World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(REVIEW ARTICLE)

Check for updates

ASSESSING THE ROLE OF POLYETHERETHERKETONE AS A DENTAL IMPLANT MATERIAL

Hafizha [1], Nafilah Karimah [1], Aulia Rahma Ananda [1], Devina Indrawati Wijaya [1], Izzatun Nuriy Taufik [1], Mohammad Iqbal [1], Asma Suhail [1], Moudah Mustafa Abdulmajid Mujabbir [1], Diana Zakiyah [1], Alya Sahilla Fahri [1], Lily Fernandani Az Zahra Natatimur [1] and Anita Yuliati [2, *]

[1] Master Degree Program of Dental Medicine Science, Faculty of Dental Medicine, Universitas Airlangga, Surabaya, Indonesia, 60132.
[2] Department of Dental Materials, Faculty of Dental Medicine, Universitas Airlangga, Surabaya, Indonesia, 60132.
* Corresponding Author

ORCID Details
Hafizha: https://orcid.org/0009-0004-2643-5464
Nafilah Karimah: https://orcid.org/0009-0002-1607-4795
Aulia Rahma Ananda: https://orcid.org/0009-0000-2563-8930
Devina Indrawati Wijaya: https://orcid.org/0009-0002-8756-2833
Izzatun Nuriy Taufik: https://orcid.org/0009-0002-3854-8760
Mohammad Iqbal: https://orcid.org/0009-0008-3994-884X
Asma Suhail: https://orcid.org/0009-0007-1576-4651
Moudah Mustafa Abdulmajid Mujabbir: https://orcid.org/0009-0008-0670-1285
Diana Zakiyah: https://orcid.org/0009-0002-7031-5692
Alya Sahilla Fahri: https://orcid.org/0009-0008-7569-3258
Lily Fernandani Az Zahra Natatimur: https://orcid.org/0009-0005-8378-3235
Anita Yuliati: https://orcid.org/0000-0001-7040-0243

World Journal of Advanced Research and Reviews, 2026, 31(03), 481–495

Publication history: Received on 26 July 2026; revised on 07 September 2026; accepted on 09 September 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.31.3.2280

ABSTRACT

Background: Titanium is the standard material used in dental implants due to its biocompatibility and osseointegration capacity, but because of its high elastic modulus, allergic response, and aesthetic problems, alternatives have been sought. Because of its elastic modulus close to that of bone, good chemical stability, and high biocompatibility, polyetheretherketone is a promising alternative for them despite its bioinert properties, which inhibit osseointegration. However, experimental findings demonstrated that the properties of PEEK could be optimized through surface modifications, including titanium-coated PEEK and carbon-fiber-reinforced PEEK.

Objective: To analyze and compare pure PEEK, titanium (Ti), Ti-coated PEEK, and carbon-fiber-reinforced PEEK at the mechanical, physical, chemical, biological, and clinical levels.

Methods: Using PRISMA 2020, a literature review was conducted across databases for studies published between 2020 and 2025. Original studies evaluating pure PEEK and modified PEEK, including titanium-coated PEEK and carbon-fiber-reinforced PEEK, as dental implant materials through in silico, in vitro, in vivo, and clinical investigations were included.

Results: A total of 35 articles met the inclusion criteria. Titanium-coated PEEK has been reported to enhance surface bioactivity and osseointegration. CFR-PEEK offers substantial gains in structural strength and stiffness while maintaining an elastic modulus closer to that of bone. Both modifications demonstrate superiority over native PEEK and, to an extent, achieve and surpass it in certain parameters, approaching the properties of titanium.

Conclusion: Titanium-coated PEEK seems to be the most promising implant material based on its osteoconductive properties, but large-scale clinical trials validating biocompatibility and safety are still needed.

Keywords: Polyetheretherketone, Titanium-coated PEEK, Carbon-fiber reinforced PEEK, Titanium, Dental implants, Implant materials

1 INTRODUCTION

In the past decade, dental implants have evolved very quickly. Over the past two decades, titanium has been seen as an ideal material for dental implants [1]. Titanium is widely used due to its biocompatibility and ability to osseointegrate; it has a higher elastic modulus than cortical bone, resulting in a stress-shielding effect, which plays a role in the long-term resorption of the surrounding bone [2]. Although allergic reactions to titanium are extremely rare (~0.6%), aesthetic concerns may arise when metallic components are visible through the peri-implant mucosa [3–5]. Previous studies have indicated that complications occur in about 10% of implants and in about 20% of patients, either before or after the use of a dental implant for abutment purposes, over approximately 5–10 years [1]. These limitations have led to the search for alternative materials.

Polyetheretherketone (PEEK) is a very promising alternative as an implant material because it has relatively high chemical stability, heat resistance, and, importantly, corrosion resistance, and its elastic modulus is lower than that of many common metals, at 3–4 GPa [6–7]. Also, despite the biological inertness of PEEK due to its non-toxicity [8], the bioinert and hydrophobic nature of PEEK restricts the formation of bonds between bone cells in vivo and thus leads to suboptimal osseointegration [9]. Previous research has demonstrated that pure unmodified PEEK elicits less biological activity and osseointegration than titanium [7].

Several strategies have been developed to overcome the limitations of polyetheretherketone. Several surface modification approaches have been proposed, including PEEK with Titanium coating and carbon-fiber reinforcement (carbon-fiber-reinforced PEEK) [8,10]. Several experimental studies have shown that these modifications can ameliorate the shortcomings of pure PEEK with respect to its mechanical and biological properties. The present study focuses on PEEK coated with titanium, with the purpose of increasing the bioactivity of its surface and improving its self-primer property for osseointegration, in order to obtain direct bonding with bone tissue without compromising the mechanical properties of PEEK [10]. Carbon-fiber-reinforced PEEK enhances mechanical properties (i.e., strength, stiffness), effectively reducing the mechanical limitations of pure PEEK and bringing it closer to those of natural bone [11].

Titanium-coated PEEK and carbon fiber-reinforced PEEK are hypothesized to be viable alternatives that could synergize PEEK's mechanical properties with bioactivity and additional stability. Titanium-coated PEEK is anticipated to combine titanium osteoconductivity with PEEK's mechanical flexibility. At the same time, carbon fiber-reinforced PEEK would provide increased mechanical strength while maintaining compatibility with the elastic modulus of bone tissue [10,12].

We performed a systematic review to analyze and compare available scientific evidence on the mechanical, physical, chemical, biological, and clinical findings of pure PEEK, titanium, titanium-coated PEEK, and CFR-PEEK, using in silico, in vitro, in vivo, and clinical trial data. The results from this study could potentially shed light on the future clinical applications of PEEK as a dental implant fixture material.

2 METHODS

2.1 Strategy

Articles were retrieved from PubMed, Scopus, and Web of Science and reported in accordance with the PRISMA 2020 guidelines to identify studies (2020–2025) evaluating polyetheretherketone as a dental implant material. The literature search used the following keywords: ("carbon fiber reinforced PEEK" OR "CFR-PEEK" OR "polyetheretherketone" OR

"PEEK" OR "Ti-coated PEEK" OR "titanium-coated PEEK" OR "PEEK coated with titanium" OR "titanium coating on PEEK" OR "PEEK surface modification with titanium") AND ("implant" OR "dental implant").

2.2 Inclusion Criteria

Eligibility criteria were as follows: (1) studies published between 2020 and 2025; (2) original research articles; (3) full-text articles available; (4) publications in English and published in scientifically indexed academic journals; and (5) articles containing the specified keywords in the title or abstract. Three reviewers (H., N.K., and I.N.T.) independently selected the studies. An initial screening based on publication year, article type, and relevance to the predetermined inclusion and exclusion criteria was conducted using titles and abstracts. Articles that did not meet the criteria were excluded. Eligible articles were subsequently assessed in full text. All studies meeting the eligibility criteria were included in the qualitative synthesis.

