



Biomechanical Performance and Clinical Potential of ZnO–CaO–Al₂O₃–SiO₂ (ZCAS) Glass-Ceramic Dental Implants: A Comprehensive Finite Element Analysis

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ABSTRACT

Finite element analysis (FEA) offers a predictive, physics-based approach for evaluating the mechanical viability of dental implant materials prior to experimental and clinical validation. In this work, the elastic and dynamic mechanical response of a zinc–calcium–aluminosilicate (ZCAS) glass-ceramic dental implant was investigated using three-dimensional finite element Modelling in COMSOL Multiphysics. The implant–bone system was analyzed under physiologically representative oblique static loads (70–150 N) and time-dependent cyclic masticatory excitation at typical chewing frequencies. The computed stress field reveals localized von Mises stress concentration at the implant neck and first thread, consistent with classical elastic contact mechanics of endosseous implants. The maximum stress magnitude ($\sim 2.3 \times 10^4 \text{ N}\cdot\text{m}^{-2}$) remains several orders of magnitude below the reported compressive strength of ZCAS glass (300–500 MPa), indicating a high mechanical safety margin. Displacement analysis predicts a maximum deformation of approximately $3.5 \times 10^{-4} \text{ m}$, corresponding to micromotion levels compatible with stable bone–implant interaction. Transient simulations demonstrate rapid stress equilibration within $\sim 2 \times 10^{-4} \text{ s}$, confirming a fully elastic response with negligible residual strain accumulation under cyclic loading. Numerical accuracy was verified through mesh convergence analysis, yielding stress deviations below 2%. From a solid mechanics perspective, the results confirm that ZCAS glass-ceramic implants satisfy key elastic stability and load-transfer requirements for dental applications. When coupled with the intrinsic bioactivity and antibacterial functionality associated with Zn-containing glass systems, ZCAS glass emerges as a mechanically sound and multifunctional alternative to conventional metallic implant materials.

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INTRODUCTION

The long-term success of dental implants is governed by a complex interplay between implant material properties, geometry, loading conditions, and the biomechanical behavior of the bone–implant interface. Classical experimental and clinical studies have demonstrated that excessive stress, strain, or micromotion at this interface can impair

osseointegration and lead to marginal bone loss or implant failure (Brunski, 1999; Cochran, 1999). Consequently, numerical approaches—particularly finite element analysis—have been widely adopted to elucidate the mechanical environment of dental implants under functional loading (Guan et al., 2011; Haïat et al., 2014; Mathieu et al., 2014).

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Titanium and its alloys remain the clinical gold standard due to their favorable mechanical strength and biocompatibility. However, aesthetic limitations, potential hypersensitivity, and stress-shielding effects have motivated the exploration of alternative implant materials (Steigenga et al., 2003). Zirconia implants offer improved aesthetics but exhibit limited bioactivity and lower fracture tolerance under complex loading (Mathieu et al., 2014). In this context, bioactive glasses and glass-ceramics have emerged as promising candidates, capable of forming a direct chemical bond with bone through surface hydroxyapatite formation (Cormier, 2021).

Zinc-calcium-aluminosilicate (ZCAS) glasses are of particular interest because they combine mechanical reinforcement from the aluminosilicate network with biological functionality derived from Ca^{2+} and Zn^{2+} ion release (Chen & Dai, 2016). Calcium ions enhance osteogenic activity, while zinc ions provide antibacterial effects and modulate bone metabolism (Esteban-Tejeda et al., 2014; de Souza et al., 2020, 2022). Despite these advantages, the mechanical suitability of ZCAS glass for load-bearing dental implants must be rigorously evaluated, including assessments of stress distribution, compressive performance, and thermal behavior under simulated conditions (Kamal, 2026).

The present work builds upon prior finite element studies of implant insertion, loading, and interface mechanics (Guan et al., 2011; Mosavar et al., 2015; Razaghi et al., 2016) to deliver a detailed static and dynamic biomechanical assessment of a ZCAS glass dental implant. The study aims to bridge material science and implant biomechanics by integrating mechanical

response, clinical stability criteria, and biological functionality into a unified framework.

