Research Article

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Integrated Fuzzy-Topsis Methodology Based On Abutment Selection In Dental Implants And Comprehensive Fatigue Life Evaluation By Matlab.

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ABSTRACT

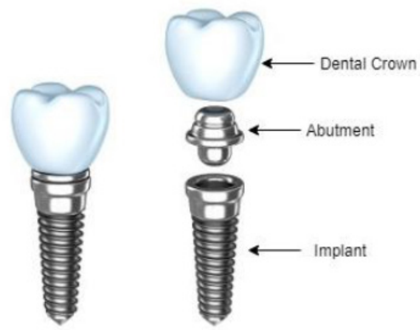
Dental implants have become the preferred solution for tooth replacement, offering both functional and aesthetic benefits that closely mimic natural teeth. This research investigates advancements in dental implant technology, including material innovations, surface treatments, and osseointegration techniques, which contribute to improved patient outcomes. We conducted a systematic review of material selection, design, and stress analysis and fatigue life for better treatment. Additionally, this study explores the role of biocompatible materials, such as titanium, zirconia alloys and ceramic composites, in enhancing implant durability and integration. The impact of digital dentistry tools, including computer-aided design and manufacturing (CAD/CAM) for custom implants, was analysed to determine their effect on surgical precision and recovery times. Results indicate that enhanced surface treatments and optimized implant geometries significantly increase stability and longevity, reducing complications associated with traditional implants. These findings highlight the importance of interdisciplinary advancements in improving the reliability of dental implants and suggest future directions for further refinement.

Keywords : Biocompatibility; Material Selection; Entropy; Stress Analysis; MCDM; Health sector.

INTRODUCTION

In this new era of technology, it is an essential requirement to choose a potential dental implant material which proves in terms of good mechanical properties, biocompatibility and good optical properties and aesthetics in dental implantology. In several studies, conventional based dental implants and their fabrication techniques have not proven higher success rates in terms of the onset hypersensitivity reactions, biocompatibility issues, aesthetics, manufacturing time and cost, human errors, and defects during prosthetic rehabilitation in dentistry [**Fig:1**].

Figure 1: Osseointegration of Dental Implant.



1.1 Dental implant

Dental implant systems are composed of several key components, each with specific functions to ensure stability, functionality, and aesthetic appeal. Here are the main components:

Implant Fixture (Implant Post or Body):

- This is the part that is surgically placed into the jawbone and acts as the artificial root of the tooth.
- Typically made from biocompatible materials like titanium or zirconia to allow osseointegration (bonding with the bone).

Abutment:

- A connector placed on top of the implant fixture, connecting it to the crown.
- The abutment is screwed or cemented onto the fixture and can be customized for proper alignment and fit.
- Made from titanium, gold, or ceramic, depending on the

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aesthetic and structural needs.

Crown (Prosthetic Tooth):

- The visible part of the implant that resembles a natural tooth.
- Made from materials like porcelain, ceramic, or metal alloys for durability and natural appearance.

Healing Cap (Healing Abutment):

- A temporary component placed over the implant post during the healing process.
- It keeps the tissue from growing over the implant and shapes the gum tissue for the final restoration.

Screw (Abutment Screw or Fixture Screw):

- Used to secure the abutment to the implant fixture, providing stability.
- Often made from titanium for strength and durability.

Cover Screw:

- Temporarily covers the implant during the initial healing period after the surgery.
- Keeps the implant protected from tissue growth and contamination before the abutment and crown are placed.

Other Accessories:

- Impression Coping: Used during the impression process to create a mold for a precise fit.
- Laboratory Analog: A model of the implant used by technicians to design the prosthetic components.

Each component plays a crucial role in ensuring that the implant is functional, stable, and esthetically pleasing. The type and design of each part can vary depending on the specific dental implant system and the patient's individual needs.

1.2 Abutment material properties and name

Abutments are made from various materials, each with unique properties suited to different clinical and aesthetic needs. Here are some commonly used materials for dental abutments and their key properties:

Titanium Abutments

- **Properties:** Titanium is known for its high strength, corrosion resistance, and biocompatibility, making it ideal for integrating with bone (osseointegration).
- **Usage:** Often used for posterior (back) teeth where strength is critical.
- **Types:** Pure titanium (Grade 4) or titanium alloys like Ti-6Al-4V (Grade 5), which have even greater strength.

Zirconia Abutments

- **Properties:** Zirconia is a high-strength ceramic with excellent biocompatibility and aesthetics. It has a natural tooth color, making it suitable for highly visible areas.
- **Usage:** Commonly used in anterior (front) regions where aesthetics are a priority.
- **Types:** Full zirconia or layered with porcelain for enhanced aesthetics.

Gold Alloy Abutments

- **Properties:** Gold alloys have excellent biocompatibility, are strong, and have low reactivity in the body. Gold is also highly customizable and has some flexibility, which can absorb occlusal forces effectively.
- **Usage:** Often used in posterior areas or for patients with metal allergies or sensitivities, though less common today due to cost and aesthetics.
- **Types:** Various alloys containing gold, platinum, or palladium.