2.3 Exclusion Criteria

Studies published outside the specified period, non-English-language publications, non-academic sources, articles without accessible full text, and non-original publications such as reviews, editorials, and scientific commentaries were excluded. Studies unrelated to dental implant applications or peri-implant material performance were also excluded. Studies evaluating PEEK in dental implant fixtures, implant-supported components, or peri-implant tissue interactions were considered eligible when their outcomes were relevant to the mechanical, physical, chemical, biological, or clinical performance of PEEK.

2.4 PCC Framework

The systematic review question was developed by adapting the Population–Concept–Context (PCC) framework. The population (P) consisted of experimental and clinical studies assessing dental implant materials, including in silico, in vitro, in vivo, and clinical investigations. The concept (C) comprised the mechanical, physical, chemical, biological, and clinical properties of PEEK and its modified forms used as dental implant materials: pure PEEK, carbon fiber–reinforced PEEK (CFR-PEEK), or titanium-coated PEEK versus titanium implants. The context (C) referred to the use of these materials relevant to implant fixture performance, osseointegration, osteoinduction, osteogenesis, and soft- and hard-tissue interactions around dental implants.

2.5 Data Collection

Data were extracted from all eligible studies into a data extraction table. The data extraction table included: (1) Author and year; (2) Title and DOI of the article; (3) Research method; (4) Results. The data gathered were tabulated accordingly.

3 RESULTS

A literature search was performed in the aforementioned databases, with a large number of publications initially identified (26,862), which were filtered before our selection process based on year of publication, language, article type, and duplication. Most articles were excluded after applying a multi-layered selection process (Rayyan) and an eligibility assessment, since most were not original research, did not address dental implants, or did not discuss PEEK material and its modifications. A total of 35 studies were included in this systematic review; the study selection process is presented in the PRISMA 2020 diagram (Figure 1). The 35 included studies comprised 17 exclusively in vitro studies, 8 exclusively in silico studies, 4 combined in vitro and in vivo studies, 1 combined in silico and in vivo study, 1 animal in vivo study, 1 human clinical study, and 3 additional experimental or numerical studies. Table 1 summarizes the characteristics, methodology, and main outcomes of each study.

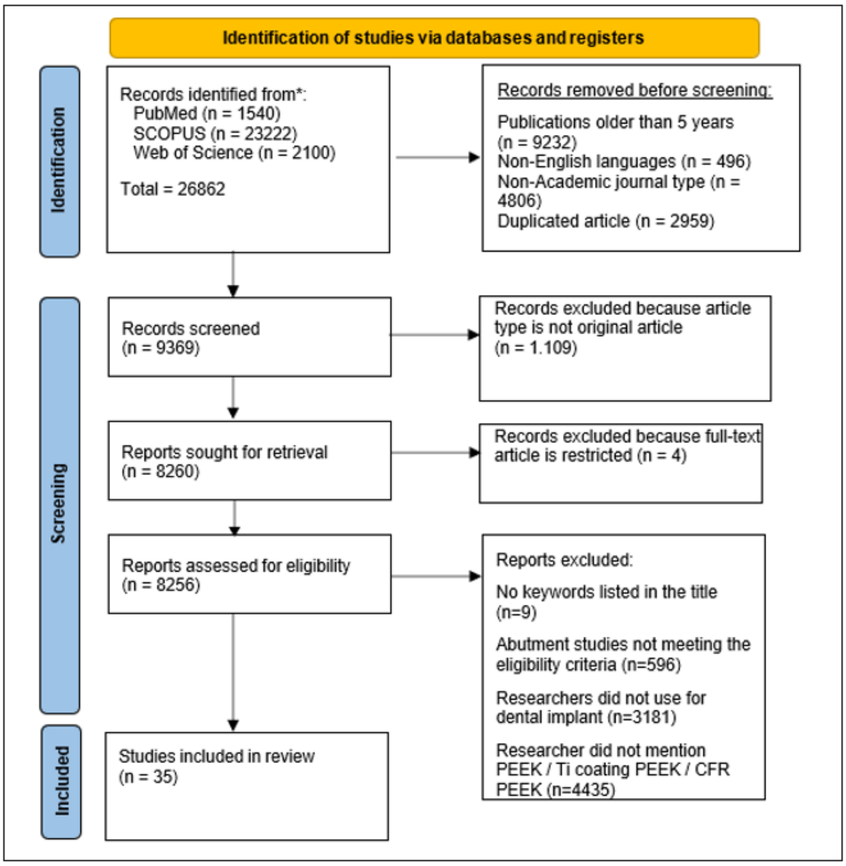

Figure 1: PRISMA 2020 flow diagram

Table 1: Characteristics of included studies

No	Author (Year)	Study design	Material / Intervention	Main findings
1	Liu et al. (2021) [2]	In vitro	Cold plasma–treated PEEK (Ar, N_2, Ar/N_2)	Plasma treatment increased surface hydrophilicity and roughness; N_2 plasma showed the highest osteogenic activity, while Ar/N_2 plasma demonstrated the strongest antibacterial effect.
2	Qiu et al. (2023) [3]	In vitro	CPP-modified PEEK	CPP coating enhanced osteoblast adhesion, proliferation, mineralization, and osteogenic gene expression compared with unmodified PEEK.
3	Guo et al. (2021) [5]	In vitro	Graphene oxide–coated sulfonated PEEK	GO-coated SPEEK showed improved antibacterial activity and enhanced osteogenic differentiation compared with untreated PEEK.
4	Zhou et al. (2022) [11]	In vitro	CFR-PEEK (short and continuous fibers)	CFR-PEEK exhibited mechanical properties closer to cortical bone and reduced stress-shielding compared with titanium.
5	Sarfraz et al. (2022) [13]	In vitro	PEEK and titanium	Bacterial adhesion depended more on saliva contamination than implant material; PEEK showed variable bacterial adherence compared with titanium.
6	Bilginaylar & Ayali (2023) [14]	In silico (FEA)	CFR-PEEK implants	CFR-PEEK demonstrated homogeneous stress distribution and reduced stress-

