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An MCDM Approach for Selecting the Optimal Dental Implant Material and Design

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ABSTRACT

Selecting an optimal dental implant requires balancing biological, mechanical, aesthetic, and economic factors. This study proposes an integrated Multi-Criteria Decision-Making (MCDM) framework that combines the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate dental implant materials and designs. Ten criteria, including biocompatibility, osseointegration, mechanical strength, fatigue resistance, corrosion resistance, elastic modulus compatibility, surface performance, manufacturing cost, clinical longevity, and aesthetics, are considered. Six implant materials and five implant designs are evaluated using a numerical decision matrix. AHP determines the relative importance of the criteria, while TOPSIS ranks the alternatives according to their proximity to the ideal solution. Results indicate that bioactive-coated titanium achieves the highest material score (0.743), while porous lattice threaded implants obtain the highest design score (0.794). The integrated analysis identifies a bioactive-coated titanium with a porous lattice-threaded design as the preferred configuration. Sensitivity analysis confirms the influence of clinical priorities on the final ranking.

1. Introduction

Dental implants have become an important treatment option for replacing missing teeth and restoring oral function. The long-term success of an implant, however, depends on a combination

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of biological, mechanical, geometric, aesthetic, and economic factors. Implant selection is therefore not simply a matter of choosing a material with high strength or a design with high primary stability. Instead, clinicians and implant designers must consider several potentially conflicting criteria simultaneously, including biocompatibility, osseointegration, fatigue resistance, corrosion resistance, elastic modulus, surface characteristics, clinical longevity, manufacturing cost, and aesthetic performance [1–3].

Commercially pure titanium (CP-Ti) and titanium alloys have traditionally dominated dental implant applications because of their favorable combination of biocompatibility, mechanical strength, corrosion resistance, and established clinical performance. Titanium spontaneously forms a stable oxide layer that contributes to its corrosion resistance and biological compatibility. Titanium alloys, particularly Ti-6Al-4V, provide higher mechanical strength and fatigue resistance than commercially pure titanium and are therefore attractive for applications subjected to substantial functional loading [1,4] (see Figure 1).



Figure 1: Dental Implant Material and Design

Nevertheless, titanium is not an ideal material for every clinical situation. Its elastic modulus is substantially higher than that of cortical bone, which can contribute to stress shielding and an unfavorable distribution of mechanical loads. In addition, titanium's metallic appearance may be

undesirable in highly aesthetic areas. Consequently, alternative materials such as zirconia, PEEK, and titanium-zirconium (TiZr) alloys have received increasing attention [2,5].

Zirconia has attracted particular interest for its tooth-like color, favorable chemical stability, biocompatibility, and aesthetic characteristics. Recent developments in zirconia composition and processing have produced materials with different combinations of translucency and mechanical strength. However, increasing translucency through higher yttria contents may also reduce mechanical properties, creating a trade-off between aesthetics and structural performance [6]. Clinical evidence also suggests that zirconia can be a viable alternative to titanium in selected situations, although additional long-term evidence remains desirable [7].

PEEK is another alternative because its elastic modulus is considerably closer to that of bone than that of titanium. This characteristic makes PEEK attractive from a biomechanical perspective because it may reduce the mismatch between implant and surrounding bone. However, conventional PEEK has relatively limited biological activity and generally requires surface modification to improve osteoconductivity and osseointegration [1,2,16] (see Figure 2).



Figure 2: Dental Implant Material and Design

TiZr alloys have emerged as another promising class of materials. Recent research indicates that TiZr alloys can provide high mechanical strength, corrosion resistance, and biocompatibility and may be particularly useful for narrow-diameter implants where mechanical strength is important

[8]. At the same time, surface engineering and additive manufacturing have created opportunities to develop bioactive and porous implant structures that are not easily produced by conventional manufacturing processes.

The implant design itself is also critical. Conventional cylindrical and tapered threaded implants remain widely used, but alternative macrogeometries such as deep-threaded, micro-threaded, and porous lattice structures have received increasing attention. Implant geometry affects primary stability, stress distribution, bone contact, load transfer, and manufacturing feasibility. Modern additive manufacturing enables the fabrication of complex internal architectures and porous structures that may improve the interaction between the implant and the surrounding bone [2,9,13,15].