Stainless Steel and Cobalt-Chromium Alloy Abutments

- **Properties:** Both stainless steel and cobalt-chromium alloys are strong and durable but less biocompatible than titanium or zirconia. Cobalt-chromium, in particular, is highly resistant to corrosion.
- **Usage:** Less commonly used for permanent abutments but sometimes seen in provisional or temporary abutments.

Polyether Ether Ketone (PEEK) Abutments

- **Properties:** PEEK is a high-performance polymer that is lightweight, flexible, and has a color close to that of natural dentin. While not as strong as titanium, it offers a gentler load distribution.
- **Usage:** Often used in temporary or provisional abutments rather than permanent applications.

Each material offers distinct advantages depending on the clinical requirements, location of the implant, and aesthetic considerations. Titanium and zirconia are the most commonly used materials for permanent abutments due to their combination of strength, biocompatibility, and aesthetic suitability.

1.3 Table of Beneficial Properties

Each material is chosen based on the clinical requirements, patient comfort, and aesthetic needs of the dental implant case.

Material	Beneficial Properties	Best For
Titanium	Strength, biocompatibility, corrosion resistance	General-purpose, posterior teeth
Zirconia	Aesthetics, strength, low thermal conductivity	Aesthetic cases, anterior teeth
Gold Alloy	Biocompatibility, malleability, corrosion resistance	Posterior teeth, custom cases
Cobalt-Chromium	Strength, corrosion resistance, durability	High-load cases, frameworks
PEEK	Lightweight, flexibility, shock absorption	Temporary abutments

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2.LITERATURE REVIEW

The purpose of this literature review is to suggest a suitable dental implant material and appropriate additive manufacturing technique as a viable alternative for the conventional methods used in dentistry.

Len Tolstunov (2006) This article shows the factors of importance in the long-term success and failure of oral implants based on literature review. Dental Implant Success-Failure Analysis-A Concept of Implant Vulnerability was proposed.

Łodygowski T. et al. (2009) did a study using genetic algorithm in dental implant. The subject of the present work is optimization of the modern implant system Osteoplant.

Ikebe K. et al. (2009) try to described the old age factor of dental implants. Patient's condition is distinctly different among individuals especially in the elderly.Dental implant failure seems to be a multi-factorial problem; therefore, it is unclear that aging itself is a risk factor for the placement of implants. This review reorders and discusses age-related risk factors for the success of dental implants.

Lee S. et al (2012) have developed a decision-making system for selection of dental implant abutments based on the fuzzy cognitive map.

Dmitriy V. Ivanov, Aleksandr V. Dol and Dmitriy A. Smirnov (2016) This work is devoted to the "bone-implant" system investigation aiming on the optimization of dental prostheses installation. The objective of this study was to develop the implant treatment planning technique. Modern non-invasive methods such as computer tomography (CT) and 3D-scanning as well as numerical calculations and 3D-prototyping allow optimizing all of dental prosthetics stages.

Gatto A. et al.(2017) try to find out the failure analysis of Dental implant. For more than thirty percent of patients with implant-supported fixed dental prosthesis, various complications can be observed over five-years of function. In some cases, failure can be ascribed to mechanical reasons such as loosening of the retaining screws or fracture of the implant components.

Ercan ŞENYİĞİT and Bilal DEMİREL (2018) proposed a model of the selection of material in dental implant with entropy based simple additive weighting and analytic hierarchy process methods.

Chang Cheng Y. et al (2018) This study presents an optimization procedure for the design of a one-piece zirconia ceramic dental implant that uses finite element simulation with dynamic loads and experimental validation using a fatigue test.

Ivvala J. et al (2019) have described a review on the selection of dental implant material and suitable additive manufacturing technique in dentistry.

Hemalatha B and Rajkumar N (2020) Proposed a versatile approach for dental age estimation using fuzzy neural network with teaching learning - based optimization classification.

Staedt H. et al (2020) This study represents that Potential risk factors for early and late dental implant failure: a retrospective clinical study on 9080 implants.

Pradhan M. et al (2020) in this paper an effort is taken to priortize the best dental implant material by Fuzzy Ahp method on the basis of characteristics of dental implant.

Nancy Abdelhay et al (2021) The purpose of this systematic review and meta-analysis was to evaluate implant failure rates and their association with guided and free-hand implant placement techniques.

3.METHODOLOGY

3.1 Multi Criteria Decision Making (MCDM)

Considering multiple conflicting criteria, selecting the best path from a set of feasible alternatives known as Multiple criteria decision making (MCDM). This process always goes through at least two alternatives and two conflicting criteria. MCDM are divided two broad categories: Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). Several useful tools for solving of MCDM problems are

- Simple Additive Weighting method (SAW)
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
- Multi Objective Optimization Ratio Analysis (MOORA)
- Analytical Hierarchy Method (AHP)
- Analytical Network Method ANP etc.