				shielding under traumatic loading conditions.
7	Haseeb et al. (2022) [15]	In silico (FEA)	CFR-PEEK and titanium	CFR-PEEK showed stress distribution patterns comparable to titanium, with more homogeneous load transfer.
8	Martin et al. (2020) [16]	In vitro	Titanium-coated PEEK	Titanium coating significantly increased PEEK bioactivity and apatite formation in simulated body fluid.
9	Ouldyerou et al. (2022) [17]	In silico (FEA)	Ti-PEEK composite implants	Ti-PEEK reduced stress-shielding and improved biomechanical performance compared with titanium implants.
10	Peng et al. (2021) [18]	In vitro	PEEK and titanium and zirconia	PEEK demonstrated lower biofilm formation and comparable osteoblast viability to titanium and zirconia.
11	Mondragon et al. (2023) [19]	In silico (FEA)	CFR-PEEK implants	CFR-PEEK showed lower critical stress values and elastic modulus closer to bone than titanium.
12	Liu et al. (2021) [20]	In silico (FEA)	Ti–PEEK composite structures	Ti–PEEK designs provided adjustable stiffness and stress distribution similar to alveolar bone.
13	Reddy et al. (2025) [21]	In vitro	Extruded and 3D-printed PEEK	Both fabrication methods showed comparable tribological performance; saliva reduced friction and wear.
14	Su et al. (2022) [22]	In vitro	Ti, Zr, PEEK, CFR-PEEK	PEEK and CFR-PEEK exhibited elastic moduli closer to bone but lower osteogenic activity than Ti and Zr.
15	Saini et al. (2025) [23]	In vitro	Titanium-coated PEEK	Ti-coated PEEK improved surface roughness, hydrophilicity, and osteogenic differentiation.
16	Sağsöz et al. (2025) [24]	In silico (FEA, fatigue)	CFR-PEEK and titanium	CFR-PEEK reduced stress-shielding but showed lower fatigue resistance, particularly in low-density bone.
17	Srilakshmi et al. (2025) [25]	In vitro	Titanium, zirconia, and PEEK implants	Titanium showed the highest osseointegration parameters, zirconia showed intermediate performance, while PEEK exhibited the lowest bone–implant interaction, indicating the need for surface modification.
18	Liu et al. (2025) [26]	In silico and in vivo	Porous PEEK implants	Optimized porous PEEK promoted bone ingrowth and demonstrated improved long-term stability.
19	Cecato et al. (2022) [27]	In vitro	PEEK, stainless steel, and titanium discs evaluated using gingival keratinocytes and fibroblasts	PEEK demonstrated comparable cell viability, adhesion, and normal cellular morphology to titanium and stainless steel across observation periods, supporting its potential use for implant-supported prosthetic components.
20	Irudhayam & Venkatesan (2024) [28]	In silico (FEA)	30% CFR-PEEK (thread design)	Thread design influenced stress distribution; CFR-PEEK showed bone-like biomechanical behavior.
21	Afazal et al. (2025) [29]	In silico (FEA)	PEEK, PEKK, titanium	Titanium showed superior biomechanical performance; PEKK outperformed PEEK among polymeric materials.

22	Wang et al. (2023) [31]	In vitro and in vivo	Multifunctional CFR-PEEK	Modified CFR-PEEK enhanced antibacterial activity and accelerated osseointegration.
23	Maillet et al. (2023) [32]	In vitro	Sterilized PEEK and titanium	Oxygen plasma sterilization preserved cytocompatibility of PEEK and titanium surfaces.
24	Akimchenko et al. (2022) [33]	In vitro	Ultra-thin Ti- and Zr-coated PEEK	Ti and Zr coatings improved surface roughness, wettability, and surface energy without altering PEEK crystallinity.
25	Bańczerowski & Pawlikowski (2025) [34]	Experimental and numerical (FEM)	Commercially pure Grade 2 titanium subjected to thermomechanical processing and Anand constitutive modeling	The adapted Anand model accurately predicted thermoplastic deformation of pure titanium at elevated temperatures, supporting process optimization to enhance mechanical properties for biomedical implant applications.
26	Bańczerowski et al. (2024) [35]	Experimental (thermoplastic deformation)	Commercially pure α-titanium (Grade 2) subjected to mid-temperature thermoplastic deformation	Thermoplastic deformation at mid-temperature ranges induced significant grain refinement, increased hardness and strength, and reduced Young's modulus, indicating improved biomechanical suitability of pure titanium for implant applications.
27	Taherian et al. (2022) [36]	In vitro and in vivo	Titanium-coated PEEK with different surface roughness produced by electron-beam PVD	Moderate surface roughness showed the best cell adhesion, while Ti-coated PEEK demonstrated good coating adhesion, biocompatibility, and early bone formation.
28	Hu et al. (2022) [37]	In vitro (surface/coating characterization)	Porous titanium/hydroxyapatite (Ti/Ti/HA) composite coating on PEEK fabricated by vacuum plasma spraying	The Ti/Ti/HA composite coating exhibited a three-layer porous architecture with high roughness, >90% HA crystallinity, and strong coating adhesion (~32 MPa), while preserving the thermal and chemical stability of the PEEK substrate, indicating improved osseointegration potential.
29	Yang et al. (2025) [38]	In vitro (phantom-based radiotherapy study)	PEEK, 3D-printed titanium mesh, and solid titanium implants evaluated using extended-CT and VMAT planning	PEEK demonstrated the lowest HU distortion and consistently high gamma pass rates (>96%), titanium mesh showed intermediate performance, while solid titanium exhibited severe HU distortion and reduced dose calculation accuracy, indicating superior radiotherapy compatibility of PEEK.
30	Hayashi et al. (2021) [41]	In vitro and in vivo	TiO_2-coated PEEK	Thin TiO_2 coatings significantly enhanced bone bonding regardless of layer thickness.
31	Dorovskikh et al. (2022) [44]	In vitro and in vivo	CFR-PEEK and carbon composite materials modified with noble metal thin films (Ir, Pt, PtIr) and Au/Ag nanoparticle heterostructures	Noble-metal and nanoparticle heterostructures enhanced radiopacity and antibacterial properties while maintaining acceptable cytocompatibility; Au-based heterostructures showed the most favorable balance between biocompatibility and antibacterial activity.
32	Li & Lou (2020) [45]	Experimental (FDM 3D printing)	PEEK fabricated by fused deposition modelling with multi-factor parameter optimization	Optimized FDM parameters significantly improved tensile and bending strength and increased crystallinity of PEEK, achieving mechanical performance comparable to injection-molded PEEK.
33	Gaikwad et al. (2025) [46]	In vitro	PEEK implant surfaces treated with airborne-particle abrasion using	Airborne-particle abrasion with moderate Al_2O_3 grit sizes (110–150 µm) significantly improved surface hydrophilicity, osteoblast

			Al_2O_3 particles of different grit sizes (50, 110, 150 µm)	adhesion, metabolic activity, and mineralization compared with untreated PEEK.
34	Wiessner et al. (2023) [47]	In vivo (human, prospective clinical study)	Implant abutment specimens of titanium, zirconia, PEEK, and modified PEEK (BioHPP) worn intraorally for 24 h	Biofilm accumulation was material-dependent, with the lowest biofilm formation on zirconia, followed by titanium, while both PEEK materials showed significantly higher biofilm coverage, indicating a higher susceptibility of PEEK abutments to early microbial adhesion compared with conventional materials.
35	El Awadly et al. (2020) [50]	In vivo (animal)	Treated and untreated PEEK implants	Surface-treated PEEK implants demonstrated improved bone–implant contact compared with untreated PEEK.

4 DISCUSSION

Due to its mechanical strength, chemical inertness, and radiolucency [30], polyetheretherketone (PEEK) is now being investigated as a metal-free alternative polymeric biomaterial in dentistry and orthopedics. Nonetheless, the clinical use of PEEK is highly reliant on its biocompatibility, encompassing interactions with cells, tissues, and microbiomes.

Pure PEEK is bioinert, which limits biointegration and has driven extensive investigations into different modification approaches. Nanostructuring, ion implantation, and composite coatings consistently improve biological response. For instance, a hierarchical PEEK/SiNx coating simultaneously induces osteogenesis and controlled bacteriostasis, reflecting multifunctionality enabled by advanced surface engineering [30].

To increase interfacial fixation with bone, maintain mechanical strength, and thus improve biomechanical performance, titanium plasma ion implantation (TPPI)-modified carbon fiber-reinforced PEEK has been studied [31]. Osteoblast adhesion on nano-roughened and plasma-treated surfaces supports the studies that emphasize that acceleration of protein adsorption by nucleation on surfaces characterized by nano-roughness provides the first biomolecular basis for successful osseointegration [32]. These developments provide evidence that surface modification not only has advantages but is also necessary to maximize the biocompatibility of PEEK.