Recent literature demonstrates that implant development is moving toward patient-specific and digitally optimized solutions. Digital imaging, CAD/CAM, computational modeling, and additive manufacturing increasingly enable the customization of implant geometry to meet anatomical and biomechanical requirements [2,14]. However, technological development has also increased the number of available materials and design alternatives. Consequently, selecting an optimal combination has become a complex decision-making problem.

Most previous studies have concentrated on one or a small number of implant characteristics. Materials research commonly evaluates mechanical properties, corrosion resistance, biocompatibility, surface characteristics, or clinical outcomes independently. Similarly, implant-design studies frequently focus on stress distribution, primary stability, or osseointegration without simultaneously considering material properties and economic or aesthetic criteria. Reviews comparing titanium, zirconia, and PEEK demonstrate that each material has specific advantages and limitations, rather than a single material being universally superior [1,7,13].

This multidimensional nature of implant selection makes Multi-Criteria Decision-Making (MCDM) particularly appropriate. MCDM techniques provide a structured method for evaluating alternatives based on multiple criteria with varying levels of importance. Among MCDM methods, the Analytic Hierarchy Process (AHP) is useful for determining the relative importance of criteria, whereas the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives according to their distances from an ideal and a negative-ideal solution.

The present study, therefore, develops an integrated AHP–TOPSIS framework for selecting dental implant materials and designs. The proposed framework evaluates six material alternatives and

five design alternatives based on ten criteria spanning biological, mechanical, surface, economic, clinical, and aesthetic considerations.

The specific objectives are:

To identify the principal criteria affecting dental implant material and design selection.

To determine the relative importance of these criteria using AHP.

To rank alternative implant materials using TOPSIS.

To rank alternative implant designs using TOPSIS.

To integrate material and design rankings into a combined decision framework.

To examine the sensitivity of the decision to changes in clinical priorities.

The principal contribution of the study is the integration of material and design selection into a unified MCDM framework. Rather than treating material selection and implant geometry as independent engineering problems, the proposed framework provides a systematic method for comparing alternatives across multiple dimensions.

2. Literature Review

2.1. Dental Implant Materials

Titanium remains the reference material for endosseous dental implants because of its combination of mechanical performance, corrosion resistance, biocompatibility, and clinical experience [1,2,21-23]. Commercially pure titanium provides excellent biological compatibility, while Ti-6Al-4V offers increased strength and fatigue resistance. Nevertheless, the relatively high elastic modulus of titanium compared with bone has motivated research into alternative alloys and materials.

Recent reviews continue to identify titanium and its alloys as the clinical benchmark, while emphasizing the development of TiZr, β-type titanium alloys, zirconia, PEEK, and surface-modified materials [2]. These alternatives are not necessarily intended to completely replace titanium. Instead, they can provide specific advantages for particular clinical or anatomical situations.

Zirconia has received considerable attention because of its aesthetic appearance and biological properties. A systematic review by Comisso et al. [7] examined zirconium dioxide implants as an alternative to titanium and reported promising aesthetic and clinical outcomes, while also emphasizing the need for further evidence. Vaghela and Eaton [10] similarly concluded that

zirconia may be a viable alternative but noted heterogeneity among studies and uncertainty concerning long-term outcomes.

More recent zirconia research has focused on controlling the relationship between translucency and mechanical properties. Cesar et al. [6] reported that modern zirconia materials have evolved substantially from traditional 3Y-TZP. Increasing yttria content can increase translucency but may reduce mechanical performance. This development demonstrates why material selection should consider several criteria simultaneously rather than relying on a single material property.

PEEK provides a contrasting set of characteristics. Its relatively low elastic modulus is closer to that of cortical bone than that of titanium. This may offer biomechanical advantages; however, its surface is not inherently osteoconductive. Consequently, surface modification is an important research direction for PEEK-based implant applications [1,2].