3.2 Entropy Method

Entropy was originally a thermodynamic concept, first introduced into information theory by Shannon. It has been widely used in the engineering, socioeconomic and other fields. According to the basic principles of information theory, information is a measure of system's ordered degree, and the entropy is a measure of system's disorder degree [Table 2]

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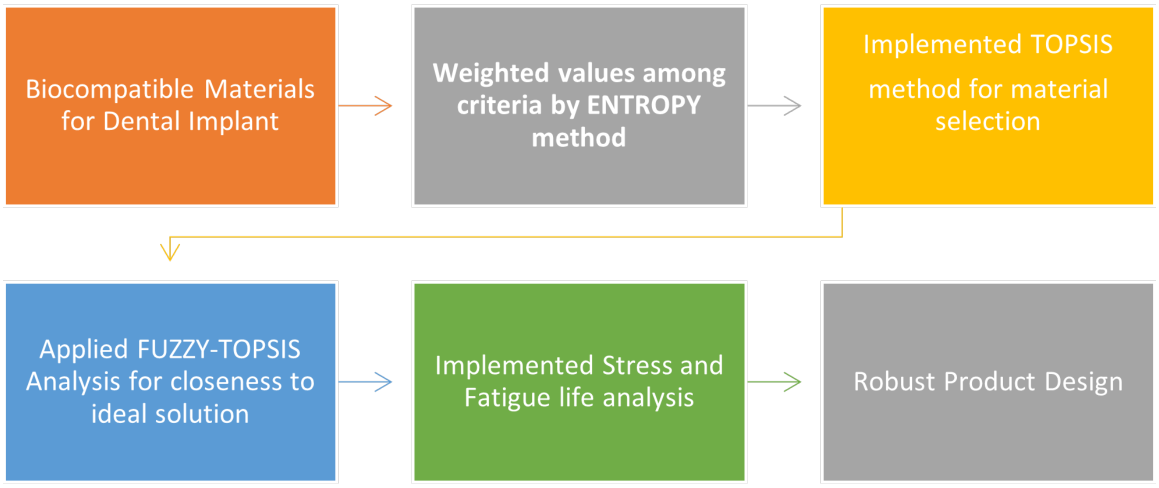
3.3 The Flowchart of the Proposed Methods

Figure 2: Flowchart of Methodology.



4. MATERIAL

The selection of dental implant materials in health sector considering technical, economic aspects. The paper involves identification of different material **[Table.1**] that are used in the manufacturing of bio-material and to give a best result. Five materials with six important properties are considered. The decision maker has to compare all the materials regarding each aspect and has to judge the best one, and this is difficult decision-making problem. So, these MCDM methods is applied to select optimal material in this section.

Table 1: Dental implant material selection matrix [8].

Criteria (C) Alternative (A)	**Tensile Strength (C1)**	**Modulus of Elasticity (C2)**	**Hardness (Vickers): (C3)**	**Density (C4)**	**Cost (C5)**	**Biocompatibility (C6)**
Titanium (Ti-6Al-4V, Grade 5) – A1	965 MPa	110 GPa	349 HV	4.43 g/cm³	$300	Excellent(10)
Zirconia (Zirconium Dioxide, ZrO_2) – A2	800 MPa	210 GPa	1300 HV	6.05 g/cm³	$500	High (8)
Gold Alloy – A3	400 MPa	100 GPa	200 HV	19 g/cm³	$1,000	Excellent (10)
Cobalt-Chromium Alloy – A4	900 MPa	240 GPa	400 HV	8.29 g/cm³	$300	Good (4)
Polyether Ether Ketone (PEEK)—A5	100 MPa	4 GPa	90 (Shore D Scale, as it is a polymer)	1.32 g/cm³	$200	Very Good (6)

5.RESEARCH GAP

Identifying research gaps in the material selection and fatigue life analysis of dental implants can be crucial for advancing the field. Here are several potential research gaps based on current literature and trends:

- Material Characterization under Complex Load Conditions: Although various materials (e.g., titanium alloys, zirconia, and composites) have been explored for dental implants, their behavior under complex, multi-axial loading conditions typical of the oral environment requires more in-depth study. Research focusing on material fatigue under cyclic loads, including bending, torsion, and compression, could provide insights into long-term performance.
- Biocompatibility and Long-term Performance of New Materials: Emerging materials and alloys, such as magnesium-based and composite materials, are showing potential in dental implant applications. However, detailed research on their biocompatibility, osseointegration, and long-term fatigue performance is limited. Investigations comparing the biological response and mechanical endurance of these newer materials with traditional ones can help define their clinical viability.
- Effect of Surface Modifications on Fatigue Life: Surface treatments, such as coatings and roughening techniques, are commonly applied to improve osseointegration and wear resistance of dental implants. However, the impact of these modifications on fatigue life and overall durability under in vivo conditions is not fully understood. More research is needed to evaluate how surface treatments influence the fatigue resistance and life expectancy of implants, especially for newer materials.
- Multiscale Modelling of Fatigue and Failure Mechanisms: Current fatigue life analysis often focuses on macroscale or microscale testing, but the complex interactions at multiple scales (nano, micro, and macro) are still not comprehensively addressed. Multiscale models that incorporate fatigue and failure mechanisms could offer a better understanding of how different materials behave over an implant's lifetime, especially under variable patient-specific conditions.
- Patient-specific Optimization and Fatigue Life Prediction: The variation in bone quality, load patterns, and healing capacity among patients can significantly influence implant success. Patient-specific modelling that considers these factors, combined with advanced material selection techniques (e.g., fuzzy TOPSIS), could improve fatigue life predictions and material choices tailored to individual patients.
- Lifecycle and Environmental Impact of Implant Materials: While research on sustainable materials for medical applications is growing, there is limited focus on lifecycle analysis for dental implants. Studies examining the environmental impact, recyclability, and sustainability of different implant materials could provide insights into the broader implications of material choice beyond fatigue life.
- Integration of Machine Learning for Fatigue Prediction Models: Machine learning techniques are underutilized in predicting fatigue life for dental implants. Incorporating data-driven approaches into fatigue analysis could improve prediction accuracy by analyzing large datasets of material properties, loading conditions, and clinical outcomes.