4.1 Mechanical Aspects

The elastic modulus of pure PEEK is around 3.6-4.0 GPa, which, compared to metals, can reduce the stress shielding effect. However, for high pressure and load on posterior dental implants, and in some applications, most cases still have a limited load capacity of PEEK material if used alone. Depending on the method used to fabricate PEEK, its tensile strength can vary from 90–100 MPa and depends also on molecular orientation. It has good compressive strength for light to moderate dynamic masticatory stresses, but its suitability for fatigue or cyclic loading remains lower than that of metal materials. However, PEEK has relatively low hardness and wear resistance, so it is common to reinforce or coat it to improve its mechanical behavior. One of its main advantages is its low density (about 1.3 g/cm^3) and an elastic modulus similar to bone, making it more physiologically acceptable for use in implants [28].

Titanium remains the benchmark for mechanical strength and durability in dental implants. The elastic modulus lies between 100 and 115 GPa, which is higher than that of bone and poses a risk of stress shielding. Its tensile strength exceeds 800 MPa, and it has significantly greater resistance to long-term cyclic loads. Titanium has good hardness and wear resistance, making it suitable for implants that require high durability. Titanium is also highly ductile and tough, allowing plastic deformation without fracture despite its higher density (4.5 g/cm^3). That demonstrates that titanium performs well in terms of mechanical properties in high-load environments. Still, its overly stiff behavior in service has made it less than ideal for use in fragile or atrophic bone conditions [29].

PEEK with titanium coating retains the bulk mechanical properties of PEEK as a substrate material, namely an elastic modulus in the range 3–4 GPa. Titanium coatings produced by plasma spraying or sputtering offer higher hardness and wear resistance. With the titanium coating, local load-transfer capacity and contact stiffness could be increased without altering the flexibility properties of the PEEK core. The bonding forces between the titanium coating and the PEEK material are determined by the respective fabrication methods, and surface treatments, such as plasma treatment, can improve mechanical anchoring. Multiple studies show significant resistance of Ti-PEEK to wear and subsidence compared with pure titanium in the medium term, while also demonstrating a lower modulus, thereby preventing stress shielding. It means that Ti-PEEK represents a micro-scale compromise between the flexibility of PEEK and the hardness of titanium [24].

The addition of approximately 30% carbon fiber by weight to PEEK results in a significant improvement in its mechanical properties. The elastic modulus of CFR–PEEK is about 18–23.5 GPa, depending somewhat on fiber orientation and volume fraction. The tensile strength is also much higher than that of pure PEEK, making it suitable for applications with high mastication loads. CFR-PEEK is much more fatigue-resistant than pure PEEK because it absorbs and distributes loads on carbon fibers. Additionally, this material exhibits more rigid fracture behavior due to energy-absorption mechanisms associated with delamination and fiber release. In summary, CFR-PEEK represents a very good compromise of the mechanical properties among strength, stiffness, and flexibility for medium- to high-load applications [26].

Consequently, considering the mechanical characteristics of the four materials, Pure PEEK may tend to lower stress shielding with a modulus of elasticity close to bone, but its mechanical strength is self-limiting. The mechanical balance of CFR-PEEK is accompanied by a significant increase in modulus of elasticity and resistance to load and fatigue. Materials such as Titanium-Coated PEEK take advantage of the hard-wearing surface provided by a titanium coating, whilst still maintaining the flexibility, lower mass, and density characteristics of the natural PEEK substrate. In contrast, pure titanium is stronger and tougher but also reinforces stress shielding. CFR PEEK is the ideal choice when mechanical bone compatibility and strength are both required, whereas titanium is still the standard for maximum durability.

4.2 Physical Aspects

Physical property evaluation: This is the study of surface morphology, density, porosity, contact angle, and thermal stability parameters, as these factors may affect surface interactions with the biological environment and the osseointegration capability of implant materials.

The density of pure PEEK is low (about 1.30–1.43 g/cm^3), similar to natural bone. The reinforcement with carbon fibers raises the density of CFR-PEEK to 1.40–1.50 g/cm^3 [17]. Ti-coated PEEK has a density close to that of uncoated PEEK (1.30–1.40 g/cm^3) owing to the very thin titanium coating (<100 nm)[33]. However, the density of pure titanium is approximately 4.51 g/cm^3 [17,34,35].

Pure PEEK has a high thermal stability with a glass transition temperature (Tg) of 143°C and a melting point of 335-350°C [19]. TGA analysis [21] indicates that CFR-PEEK is thermally stable with a relatively low mass loss. The retention of PEEK's thermal properties (low-temperature deposition does not affect crystallinity, [33]) is due to its Ti-coated form. As a result, pure titanium offers the highest resistance to heat and thermal effects, as its melting temperature is 1668°C [34].

Pure PEEK is a bioinert polymer with a smooth surface due to its semi-crystalline nature [22]. The structure of CFR-PEEK is more complex owing to the presence of carbon fibers [17]. The PEEK was coated with a fresh Ti layer, resulting in a uniform, moderately rough surface to improve cell adhesion [36]. Pure titanium typically exhibits a micro-rough surface topography (Ra 1–3 μm) covered by a TiO_2 layer [19].

Pure PEEK has low porosity (<5%). CFR-PEEK has been reported to show higher porosity (5–10%) because of the fiber reinforcement [17]. The PEEK titanium (Ti) coating with 25–35% porosity is produced by the VPS method. However, pure titanium is non–porous, and only engineered structures can achieve porosities of 10— 30% [37].

Pure PEEK is inherently hydrophobic because of its C–H-rich surface, with a reported contact angle greater than 99°. CFR-PEEK also showed hydrophobicity at similar or slightly higher angles (98–112°) [22]. After TiO_2 formation, the Ti-coated PEEK becomes even more hydrophilic (≈55–60°). The hydrophilicity of pure titanium is ≈35–40° before and <10° after UV/plasma treatment [19].

However, pure PEEK is radiolucent and produces less MRI artifact [17]. Similarly low radiolucency, with negligible artifacts on imaging, has been reported for CFR-PEEK [14]. Despite the Ti coating, they will not lose their radiolucency because of the extremely thin Ti coating on PEEK. Pure titanium is radiopaque and can cause significant CT/MRI artifacts [38].

Untreated PEEK has a greyish-cream color (like teeth) as its natural appearance [33]. CFR-PEEK has a darker appearance due to carbon-fiber reinforcement. Ti-coated PEEK maintains a dental aesthetic cream-grey colour [36]. Titanium has a shiny grey color, which is not as attractive [34].

4.3 Chemical Aspects

Polyetheretherketone (PEEK) is a material that is, by nature, highly inert [39]. The extremely low number of functional groups in its chemical structure is only 2 — ether (-O-) and ketone (C=O) groups — excluding more reactive groups such as hydroxyl (-OH) or carboxyl (-COOH). Thanks to its aromatic chains and stable ketone groups, PEEK is highly resistant to chemical degradation by acids, bases, and organic solvents. PEEK has slow osseointegration due to its bioinert and hydrophobic properties, which inhibit interaction with bone cells during the early implantation stage. One of the most commonly used approaches is surface modification to overcome this limitation [9].

Titanium has chemical properties that enable it to form a stable, inert passive layer of titanium dioxide (TiO_2), continuously protecting the metal from corrosion and enhancing biocompatibility. This way, the layer forms when titanium comes into contact with oxygen or water, which helps with osseointegration. C–O–Ti binding was semi-covalent, being the consequence of the bonding interaction between the carbonyl or ether group of PEEK and the titanium atom of TiO_2 layer. It increases adhesion, chemical stability, and bioactivity of the surface due to hydrogen bonds and van der Waals forces formed between polymer chains [40–41].