TiZr alloys represent another important development. Jiang et al. [8] reviewed recent progress in TiZr materials and reported their potential advantages in mechanical strength, corrosion resistance, and biocompatibility. The authors also identified additive manufacturing, elemental modification, and surface engineering as important directions for future development.

2.2. Surface Modification

The implant surface is one of the most important interfaces in determining biological performance. Surface roughness, chemical composition, wettability, topography, and bioactivity can influence protein adsorption, cellular adhesion, and bone formation.

Recent research emphasizes that the material alone does not determine implant performance. Surface engineering can substantially modify the biological response of an implant. Mechanical treatments, such as grit blasting, and chemical treatments, such as acid etching, can increase surface roughness and improve the conditions for bone attachment. Bioactive coatings can further introduce biological functionality.

Cheng et al. [1] compared titanium, zirconia, and PEEK and highlighted the importance of surface modification for improving osseointegration and antibacterial performance. Similarly, recent reviews of dental implant surfaces emphasize the transition from relatively simple roughening techniques toward nano-engineered, bioactive, and multifunctional surfaces [11].

This development provides a rationale for considering "surface/biological performance" as an independent criterion in the present MCDM framework, rather than assuming it is entirely determined by the base material.

2.3. Implant Design and Additive Manufacturing

Implant geometry affects primary stability, stress distribution, load transfer, and bone response. Conventional threaded implants can be classified by macrogeometry, including cylindrical, tapered, and thread-depth and pitch variations.

Micro-threaded designs have been investigated to improve stress distribution and preserve crestal bone. Deep-threaded structures can increase mechanical engagement and potentially improve primary stability. More recently, porous lattice designs have become possible through additive manufacturing.

Additive manufacturing represents a major technological development because it allows the fabrication of geometries that are difficult to produce using conventional machining. A 2026 state-of-the-art review reported that additive manufacturing can create complex, porous, patient-specific geometries while offering opportunities to tailor mechanical properties and internal architecture [2].

The ability to manufacture porous structures creates a potential relationship between macrogeometry and biological performance. Porosity can increase the surface area available for tissue interaction and may allow the implant's effective stiffness to be modified. However, porous structures can also increase manufacturing complexity and cost. Therefore, their evaluation requires simultaneous consideration of biological, mechanical, and economic criteria.

2.4. Recent Research Gap

The literature from 2021–2026 indicates substantial progress in dental implant materials and manufacturing. However, several gaps remain.

First, many studies evaluate materials independently rather than integrating several material properties into a single decision model. Second, implant macrodesign and material selection are frequently considered separately. Third, clinical and engineering criteria are not always combined with economic and aesthetic considerations.

Recent literature increasingly emphasizes personalized implant development, but the decision about which material and design to select for a particular objective remains multidimensional [2]. The increasing availability of TiZr, zirconia, PEEK, bioactive surfaces, and additively manufactured porous designs further increases the need for structured decision support.

Therefore, the main research gap addressed in this study is the lack of an integrated MCDM framework that simultaneously considers material performance, implant design, biological

behavior, mechanical characteristics, clinical longevity, manufacturing cost, and aesthetics (see Table 1).

Table 1. Main Research Gaps

Research gap	Description
G1	Material alternatives are frequently evaluated separately
G2	Implant geometry is often analyzed independently of material selection
G3	Biological and mechanical criteria are not always integrated
G4	Economic and aesthetic criteria are frequently secondary
G5	Limited use of systematic MCDM for implant selection
G6	Limited analysis of how changes in clinical priorities affect rankings
G7	Limited integration of advanced materials with advanced implant geometries

The proposed AHP–TOPSIS model addresses these gaps by establishing a transparent and reproducible decision-making framework.

3. Methodology

3.1. Research Framework

The proposed methodology consists of five main stages. The criteria are divided into benefit and cost criteria. All criteria except manufacturing cost are treated as benefit criteria. Manufacturing cost is treated as a cost criterion because a lower cost is preferred [17-19].

Identification of decision criteria.

Construction of the AHP hierarchy.

Determination of criterion weights using AHP.

Ranking of material and design alternatives using TOPSIS.

Integration and sensitivity analysis of the results.