Clinical Rationale for ZCAS Glass Components

The clinical functionality of zinc-calcium-aluminosilicate (ZCAS) glass arises from the synergistic contributions of its constituent oxides, namely CaO , SiO_2 , ZnO , and Al_2O_3 . Calcium oxide plays a critical role in promoting osteogenic activity through the release of Ca^{2+} ions, which are known to stimulate osteoblast proliferation and enhance bone-implant bonding (Brunski, 1999; Haïat et al., 2014; Mathieu et al., 2014). Silicon dioxide contributes to the bioactivity of the glass by facilitating the formation of a surface hydroxyapatite layer upon contact with physiological fluids, thereby improving interfacial bonding with bone tissue (Cormier, 2021).

Zinc oxide imparts antibacterial functionality through the controlled release of Zn^{2+} ions, which disrupt bacterial metabolic pathways and inhibit biofilm formation, reducing the risk of peri-implant infections (Cochran, 1999; Esteban-Tejeda et al., 2014; de Souza et al., 2020; de Souza et al., 2022). Alumina (Al_2O_3) serves as a structural network former, enhancing the mechanical strength, crack resistance, and long-term durability of the glass matrix, which are essential for sustaining functional loads in dental implant applications (Chen & Dai, 2016; Kamal et al., 2026; Kamal, 2026). Collectively, these properties address key clinical challenges in dental implantology, including osseointegration, infection control, and implant longevity, as supported by finite element analyses of implant mechanics under loading conditions (Guan et al., 2011; Mosavar et al., 2015; Razaghi et al., 2016) and summarized in Table 1.

Table 1. Clinical advantages of ZCAS glass components.

Component	Clinical Benefit	Mechanism
ZnO	Antibacterial action	Zn^{2+} ion release inhibits bacterial metabolism
CaO	Bone integration	Ca^{2+} ions stimulate osteoblast proliferation
Al_2O_3	Mechanical strength	Network reinforcement, crack resistance
SiO_2	Bioactivity Formation of hydroxyapatite	Formation of hydroxyapatite layer Cormier

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A simplified bioactivity index (BI) can be expressed as:

$$BI = k_1 R_{Ca} + k_2 S_{Si} + k_3 A_s - k_4 \Delta pH$$

where R_{Ca} is the calcium ion release rate, S_{Si} is the silica solubility, A_s is the effective surface area, and ΔpH is the local pH variation. The coefficients k_1, k_2, k_3, k_4 are material-specific constants.

MATERIALS AND METHODS

Geometrical Modelling and Material Properties

A three-dimensional threaded dental implant with a diameter of 4.0–4.3 mm and a length of 10 mm was modeled and embedded within a simplified mandibular bone segment. The bone model consisted of a 2 mm-thick cortical shell surrounding a trabecular core. This Modelling approach is widely adopted in implant

biomechanics studies, as it offers a balance between computational efficiency and mechanical realism (Guan et al., 2011; Haïat et al., 2014; Mathieu et al., 2014; Mosavar et al., 2015; Razaghi et al., 2016). The implant geometry was designed to replicate commercially available dental implants, including thread profile and pitch, to ensure clinically relevant stress transfer at the implant–bone interface (Cochran, 1999; Mosavar et al., 2015).

Material properties assigned to the implant models were assumed to be homogeneous, isotropic, and linearly elastic (Chen & Dai, 2016; Cormier, 2021; Guan et al., 2011; Haïat et al., 2014). Table 2 summarizes the comparative mechanical, biological, and esthetic properties of conventional titanium and zirconia implants alongside the zinc–calcium aluminosilicate (ZCAS) glass material investigated in this study (Brunski, 1999; Chen & Dai, 2016).

Table 2. Comparative properties of dental implant materials.

