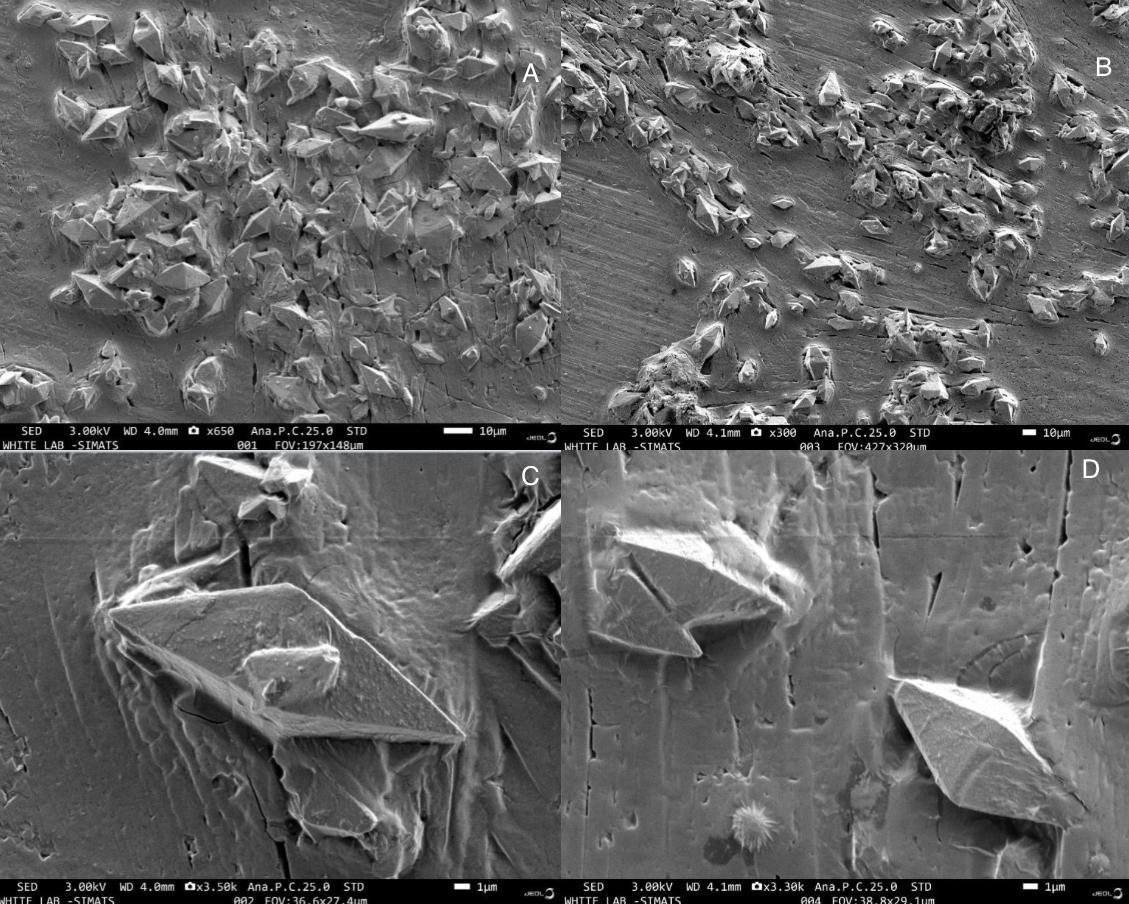
This study used lyophilized lysozyme (LSZ, Sigma-Aldrich) for its protein adsorption study. The LSZ is dissolved in PBS at pH 7.4 to attain a solution containing 10 ml of a 1mg/ml concentration. Further, both uncoated and coated Ti with Gd soaked in LSZ solution for 12 and 24 hours. We then gently agitated the mixture while it incubated at 37 °C. After determined time intervals, the centrifugation at 12,000 rpm for 10 minutes at 4 °C was performed. An analysis of the LSZ adsorption amount was performed using Lowry's method [(Muñoz-Bonilla et al., 2014)](https://paperpile.com/c/8x5UFx/3tJp).