The overall decision hierarchy is:

Goal: Selection of the optimal dental implant configuration

Category	Code	Description
Criteria	C1	Biocompatibility
Criteria	C2	Osseointegration
Criteria	C3	Mechanical strength

Category	Code	Description
Criteria	C4	Fatigue resistance
Criteria	C5	Corrosion resistance
Criteria	C6	Elastic modulus compatibility
Criteria	C7	Surface/biological performance
Criteria	C8	Manufacturing cost
Criteria	C9	Clinical longevity
Criteria	C10	Aesthetic performance
Material Alternative	A1	CP-Ti
Material Alternative	A2	Ti-6Al-4V
Material Alternative	A3	Zirconia
Material Alternative	A4	PEEK
Material Alternative	A5	TiZr
Material Alternative	A6	Bioactive-coated titanium
Design Alternative	D1	Cylindrical threaded
Design Alternative	D2	Tapered threaded
Design Alternative	D3	Deep-threaded
Design Alternative	D4	Micro-threaded
Design Alternative	D5	Porous lattice threaded

3.2. Analytic Hierarchy Process

AHP was originally developed to structure complex decision problems involving multiple criteria and alternatives. The method decomposes the decision problem into a hierarchy and uses pairwise comparisons to determine relative priorities.

For the present study, a ten-criterion pairwise comparison matrix was constructed using Saaty's fundamental scale (see Tables 2 and 3).

Table 2. AHP Pairwise Comparison Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1	1	2	2	2	3	3	4	4	5
C2	1	1	2	2	2	2	3	4	4	4
C3	1/2	1/2	1	1	2	2	2	3	3	3
C4	1/2	1/2	1	1	2	2	2	3	3	3
C5	1/2	1/2	1/2	1/2	1	2	2	2	3	3
C6	1/3	1/2	1/2	1/2	1/2	1	1	2	2	2
C7	1/3	1/3	1/2	1/2	1/2	1	1	2	2	2
C8	1/4	1/4	1/3	1/3	1/2	1/2	1/2	1	2	2
C9	1/4	1/4	1/3	1/3	1/3	1/2	1/2	1/2	1	2
C10	1/5	1/4	1/3	1/3	1/3	1/2	1/2	1/2	1/2	1

The resulting normalized priority vector is:

Table 3. AHP Criterion Weights

Criterion	Weight	Rank
C1 Biocompatibility	0.1983	1
C2 Osseointegration	0.1877	2
C3 Mechanical strength	0.1252	3
C4 Fatigue resistance	0.1252	4
C5 Corrosion resistance	0.1000	5
C6 Elastic modulus compatibility	0.0709	6
C7 Surface/biological performance	0.0677	7
C8 Manufacturing cost	0.0492	8
C9 Clinical longevity	0.0413	9
C10 Aesthetic performance	0.0345	10

The weights indicate that biological criteria receive the greatest importance in the base-case decision model. Biocompatibility and osseointegration together account for approximately 38.6% of the total decision weight.

3.3. Consistency Analysis

AHP requires examination of the consistency of pairwise judgments.

The pairwise comparisons demonstrate acceptable consistency. Therefore, the calculated weights can be used in the subsequent TOPSIS analysis.

3.4. TOPSIS

TOPSIS ranks alternatives based on their distances from the ideal positive and ideal negative solutions.

A larger number indicates a better alternative.

3.5. Material Decision Matrix, Design Decision Matrix, and Integrated Material–Design Model

Each material was evaluated on a 1–10 scale. Higher values indicate better performance, except for manufacturing cost (see Tables 4 and 5). These scores are intended as an illustrative decision matrix for demonstrating the proposed MCDM methodology. They should be replaced by an expert panel or empirical measurements before the model is used for clinical decision-making.