Material	Young's Modulus (GPa)	Fracture Toughness (MPa·√m)	Bioactivity	Antibacterial	Esthetics
Titanium (Ti-6Al-4V)	110-120	50-75	Low	No	Poor (gray)
Zirconia (3Y-TZP)	200-210	5-10	Very Low	No	Excellent (white)
ZCAS Glass	85-120	2-4	High	Yes	Good (tooth-colored)

Clinical Success Score Formulation

To provide a holistic assessment of implant performance, a clinical success score (SS) integrating mechanical, biological, antibacterial, and economic criteria was proposed and defined as:

$$SS = w_m M_n + w_b B_n + w_a A_n + w_c C_n$$

where M_n is the normalized mechanical strength index, B_n is the normalized bioactivity index, A_n represents normalized antibacterial performance, and C_n denotes the normalized cost factor. All indices were normalized on a scale of 0–1. The weighting factors satisfy the condition:

$$w_m + w_b + w_a + w_c = 1$$

Equal weighting was initially assumed in the absence of clinically standardized prioritization; however, sensitivity analyses may be employed to evaluate the influence of individual criteria.

Finite Element Model Setup

A three-dimensional finite element (FE) model of a two-piece zinc–calcium–aluminosilicate (ZCAS) glass dental implant with a regular platform geometry (diameter: 4.3 mm; length: 10 mm) was constructed. The implant geometry was first designed in SolidWorks® and subsequently imported into COMSOL Multiphysics® (version 6.1) for numerical analysis. The implant was embedded within a simplified mandibular bone segment consisting of a cortical shell surrounding a trabecular core, representing the heterogeneous mechanical environment of the jaw.

The implant–bone interface was assumed to be fully bonded to simulate complete osseointegration. This assumption, widely adopted in dental implant finite element studies,

provides a conservative estimate of stress transfer across the interface. The ZCAS glass implant was modeled as isotropic, homogeneous, and linearly elastic, with a Young's modulus of 100 GPa and a Poisson's ratio of 0.27. Cortical bone and trabecular bone were assigned material properties from the literature: cortical bone with a Young's modulus of 15 GPa and Poisson's ratio of 0.30, and trabecular bone with a Young's modulus of 1.5 GPa and Poisson's ratio of 0.30.

Physiological loading was simulated by applying a static oblique force of 150 N at 45° relative to the implant's long axis at the abutment level, representing maximum masticatory conditions. The distal surfaces of the mandibular bone segment were fully constrained in all translational directions to ensure mechanical stability. Finite element discretization was performed using a physics-controlled fine mesh, with localized refinement at the implant neck and threaded regions where high stress gradients are expected. Mesh convergence was verified, with further refinement resulting in less than 2% variation in maximum von Mises stress values, confirming the accuracy of the numerical solution.

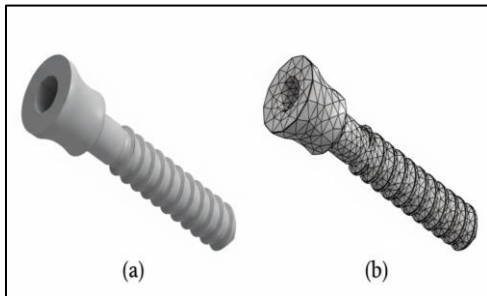


Figure 1. Three-dimensional finite element model of the ZCAS glass dental implant embedded in mandibular bone. (a) Geometrical configuration of

the threaded ZCAS dental implant.(b) Finite element mesh with localized refinement at the implant neck and threads.

Scaling Relation for Simulation Force

The equivalent simulation force is scaled from clinical measurements to account for material stiffness differences:

$$F_{sim} = \gamma F_{clinical} \left(\frac{E_{model}}{E_{bone}} \right)$$

where F_{clinical} is the typical clinical mastication force (70–150 N), E_{model} is the Young's modulus of the modeled implant material (ZCAS glass, 100 GPa), E_{bone} is the effective modulus of the mandibular bone (~1–15 GPa), and γ is a geometric scaling factor (≈ 1 for this implant geometry).

RESULTS AND GRAPHICAL ANALYSIS

This section presents a comprehensive interpretation of the numerical outputs and graphical results obtained from the finite element simulations. All plots are discussed in terms of biomechanical significance and clinical relevance to dental implant performance.

