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Review

Recent Advances in Poly(ether Ketone) and its Composites for Orthopedic Implant Applications

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Abstract

Orthopedic implants have experienced significant evolution in recent decades, with polyether ether ketone (PEEK) emerging as a promising alternative to traditional metallic materials. This comprehensive review examines the latest developments in PEEK and its composites for orthopedic applications, focusing on material properties, manufacturing technologies, and clinical implementations. The mechanical properties of PEEK, particularly its elastic modulus similar to cortical bone, make it ideal for reducing stress shielding effects. While pure PEEK exhibits excellent biocompatibility and chemical stability, its bioinert nature presents challenges for osseointegration. Recent advances in surface modification strategies and composite development, including hydroxyapatite/PEEK and carbon fiber/PEEK systems, have significantly enhanced both biological and mechanical performance. The emergence of additive manufacturing technologies, specifically Fused Filament Fabrication and Selective Laser Sintering, has revolutionized the production of patient-specific PEEK implants. Clinical applications spanning spinal fusion devices, joint replacements, and cranial implants have demonstrated promising outcomes, with studies showing fusion rates exceeding 90 % in spinal applications. This review also addresses current challenges in manufacturing optimization, quality control, and regulatory compliance, while highlighting future directions in smart composite development and therapeutic capabilities. The integration of novel bioactive materials and advanced manufacturing techniques continues to expand the potential of PEEK-based implants in orthopedic medicine.

Keywords: Osseointegration, biomechanical properties, surface modification, additive manufacturing, clinical outcomes

I. Introduction

The field of orthopedic implants has witnessed remarkable advancement over the past few decades, driven by an increasing demand for solutions to address musculoskeletal disorders, traumatic injuries, and age-related degenerative conditions. Orthopedic implants serve as crucial medical devices designed to replace or augment damaged skeletal structures, restore mobility, and improve patients' quality of life [1]. The significance of these implants continues to grow with the aging global population and rising incidence of bone-related disorders, making them an indispensable component of modern medical care [2,3]. Traditionally, metallic materials such as stainless steel, cobalt-chromium alloys, and titanium alloys have dominated the orthopedic implant market due to their excellent mechanical properties and proven clinical track record [4]. However, these conventional materials present several limitations that have prompted the search for alternative solutions. One of the primary concerns is the phenomenon known as stress shielding, where the significant mismatch between the elastic modulus of metallic implants and natural bone leads to bone resorption and potential implant loosening [5,6]. Additionally, metallic implants can release ions through corrosion processes, potentially triggering adverse biological responses and compromising long-term implant stability [7].

The evolution of biomaterials in orthopedic applications reflects a continuous pursuit of materials that better mimic the properties of natural bone while maintaining the necessary mechanical strength and biocompatibility [8]. This journey has progressed from first-generation metallic implants through various materials, including ceramics and polymers, each offering distinct advantages and limitations. The development of advanced polymeric materials marks a significant milestone in this evolution, particularly with the emergence of high-performance polymers that combine excellent mechanical properties with enhanced biocompatibility. Polyether ether ketone (PEEK, chemical formula shown in Fig. 1) has emerged as a promising alternative to traditional metallic implants, representing a paradigm shift in orthopedic biomaterials [9]. First developed in the 1970s for industrial applications, PEEK's potential in medical applications was recognized in the 1980s, leading to its widespread adoption in ortho-

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pedic surgery by the late 1990s [10]. This high-performance thermoplastic polymer offers a unique combination of properties that make it particularly suitable for orthopedic applications. Its elastic modulus closely matches that of cortical bone, significantly reducing the risk of stress shielding [11,12]. Furthermore, PEEK exhibits excellent chemical stability, fatigue resistance, and biocompatibility, while its radiolucency allows for better post-operative imaging assessment [13,14].

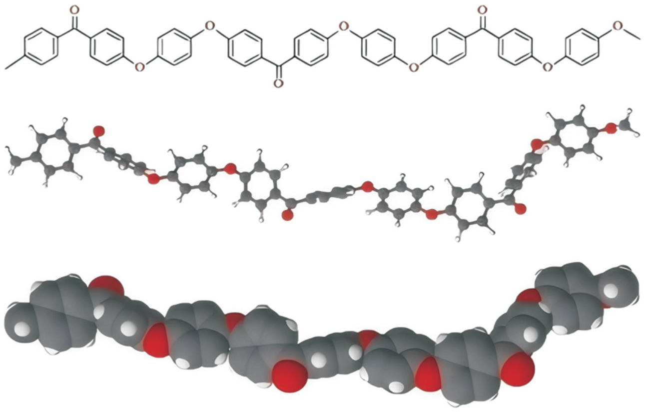

Fig. 1: Chemical structure of the PEEK repeating unit, including atomic labels and bond connectivity. The molecular weight of the repeating unit ($C_{19}H_{12}O_3$) is approximately 288.29 g/mol.

Despite these advantages, the clinical application of PEEK implants faces several challenges that need to be addressed. The material's bioinert nature results in limited osseointegration, potentially affecting long-term implant stability. Surface modification strategies and the development of bioactive PEEK composites have emerged as potential solutions to enhance bone-implant integration [15]. Additionally, the manufacturing of complex geometries and ensuring consistent material properties across different processing methods remain important considerations [16]. The advent of advanced manufacturing technologies, particularly additive manufacturing, has opened new possibilities for addressing these challenges while enabling the production of patient-specific implants [17]. Current challenges in orthopedic implant development extend beyond material properties to include regulatory compliance, cost-effectiveness, and the need for long-term clinical validation. The increasing demand for personalized medical solutions has created a need for manufacturing processes that can efficiently produce custom implants while maintaining strict quality standards [18,19]. Furthermore, the development of new PEEK-based composites and surface treatments must balance enhanced biological performance with mechanical stability and manufacturability.

This comprehensive review aims to analyze recent advances in PEEK and its composites for orthopedic implant applications, focusing on developments over the past decade. The scope encompasses materials science aspects, manufacturing technologies, surface modification strategies, and clinical applications. Special attention is given to emerging trends in PEEK composites, including binary and ternary systems that combine enhanced biological activity with improved mechanical properties. The review also examines the role of advanced manufacturing technologies in expanding the possibilities for PEEK-based implants and discusses future perspectives for research and development in this field. By critically analyzing current literature and research trends, this review seeks to provide insights into the state-of-the-art in PEEK-based orthopedic implants while identifying gaps in current knowledge and potential directions for future research. The comprehensive examination of materials, processing methods, and clinical applications will serve as a valuable resource for researchers, medical professionals, and industry stakeholders working in the field of orthopedic biomaterials. Understanding these advances and challenges is crucial for the continued development of improved orthopedic implants that better serve patient needs while addressing the limitations of current solutions.

II. Properties and Requirements of PEEK for Orthopedic Applications

The successful implementation of PEEK in orthopedic applications demands a comprehensive understanding of its properties and the specific requirements that must be met for clinical use. This section examines the mechanical, chemical, and biological properties of PEEK, analyzing how these characteristics align with the demanding requirements of orthopedic implants.

(1) Mechanical properties

The mechanical properties of PEEK make it an exceptional candidate for orthopedic applications, particularly in load-bearing situations. The most distinctive advantage of PEEK is its elastic modulus, typically reported in the range of 3.6 – 4.0 GPa, which closely approximates that of cortical bone (7 – 30 GPa) [20]. This range reflects commonly observed values for unfilled, biomedical-grade PEEK under standard testing conditions and corresponds to the values summarized in Table 1. This average value reflects typical measurements for unfilled PEEK under dry conditions, though variability may occur depending on processing and testing conditions. This mechanical similarity provides a significant advantage over traditional metallic implants like titanium alloys and stainless steel, whose substantially higher elastic moduli can lead to stress shielding effects. When implant materials have much higher stiffness than surrounding bone, they bear a disproportionate share of the physiological load, leading to bone resorption and potential implant loosening [21]. Studies have shown that PEEK's modulus compatibility promotes more physiological load transfer patterns, which is particularly crucial in spinal applications where load distribution significantly impacts fusion outcomes [22]. The material's ability to maintain mechanical properties under physiological conditions has been demonstrated in various clinical applications, from spinal fusion cages to trauma fixation devices, where long-term stability is paramount for successful outcomes.

The strength characteristics and fatigue resistance of PEEK are equally crucial for its success in orthopedic applications. With tensile strength ranging from 90 – 100 MPa and excellent fatigue resistance, PEEK demonstrates remarkable mechanical durability under

Table 1: Comparative mechanical, chemical, and biological properties of PEEK and conventional orthopedic materials.