The titanium studies applied to PEEK coating modification methods were useful for enhancing physical, biological, and mechanical performance [17,20]. Titanium coating changes the chemical properties of the surface but not the internal chemical structure of the PEEK surface. In new bonds that include hydroxyl (−OH) and reactive oxygen groups, the TiO_2 layer leads to further increases in surface energy and hydrophilicity [38]. Ultraviolet (UV) light activation further enhances this effect by evaporating hydrocarbon surface contaminants and incorporating active oxygen species on the surface. The chemical transformations convert TiO_2-coated PEEK into a more bioactive and osteoconductive surface that promotes the adhesion and proliferation of osteoblasts [17].

4.4 Biological Aspects

Pure PEEK was also first examined to investigate its biocompatibility. It has been demonstrated in vitro that pure PEEK is highly compatible with bone cells and soft tissues and supports fibroblast, osteoblast, and gingival cell viability without exerting any notable toxic effects [8]. In terms of biofilm formation, Peng et al. (2021) found that, under certain conditions, metal implants have a greater risk of bacterial adhesion to their surfaces and are thus not as safe against surface-related infections as PEEK [18]. However, due to the inertness and hydrophobicity of the PEEK surface, it still has limited potential for osseointegration. Srilakshmi et al. (2025) compared the osseointegration potential of PEEK implants with Ti and Zr using a synthetic bone model [25]. While PEEK showed good cell viability, osteoblast adhesion, and bone integration, the study reported that these were still inferior to titanium and zirconia. Cecato et al. (2022) demonstrated tissue compatibility of the PEEK surface, with gingival keratinocytes and fibroblasts adhering and spreading well on the polymer.

To improve osteogenesis, it is suggested that surface modifications be employed, such as titanium coating, plasma treatment, hydroxyapatite addition, or nanotexture formation, to increase the bioactivity of PEEK and make it more competitive with traditional Ti.

Conversely, titanium remains the benchmark for implants, as it achieves direct bonding with bone tissue via the formation of a surface oxide layer (TiO_2) that underlies or promotes protein adhesion and integration, thereby promoting osseointegration [42]. In an in vitro study, Su et al. reported that the expression of osteogenic-related genes, including Alpl, Col1a1, and Bglap in mesenchymal stem cells (BMSCs) on titanium surface was consistently greater than that on PEEK and CFR PEEK after 7 and 14 days ($P < 0.05$), suggesting excellent osteogenic activity over the entire period [22]. However, the elastic modulus of titanium is much higher than that of human bone, leading to stress shielding that can ultimately cause long-term bone resorption. An in silico computational analysis by Afazal et al. revealed that titanium produces the lowest stress and deformation forces in the peri-implant bone among PEEK/PEKK, but localized mechanical overload within the 3D microarchitecture can provoke non–physiological remodeling [29]. Moreover, metal hypersensitivity or aesthetic problems related to visible metal have also been reported, which is why we see increased attention to non-metallic materials like PEEK and CFR-PEEK in modern implant design.

Titanium-coated PEEK implants were prepared to combine the biocompatibility properties of PEEK and the ability of titanium to stimulate bone regeneration. The titanium-coated PEEK surface exhibited better biological properties and biocompatibility compared with pure PEEK. Han et al. (2010) stated that titanium coating produced by electron-beam deposition is dense and crystalline and drastically increases wettability by up to 180% [43]. In cell culture experiments, MC3T3-E1 cell proliferation more than doubled ($P < 0.001$), and alkaline phosphatase (ALP) activity, an indicator of osteoblast differentiation, also increased ($P < 0.01$). In animal models, the BIC ratio was significantly higher than that of uncoated PEEK. In addition, Saini et al. reported that titanium surface modification of PEEK reduced the contact angle, increased hydrophilicity, and enhanced osteoblast adhesion [23]. This titanium coating enhances osteogenic cell differentiation by increasing ALP, COL-I, and OCN levels, as well as accelerating apatite layer formation in a simulated body fluid test. Biologically, this material integrates the basic biocompatibility of PEEK with titanium's osteoconductivity to potentially provide an implant interface that rapidly and stably anchors cells to bone. Besides surface modification, reinforcing polyether ether ketone (PEEK), a biocompatible polymer, with carbon fibers is another way to improve its mechanical properties while retaining the beneficial properties of PEEK. CFR-PEEK as an implant material presents advantages of bioactivity and biocompatibility. In an in vitro study by Su et al. (2022), mesenchymal stem cells proliferated and underwent osteogenic differentiation on CFR-PEEK surfaces, but the maximum values were lower than those observed with titanium or zirconia [22]. It also correlates with previous cytocompatibility studies, which reported that the surface energy of CFR-PEEK is lower than that of other materials due to a higher contact angle [22], indicating that CFR-PEEK is less hydrophilic and therefore limits initial cell adhesion [22].

Furthermore, Dorovskikh et al. (2022) reported that CFR-PEEK-based samples displayed high biocompatibility through in vitro assays, despite the need for further modification of the composite structure to render the implant more responsive to bone and soft tissue [44]. In the meantime, according to the finite element analysis (FEA) from Sağsöz et al., CFR-PEEK evenly distributes stress on cortical and trabecular bone better than titanium due to the possibility of reducing the stress shielding effect [24]. Nevertheless, spontaneous bone integration in CFR-PEEK is lower than that of titanium; therefore, to improve osseointegration and balance the mechanical and biological properties, surface modifications such as hydroxyapatite addition, nanotexturing, or active coatings are often suggested.

In summary, many studies demonstrate that PEEK and its derivatives have excellent biological compatibility, with low irritant potential and minimal inflammatory response in both hard and soft tissues. Although pure PEEK displays inert and stable characteristics in a biological environment, it has low osteogenic activity due to poor cell adhesion, limited capability for apatite formation [16]. The elastic modulus of CFR-PEEK is more similar to that of bone, thereby reducing stress shielding and stimulating physiological bone remodeling, leading to better mechanical and biological interactions [15,24]. On the other hand, titanium-coated PEEK shows a dramatic increase in hydrophilicity, osteogenic gene (ALP and COL-I) expression, and apatite layer formation rate throughout in vitro bioactivity tests [19].

Titanium is the gold standard for bone incorporation due to its high osteoblastic activity and chemical stability [29]. However, due to its high elastic modulus, stress shielding and bone resorption are also commonly observed [22]. Biologically, Ti-coated PEEK is the best compromise candidate since it combines both (1) biocompatibility and flexibility of PEEK with (2) bioactivity and osteoconductivity from titanium. It offers the best compromise between biological integration and mechanical stability at the implant-bone interface [9, 10].

4.5 Clinical Relevance

From a clinical perspective, PEEK offers several potential advantages over metallic biomaterials. Moreover, it has an elastic modulus close to that of cortical bone, thereby minimizing stress shielding and promoting physiological load transfer [45]. Radiolucent PEEK implants enable enhanced imaging clarity after the operation, making their use among patients receiving this implant both beneficial and easier for postoperative disease monitoring [46]. Furthermore, because PEEK is a metal-free material, it may be advantageous for patients with metal hypersensitivity [47].

Studies in craniofacial and orthopedic applications have also demonstrated that PEEK-based implants provide long-term functional stability and high patient satisfaction [30]. These results strongly suggest that PEEK is a feasible option for modern clinical applications, particularly when bioactive surfaces are modified.