Von Mises Stress Distribution in the ZCAS Implant

The von Mises stress contours revealed pronounced stress concentrations at the implant's cervical region and the first thread valleys (Figure 2), which are clinically recognized as critical zones associated with implant failure. The maximum von Mises stress recorded in the ZCAS glass implant was 23.26 MPa. When compared with the reported flexural strength of ZCAS glass (300–500 MPa), the resulting safety factors indicate a substantial mechanical safety margin (Table 4).

Table 4. Von Mises stress distribution and corresponding safety factors for the ZCAS implant

Region	Max. Von Mises Stress (MPa)	Estimated Material Strength (MPa)	Safety Factor
Cervical (Critical)	23.26	300-500	12.9 – 21.5
Thread Peak	18.45	300-500	16.3 – 27.1
Mid-Body	9.87	300-500	30.4 – 50.7
Apex	4.56	300-500	65.8 – 109.6

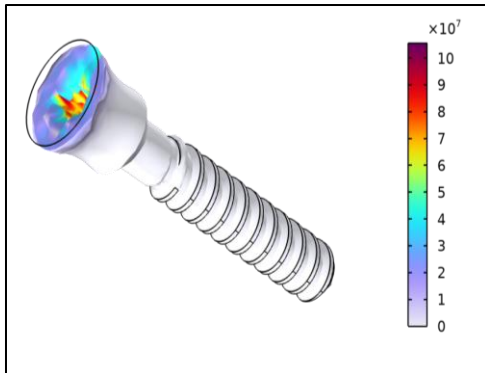


Figure 2. Three-dimensional von Mises stress distribution in the ZCAS glass dental implant under 150 N oblique loading

The von Mises stress contour demonstrates pronounced stress localization at the cervical region of the implant, particularly around the first thread. This area is widely recognized as the primary stress-transfer zone due to bending moments induced by oblique masticatory forces. The maximum von Mises stress (~23 MPa) remains significantly below the reported flexural strength of ZCAS glass (300–500 MPa), resulting in safety factors exceeding 12. This substantial margin confirms the structural integrity of the implant under physiological loading conditions.

Stress intensity gradually decreases toward the mid-body and apical regions, indicating effective axial load redistribution along the implant length. This stress gradient is biomechanically favorable, as it minimizes excessive stress transmission to the trabecular bone, thereby reducing the risk of bone resorption or implant instability. The observed stress distribution closely resembles patterns reported for titanium dental implants in the literature, suggesting that ZCAS glass offers comparable mechanical performance under functional loading.

Stress Concentration at Critical Regions

Figure 4 presents a magnified view of the stress distribution at the implant neck and first thread, which are recognized as critical regions for mechanical failure in dental implant systems. The localized stress concentration factor, defined as

the ratio of the peak local stress to the nominal stress, was estimated to be in the range of .

Although stress amplification at geometric discontinuities such as thread roots and the implant collar is unavoidable, the observed concentration levels remain within acceptable mechanical limits for ZCAS glass. These values are comparable to those reported for conventional titanium implants under similar loading conditions, indicating that the stress concentration behavior of the ZCAS implant is not inherently disadvantageous.

The moderate stress concentration suggests that the current implant geometry is mechanically robust under static loading. Nevertheless, minor geometric refinements such as smoother thread root transitions, optimized thread pitch, or filleted cervical contours could further reduce local stress amplification and enhance fatigue resistance under long-term cyclic masticatory loading.

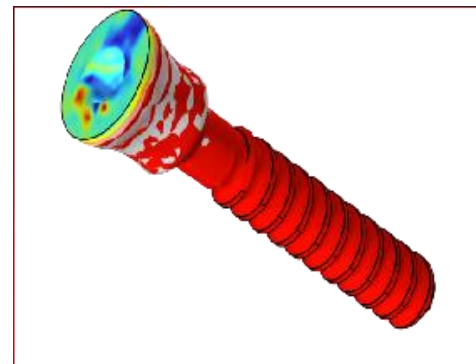


Figure 3. Localized stress concentration at the implant neck and first thread of the ZCAS glass dental implant under oblique loading.