Property	PEEK	Titanium Alloy	UHMWPE	CoCr Alloy
Elastic Modulus (GPa)	3.6 – 4	~ 110	~ 1	~ 200
Tensile Strength (MPa)	90 – 100	900 – 1 000	20 – 40	900 – 1000
Radiolucency	Yes	No	Yes	No
Biocompatibility	Excellent	Excellent	Good	Good
Osseointegration (Native)	Low	High	Low	High
Wear Resistance	High	Medium	Medium	High
Corrosion Resistance	Excellent	Moderate	Not applicable	Moderate

cyclic loading conditions [23]. This is particularly evident in spinal fusion applications, where PEEK cages have shown excellent clinical performance under repetitive loading conditions. The material‘s fatigue behavior has been extensively studied, with research demonstrating its ability to maintain structural integrity under physiological loading conditions comparable to those experienced in the spine [24]. Furthermore, the introduction of carbon fiber reinforcement has shown to significantly enhance these properties, with CF/PEEK composites demonstrating even higher strength and fatigue resistance while maintaining favorable elastic modulus characteristics [25]. These improvements have expanded the potential applications of PEEK in high-load bearing situations, including femoral stems and acetabular components in hip arthroplasty.

The wear behavior of PEEK represents another critical mechanical aspect that has been extensively investigated for orthopedic applications. The material exhibits favorable tribological properties, with low friction coefficients and good wear resistance, particularly when enhanced with appropriate reinforcements [26]. Studies have shown that PEEK‘s wear characteristics can be significantly improved through surface modifications and composite formulations. For instance, CF/PEEK has demonstrated superior wear resistance compared to conventional PEEK, with wear rates comparable to or better than ultra-high molecular weight polyethylene (UHMWPE) in joint replacement applications [27]. The biological response to PEEK wear particles has also been studied, with research indicating that PEEK wear debris generates less inflammatory response compared to metal wear particles, contributing to its favorable long-term biocompatibility profile [28].

The impact resistance and toughness of PEEK provide additional mechanical advantages that are particularly relevant in orthopedic trauma applications. Unlike ceramic materials that may exhibit brittle failure modes, PEEK demonstrates superior impact resistance and energy absorption capabilities without catastrophic failure [29]. This property is especially beneficial in applications subject to sudden loading conditions, such as trauma fixation devices and spinal implants. Recent studies have investigated the impact resistance of various PEEK formulations, including porous PEEK and titanium-coated PEEK cervical cages, finding that porous PEEK structures maintain their integrity better under impact conditions compared to surface-modified alternatives [30]. The material‘s ability to withstand impact while maintaining structural integrity has been further demonstrated in finite element analyses, which show that PEEK implants can effectively distribute impact loads without compromising their structural integrity [31]. This characteristic, combined with its other mechanical properties, makes PEEK particularly suitable for applications requiring both strength and impact resistance, such as trauma fixation devices and load-bearing spinal implants. To provide a clearer comparison of material properties relevant to orthopedic implants, Table 1 summarizes the mechanical, chemical, and biological characteristics of PEEK and commonly used materials such as titanium alloys, ultra-high-molecular-weight polyethylene (UHMWPE), and cobalt-chromium alloys. To further emphasize the comparative advantages of PEEK over traditional orthopedic materials, Fig. 2 presents a graphical summary contrasting critical mechanical, biological, and imaging-related parameters of PEEK with titanium alloy, cobalt-chromium alloy, and UHMWPE.

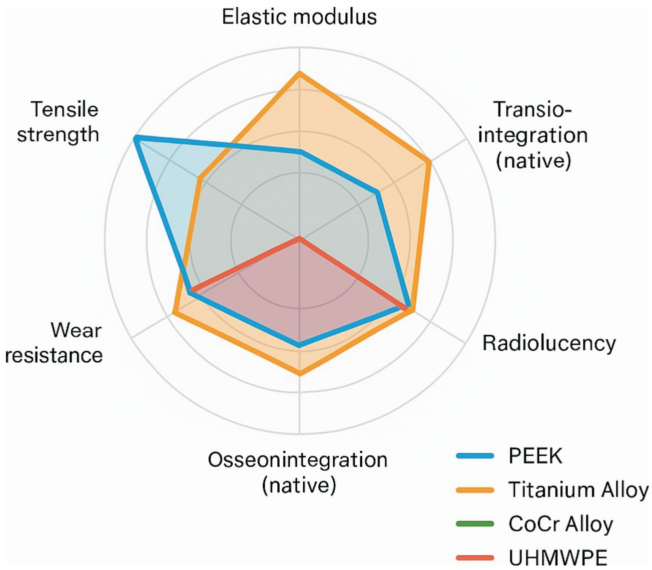

Fig. 2: Comparative performance of PEEK and conventional orthopedic implant materials (titanium alloy, CoCr alloy, UHMWPE) across seven key parameters: elastic modulus, tensile strength, biocompatibility, osseointegration (native), radiolucency, corrosion resistance, and wear resistance. The radar chart highlights the balanced mechanical and biological profile of PEEK, particularly its bone-matching modulus, radiolucency, and superior chemical stability, contrasted with the strengths and limitations of traditional materials.

(2) Chemical properties

PEEK's exceptional chemical stability stems from its rigid aromatic backbone structure combined with ketone and ether linkages, making it highly resistant to chemical degradation in the physiological environment. Unlike biodegradable polymers that undergo hydrolysis, PEEK maintains its structural integrity even after prolonged exposure to bodily fluids. Studies have demonstrated minimal weight loss and negligible changes in mechanical properties after extended immersion in simulated body fluid, confirming its stability under physiological conditions [22, 32]. This chemical inertness is particularly advantageous in load-bearing applications where material degradation could compromise implant function. The material's stability also prevents the release of potentially harmful degradation products that could trigger inflammatory responses or affect surrounding tissues, a significant advantage over some metallic implants that may release metal ions through corrosion [33, 34].

The corrosion resistance of PEEK represents a major advantage over traditional metallic implants used in orthopedic applications. Metallic devices exposed to the harsh body fluid environment can undergo various forms of corrosion, potentially leading to the release of metal ions and degradation of mechanical properties [33, 34]. In contrast, PEEK's polymer structure makes it inherently resistant to electrochemical corrosion processes. Studies have shown that polymer materials like PEEK demonstrate superior corrosion resistance against organic fluids compared to metals [35–37]. This property has led to investigations of PEEK-based coatings for metallic implants to improve their corrosion resistance. For example, Wei *et al.* [35] demonstrated that polymer coatings could enhance the corrosion resistance of magnesium alloys in physiological environments, highlighting PEEK's potential in protective coating applications. The electrochemical behavior of PEEK composites, particularly those incorporating metallic fillers such as titanium, tantalum, or magnesium, is more complex and warrants detailed evaluation. While pure PEEK is electrochemically inert, the introduction of conductive or metallic phases may modify its interfacial behavior in physiological environments.

While PEEK's chemical stability is advantageous for long-term implant performance, its surface chemistry presents certain challenges for biological integration. The material's inherently hydrophobic nature, resulting from its aromatic structure, can limit protein adsorption and cell attachment [38, 39]. However, this limitation has driven extensive research into surface modification strategies. Various approaches have been developed to alter PEEK's surface chemistry while maintaining its bulk properties. Chemical modifications introducing functional groups such as -COOH, -OH, and -PO_4H_2 have shown promise in enhancing cell adhesion and osseointegration [40]. Beyond these commonly studied groups, recent research has explored additional functionalization strategies, including sulfonation and bisphosphonation, to further enhance bioactivity. Sulfonate groups, typically introduced via sulfuric acid treatment, significantly increase surface hydrophilicity and roughness while enabling the formation of porous topologies that facilitate osteoblast attachment [41, 42]. Plasma treatment has also been effectively used to modify surface chemistry, with studies demonstrating improved cell attachment and proliferation on plasma-treated PEEK surfaces [43, 44]. The success of these modifications demonstrates that while PEEK's native surface chemistry may limit biological integration, it provides a stable platform for chemical modifications that can enhance its bioactivity.