4.6 Clinical Evidence from Human Studies

PEEK material has been extensively utilized for implant abutments and prosthetic frameworks. Similarly, as a screw material, PEEK has yet to demonstrate success, as evidenced by clinical follow-ups, but has performed well in clinical reports. Recent clinical reports on the implant-abutment interface have indicated that polyetheretherketone (PEEK) abutments positively affect peri-implant soft tissue healing. The study by Elgendi et al. reported a randomized clinical trial involving 20 patients with 22 immediately placed posterior dental implants (2025). Patients were randomized to either PEEK socket sealing abutments (SSA) or standard titanium healing abutments (SHA). The PEEK group had significantly higher aesthetic scores on the modified Pink Esthetic Score (PES) than the titanium group at 6 and 12 months after surgery, particularly for mesial and distal papillae and soft tissue contour parameters. Moreover, patients allocated to the PEEK group were more satisfied with the gingival appearance and restoration comfort; however, no statistically significant differences were found between the groups regarding crown shape and color compared with titanium. This is a solid confirmatory study demonstrating 1-year maintenance of soft tissue profile and comfort with CAD-CAM PEEK abutments compared with titanium [48].

Similar findings were also reported by Shomurodov and Mirkhusanova (2024) in a split-mouth clinical trial including 20 patients with bilateral edentulism. In that study, individual healing abutments manufactured from titanium and PEEK were placed on the contralateral side for a comparative analysis of soft tissue response. Clinical assessment after 3 weeks revealed that PD was lower (2.28 mm vs 2.63 mm), BOP was lower (10.24% vs 12.42%), and the plaque index was lower (1.20 vs 1.52) when PEEK replaced titanium [49]. Apart from clinical parameters, tissue physiology tests using laser Doppler flowmetry and optical oximetry indicated that PEEK facilitated more rapid hemodynamic and oxygenation recovery, with signs of hypoxia improving at an earlier time point than with titanium. Nevertheless, analysis of peri-implant crevicular fluid demonstrated that aMMP8 levels were slightly higher in the PEEK group compared to the other groups; however, all groups maintained normal (physiological) limits. All these data indicate a lower risk of clinical inflammation by PEEK and better biocompatibility with soft tissue [49].

Milinkovic et al. (2022) performed histological and immunohistochemical analysis of soft tissue after 3 months of implant abutment placement. A split-mouth study of 11 subjects revealed deeper epithelial infiltration and more intense subepithelial inflammation around PEEK abutments than around titanium abutments. The PEEK group had a markedly increased number of LCA+ and CD68+ inflammatory cells (indicative of total leukocytes and macrophages/histiocytes, respectively), while titanium induced significantly higher CD20+ (B cell) and CD3+ (T cell) counts. These findings indicate that titanium elicits a more classical adaptive immune response, whereas PEEK elicits a stronger histiocytic and plasmacytic inflammatory response. The study reported that, although this degree of inflammation did not affect osseointegration success during the 3-month postoperative period (implant survival 100%), these data demonstrate an ongoing potential for a soft tissue response to PEEK material [1]. Further clinical evidence is required to establish the long-term performance of PEEK as a dental implant component.

4.7 Limitations and Future Directions

Despite the promising findings, several limitations should be acknowledged. As untreated PEEK already exhibits lower osseointegration than titanium, a reproducible and consistent method of surface modification is essential [50]. The variability of in vitro and in vivo models further complicates direct comparisons; while most studies investigate short- to medium-term evaluations, long-term clinical trials are needed to provide a more definitive safety and efficacy profile across different materials and surface modifications [1]. Emerging research directions include the generation of biocompatible coatings with multifunctional osteogenic and antibacterial properties, the use of additive manufacturing for tailored and personalized implant designs, and novel bioactive composites directed towards patient-centric clinical needs [13,31], combined with ongoing translational studies to facilitate the translation of material-science advances into clinical protocols.

5 CONCLUSION

The elastic modulus of CFR-PEEK is closer to that of natural bone, which may provide better mechanical balance and reduce stress-shielding-related bone resorption. Nevertheless, titanium-coated PEEK appears to offer a favorable combination of mechanical, physical, chemical, and biological properties for potential dental implant applications. Large-scale, long-term clinical trials are needed to demonstrate the effectiveness and safety of its use.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors would like to express their sincere gratitude to the Master's Program in Dental Science, Faculty of Dental Medicine, Universitas Airlangga, for providing academic and technical support throughout this research project.

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

Statement of informed consent

Informed consent was not applicable because this systematic review was based exclusively on previously published studies and did not involve direct recruitment of human participants.

Data Availability

All data relevant to this study are included in the article.

Author's Contributions

- H. : Contributed to conception of the review topic; designed the initial review framework; led literature search strategy; participated in article screening and data extraction; drafted several sections of the introduction and discussion.

- N.K. : Conducted database searching and initial screening of studies; extracted data related to PEEK mechanical properties; contributed to writing the results synthesis.
- A.R.A. : Performed literature search, eligibility assessment, and contributed to summarizing biological responses of PEEK; assisted in drafting the methods and discussion sections.
- D.I.W. : Synthesized findings related to PEEK's biocompatibility; drafted portions of the results and discussion.
- I.N.T. : Participated in screening of articles, data extraction, and writing of sections related to surface modification of PEEK; contributed to editing and coherence of the manuscript.
- M.I. : Assisted in conceptual development, article selection, and compiling comparative tables; contributed to drafting the mechanical performance and longevity sections.
- A.S. : synthesized findings related to PEEK's physical aspect; contributed to interpretation and synthesis; drafted part of the discussion on clinical relevance.
- M.M.A.M. : Participated in literature search, data charting, and summarizing chemical and structural properties of PEEK; assisted in manuscript editing.
- D.Z. : Conducted appraisal and synthesis of clinical evidence; contributed to writing the clinical implications and recommendations sections.
- A.S.F. : Contributed to data extraction, writing discussion subsections related to limitations and future research; assisted in writing the introduction and conclusion.
- L.F.A.Z.N. : PRISMA flow documentation, extracting key variables, and synthesizing findings on implant survival outcomes; verification of inclusion/exclusion criteria.
- A.Y. (Corresponding author, Supervisor) : Provided senior supervision; guided concept development and methodological structuring; critically reviewed all sections for intellectual content; ensured accuracy, coherence, and integrity of the final manuscript.

REFERENCES

[1] Milinkovic I, Krasavcevic AD, Jankovic S, Sopta J, Aleksic Z. Immunohistochemical analysis of soft tissue response to polyetheretherketone (PEEK) and titanium healing abutments on dental implants: a randomized pilot clinical study. BMC Oral Health. 2022 Nov 11;22(1):484. https://doi.org/10.1186/s12903-022-02536-0

[2] Liu C, Bai J, Wang Y, Chen L, Wang D, Ni S, Liu H. The effects of three cold plasma treatments on the osteogenic activity and antibacterial property of PEEK. Dental Materials. 2021 Jan 1;37(1):81-93. https://doi.org/10.1016/j.dental.2020.10.007

[3] Qiu P, Wang P, Liu M, Dai T, Zheng M, Feng L. Biocompatibility and osteoinductive ability of casein phosphopeptide modified polyetheretherketone. Front Bioeng Biotechnol. 2023 Feb 8;11.1-11. https://doi.org/10.3389/fbioe.2023.1100238

[4] Chen M, Ren M, Shi Y, Liu X, Wei H. State-of-the-art polyetheretherketone three-dimensional printing and multifunctional modification for dental implants. Front Bioeng Biotechnol. 2023 Oct 19;11.1-25. https://doi.org/10.3389/fbioe.2023.1271629

[5] Guo C, Lu R, Wang X, Chen S. Antibacterial activity, bio-compatibility and osteogenic differentiation of graphene oxide coating on 3D-network poly-ether-ether-ketone for orthopaedic implants. J Mater Sci Mater Med. 2021 Nov 26;32(11):135.1-14. https://doi.org/10.1007/s10856-021-06614-7