6.PROBLEM FORMULATION

In dental implant, biomaterials are made of various materials. Among these four criteria [C] - Young's modulus (C1), Yield strength (C2), Hardness (C3) are beneficiary and rest of criteria (Cost) are non- beneficiary. Find out the optimum result among alternatives [M] are difficult task. In the matter of total Dental implant, the proper material selection is challenging task to a decision maker. This paper involved to find out the best result among the alternatives considering criteria.

7.EXPERIMENT AND RESULT

7.1 In the TOPSIS method

The weighted values got from entropy method
The waighted values are:

Table 2: Entropy method

Criteria-1	Criteria-2	Criteria-3	Criteria-4	Criteria-5	Criteria-6
0.1495	0.1813	0.2327	0.1784	0.1572	0.1009

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STEP1: Determination of normalized decision matrix [**Table: 3**]

Table 3: Determination of normalized decision matrix.

	C1	C2	C3	C4	C5	C6
A1	1.0000	0.4583	0.2685	0.2332	0.3000	0.4000
A2	0.8290	0.8750	1.0000	0.3184	0.5000	0.5000
A3	0.4145	0.4167	0.1538	1.0000	1.0000	0.4000
A4	0.9326	1.0000	0.3077	0.4363	0.3000	1.0000
A5	0.1036	0.0167	0.0692	0.0695	0.2000	0.6667

STEP 2: Determination of positive ideal solution: taking the maximum values of each column from the normalized decision matrix [Table: 4]

Table 4: Determination of positive ideal solution: taking the maximum values of each column from the normalized decision matrix.

C1	C2	C3	C4	C5	C6
1	1	1	1	1	1

Determination of negative ideal solution: taking the minimum values of each column from the normalized decision matrix [Table: 5]

Table 5: Taking the minimum values of each column from the normalized decision matrix.

C1	C2	C3	C4	C5	C6
0.1036	0.0167	0.0692	0.0695	0.2000	0.4000

STEP 3: Calculation of the separation measure from the positive ideal solution(di_Plus) [Table: 6]

Table 6: Calculation of the separation measure from the positive ideal solution(di_Plus).

A1	A2	A3	A4	A5
0.6293	0.3932	0.5620	0.4959	0.8737

Calculation of the separation measure from the negative ideal solution (di_Minus) [Table: 7]

Table 7: Calculation of the separation measure from the negative ideal solution (di_Minus)

A1	A2	A3	A4	A5
0.4136	0.6634	0.5479	0.5943	0.0847

STEP 4: Calculation of R_i [Table: 8]

Table 8: Calculation of R_i.

A1	A2	A3	A4	A5
0.3966	0.6279	0.4936	0.5451	0.0884

STEP 5: Arranging the final value in descending order :--------->>> M2 > M4 > M3 > M1 > M5 [Fig: 3&4]