## Cell culture studies

MG-63 cell lines were procured from NCCS (National Centre for Cell Science), University,Pune, India.The cells were grown in (Dulbecco Minimal Essential Medium)were improved with (fetal bovine serum) 10% ,100 units per milliliter of an antibiotic or antimycotic, and 50 grams per milliliter of carbon dioxide ,temperature remained constant at 37 °C. A 96-well plates were taken, cells (1x 105/well) were seeded and cultured under conditions of 37 °C and 5 percent CO2. The sample is introduced once the cell has reached fluency, and 72 hours are then spent incubating it. After being incubated, the sample containing the old medium was washed in DMEM without serum or without saline (phosphate buffer) (pH 7.4).50 L/well and 5 mg/ml of warm plates were treated for four hours with 0.5% of MTT. Each well received 50 L (DMSO) following the incubation period. ELISA was used to measure the absorbance rate at 570 nm.Visual calculations are made using measurements to determine the concentration required to inhibit an organism by 50% (IC50) [(Radha, G., S. Raghunandhakumar, and S. Balakumar, n.d.)](https://paperpile.com/c/8x5UFx/Sgx0) .

# Results

**Surface Morphology**



**Figure 1** SEM images of Gd quantum dots coated Ti surface for 10 µm and 1µm magnification

The surface morphology of Gd-quantum dots was displayed in Fig.1. The morphological structure observed at the diamond-like structure was observed at nm size. The 1 µm was observed in Fig. 1c and D and clearly depicts the diamond shape.

## FT–IR studies

Fig. 2 the functional group of Gd quantum dots on Ti coating .The presence of 3340 cm-1 obtained OH group and 1634 cm-1 observed the water molecules. The metal oxide of (Gd-O) peak was observed at 578 cm-1. In the presence of 1299 cm-1, the C-O was observed due the presence of a carboxylic group.