Beyond hydrophilicity and topographical changes, surface treatments significantly influence the electrochemical behavior of PEEK at the biointerface. For instance, sulfonation introduces negatively charged sulfonic acid groups (-SO_3H), which not only enhance wettability but also increase the surface negative charge density, leading to a more negative zeta potential [35]. This shift in zeta potential has been shown to promote the electrostatic adsorption of positively charged proteins such as fibronectin, facilitating early-stage cell adhesion and osteoblast proliferation. Similarly, oxygen plasma treatments incorporate polar functional groups (e.g., -OH, -COOH) that alter the interfacial capacitance by increasing dielectric permittivity and surface polarization [31]. These changes are reflected in elevated double-layer capacitance values measured via electrochemical impedance spectroscopy (EIS), indicating improved ion exchange and protein adsorption at the interface. Moreover, surface modifications can modulate the electron transfer characteristics of PEEK, which, although inherently insulating, can exhibit increased surface conductivity when doped or chemically activated. For example, UV-induced graft polymerization of carboxylic acid-containing monomers has been reported to enhance redox activity at the surface, enabling more efficient electron exchange with the surrounding electrolyte and mimicking natural bioelectrical signaling processes involved in tissue healing [24]. These findings underscore that electrochemical metrics such as interfacial capacitance, surface potential, and zeta potential are not only important indicators of surface modification success but also critical parameters that influence the biological performance of PEEK-based implants *in vivo*.

The chemical structure of PEEK, particularly its aromatic rings connected by ketone and ether linkages, contributes to exceptional thermal stability that is crucial for both processing and sterilization. With a glass transition temperature of 143 °C and melting temperature around 343 °C [22, 32, 45], PEEK can withstand common sterilization methods without degradation. This thermal stability allows for processing using various techniques, including injection molding, extrusion, and compression molding, typically performed between 360–400 °C [22]. The material's ability to maintain its chemical structure and properties at elevated temperatures ensures consistent performance through multiple processing cycles and sterilization procedures. Additionally, this thermal stability contributes to PEEK's excellent creep resistance [46], an important consideration for load-bearing implant applications where dimensional stability under sustained stress is crucial.

(3) Biological properties

The biological properties of PEEK are fundamental to its success as an orthopedic implant material. Biocompatibility, the most crucial biological requirement, has been extensively documented through numerous *in vitro* and *in vivo* studies. Research has shown that PEEK demonstrates excellent compatibility with living tissues, exhibiting minimal inflammatory response and no evidence of systemic toxicity [22, 47]. This favorable biological response is maintained over extended periods, making PEEK particularly suitable for long-term implantation [48]. Studies have demonstrated stable tissue integration and minimal foreign body reaction even after years of implantation, supporting its use in permanent orthopedic applications. Ma *et al.* [49] reported that nano-calcium silicate/PEEK bioactive composites significantly promoted cell attachment, proliferation, and osteogenic differentiation compared to unmodified PEEK.

Sterilization compatibility represents another critical biological consideration for PEEK implants. The material‘s ability to withstand various sterilization methods, including steam autoclaving, gamma radiation, and ethylene oxide treatment, without significant degradation of properties is crucial for clinical applications [50]. Research has shown that PEEK maintains its structural integrity and biological properties across multiple sterilization cycles, although specific protocols may need to be optimized depending on the particular PEEK formulation or surface modification [51]. This versatility in sterilization options provides flexibility in processing while ensuring the maintenance of material properties and sterility requirements.

The interaction between PEEK and surrounding tissues extends beyond simple biocompatibility to include considerations of protein adsorption, cell adhesion, and tissue response. Studies by Zhao *et al.* [52] have shown that while the native PEEK surface may not actively promote cell attachment and tissue integration, various surface modification strategies can significantly enhance these biological interactions. For instance, plasma treatment and chemical modification methods have been developed to improve surface hydrophilicity and bioactivity. The introduction of functional groups through surface modification has been shown to enhance protein adsorption and cell adhesion, leading to improved tissue integration [53].

The biological response to wear particles generated from PEEK implants has also been extensively studied, particularly in comparison to metallic alternatives. Unlike metallic wear debris that can trigger significant inflammatory responses and osteolysis, PEEK wear particles generally elicit minimal biological reaction. This favorable response to wear debris contributes to the material‘s long-term biocompatibility and reduces the risk of wear-induced complications. Research has demonstrated that PEEK wear particles are generally well-tolerated by surrounding tissues, with minimal inflammatory cell recruitment and cytokine production [22]. This characteristic is particularly important for load-bearing applications where wear particle generation is inevitable over the implant‘s lifetime.

III. Advanced Manufacturing Technologies for PEEK Implants

The manufacturing of PEEK orthopedic implants requires sophisticated technologies that can ensure precise geometries, consistent material properties, and reliable performance. This section explores both traditional and advanced manufacturing methods, with particular emphasis on emerging additive manufacturing technologies that are revolutionizing the field of orthopedic implants.

(1) Traditional manufacturing methods

Conventional manufacturing techniques for PEEK implants primarily rely on machining and injection molding processes. These established methods have served as the backbone of PEEK implant production for many years, offering reliable and well-understood manufacturing routes. Machining processes, including computer numerical control (CNC) milling and turning, allow for the creation of complex geometries from solid PEEK blocks. These subtractive manufacturing methods provide excellent dimensional accuracy and surface finish but are often associated with significant material waste and limited geometric freedom. The machining process must be carefully controlled, as PEEK‘s mechanical properties can be affected by processing conditions such as cutting speed and tool temperature. Additionally, machining operations require specialized tooling and cooling strategies to prevent thermal degradation of the polymer, which can compromise the implant‘s biocompatibility and mechanical integrity [54].

Injection molding represents another traditional approach to PEEK implant manufacturing. This process involves melting PEEK pellets and injecting the molten material into precisely designed molds under high pressure. While injection molding offers excellent reproducibility and cost-effectiveness for high-volume production, it requires substantial initial investment in tooling and is less flexible for customized or small-batch production. The process also presents challenges in controlling the crystallinity of PEEK, which significantly affects the mechanical properties of the final implant. As demonstrated by recent research, the crystallinity of PEEK components is highly dependent on processing parameters such as mold temperature, injection pressure, and cooling rate [55]. These parameters must be carefully optimized to achieve the desired balance of mechanical properties and biocompatibility. Furthermore, the high processing temperatures required for PEEK (approximately 400 °C) necessitate specialized equipment and careful process control to prevent degradation and ensure consistent part quality. The mold design must also account for the material‘s high shrinkage rate and tendency to develop residual stresses during cooling, which can affect the dimensional accuracy and long-term stability of the implant [56]. Despite these challenges, traditional manufacturing methods continue to play a crucial role in PEEK implant production, particularly for standardized components produced in large volumes.