Figure 3

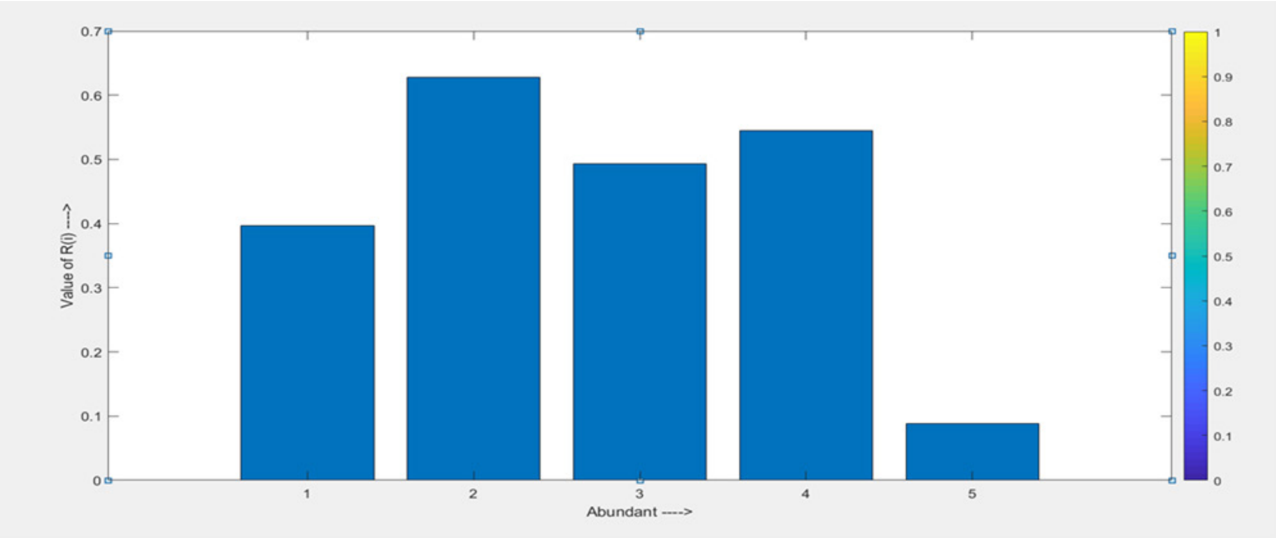
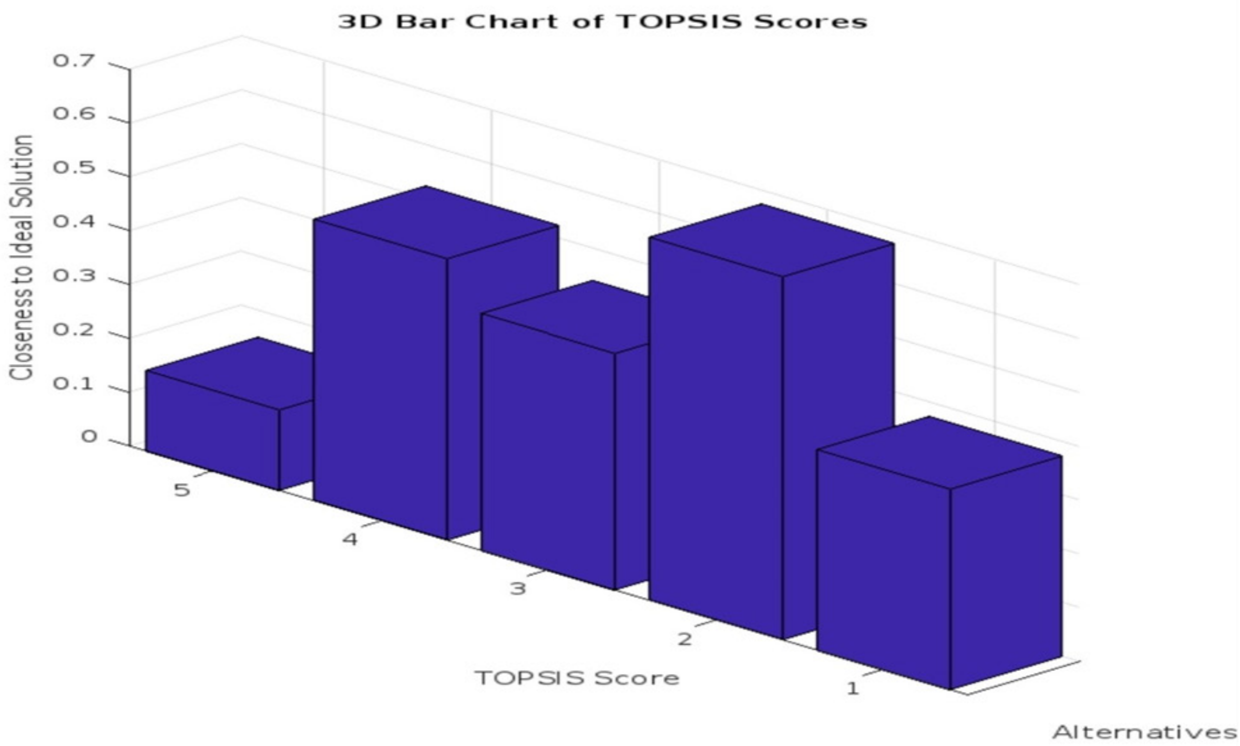


Figure 4.



7.2 Overview of Stress Analysis for Dental Implants

Key Mechanical Properties of Zirconia:

- Tensile Strength: 200-800 MPa
- Modulus of Elasticity: 200-210 GPa
- Hardness (Vickers): 1200-1300 HV
- Density: 6.05 g/cm³
- Biocompatibility: High

Objectives:

1. Determine the types of stresses acting on the implant (e.g., axial, bending).

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2. Calculate the stress values using appropriate formulas.
3. Assess the safety by comparing calculated stresses with zirconia's tensile strength.
4. Visualize stress distribution (optional for more advanced analysis).