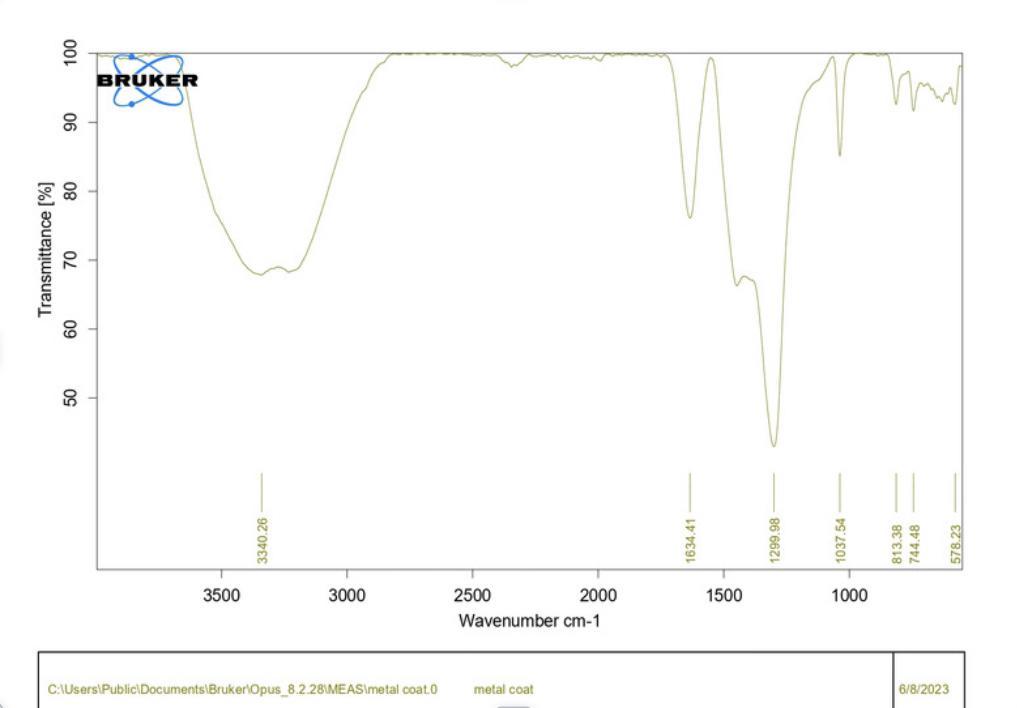
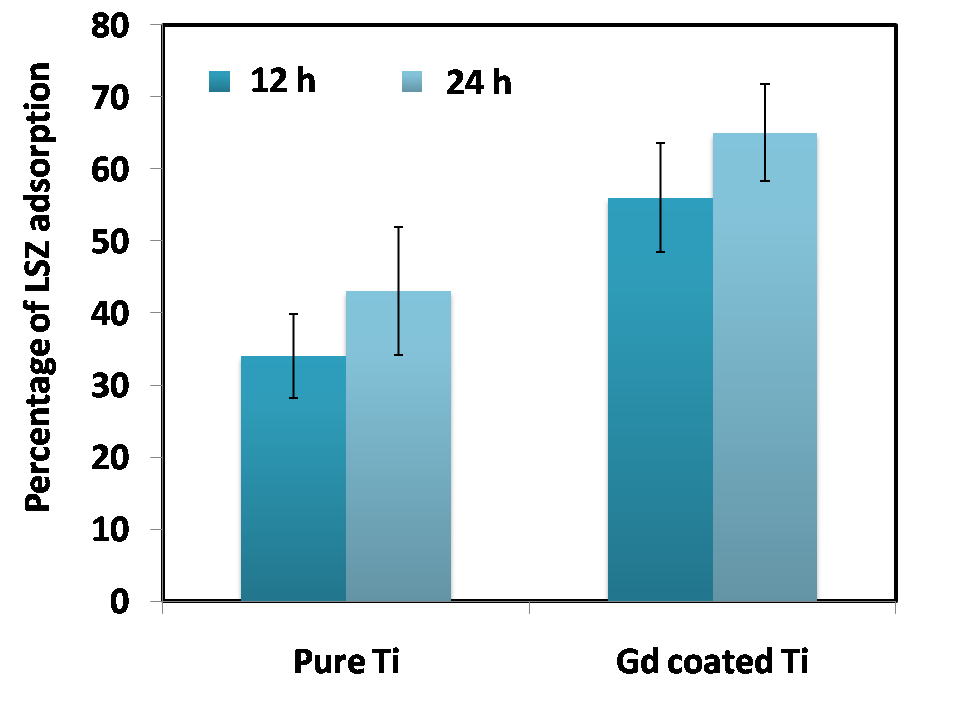