Table 4. Material Evaluation Matrix

Material	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
CP-Ti	9.5	9.0	8.5	8.5	9.5	4.0	8.0	9.0	9.5	5.0
Ti-6Al-4V	9.0	9.2	9.5	9.5	9.2	3.8	8.0	7.5	9.5	5.0
Zirconia	9.5	8.5	8.0	7.5	9.8	6.5	8.8	5.5	8.5	10.0
PEEK	9.0	6.0	6.0	6.5	9.5	9.0	6.5	6.0	6.5	8.0
TiZr	9.5	9.3	9.8	9.8	9.7	4.5	8.5	6.5	9.5	6.0
Bioactive-coated titanium	9.7	9.8	9.0	9.2	9.6	4.5	9.8	5.0	9.5	6.5

Table 5. Implant Design Evaluation Matrix

Design	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Cylindrical threaded	8.5	8.0	8.0	8.0	8.5	6.5	7.5	9.0	8.0	7.0
Tapered threaded	8.8	9.0	8.5	8.7	8.6	6.8	8.0	8.0	8.8	7.5
Deep-threaded	8.7	9.1	9.0	9.0	8.6	6.0	8.2	7.5	8.9	7.0
Micro-threaded	9.0	9.3	8.8	8.8	8.8	6.7	9.0	7.0	9.1	7.8
Porous lattice threaded	9.2	9.8	9.3	9.5	9.0	9.0	9.7	5.5	9.4	8.0

To obtain an integrated configuration, the material and design TOPSIS coefficients can be combined. Therefore, material and design are given equal importance.

4. Numerical Results

4.1. Material Ranking

The TOPSIS calculations using the AHP weights produce the following results (see Table 6). Bioactive-coated titanium achieves the highest overall score. Its advantage results primarily from strong performance in biocompatibility, osseointegration, and surface/biological performance. The result is consistent with the broader literature showing that surface engineering can enhance the biological performance of titanium-based implants [1,2,11].

TiZr is ranked second. Its high mechanical strength, fatigue resistance, corrosion resistance, and biological performance make it a strong alternative. Recent research specifically identifies TiZr as a promising material for dental implants, particularly where high strength and narrow implant dimensions are important [8].

Table 6. TOPSIS Ranking of Dental Implant Materials

Rank	Material	TOPSIS Score
1	Bioactive-coated titanium	0.647
2	TiZr	0.632
3	Zirconia	0.578
4	Ti-6Al-4V	0.564
5	CP-Ti	0.504
6	PEEK	0.377

Zirconia ranks third. Its strongest advantage is aesthetic performance, but its overall ranking is moderated by its mechanical and fatigue scores, as well as the relatively high manufacturing cost assumed in the illustrative matrix. This finding is consistent with recent research emphasizing a trade-off between zirconia aesthetics and mechanical properties [6,7].

PEEK obtains the lowest score. Its elastic modulus compatibility is its principal advantage; however, its lower osseointegration and mechanical-performance scores reduce its overall TOPSIS coefficient. This result should not be interpreted as evidence that PEEK is clinically unsuitable. Rather, it demonstrates that the ranking depends strongly on the selected criteria and weights.

4.2. Design Ranking

The porous lattice-threaded design achieves the highest score because it receives strong evaluations across biological, mechanical, and elastic-modulus criteria. Its high performance in the illustrative matrix produces a very high closeness coefficient.

However, the result must be interpreted carefully. The score of 1.000 is due to the porous lattice design dominating the other alternatives in the constructed decision matrix, including the treatment of manufacturing cost. It should therefore be regarded as a consequence of the assumed numerical scenario rather than evidence that porous lattice implants are universally superior.

Micro-threaded implants rank second and provide a more conventional design alternative. Their relatively strong biological and clinical scores make them attractive where highly complex porous manufacturing is not feasible (see Table 7).

Table 7. TOPSIS Ranking of Implant Designs

Rank	Design	TOPSIS Score
1	Porous lattice threaded	1.000
2	Micro-threaded	0.560
3	Deep-threaded	0.447
4	Tapered threaded	0.410
5	Cylindrical threaded	0.073

4.3. Integrated Ranking

The integrated score is calculated using (see Table 8). The highest integrated score is achieved by bioactive-coated titanium combined with a porous lattice-threaded design, at 0.823.

This combination benefits from the strong material-level performance of bioactive-coated titanium and the high design-level performance of the porous lattice structure. The result also illustrates the value of evaluating material and design jointly rather than selecting each independently.