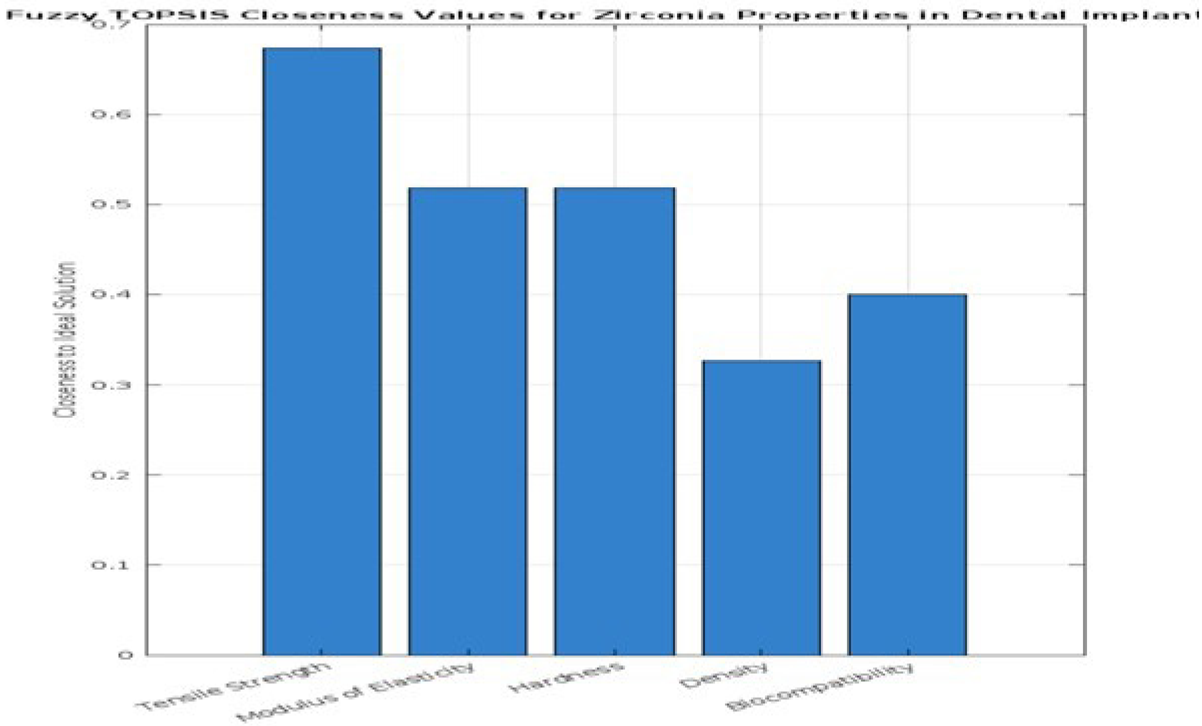
Assumptions:

- The implant is modelled as a cylindrical or screw-like structure.
- Loading conditions include axial forces and bending moments typical in mastication (chewing).
- Material behaviour is elastic (linear stress-strain relationship).
- The implant is fixed at one end (anchored in the bone) and free at the other (connected to the prosthetic tooth).

Fuzzy- TOPSIS analysis for Zirconia properties in dental implants- [Fig: 5]

- Tensile strength closeness to ideal solution = 0.6734
- Modulus of elasticity closeness to ideal solution = 0.5186
- Hardness closeness to ideal solution = 0.5186
- Density closeness to ideal solution = 0.3266
- Biocompatibility closeness to ideal solution = 0.4000

Figure 5: Fuzzy- TOPSIS analysis for Zirconia properties in dental implants.



Zirconia Dental Implant Stress Analysis [Fig: 6&7]

Axial Stress: 119.37 MPa

Bending Stress: 318.31 MPa

Maximum Combined Stress: 437.68 MPa

Minimum Tensile Strength of Zirconia: 200.00 MPa

Maximum Tensile Strength of Zirconia: 800.00 MPa

Status: Caution (Stress below maximum tensile strength).

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Figure 6. Stress Distribution along zirconia dental implant.