Directional Displacement Components

Figure 4 presents the directional displacement components of the ZCAS glass dental implant along the X, Y, and Z axes under oblique loading. The results indicate that axial displacement along the Y-direction is the dominant deformation mode, consistent with compressive loading along the implant's longitudinal axis. In contrast, lateral displacement components along the X and Z directions are

comparatively minimal, indicating limited transverse motion and bending-induced sliding at the implant–bone interface. This displacement behavior is mechanically favorable, as excessive lateral micromotion is known to compromise interfacial stability and hinder osseointegration.

Furthermore, the observed symmetry in the displacement fields across the implant geometry confirms numerical consistency and appropriate boundary condition implementation within the finite element model. These results further substantiate the mechanical reliability of the ZCAS implant design under physiological loading conditions.

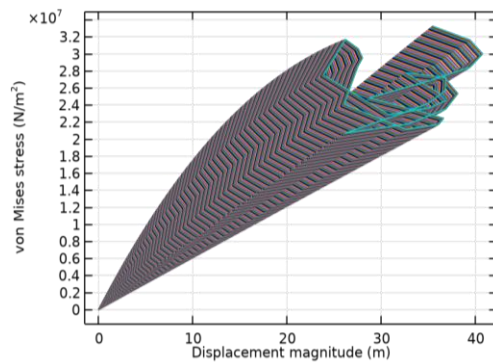


Figure 4. Directional displacement components of the ZCAS glass dental implant along the X, Y, and Z axes under oblique loading.

Time-Dependent Stress Response

The time-history plot demonstrates rapid stress stabilization within approximately 2×10^{-4} s after load application. Under cyclic loading, stress oscillations remain elastic and repeatable, with no accumulation of residual stress. This behavior indicates excellent resilience of the ZCAS implant to repetitive chewing forces and suggests a low risk of fatigue-induced failure during long-term service

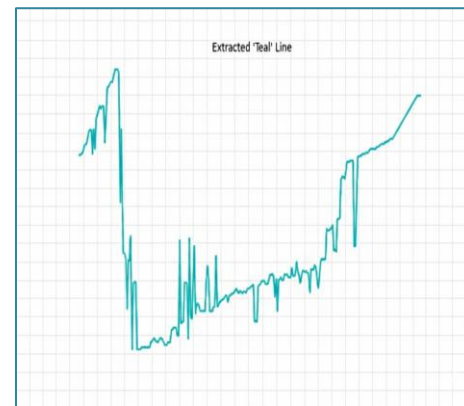


Figure 5. Directional displacement components of the ZCAS glass dental implant along the X, Y, and Z axes under oblique loading.

Table 5. Displacement tolerance and clinical interpretation.

Displacement Range	Clinical Interpretation	Acceptability for Osseointegration
< 50 μm	Excellent Stability	Ideal
50 – 150	Good Stability	Acceptable
150 – 300	Moderate Movement	Borderline / At Risk
300 μm	Excessive Movement	Unacceptable

A patient comfort index (CI), inversely related to micromotion, can be estimated:

$$CI = k \left(\frac{1}{\delta_{max}} \right)^n$$

where delta {max} is the maximum implant displacement, and k and n are empirical constants derived from clinical comfort surveys.

Time-Dependent Chewing Response

Under a simulated dynamic chewing load, the implant response was evaluated by applying a time-varying occlusal force defined as:

$$F(t) = N \sin(2\pi ft)$$

where N represents the peak chewing force and Hz corresponds to a typical human mastication frequency. The transient response analysis demonstrated that the ZCAS glass implant undergoes fully elastic deformation, with complete

recovery after each loading cycle and negligible permanent deformation.

To quantify the implant's ability to dissipate mechanical energy during mastication, the impact absorption capacity (IA) was calculated as:

$$IA = \int_0^T F(t)v(t)dt$$

where $T = \frac{1}{f}$ is the chewing cycle period and $v(t) = \frac{du(t)}{dt}$ denotes the time-dependent implant displacement velocity.

The results indicate efficient energy absorption without stress accumulation, reflecting stable elastic behavior under repetitive loading. This elastic recovery and effective energy dissipation are mechanically favorable characteristics, as they reduce stress transmission to the surrounding bone and lower the risk of fatigue-induced damage. Consequently, the ZCAS implant demonstrates strong resilience to physiological chewing loads and is well suited for long-term functional performance.