[6] Moharil S, Reche A, Durge K. Polyetheretherketone (PEEK) as a Biomaterial: An Overview. Cureus. 2023 Aug 29;1-8. https://doi.org/10.7759/cureus.44307

[7] Hao Y, Shi C, Zhang Y, Zou R, Dong S, Yang C, Niu L. The research status and future direction of polyetheretherketone in dental implant—A comprehensive review. Dental Materials Journal. 2024 Sep 25;43(5):609-20. https://doi.org/10.4012/dmj.2024-076

[8] Azhar I, Syaharani R, Smeer V, Multazan M. Polyether ether ketones (PEEK): Properties and applications as implants for alternative dentistry materials: A narrative review. Journal of International Oral Health. 2023;15(1):28-33. https://doi.org/10.4103/jioh.jioh_10_22

[9] Sikder P. A comprehensive review on the State of the Art in the research and development of poly-ether-ether-ketone (PEEK) biomaterial-based implants. Acta Biomater. 2025 Jan;191:29–52. https://doi.org/10.1016/j.actbio.2024.11.033

[10] Dondani JR, Iyer J, Tran SD. Surface treatments of PEEK for osseointegration to bone. Biomolecules. 2023 Mar 2;13(3):464. https://doi.org/10.3390/biom13030464

[11] Zhou Z, Han X, Gao W, Li Y, Yu W, Yang S, Zhang J, Wang J, Shi R, Zhou Y, Zhao J. Fabrication and mechanical properties of different types of carbon fiber reinforced polyetheretherketone: a comparative study. Journal of the Mechanical Behavior of Biomedical Materials. 2022 Nov 1;135:105472. https://doi.org/10.1016/j.jmbbm.2022.105472

[12] Pidhatika B, Widyaya VT, Nalam PC, Swasono YA, Ardhani R. Surface Modifications of High-Performance Polymer Polyetheretherketone (PEEK) to Improve Its Biological Performance in Dentistry. Polymers (Basel). 2022 Dec 16;14(24):5526.1-38. https://doi.org/10.3390/polym14245526

[13] Sarfraz S, Mäntynen PH, Laurila M, Rossi S, Leikola J, Kaakinen M, Suojanen J, Reunanen J. Comparison of titanium and PEEK medical plastic implant materials for their bacterial biofilm formation properties. Polymers. 2022 Sep 15;14(18):3862. doi.org/10.3390/polym14183862

[14] Bilginaylar K, Ayali A. Biomechanical Behavior of Carbon Fiber-Reinforced Polyetheretherketone as a Dental Implant Material in Implant-Supported Overdenture under Mandibular Trauma: A Finite Element Analysis Study. Niger J Clin Pract. 2023 Oct;26(10):1538–1546. https://doi.org/10.4103/njcp.njcp_239_23

[15] Haseeb SA, Vinaya KC, Vijaykumar N, Kumar AS, Sruthi MK. Finite element evaluation to compare stress pattern in bone surrounding implant with carbon fiber-reinforced poly-ether-ether-ketone and commercially pure titanium implants. National Journal of Maxillofacial Surgery. 2022 May 1;13(2):243-7. https://doi.org/10.4103/njms.njms_354_21

[16] Martin A, Azhagarasan NS, Ravichandran M, Ramakrishnan H, Jaya Krishnakumar S, Mahadevan V. Evaluation of the Bioactivity of Surface Modified Polyetheretherketone (PEEK) as an Implant Material: An In Vitro Study. Contemp Clin Dent. 2020 Oct;11(4):356–366. https://doi.org/10.4103/ccd.ccd_258_19

[17] Ouldyerou A, Merdji A, Aminallah L, Roy S, Mehboob H, Özcan M. Biomechanical performance of Ti-PEEK dental implants in bone: An in-silico analysis. J Mech Behav Biomed Mater. 2022 Oct;134:105422. https://doi.org/10.1016/j.jmbbm.2022.105422

[18] Peng TY, Lin DJ, Mine Y, Tasi CY, Li PJ, Shih YH, Chiu KC, Wang TH, Hsia SM, Shieh TM. Biofilm formation on the surface of (poly) ether-ether-ketone and in vitro antimicrobial efficacy of photodynamic therapy on peri-implant mucositis. Polymers. 2021 Mar 18;13(6):940. https://doi.org/10.3390/polym13060940

[19] Martinez-Mondragon M, Urriolagoitia-Sosa G, Romero-Ángeles B, Pérez-Partida JC, Cruz-Olivares IM, Urriolagoitia-Calderón G. Bilinear Numerical Analysis of the Structural Behavior of a Dental Implant Applied as a Biomaterial Carbon Fiber Reinforced Polyether-Ether-Ketone (CFR-PEEK). Dent Hypotheses. 2023 Apr;14(2):45–48. https://doi.org/10.4103/denthyp.denthyp_42_23

[20] Liu C, Lin J, Tang L, Liu Z, Jiang Z, Lian K. Design of metal-polymer structure for dental implants with stiffness adaptable to alveolar bone. Composites Communications. 2021 Apr;24:100660. https://doi.org/10.1016/j.coco.2021.100660

[21] Reddy KU, Narala SK, Verma PC, Babu PJ, Saravanan P. A Comprehensive Study on the Tribological Behavior of Extruded and 3D-Printed PEEK for Low-Cost Dental Implant Solutions Under Simulated Oral Conditions. Tribology Letters. 2025 Jun;73(2):67. https://doi.org/10.1007/s11249-025-02001-3

[22] Su J, Xing X, Lin Y, Gao Y, Xing Y, Xu Z, Chen J. In vitro physicochemical and biological properties of titanium alloy, zirconia, polyetheretherketone, and carbon fiber-reinforced polyetheretherketone. Frontiers in Materials. 2022 Sep 7;9:992351. https://doi.org/10.3389/fmats.2022.992351

[23] Saini M, Paliwal J, Sharma V, Gupta N, Meena KK, Singhal P. Influence of PEEK surface modification with titanium for improving osseointegration: an in vitro study. Scientific Reports. 2025 Jun 5;15(1):19801. https://doi.org/10.1038/s41598-025-05214-7

[24] Polat Sağsöz N, Murat F, Sevinç Gül SN, Şensoy AT, Kaymaz I. CF-PEEK vs. titanium dental implants: stress distribution and fatigue performance in variable bone qualities. Biomimetics. 2025 Sep 14;10(9):619. https://doi.org/10.3390/biomimetics10090619

[25] Srilakshmi J, Jilani ZI, Saad S, Patil C, Kurian J, Vyavahare SA. Comparative In vitro Study on the Osseointegration Potential of Titanium, Zirconia, and PEEK Dental Implants Using Simulated Bone Models. Journal of Pioneering Medical Sciences. 2025 Apr 27;14:371-5. https://doi.org/10.47310/jpms202514S0148

[26] Liu Y, Wang L, Zhang J, Liu S, Zheng J, Kang J, Dong E, Sun C, A R, Liu C, Yang C. A design strategy for long-term stability of porous PEEK implants by regulation of porous structure and in vivo mechanical stimulation. Bio-Design and Manufacturing. 2025 Mar;8(2):275-87. https://doi.org/10.1631/bdm.2400259

[27] Cecato RC, Martinez EF, Benfatti CAM. Analysis of the Viability and Morphology of Gingival Cells on Materials Used in Novel Prosthetic Components: In Vitro Study. J Contemp Dent Pract. 2022 May 21;23(1):22–30. https://doi.org/10.5005/jp-journals-10024-3271