Figure 2 FT-IR spectrum of Ti coated Gd quantum dots

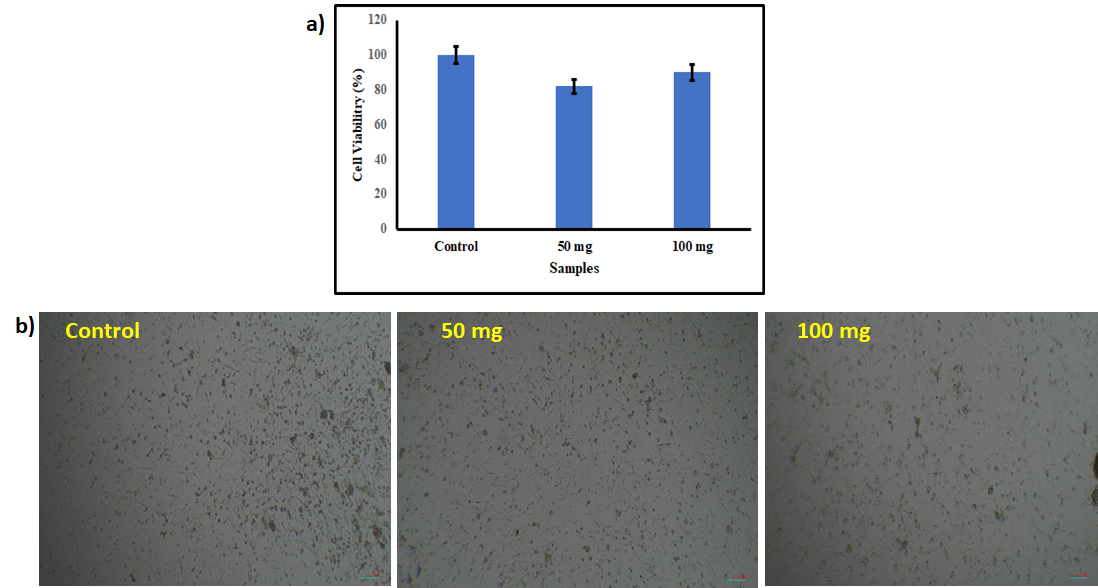
## Protein adsorption study



**Fig. 3** LSZ protein adsorption capacity on pure and Gd coated Ti implant surface.

The adsorption of lysozyme on Gd-Ti surfaces increased dramatically with time, reaching a level that was 65% higher after 24 hours compared to the adsorption that was seen at 12 hours (56%), as depicted in Figure 3. At the 24-hour label, the surface of pure titanium has a protein adsorption value of 34%. When compared to pure titanium implants, Gd-coated titanium exhibits a higher level of adsorption overall.

## Cell culture



**Figure 3** a) Cell viability (%) of MG 63 osteoblast cell and b) Optical image of Gd-Ti coated a) control, b) 50 mg c)100 mg of

In Fig 3 b depicts the concentrations of cells of TGQDs and fig a)depicts the cell viability percentage of Gd-Ti .Cell culture test was performed for cell viability 50 mg showed 82% and 100 mg showed 95% as it is more than 70% we can conclude that it has good cell viability.