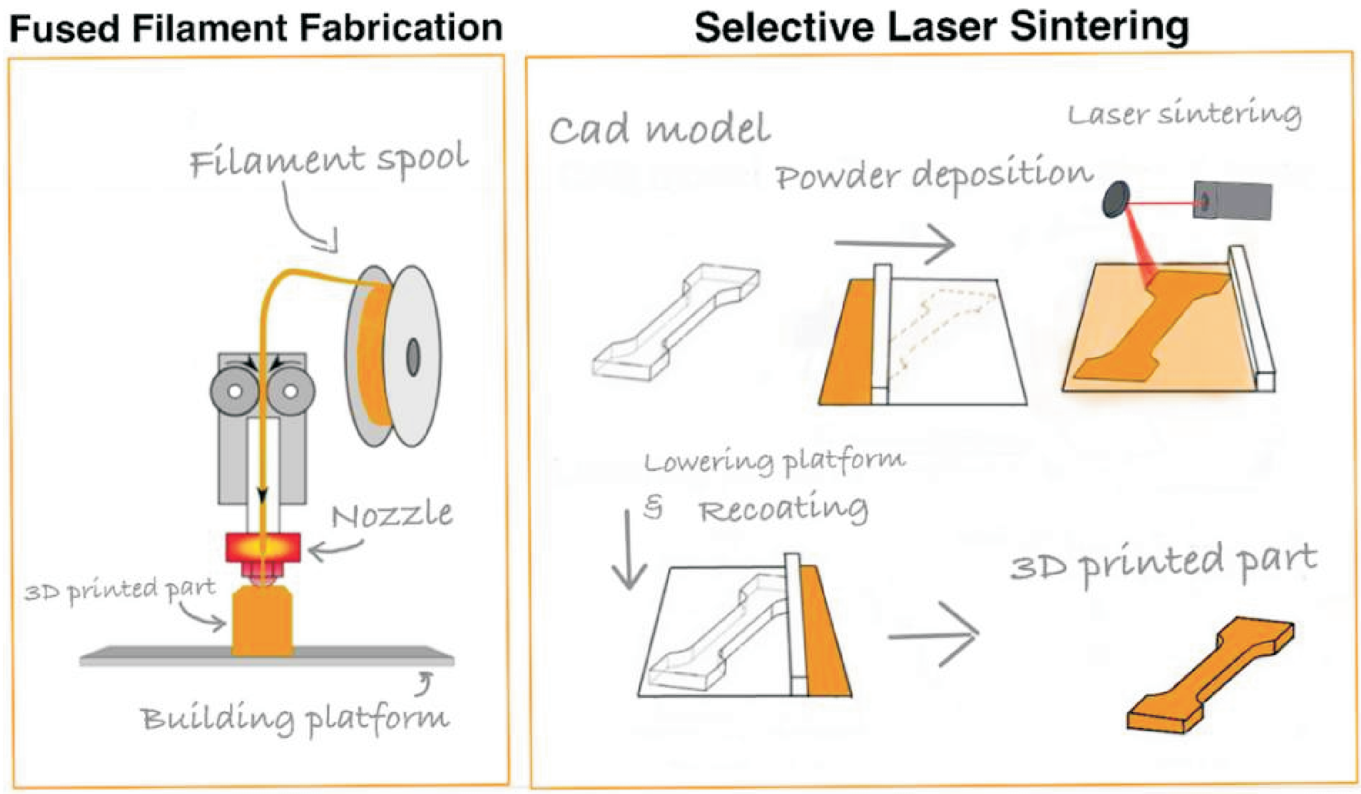

Fig. 3: Schematic representation of AM methods for PEEK processing: Fused Filament Fabrication (FFF) showing filament extrusion, build platform, and thermal management system; Selective Laser Sintering (SLS) highlighting laser scanning over the powder bed and post-processing considerations [58].

(2) Additive manufacturing technologies

The advent of additive manufacturing (AM) technologies has revolutionized the production of PEEK implants, offering unprecedented capabilities in creating customized medical devices. Among the various AM approaches, Fused Filament Fabrication (FFF) and Selective Laser Sintering (SLS) have emerged as the dominant technologies for processing PEEK materials (Fig. 3). These manufacturing methods have enabled the development of patient-specific implants with intricate internal architectures that would be impossible to achieve through conventional manufacturing techniques [57].

FFF technology, also referred to as Fused Deposition Modeling (FDM), involves extruding molten PEEK filament through a heated nozzle, typically at temperatures between 390 °C and 420 °C. The build platform is maintained at approximately 120 °C to 130 °C, and the heated chamber is often kept at ~130 °C to minimize thermal gradients and warping. Common layer thicknesses range from 0.1 mm to 0.25 mm, and cooling rates are carefully controlled via passive or active chamber heating to promote interlayer adhesion and semi-crystalline development. Printing speeds vary from 15 to 60 mm/s depending on nozzle diameter and part complexity [58]. The technical challenges associated with processing PEEK via FFF have been largely addressed through sophisticated equipment developments. For instance, advanced systems now incorporate controlled thermal management strategies, including heated build chambers and optimized thermal gradients, which are crucial for managing PEEK‘s crystallization behavior. Studies have shown that the mechanical properties of FFF-printed PEEK can vary significantly based on processing parameters, with tensile strengths ranging from 65 MPa to 84 MPa and elastic moduli from 3 to 4 GPa [55]. The orientation of printed parts also plays a crucial role, with samples printed in the XY plane showing mechanical properties comparable to injection-molded parts, while Z-direction prints may exhibit reduced strength due to interlayer bonding characteristics (Fig. 4) [59]. Recent developments in FFF technology have focused on improving the interlayer adhesion through techniques such as hot isostatic pressing (HIP) post-processing, which has demonstrated up to 10-times increase in tensile strength for continuous-carbon-fiber-reinforced PEEK composites [60].

SLS processing of PEEK requires powder bed temperatures maintained in the range of 280 °C to 300 °C, with optimal laser powers typically between 15 W and 30 W, and scan speeds ranging from 2 000 mm/s to 5 000 mm/s depending on part geometry and resolution requirements. Representative optimized parameters reported include laser power = 20 W, scan speed = 3 000 mm/s, powder bed temperature = 290 °C, and layer thickness = 100 – 150 µm [57, 61]. These settings have demonstrated favorable mechanical properties, dimensional stability, and interlayer bonding for medical-grade PEEK parts. Cooling must be gradual – ideally less than 5 K/min post-build – to prevent thermal shock and reduce internal stress accumulation. Research has shown that SLS-processed PEEK can achieve comparable mechanical properties to traditional manufacturing methods, though the presence of residual porosity can affect final part performance [62]. The

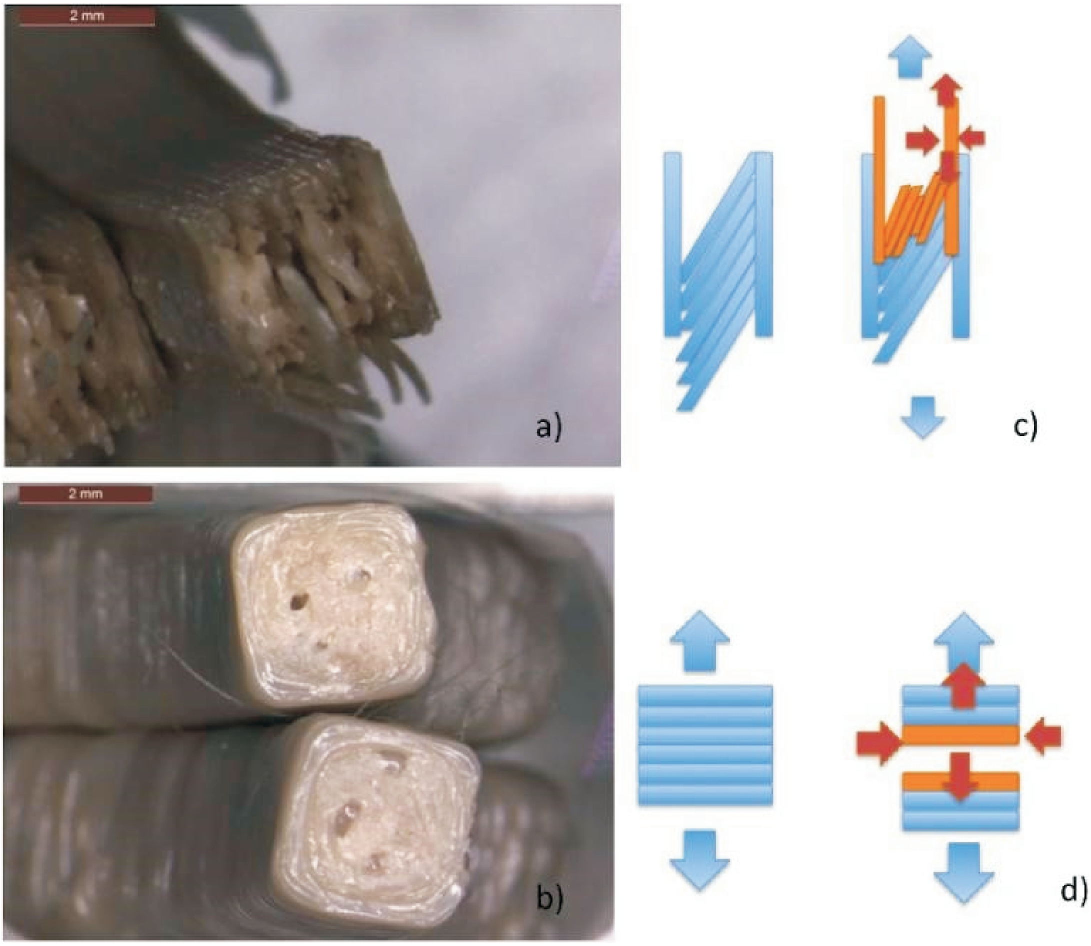

Fig. 4: Fracture after tensile test a), b) XY-printed samples and c), d) Z-printed samples [60].

technology has enabled the creation of complex lattice structures and gradient porosity designs that can enhance osseointegration in orthopedic implants. For example, studies have demonstrated the ability to create PEEK implants with controlled pore sizes ranging from 200 to 500 µm, which is optimal for bone ingrowth [61,63]. However, the high cost of SLS equipment and challenges in powder recycling have somewhat limited its widespread adoption [64,65].

Both AM technologies have demonstrated significant potential in enhancing PEEK implant functionality through the incorporation of various additives and reinforcements. For instance, carbon fiber-reinforced PEEK composites processed via FFF have shown improved mechanical properties, with flexural strengths reaching up to 146 MPa for vertically printed samples [66]. Similarly, the addition of bioactive materials such as hydroxyapatite or β-tricalcium phosphate has been successfully demonstrated in both FFF and SLS processes, enhancing the bioactivity of PEEK implants [57,59]. Recent developments have also focused on addressing the thermal management challenges in AM processing, with studies showing that the incorporation of carbon nanotubes or graphene nanoplatelets can improve the thermal conductivity and processing characteristics of PEEK materials [67,68]. The surface quality of AM-produced PEEK implants has been another area of focus, with various post-processing techniques being developed to achieve surface roughness values comparable to traditional manufacturing methods. Surface roughness values ranging from 7 µm to 22 µm have been reported for FFF-printed PEEK, with vertical builds typically showing higher roughness than horizontal ones [69].