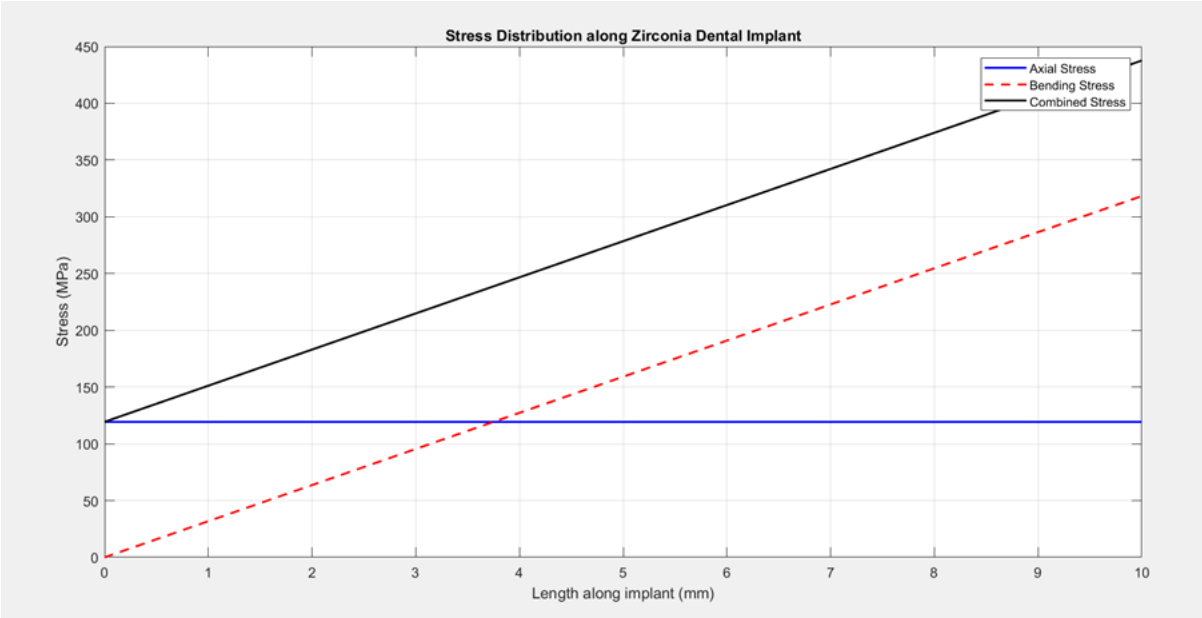
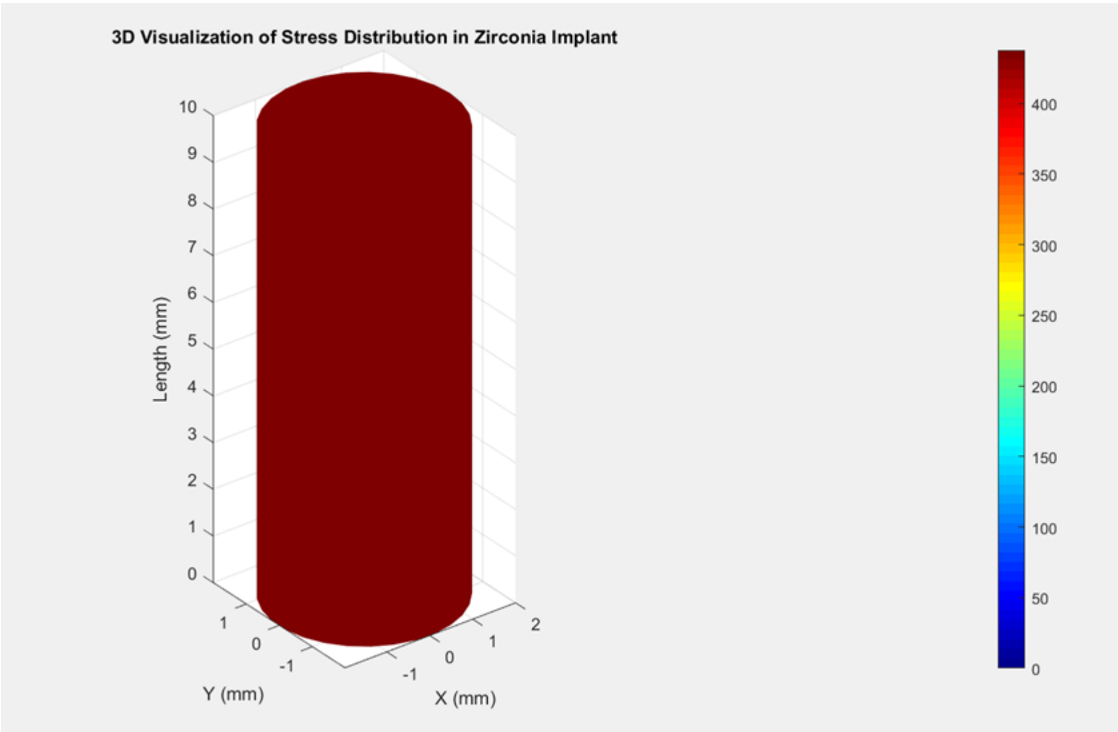


Figure 7. 3D Visualization of stress Distrubution in Zirconia implant.



Fatigue Analysis

To perform a fatigue life analysis of a zirconia dental implant, we'll use the material properties provided and apply fatigue analysis methods to estimate the life cycle. Since fatigue analysis [Fig: 8&9] can involve complex load cycles, assumptions are typically made based on stress range, mean stress, and a fatigue model, such as the S-N (stress-life) curve or Basquin's law. Here's an outline for the analysis:

1. **Assumptions and Loading Conditions:** Assume a sinusoidal loading cycle (typical in dental applications) with a specific mean stress and amplitude.
2. **Fatigue Model:** Use Basquin's equation for high-cycle fatigue:

$$N_f = (\sigma_a/\sigma'_f)^{-b}$$

where:

- o Nf: Number of cycles to failure,
- o σa: Alternating stress amplitude,
- o σ′f: Fatigue strength coefficient,
- o b: Fatigue strength exponent.

3. **S-N Curve Parameters:** Set values for σ′f and b based on empirical data or approximate values for ceramics.

Zirconia Dental Implant Fatigue Life Analysis

Mean Combined Stress: 437.68 MPa

Stress Amplitude: 218.84 MPa

Estimated Fatigue Life (Cycles): 4.58e+04

Figure 8. S-N Curve Zirconia Dental Implant.