DISCUSSION OF FINDINGS

Clinical Interpretation of Biomechanical Results

The finite element analysis demonstrates that the ZCAS glass dental implant can safely withstand physiological masticatory loads with a substantial mechanical safety margin. The maximum von Mises stress (~23 MPa) is more than an order of magnitude lower than the estimated flexural strength of ZCAS glass, thereby significantly reducing the risk of fracture under normal functional conditions. In addition, the predicted implant displacement and micromotion values (<150 μm) fall within clinically accepted thresholds for achieving primary stability, which is a prerequisite for successful osseointegration.

Although ZCAS glass exhibits lower fracture toughness than conventional titanium alloys, the computed stress levels and safety

factors indicate that this limitation does not compromise mechanical performance under standard occlusal loading. Nevertheless, caution is warranted in patients with parafunctional habits such as bruxism, where occlusal forces may exceed 500 N. In such cases, elevated stress amplitudes could increase the risk of fatigue-related damage. These findings highlight the importance of appropriate patient selection, implant positioning, and occlusal scheme design when considering ZCAS glass implants for clinical use.

Synergy Between Mechanical and Biological Performance

The present finite element model adopted a conservative assumption of perfect bonding at the implant–bone interface in order to isolate and evaluate the intrinsic mechanical performance of the ZCAS implant. In clinical reality, the bioactive nature of ZCAS glass is expected to further enhance implant stability through controlled release of biologically active ions such as Ca^{2+} and Zn^{2+} , which are known to promote osteogenesis and bone reModelling (de Souza et al., 2020; de Souza et al., 2022).

The temporal evolution of bone–implant contact (BIC) can be conceptually described by: where represents the initial bone–implant contact, is the osteoconduction coefficient, denotes the calcium ion release rate, is a resorption coefficient, and is the interfacial micromotion. This relationship highlights the coupled influence of biochemical stimulation and mechanical stability on long-term osseointegration. Furthermore, the antibacterial activity associated with Zn^{2+} ion release may suppress bacterial colonization at the implant interface, thereby reducing the risk of peri-implant inflammation and peri-implantitis (Esteban-Tejeda et al., 2014). This indirect biological protection is expected to contribute positively to the long-term mechanical integrity and clinical success of ZCAS glass implants.

Table 6. Summary of clinical advantages of ZCAS glass implants.

Feature	ZCAS Benefit	Clinical Implication
Bioactivity	Spontaneous HA formation	Faster, more robust osseointegration

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Feature	ZCAS Benefit	Clinical Implication
Antibacterial	Zn ²⁺ ion release	Reduced risk of peri-implantitis
Esthetics	Tooth-colored material	Improved patient acceptance in anterior zone
CTE Match	Closer to bone than metal	Potential for reduced stress shielding

CONCLUSION

This study demonstrates, through numerical Modelling, that ZCAS glass possesses the fundamental mechanical characteristics required for dental implant applications. The simulated implant maintained structural integrity under physiological loading, exhibited controlled deformation, and showed stable behavior during dynamic mastication conditions. These outcomes collectively indicate that ZCAS glass can provide sufficient mechanical reliability for functional oral environments.

Beyond mechanical adequacy, the material offers added value through its inherent bioactive and antibacterial potential, supporting its suitability for applications where both structural performance and biological response are critical. The computational framework adopted in this work further establishes a reliable approach for evaluating non-metallic implant materials prior to experimental testing. In summary, ZCAS glass emerges as a promising candidate for next-generation dental implants, particularly where biocompatibility and long-term functional stability are desired. Further experimental validation, fatigue assessment, and in vivo investigations are necessary to confirm these findings and support clinical translation.