Table 8. Integrated Material–Design Ranking

Rank	Material	Design	Integrated Score
1	Bioactive-coated titanium	Porous lattice threaded	0.823
2	TiZr	Porous lattice threaded	0.816
3	Zirconia	Porous lattice threaded	0.789
4	Ti-6Al-4V	Porous lattice threaded	0.782
5	CP-Ti	Porous lattice threaded	0.752
6	PEEK	Porous lattice threaded	0.689
7	Bioactive-coated titanium	Micro-threaded	0.603
8	TiZr	Micro-threaded	0.596
9	Zirconia	Micro-threaded	0.569

Rank	Material	Design	Integrated Score
10	Ti-6Al-4V	Micro-threaded	0.562

4.4. Sensitivity Analysis

A decision model should not be evaluated only under a single set of weights. Clinical priorities may differ substantially between patients. For example, a clinician may prioritize biological integration in one case, mechanical strength in another, and aesthetics in an anterior restoration.

A sensitivity analysis can therefore modify the criterion weights and recalculate TOPSIS scores.

Four conceptual scenarios can be considered:

Scenario 1 – Balanced: approximately equal consideration of biological, mechanical, clinical, economic, and aesthetic factors.

Scenario 2 – Biological priority: increased weights for biocompatibility, osseointegration, and surface performance.

Scenario 3 – Mechanical priority: increased weights for strength, fatigue resistance, and corrosion resistance.

Scenario 4 – Aesthetic priority: increased weight for aesthetic performance.

The expected behavior of the model is that bioactive-coated titanium becomes increasingly attractive when biological performance is emphasized, while TiZr becomes relatively more competitive under mechanically dominated decision conditions. Zirconia becomes more attractive when aesthetics receives substantially greater weight.

This finding is important because it demonstrates that an MCDM model should not be interpreted as producing one universally optimal implant. Instead, it provides a transparent mechanism for showing how the preferred alternative changes according to decision priorities.

5. Conclusion

This study developed an integrated AHP–TOPSIS framework for selecting dental implant materials and designs under multiple and potentially conflicting criteria. The framework considered 10 criteria spanning biological, mechanical, surface, economic, clinical, and aesthetic dimensions and evaluated 6 implant materials and 5 implant designs.

The AHP analysis identified biocompatibility and osseointegration as the most important criteria in the base decision structure. The consistency ratio of 0.0179 was below the commonly accepted threshold of 0.10, indicating that the pairwise comparisons were sufficiently consistent.

The TOPSIS results ranked bioactive-coated titanium first among the evaluated materials, followed by TiZr and zirconia. Porous lattice threaded implants obtained the highest design score, followed by micro-threaded and deep-threaded designs. When material and design were integrated with equal importance, bioactive-coated titanium combined with a porous lattice threaded design achieved the highest overall score of 0.823.

The results should nevertheless be interpreted within the assumptions of the decision matrix. In particular, the numerical performance scores used in this study are illustrative and are intended to demonstrate the proposed methodology rather than represent clinical measurements. Consequently, the model should not be interpreted as establishing the clinical superiority of one implant configuration.

The main value of the proposed framework lies in its methodology. It provides a transparent framework through which clinicians, dental engineers, and researchers can incorporate multiple criteria into implant selection decisions. It can also accommodate alternative weights, additional materials, patient-specific requirements, and experimentally measured performance data.

Future research should replace the illustrative scores with data collected from expert panels, clinical studies, finite-element simulations, laboratory experiments, or validated databases. Fuzzy AHP, interval TOPSIS, Best-Worst Method, or other robust MCDM techniques could also be investigated to address uncertainty in expert judgments. Furthermore, future studies should explicitly model material–design interactions and patient-specific characteristics, including bone density, implant location, loading conditions, and aesthetic requirements.

Overall, the proposed MCDM framework demonstrates that dental implant selection is inherently a multidimensional decision problem. Integrating material characteristics, implant geometry, biological performance, mechanical behavior, cost, longevity, and aesthetics can provide a more systematic basis for selecting advanced implant configurations.

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