The advancements in AM technologies have not only improved the quality and reproducibility of PEEK implants but have also opened new possibilities in implant design and functionality. The ability to create patient-specific implants with optimized mechanical properties and biological response represents a significant step forward in orthopedic medicine. As these technologies continue to evolve, further improvements in process control, material properties, and cost-effectiveness are expected to drive wider adoption in clinical applications.

(3) Process parameters and optimization

The successful manufacturing of PEEK implants through AM technologies requires careful optimization of numerous process parameters. In FFF processing, critical parameters include nozzle temperature (typically 360 – 400 °C), bed temperature (120 – 130 °C), chamber temperature, printing speed, layer height, and cooling rate. These parameters significantly influence the bonding between layers, crystallinity development, and ultimately the mechanical properties of the printed implant. For instance, Zhao *et al.* demonstrated that the nozzle temperature directly affects the inter-layer bonding strength, with higher temperatures generally promoting better fusion between layers but potentially leading to material degradation above 400 °C [70]. Studies have shown that maintaining a stable chamber temperature around 130 °C helps prevent warping and delamination issues common with high-performance polymers like PEEK. The printing speed must be carefully balanced – too fast can lead to incomplete fusion between layers, while too slow may cause material degradation due to prolonged exposure to high temperatures.

The relationship between processing parameters and material properties is particularly complex for PEEK due to its semi-crystalline nature. The degree of crystallinity achieved during processing directly affects mechanical properties, with higher crystallinity generally resulting in increased stiffness and strength but potentially reduced toughness. Importantly, recent studies have revealed that variations in crystallinity and domain morphology introduced during additive manufacturing also influence electrochemical and surface interaction behaviors. Crystalline regions typically exhibit lower surface energy and reduced ionic permeability compared to amorphous zones, which are more hydrophilic and susceptible to ionic diffusion and chemical interaction. This spatial heterogeneity can result in localized differences in protein adsorption, surface charge distribution, and even susceptibility to oxidative or hydrolytic degradation under physiological conditions. In complex AM-fabricated parts, where layer-by-layer deposition and thermal gradients create non-uniform crystallization, these effects may lead to preferential pathways for ionic transport or focal degradation sites, especially near crystalline-amorphous boundaries. Moreover, EIS studies have shown that interfaces enriched in amorphous domains exhibit higher double-layer capacitance and increased interfacial conductivity, indicative of enhanced ionic mobility and surface reactivity. This differential behavior may affect not only corrosion resistance but also the osseointegration potential, as the initial stages of protein adsorption and cellular interaction are governed in part by surface energy and electrochemical stability. Thus, the thermal history and crystallization kinetics intrinsic to AM not only impact mechanical integrity but also bear long-term consequences for the chemical resilience and biological performance of PEEK implants. Yang *et al.* [55] found that the cooling rate significantly influences the crystallization behavior, with slower cooling promoting higher crystallinity but potentially introducing more internal stresses. For dental applications, Schwitalla *et al.* demonstrated that optimized processing parameters could achieve mechanical properties comparable to traditional manufacturing methods, with tensile strengths of 90 – 100 MPa and Young‘s modulus of 3.6 GPa [71]. These properties make PEEK implants suitable for various dental applications, from fixed prostheses to removable dental frameworks. The post-processing thermal history also plays a crucial role, as demonstrated in several studies where annealing treatments were used to enhance crystallinity and improve mechanical properties.

For SLS processing, key parameters include laser power, scan speed, powder bed temperature, and layer thickness. The interaction between these parameters determines the energy density delivered to the powder bed, which in turn affects the fusion between particles and the development of the material‘s microstructure. Honigmann *et al.* reported that maintaining powder bed temperatures between 250 – 300 °C is crucial for achieving optimal part density and mechanical properties [72]. The layer thickness typically ranges from 0.1 to 0.2 mm, with thinner layers generally resulting in better surface quality but longer build times. Studies have shown that the energy density, calculated as a function of laser power, scan speed, and layer thickness, should be optimized within a specific window to achieve full density while avoiding material degradation. For instance, too high energy density can lead to excessive molecular weight reduction and deterioration of mechanical properties, while insufficient energy density results in poor particle fusion and reduced strength. The optimization of these parameters requires understanding their complex interrelationships and their impact on final part properties, particularly for medical applications where consistency and reliability are paramount.

(4) Quality control and standardization

Quality control in AM-produced PEEK implants demands a comprehensive approach encompassing multiple evaluation stages. Raw material characterization is particularly critical, as variations in molecular weight distribution and particle morphology can significantly impact processability and final part properties. Studies have shown that the thermal history of PEEK materials can affect their crystallization behavior and subsequent mechanical properties, with varying crystallinity values reported between 30 % and 48 % [73,74]. Surface quality assessment has become increasingly sophisticated, with advanced metrology techniques revealing that printing parameters significantly influence surface characteristics. For instance, research has demonstrated that vertically printed PEEK components typically exhibit higher surface roughness (Ra = 23.87 µm) compared to horizontally printed parts (Ra = 16.37 µm) (Fig. 5), necessitating specific post-processing treatments for different build orientations [57,69].

Non-destructive evaluation methods have evolved significantly for AM PEEK implant inspection. Advanced CT scanning technologies now enable detection of internal defects as small as 100 µm, crucial for identifying potential failure points in load-bearing implants [59]. Real-time monitoring systems have been developed to track critical process parameters, including melt pool dynamics and thermal gradients during printing. For example, studies utilizing infrared thermography have shown that maintaining precise temperature control within ± 5 °C during the printing process is essential for achieving consistent mechanical properties [75,76] The implementation of acoustic emission monitoring has also proven effective in detecting layer delamination during the FFF process, allowing for immediate process adjustments to prevent part failure [77,78].

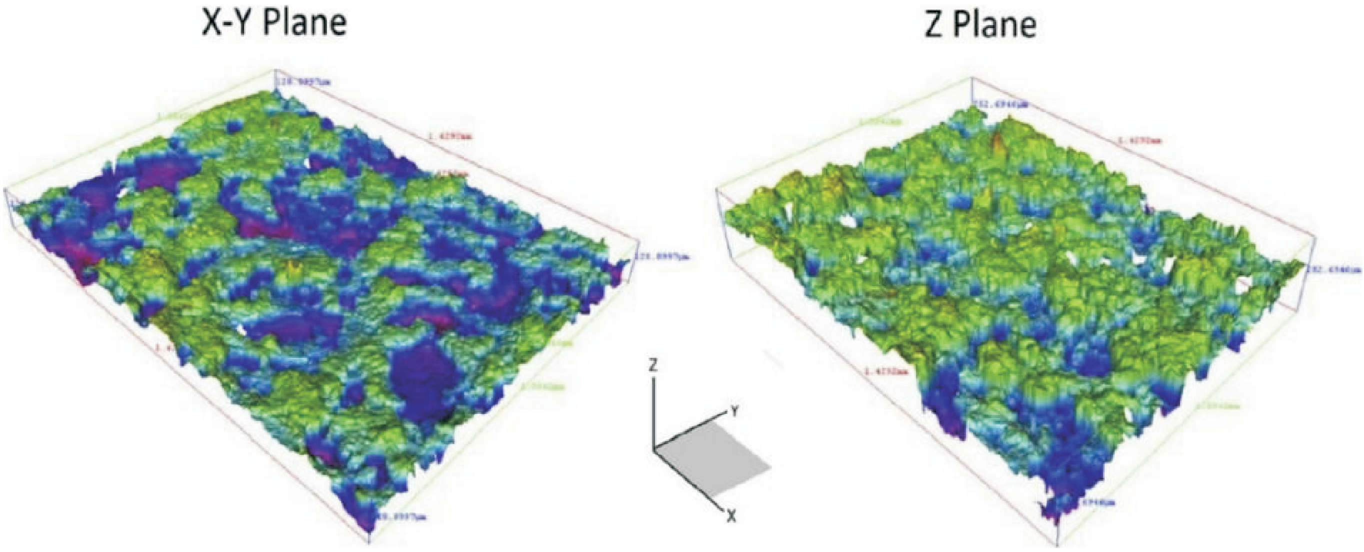

Fig. 5: Surface roughness profile for EOS PEEK HP3.