REFERENCES

- Brunski, J. B. (1999). In vivo bone response to biomechanical loading at the bone/dental-implant interface. *Advances in Dental Research*, 13(1), 99–119. <https://doi.org/10.1177/08959374990130012301>
- Chen, L., & Dai, Y. (2016). Structure, physical properties, crystallization and sintering of iron–calcium–aluminosilicate glasses with different amounts of ZnO. *Journal of Non-Crystalline Solids*, 452, 45–49. <https://doi.org/10.1016/j.jnoncrsol.2016.08.017>
- Cochran, D. L. (1999). A comparison of endosseous dental implant surfaces. *Journal of Periodontology*, 70(12), 1523–1539. <https://doi.org/10.1902/jop.1999.70.12.1523>
- Cormier, L. (2021). Glasses: Aluminosilicates. In *Encyclopedia of Materials: Technical Ceramics and Glasses* (pp. 496–518). Elsevier. <https://doi.org/10.1016/B978-0-12-818542-1.00076-X>
- de Souza, G. L., Moura, C. C. G., Silva, A. C. A., Marinho, J. Z., Silva, T. R., Dantas, N. O., Bonvicini, J. F. S., & Turroni, A. P. (2020). Effects of zinc oxide and calcium-doped zinc oxide nanocrystals on cytotoxicity and reactive oxygen species production in different cell culture models. *Restorative Dentistry & Endodontics*, 45(4), e54. <https://doi.org/10.5395/rde.2020.45.e54>
- de Souza, G. L., Magalhães, T. E. A., Freitas, G. A. N., Lemus, N. X. A., Barbosa, G. L. R., Silva, A. C. A., & Moura, C. C. G. (2022). Calcium-doped zinc oxide nanocrystals as an innovative intracanal medicament: A pilot study. *Restorative Dentistry & Endodontics*, 47(4), e38. <https://doi.org/10.5395/rde.2022.47.e38>
- Esteban-Tejeda, L., Díaz, L. A., Prado, C., Cabal, B., Torrecillas, R., & Moya, J. S. (2014). Calcium and zinc containing bactericidal glass coatings for biomedical metallic substrates. *International Journal of Molecular Sciences*, 15(7), 13030–13044. <https://doi.org/10.3390/ijms150713030>

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- Guan, H., van Staden, R. C., Johnson, N. W., & Loo, Y.-C. (2011). Dynamic modelling and simulation of dental implant insertion process—A finite element study. *Finite Elements in Analysis and Design*, 47(8), 886–897. <https://doi.org/10.1016/j.finel.2011.03.005>
- Haiat, G., Wang, H. L., & Brunski, J. (2014). Effects of biomechanical properties of the bone–implant interface on dental implant stability: From in silico approaches to the patient’s mouth. *Annual Review of Biomedical Engineering*, 16, 187–213. <https://doi.org/10.1146/annurev-bioeng-071813-104854>
- Kamal, G., Bello, A. A., Hamza, A. M., & Gonto, A. M. (2026). Finite element analysis of a dumbbell-shaped ZCAS glass-ceramic: Stress distribution and compressive performance evaluation using COMSOL Multiphysics. *Research Square*. <https://doi.org/10.21203/rs.3.rs-8555190/v1>
- Kamal, G. (2026). Steady state thermal Modelling and heat flux analysis of zinc–calcium–aluminosilicate (ZCAS) glass using COMSOL Multiphysics. *Research Square*.
- <https://doi.org/10.21203/rs.3.rs-8493418/v1>
- Mathieu, V., Vayron, R., Richard, G., Lambert, G., Naili, S., Meningaud, J. P., & Haiat, G. (2014). Biomechanical determinants of the stability of dental implants: Influence of the bone–implant interface properties. *Journal of Biomechanics*, 47(1), 3–13. <https://doi.org/10.1016/j.jbiomech.2013.09.021>
- Mosavar, A., Ziaei, A., & Kadkhodaei, M. (2015). The effect of implant thread design on stress distribution in anisotropic bone with different osseointegration conditions: A finite element analysis. *International Journal of Oral and Maxillofacial Implants*, 30(6), 1317–1326. <https://doi.org/10.11607/jjomi.4091>
- Razaghi, R., Mallakzadeh, M., & Haghpanahi, M. (2016). Dynamic simulation and finite element analysis of the maxillary bone injury around dental implant during chewing different food. *Biomedical Engineering: Applications, Basis and Communications*, 28(2), 1650014. <https://doi.org/10.4015/S1016237216500149>