## Discussion

The term *peri-implantitis* was first introduced by Mombelli et al. in 1987 to describe infectious pathological conditions affecting the peri-implant tissues. Since its definition, peri-implantitis has been recognized as a significant complication in dental implantology, characterized by inflammation of the mucosa and progressive loss of supporting bone. Despite ongoing advancements in implant materials and techniques, the high prevalence and complex etiology of peri-implantitis continue to pose challenges in clinical practice.Various therapeutic strategies have been investigated to manage and mitigate this condition. Krisztina Ungvari et al. (2010) explored the use of chemical agents on titanium implants and demonstrated that such treatments significantly enhance cell proliferation and regeneration, accelerating the healing process in peri-implantitis [(Barrak et al., 2020)](https://paperpile.com/c/8x5UFx/lbWP). Similarly, D.M. Ferris reported that implants coated with RGD peptides promoted increased bone formation by modulating osteoblastic gene expression, contributing to the resolution of peri-implant inflammation(Nikalje et al., 2024). These findings underscore the importance of surface biofunctionalization in improving implant integration and preventing infection [(Ferris et al., 1999)](https://paperpile.com/c/8x5UFx/OAyG) .Nanotechnology has emerged as a promising field in addressing peri-implant complications(Chehelgerdi et al., 2023). Nayem Hossain emphasized the role of nanoparticles in enhancing implant performance, noting their superior mechanical properties, high surface area-to-volume ratio, and ability to improve crack resistance and fracture toughness. Nano-coatings, in particular, have shown great potential in dental applications due to their antibacterial, osteogenic, and regenerative capabilities [(Nour, 2024)](https://paperpile.com/c/8x5UFx/BCzQ) .Fei He et al. developed antibiotic-functionalized titanium surfaces through the co-immobilization of dopamine and cefotaxime sodium [(He et al., 2022)](https://paperpile.com/c/8x5UFx/4hMf). This dual-function coating exhibited both bacteriostatic and osteogenic effects, significantly improving outcomes in the treatment of peri-implantitis. Similarly, an engineered hybrid antibacterial surface comprising ZnO-functionalized quantum dots, titanium nanotubes, and vancomycin was reported [19] . Their findings demonstrated that this combination significantly enhanced antibacterial activity and reduced the incidence of bacterial infections around implants, offering a novel approach for biomedical applications.Moradlou et al. investigated hematite and hematite-carbon quantum dot coatings on titanium substrates for their antibacterial properties against *Staphylococcus aureus* and *Escherichia coli*. FE-SEM analysis revealed prolonged antibacterial activity, especially against *S. aureus*, due to differences in bacterial cell wall structure [(Moradlou et al., 2019)](https://paperpile.com/c/8x5UFx/CGC2). Tsuchiya S. further contributed to the field by demonstrating that CM (conditioned medium) components immobilized on titanium surfaces improved early osseointegration at multiple post-implantation time points, reinforcing the value of biochemical surface enhancements [(Tsuchiya et al., 2013)](https://paperpile.com/c/8x5UFx/pVkj).Chouirfa H. examined various surface modification techniques for titanium implants, emphasizing that both chemical and physical coatings are vital for combating bacterial colonization [(Chouirfa et al., 2019)](https://paperpile.com/c/8x5UFx/ZoMe). A noteworthy study by Chifor et al. developed bioactive TiO₂ coatings modified with noble metal nanoparticles (Au/Ag) and lysozyme (LSZ) [(Chifor et al., 2022)](https://paperpile.com/c/8x5UFx/AI9v). This multi-functional surface significantly enhanced antibacterial activity and protein adsorption, suggesting a promising strategy for self-disinfecting and biocatalytic dental implants. Specifically, the study found that Gd-Ti surfaces showed a 65% higher lysozyme adsorption at 24 hours compared to uncoated Ti, demonstrating the superior protein-binding and bioactive potential of gadolinium coatings.In addition to traditional antimicrobial strategies such as antibiotic and polymer coatings, the use of inorganic antibacterial metal ions including gadolinium has gained momentum. Pratap Sur et al. conducted biocompatibility assessments on titanium-gadolinium quantum dots (TGQDs) using the HBL-100 cell line, reporting high cell viability and no significant cytotoxicity. This highlights TGQDs as a promising material for future implant applications [(Sur et al., 2020)](https://paperpile.com/c/8x5UFx/P3Fo).To advance these findings toward clinical application, it is essential to conduct extensive biocompatibility studies on TGQDs, analyzing their interactions with live tissue, their influence on inflammatory and immune responses, and their long-term stability and performance. Furthermore, translational research is needed to bridge the gap between preclinical models and real-world clinical outcomes, ensuring safety and efficacy in human use.

# Conclusion

In the present study, titanium-gadolinium quantum dots (TGQDs) were successfully synthesized and characterized using Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and cell culture analysis. SEM revealed that TGQDs exhibited a distinct diamond-shaped morphology with an average thickness of 1 µm. FTIR spectra confirmed the presence of key functional groups including hydroxyl (OH), carboxyl (C–O), water molecules, and a prominent Gd–O peak, indicating successful incorporation of gadolinium into the nanostructure. Biological analysis showed that Gd-coated titanium demonstrated significantly higher lysozyme adsorption compared to uncoated titanium, supporting its enhanced bioactive and antimicrobial properties. In vitro cell culture studies revealed favorable colonization, high cell viability, and low cytotoxicity, indicating that TGQDs support cellular functions critical for osseointegration and tissue healing. Collectively, these findings suggest that TGQDs present a multifunctional surface coating for dental and orthopedic implants, offering improved biointegration, antibacterial performance, and potential for theranostic applications. Continued research and translational efforts are essential to further optimize TGQD coatings for clinical use and to validate their long-term safety and efficacy in vivo.

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