Standardization initiatives for AM PEEK implants have made significant progress, particularly in establishing testing protocols and acceptance criteria. Organizations like ASTM and ISO have developed specific guidelines for evaluating additively manufactured polymeric implants. These standards address critical aspects such as outgassing behavior, which is particularly important for PEEK implants. Recent studies have demonstrated that 3D-printed PEEK exhibits acceptable outgassing characteristics with total mass loss (TML) values of 0.186 ± 0.001 % and collected volatile condensable material (CVCM) values of 0.01 %, well within the requirements for medical applications [79]. The development of process validation protocols has also advanced, with emphasis on establishing correlations between processing parameters and final part properties. For instance, research has shown that bed temperature control within 230 – 260 °C and nozzle temperatures between 390 – 420 °C are crucial for achieving optimal mechanical properties in FFF-printed PEEK components [59]. These standardization efforts have been instrumental in facilitating regulatory approval and clinical adoption of AM PEEK implants.

IV. PEEK Composites and Surface Modifications

The development of PEEK composites and surface modification strategies represents a significant advancement in addressing the limitations of pure PEEK for orthopedic applications. While PEEK offers excellent mechanical properties and biocompatibility, its bioinert nature and limited osseointegration capabilities have driven extensive research into methods for enhancing its biological and mechanical performance through various modification approaches.

(1) Binary composites

Hydroxyapatite (HA)/PEEK composites have emerged as a cornerstone in the development of orthopedic biomaterials, particularly for bone implant applications. By integrating hydroxyapatite – a calcium phosphate mineral that closely mimics the inorganic component of bone – into the PEEK matrix, these composites achieve a unique balance between mechanical robustness and bioactivity. The incorporation of HA enhances the bioactivity of PEEK by promoting osteoblast adhesion and proliferation, critical factors for osseointegration. Studies have shown that HA/PEEK composites with HA concentrations between 20 – 40 % by weight exhibit optimal performance, maintaining sufficient mechanical strength while significantly improving biological responses. For instance, Zhao *et al.* [80] demonstrated that UV-induced graft polymerization of acrylic acid on HA/PEEK composites further enhanced hydrophilicity and osteoblast attachment, making the material more conducive to bone integration (Fig. 6). However, higher HA concentrations often compromise the mechanical integrity of the composite by increasing brittleness and reducing toughness, which can limit its applicability in load-bearing implants [23]. A practical example of this application is in spinal fusion cages, where HA/PEEK composites provide sufficient strength to support vertebrae while fostering bone growth within the cage structure [81].

Beyond static mechanical properties, the microstructure of HA/PEEK composites plays a crucial role in their performance. Uniform dispersion of HA particles within the PEEK matrix is essential to avoid stress concentrations that could lead to premature failure [82]. Advanced manufacturing techniques, such as melt compounding and selective laser sintering, have been employed to ensure homogeneity and optimize the composite‘s properties [83]. Additionally, surface modification of HA particles, such as silanization, has been explored to improve interfacial bonding with the PEEK matrix, further enhancing mechanical performance and bioactivity. From an electrochemical perspective, the PEEK-HA interface acts as a critical site for ion exchange and protein adsorption. The interfacial adhesion determines the resistance to electrochemical stress under physiological conditions, especially where microfluidic ionic currents interact with heterogeneous surfaces.

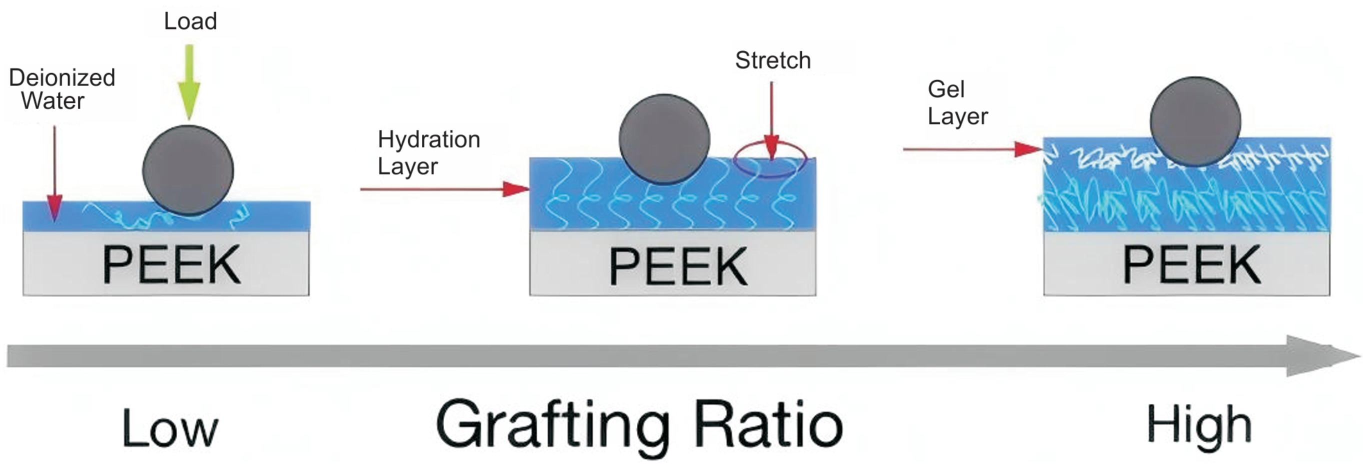

Fig. 6: Schematic representation of the mechanism for tribological model of AA-g-PEEK with different grafting ratios under water lubrication [81].

Studies using electrochemical impedance spectroscopy (EIS) have shown that poor interfacial contact leads to increased interfacial polarization resistance and reduced ion transport efficiency [84]. Recent developments in 3D printing technologies have also enabled the fabrication of porous HA/PEEK scaffolds, which mimic the trabecular architecture of bone and allow for vascularization and nutrient transport [85]. These scaffolds have demonstrated excellent potential in preclinical studies for bone defect repair, particularly in load-bearing applications where both strength and osseointegration are critical.

Carbon fiber/PEEK composites represent another transformative development in orthopedic implant materials, offering unparalleled mechanical properties tailored to mimic the anisotropic behavior of bone. The addition of carbon fibers significantly enhances the strength, stiffness, and fatigue resistance of the PEEK matrix, making these composites particularly suitable for high-stress applications such as femoral stems and spinal rods [86]. Continuous carbon fiber reinforcement provides exceptional mechanical properties along specific orientations, making it ideal for structural implants subjected to directional loads. For instance, Wu *et al.* [22] compared the performance of carbon fiber/PEEK and titanium alloy rods in a cervical fusion model and found that the composite rods reduced stress shielding effects while maintaining comparable mechanical stability. On the other hand, short-carbon-fiber reinforcement offers a more isotropic mechanical profile, which is advantageous for components requiring multidirectional strength, such as acetabular cups.

The orientation and distribution of carbon fibers within the PEEK matrix are critical determinants of the composite‘s final properties. Techniques such as filament winding and injection molding have been employed to control fiber alignment and distribution, enabling the customization of mechanical properties for specific applications [83]. Moreover, surface treatments of carbon fibers, such as oxidative or plasma treatments, have been shown to improve interfacial bonding with the PEEK matrix, further enhancing composite performance [52]. These composites also exhibit excellent wear resistance, a critical requirement for articulating surfaces in joint replacements. For example, carbon fiber/PEEK composites have been successfully used in the manufacture of prosthetic components for knee and hip replacements, where their low friction and wear rates contribute to the longevity of the implant [23].

Bioactive glass/PEEK composites have gained considerable attention for their ability to actively promote bone bonding and tissue integration, addressing one of the primary challenges of bioinert materials like pure PEEK. The inclusion of bioactive glass particles in the PEEK matrix enables the formation of a hydroxycarbonate apatite (HCA) layer on the composite surface when exposed to physiological conditions, facilitating direct bonding with bone tissue [87]. This bioactivity not only improves implant fixation but also enhances long-term stability by promoting continuous bone remodeling around the implant [85]. For instance, bioactive glass/PEEK composites have been explored for use in craniofacial implants, where their ability to bond with irregular bone surfaces is particularly advantageous. *In vivo* studies, such as those conducted by Zheng *et al.*, have shown that surface-phosphorylated PEEK implants with bioactive glass exhibited significantly higher bone-implant contact and improved osseointegration compared to unmodified PEEK.