[28] Irudhayam SJ, Venkatesan H. Finite Element Analysis of Stress Distribution in 30% CFR PEEK Implant with Varying Thread Designs. Revue des composites et des matériaux avancés. 2024 Oct 31;34(5):565–571. https://doi.org/10.18280/rcma.340504

[29] Afazal M, Afreen S, Anand V, Chanda A. Computational mechanics of polymeric materials PEEK and PEKK compared to Ti implants for marginal bone loss around oral implants. Prosthesis. 2025 Aug 1;7(4):93. https://doi.org/10.3390/prosthesis7040093

[30] Xiong J, Lu Q, Liu Z, Hu J, Cao H, Wang M, Huang W. Bioinspired hierarchical PEEK and amorphous silicon nitride composite coatings on titanium alloy biomedical implants. Small. 2025 Jul;21(26):2410313. https://doi.org/10.1002/smll.202410313

[31] Wang X, Pan L, Zheng A, Cao L, Wen J, Su T, Zhang X, Huang Q, Jiang X. Multifunctionalized carbon-fiber-reinforced polyetheretherketone implant for rapid osseointegration under infected environment. Bioactive materials. 2023 Jun 1;24:236-50. https://doi.org/10.1016/j.bioactmat.2022.12.016

[32] Maillet C, Klein FM, Le Bras F, Velard F, Guillaume C, Gangloff SC, Gelle MP. Cytocompatibility of titanium and poly (etheretherketone) surfaces after O2 non-thermal plasma sterilization. Plos one. 2023 Aug 30;18(8):e0290820. https://doi.org/10.1371/journal.pone.0290820

[33] Akimchenko IO, Rutkowski S, Tran TH, Dubinenko GE, Petrov VI, Kozelskaya AI, Tverdokhlebov SI. Polyether ether ketone coated with ultra-thin films of titanium oxide and zirconium oxide fabricated by DC magnetron sputtering for biomedical application. Materials. 2022 Nov 14;15(22):8029. https://doi.org/10.3390/ma15228029

[34] Bańczerowski J, Pawlikowski M. Numerical and experimental analysis of thermoplastic deformation in pure titanium using the anand model for biomedical implant design. Advances in Science and Technology Research Journal. 2025 Sep 1;19(9):504–515. https://doi.org/10.12913/22998624/207677

[35] Bańczerowski J, Pawlikowski M, Płociński T, Zagórski A, Sawicki S, Gieleta R. New approach to α-titanium mechanical properties enhancement by means of thermoplastic deformation in mid-temperature range. Continuum Mechanics and Thermodynamics. 2024 Nov 5;36(6):1645–1660. https://doi.org/10.1007/s00161-024-01321-4

[36] Taherian MH, Rezazadeh M, Taji A. Optimum Surface Roughness for Titanium-Coated PEEK Produced by Electron Beam PVD for Orthopedic Applications. Materials Technology. 2022 Jul 3;37(8):631–644. https://doi.org/10.1080/10667857.2020.1868209

[37] Hu F, Fan X, Peng F, Yan X, Song J, Deng C, Liu M, Zeng D, Ning C. Characterization of porous titanium-hydroxyapatite composite biological coating on polyetheretherketone (PEEK) by vacuum plasma spraying. Coatings. 2022 Mar 24;12(4):433. https://doi.org/10.3390/coatings12040433

[38] Yang S, Choi E, Park SG, Kim B, Kim YW, Kim M. Comparative Evaluation of PEEK, 3D-Printed Titanium Mesh and Solid Titanium Implants on HU Distortion and Dose Calculation Accuracy in Radiotherapy. Applied Sciences. 2025 Oct 21;15(20):11264. https://doi.org/10.3390/app152011264

[39] Waugh DG, Cosgrove D, Hussain I, Lawrence J. Laser surface engineering of polymeric materials for enhanced mesenchymal stem cell adhesion and growth. Advances in Contact Angle, Wettability and Adhesion. 2019 Oct 18;4:267-97. https://doi.org/10.1002/9781119593294

[40] Prasad S, Ehrensberger M, Gibson MP, Kim H, Monaco EA. Biomaterial properties of titanium in dentistry. J Oral Biosci. 2015 Nov;57(4):192–199. https://doi.org/10.1016/j.job.2015.08.001

[41] Hayashi M, Shimizu T, Imamura M, Fujibayashi S, Yamaguchi S, Goto K, Otsuki B, Kawai T, Okuzu Y, Matsuda S. Optimizing the layer thickness of sol–gel-derived TiO2 coating on polyetheretherketone. Scientific Reports. 2021 Aug 5;11(1):15875. https://doi.org/10.1038/s41598-021-95572-9

[42] Sarraf M, Rezvani Ghomi E, Alipour S, Ramakrishna S, Liana Sukiman N. A state-of-the-art review of the fabrication and characteristics of titanium and its alloys for biomedical applications. Biodes Manuf. 2022 Apr 26;5(2):371–395. https://doi.org/10.1007/s42242-021-00170-3

[43] Han CM, Lee EJ, Kim HE, Koh YH, Kim KN, Ha Y, Kuh SU. The electron beam deposition of titanium on polyetheretherketone (PEEK) and the resulting enhanced biological properties. Biomaterials. 2010 May 1;31(13):3465-70. https://doi.org/10.1016/j.biomaterials.2009.12.030

[44] Dorovskikh SI, Vikulova ES, Sergeevichev DS, Guselnikova TY, Zheravin AA, Nasimov DA, Vasilieva MB, Chepeleva EV, Saprykin AI, Basova TV, Morozova NB. Biological studies of new implant materials based on carbon and polymer carriers with film heterostructures containing noble metals. Biomedicines. 2022 Sep 8;10(9):2230. https://doi.org/10.3390/biomedicines10092230

[45] Li Y, Lou Y. Tensile and bending strength improvements in PEEK parts using fused deposition modelling 3D printing considering multi-factor coupling. Polymers. 2020 Oct 27;12(11):2497. https://doi.org/10.3390/polym12112497

[46] Gaikwad A, Parizi MK, Winkel A, Stiesch M. Osteoblast cell behavior on polyetheretherketone dental implant surfaces treated with different grit size aluminum oxide particles: An in vitro analysis. J Prosthet Dent. 2025 Feb;133(2):531–539. https://doi.org/10.1016/j.prosdent.2024.02.024

[47] Wiessner A, Wassmann T, Wiessner JM, Schubert A, Wiechens B, Hampe T, Bürgers R. In vivo biofilm formation on novel PEEK, titanium, and zirconia implant abutment materials. International journal of molecular sciences. 2023 Jan 16;24(2):1779. https://doi.org/10.3390/ijms24021779

[48] Elgendi MM, Hamdy IS, Sallam HI. Peri-implant soft tissue conditioning of immediate posterior implants by CAD-CAM socket sealing abutments: a randomized clinical trial. BMC Oral Health. 2025 Jan 17;25(1):83. https://doi.org/10.1186/s12903-024-05417-w

[49] Shomurodov K, Mirkhusanova R. Comparative Evaluation of Soft Tissue Reaction to Titanium and Polyetheretherketone Customized Healing Abutments: a Split-Mouth Randomised Clinical Trial. Galician Medical Journal. 2024 Sep 10;31(4). https://doi.org/10.21802/e-GMJ2024-A23

[50] El Awadly TA, Wu G, Ayad M, Radi IA, Wismeijer D, Abo El Fetouh H, Osman RB. A histomorphometric study on treated and untreated ceramic filled PEEK implants versus titanium implants: Preclinical in vivo study. Clinical Oral Implants Research. 2020 Mar;31(3):246-54. https://doi.org/10.1111/clr.13562.