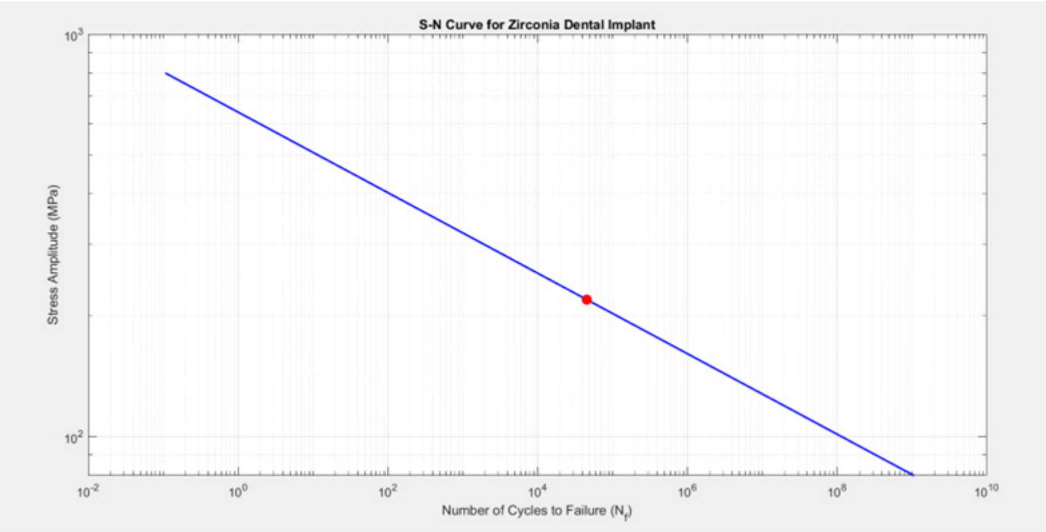
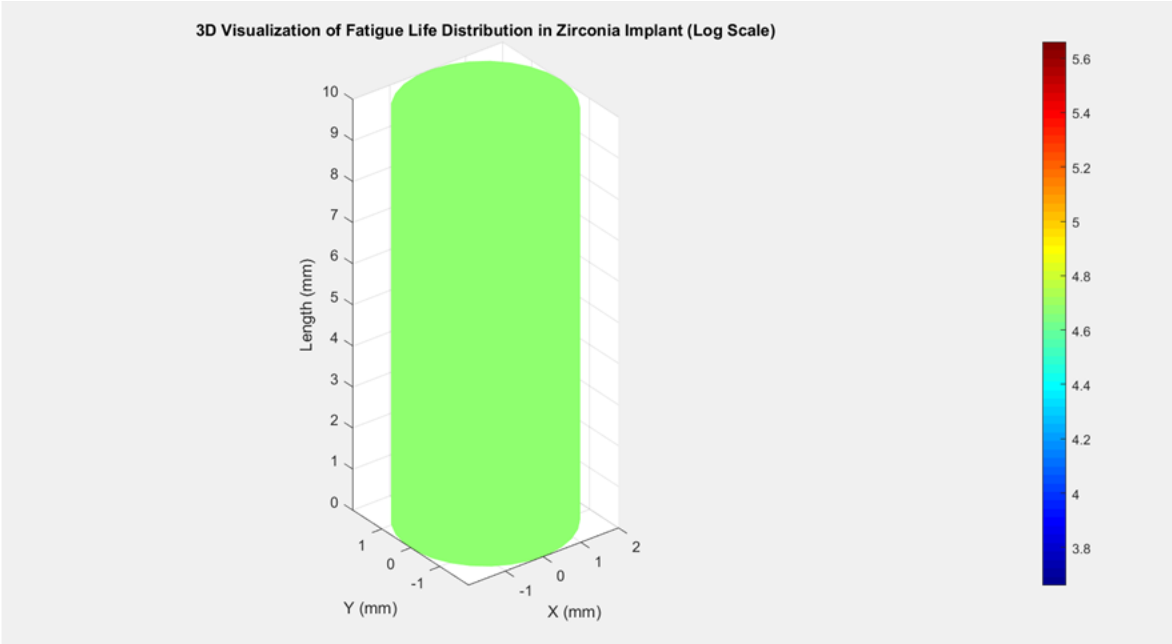


Figure 9. 3D Visualiztion of Fatigue life distribution in zirconia impalnt(Log Scale)



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8.DISCUSSION

From this experiment, Novelty of the works are:
The application of fuzzy TOPSIS for selecting optimal materials based on specific criteria in dental implants is relatively novel, offering a systematic approach to handle the uncertainty and ambiguity in decision-making. By combining material selection with fatigue life calculation, this research offers a comprehensive approach that evaluates materials not only based on initial properties but also on long-term durability and fatigue performance. The integration of MATLAB-based fuzzy TOPSIS with stress and fatigue analysis introduces a robust framework to predict the lifecycle performance, which may not be commonly addressed in dental implant research. Using fuzzy TOPSIS in a healthcare-related engineering field, such as dental implants, brings a novel perspective on how MCDM tools can aid in the biomedical device selection process.

9.CONCLUSIONS

The study likely concludes that the fuzzy TOPSIS method effectively identifies the best-suited materials for dental implants, balancing strength, durability, and biocompatibility. Through stress and fatigue life analysis, the chosen materials can be verified to support longer implant life, minimizing failure rates and enhancing patient outcomes. The research highlights fuzzy TOPSIS as a powerful, efficient tool for material selection in biomedical applications, especially where choices must balance multiple competing factors under uncertainty. The combined approach of fuzzy TOPSIS with fatigue analysis can be applied to other biomedical devices, promoting more sustainable and reliable medical materials research.

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Conflict of Interest:
The authors declare no conflict of interest.

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