The dissolution characteristics of bioactive glass further augment the functionality of these composites by releasing beneficial ions, such as calcium and phosphate, which stimulate osteogenesis and accelerate bone formation [88]. Additionally, the incorporation of bioactive glass can be tailored to achieve controlled ion release profiles, enabling the development of composites with specific therapeutic effects. For example, composites containing borate-based bioactive glass have demonstrated antibacterial properties, reducing the risk of postoperative infections [85]. Advances in manufacturing techniques, such as electrospinning and hot pressing, have enabled the production of bioactive glass/PEEK composites with tailored porosity and surface roughness, further enhancing their bioactivity and mechanical compatibility [81]. These composites are particularly promising for applications in load-bearing implants, such as tibial plates and dental implants, where both mechanical strength and bioactivity are paramount.

(2) *Ternary composites*

CF/HA/PEEK composites represent an advanced approach that strategically combines enhanced mechanical properties with improved bioactivity. These ternary systems leverage the mechanical reinforcement provided by carbon fibers while incorporating the osteoconductive properties of hydroxyapatite. For example, Ma *et al.* [89] demonstrated that incorporating 30 wt% CF and 20 wt% nano-HA into PEEK resulted in composites with significantly improved mechanical strength (tensile strength increased by 45 %) while maintaining excellent biocompatibility compared to pure PEEK. The synergistic effects between CF and HA have been shown to promote better osseointegration while maintaining mechanical integrity. Electrochemical considerations at this ternary interface are particularly important. The presence of conductive carbon fibers may facilitate localized charge transfer pathways, influencing cellular signaling and redox reactions at the biointerface. However, differential conductivity across the PEEK matrix, HA particles, and carbon fibers can introduce interfacial electrochemical gradients, which may either support or destabilize the implant's surface integrity under long-term physiological exposure. Enhanced interfacial engineering – such as amino-silanized HA and plasma-treated CFs – has been demonstrated to mitigate electrochemical mismatch and reduce potential sites for localized corrosion or ion trapping. Studies by Wu *et al.* [90] found that the presence of both CF and HA led to enhanced osteoblast adhesion and proliferation compared to binary CF/PEEK or HA/PEEK composites. However, key challenges remain in optimizing processing parameters to achieve uniform dispersion of both reinforcements. Recent work by Han *et al.* [91] showed that using surface-modified CFs with amino functionalization improved interfacial bonding with both PEEK and HA particles, resulting in more homogeneous distribution and better mechanical properties. The ratios between components must be carefully controlled – excessive HA content can compromise mechanical properties while insufficient amounts may not provide adequate bioactivity [92].

CNT/BG/PEEK composites represent another innovative approach incorporating carbon nanotubes and bioactive glass into the PEEK matrix. The addition of CNTs provides multifunctional benefits including enhanced mechanical strength, electrical conductivity, and potential for surface modification. From an electrochemical perspective, the inclusion of CNTs or other conductive nanomaterials into the PEEK matrix transforms the polymer from an insulating phase into a percolated, semi-conductive composite capable of mediating charge transfer processes. The threshold for electrical percolation – dependent on the aspect ratio, dispersion, and functionalization of CNTs – marks a critical transition in which the composite begins to exhibit significant conductivity. Studies have reported percolation thresholds as low as 0.1 – 0.5 wt% for well-dispersed CNT/PEEK systems, with conductivity increasing by several orders of magnitude beyond this point. Importantly, conductivity is not uniform but modulated by the distribution and orientation of the conductive filler, the quality of interfacial adhesion, and the potential formation of tunneling junctions between particles. In biological environments, these conductive pathways influence not only passive electrochemical behavior but also active modulation of cell signaling, especially under applied electrical fields. For example, conductive PEEK scaffolds have been shown to enhance osteogenic differentiation via electrostimulation, owing to increased surface charge density and improved electron mobility [93]. The composite's impedance characteristics, particularly R_{ct} and C_{dl}, can be tuned through materials selection and processing conditions to match the desired bioelectrical response [94]. Xu *et al.* [92] demonstrated that incorporating CNTs along with bioactive glass resulted in significant increases in mechanical properties while maintaining excellent bioactivity through controlled ion release from the bioactive glass phase (Fig. 7). The electrical conductivity imparted by CNTs has also shown promise for stimulating bone growth through electrical signals [95]. Studies by Barkarmo *et al.* [96] found that CNT/BG/PEEK composites with appropriate electrical conductivity promoted enhanced osteoblast differentiation compared to non-conductive variants. The processing of these composites requires careful consideration of CNT dispersion and interface engineering. Recent developments include the use of surface-functionalized CNTs to improve compatibility with both PEEK and bioactive glass phases. For example, Hahn *et al.* [94] utilized modified CNTs that showed better dispersion and stronger interfacial bonding, resulting in improved mechanical properties and more uniform bioactive glass distribution.

Other emerging ternary combinations continue to push the boundaries of multifunctional PEEK composites. One promising direction involves the incorporation of multiple bioactive phases with complementary functions. For instance, Zhou *et al.* [95] developed Ti-modified HA/PEEK composites where the dual bioactive phases provided enhanced osteogenesis through different mechanisms. Another innovative approach by Lee *et al.* [97] combined surface modification techniques with nano-hydroxyapatite in PEEK, where the modified surface served as both a mechanical reinforcement and a platform for improved HA distribution. The resulting composites showed synergistic improvements in both mechanical and biological properties [96]. Novel processing methods are also being explored to optimize these complex systems. For example, Walsh *et al.* [98] demonstrated advanced coating techniques to fabricate bioactive PEEK composites with controlled spatial distribution of the active phases. The development of these advanced ternary systems requires careful consideration of not just the individual components but also their interactions and spatial arrangement. Researchers continue to explore various combinations of reinforcing elements and bioactive components to achieve optimal property combinations for specific orthopedic applications [99, 100]. To better categorize the different strategies used in PEEK composite development, Table 2 presents a classification of major PEEK-based composites by reinforcement type, function, advantages, and limitations.

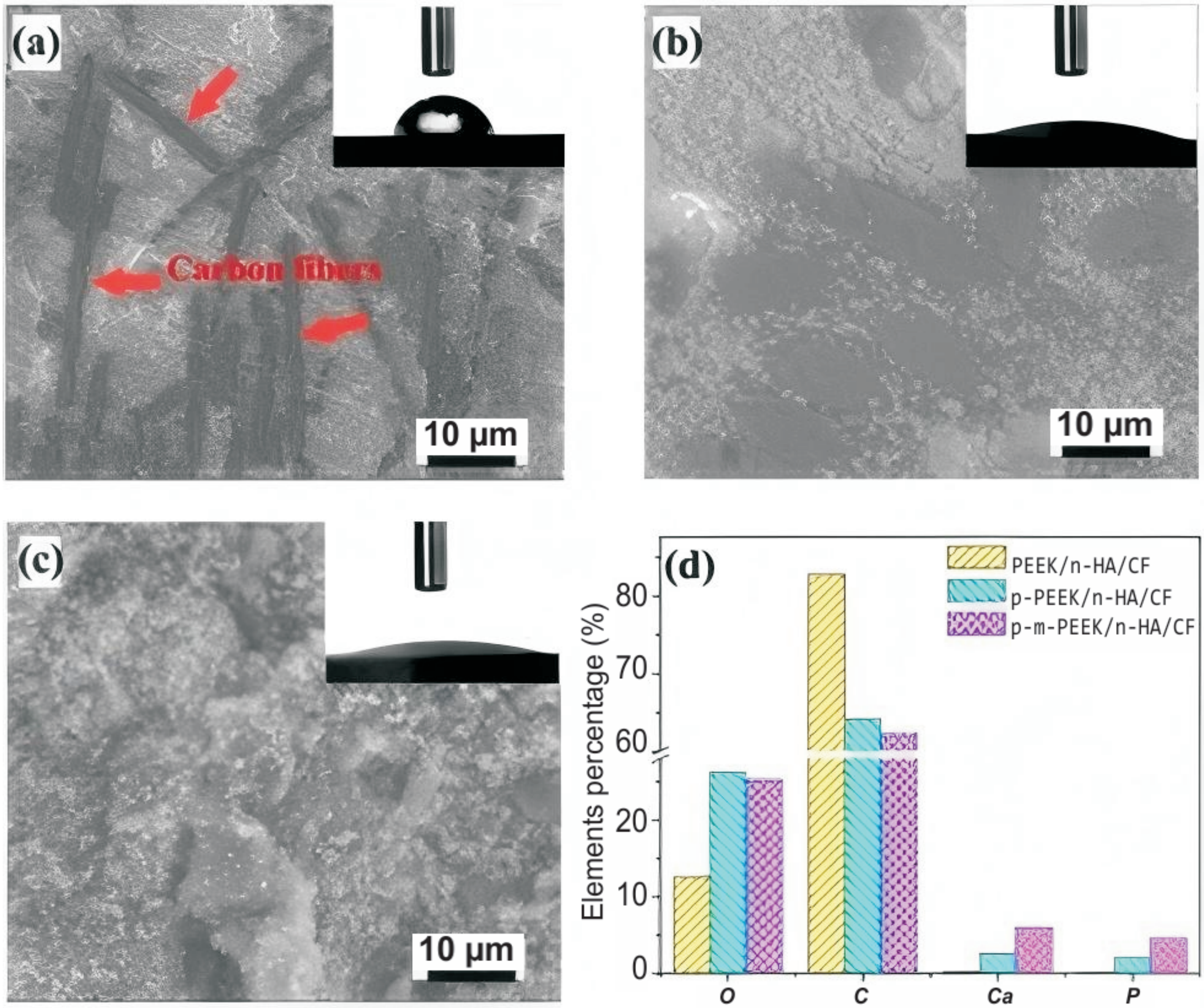

Fig. 7: Surface morphologies and contact angles of (a) PEEK/n-HA/CF, (b) p-PEEK/n-HA/CF, and (c) p-m-PEEK/n-HA/CF; (d) chemical compositions determined by XPS analysis of these biocomposites [93].

Table 2: Summary of major PEEK composite types, their reinforcing phases, functional benefits, and associated trade-offs.

Composite Type	Reinforcement	Functional Focus	Key Advantages	Limitations
HA/PEEK	Hydroxyapatite	Osseointegration	Promotes bone bonding	Reduced toughness at high HA loading
CF/PEEK	Carbon fiber	Mechanical reinforcement	High stiffness, fatigue resistance	Directional strength; challenging interface
BG/PEEK	Bioactive glass	Bioactivity & ion release	Stimulates osteogenesis, antibacterial effect	Processing and dispersion challenges
CF/HA/PEEK	Carbon fiber + HA	Dual mech-bio performance	Balanced strength and bioactivity	Complex interfacial optimization required
CNT/BG/PEEK	Carbon nanotube + glass	Mech + bio + conductivity	Multimodal reinforcement	Risk of agglomeration, manufacturing complexity

(3) Antibacterial and anti-inflammatory properties of PEEK composites

Infection remains a major complication in orthopedic implantation, particularly in patients with compromised immunity or extended surgical exposure. While PEEK exhibits excellent biocompatibility, its bioinert surface provides limited resistance to bacterial adhesion and biofilm formation [101–103]. Recent studies have focused on enhancing the antibacterial and anti-inflammatory properties of PEEK through chemical modifications and incorporation of bioactive agents.

For instance, Farjaminejad *et al.* [104] introduced a silver-doped PEEK composite using surface coating techniques, achieving broad-spectrum antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*. Similarly, Bu *et al.* [105] demonstrated a ZnO/Ag-loaded PEEK composite that not only exhibited strong bactericidal effects but also modulated macrophage polarization to an anti-inflammatory phenotype, reducing local inflammation. These advancements highlight the potential of integrating antibacterial agents and immunomodulatory components into PEEK matrices or onto their surfaces, offering dual functionality in preventing infection and promoting healing. Future developments may focus on multifunctional PEEK composites capable of sustained antimicrobial release and inflammatory response modulation.

V. Clinical Applications and Performance

The clinical implementation of PEEK-based materials in orthopedic applications has expanded significantly over the past decades, demonstrating successful outcomes across various anatomical locations and functional requirements. This section examines the diverse applications and clinical performance of PEEK implants, highlighting both achievements and areas requiring further development.

(1) Spinal implants

Spinal applications represent the most established and successful clinical use of PEEK implants. Interbody fusion cages manufactured from PEEK have become a standard option in spinal surgery since their FDA approval in 1998, offering several advantages over traditional metallic alternatives. The elastic modulus of PEEK (3 840 MPa), which more closely matches that of cancellous bone, contributes to better load distribution across the fusion site, potentially reducing the risk of subsidence and adjacent segment degeneration [30]. The radiolucency of PEEK cages facilitates post-operative imaging assessment of fusion progress, allowing for better monitoring of healing outcomes [106]. Clinical studies have demonstrated PEEK's effectiveness in various spinal procedures, with one notable study showing a 97 % fusion rate and 88 % clinical success rate at 10-year follow-up in FDA trials [107]. These results are further supported by independent clinical studies, such as Song *et al.* [108] which demonstrated a 94.6 % fusion rate in anterior cervical discectomy and fusion (ACDF) procedures using PEEK cages at a 24-month follow-up; Villavicencio *et al.* [109], which reported a 96.1 % fusion rate in lumbar interbody fusion at 36 months; and Deml *et al.* [110], which showed a 95.4 % fusion success in thoracolumbar fusion using CF/PEEK implants at 2-year follow-up. PEEK cages have demonstrated particular success in anterior cervical discectomy and fusion (ACDF) procedures, where studies have shown significantly lower subsidence rates (14.3 %) compared to titanium cages (20.5 %) [111]. Additionally, PEEK demonstrates substantial resistance to retropulsion, with pullout resistance three times greater than that of bone, making it particularly suitable for interbody fusion applications [112]. Early biomechanical tests revealed that PEEK implants exhibited lower stress with motion compared to titanium, specifically at the points where the spacer contacted the vertebral endplate, suggesting better biomechanical compatibility [113].

Dynamic stabilization systems utilizing PEEK components have emerged as an alternative to rigid fusion in select cases, supported by ongoing technological advances in surface modifications and hybrid designs. These systems aim to maintain some degree of spinal motion while providing necessary stabilization. Recent developments have focused on enhancing PEEK's integration capabilities through various surface modification techniques. For instance, plasma-sprayed titanium-coated PEEK cages have shown successful fusion rates exceeding 90 – 95 % within 12 months of surgery [114]. Hybrid technologies combining PEEK with titanium have demonstrated promising results, as evidenced by a study of titanium/PEEK composite cages in ACDF procedures showing a 96 % fusion rate with significant improvements in both neck and arm pain scores [115]. Similarly, in anterior lumbar interbody fusion (ALIF) applications, titanium/PEEK composite devices achieved a 95 % fusion rate with substantial improvements in back pain and Oswestry Disability Index scores [116]. These advancements in PEEK-based spinal implants demonstrate the material's versatility and potential for continued innovation in spinal applications, particularly when combined with surface modifications or hybrid designs to overcome its inherent limitations while maintaining its beneficial properties.

(2) Joint replacement components

The application of PEEK in joint replacement has evolved significantly, driven by its unique material properties and potential advantages over traditional materials. Early implementations focused on experimental studies to validate PEEK's wear characteristics and biocompatibility in joint replacement scenarios. The material's wear resistance and low friction properties make it particularly suitable for articulating surfaces, where PEEK-based bearings have demonstrated wear rates comparable to metal-on-metal bearing couples [117]. CF-PEEK composites have shown especially promising results in acetabular components and tibial inserts, with studies indicating that the elastic modulus can be tailored between 18 GPa (similar to cortical bone) and 110 GPa (comparable to titanium alloy) by adjusting carbon fiber orientation and length [118]. This mechanical customization capability has enabled designers to optimize stress distribution and reduce stress shielding effects commonly associated with metallic implants. Notable examples include the ABG II Hip System (Stryker SA), which incorporated CFR-PEEK in its acetabular component, and experimental PEEK-based unicompartmental knee replacements that have demonstrated favorable wear characteristics in laboratory testing [119].

Clinical implementation of PEEK-based joint components has yielded valuable insights into their *in vivo* performance. Studies have shown that PEEK demonstrates good wear resistance and biocompatibility in clinical applications, with retrieved implant analyses showing minimal wear and tissue reaction [120]. The material's reduced stiffness compared to metallic components has helped address stress shielding concerns, particularly in acetabular applications where more physiological load transfer is desirable. However, ongoing monitoring of long-term performance continues, especially in high-load applications such as knee replacements. Simulator studies have shown that PEEK-based wear particles typically fall within the 0.23 – 2.0 μm size range, with most particles being in the submicron range [121]. This particle size distribution has important implications for biological response, as particles in this range can potentially trigger macrophage activation. However, studies comparing PEEK wear particles to UHMWPE particles have generally found similar or reduced inflammatory responses, suggesting acceptable biocompatibility [122]. Recent developments have also explored the potential of PEEK in total disc replacements, where its radiolucency offers additional advantages for postoperative monitoring [123]. The NUBAC nucleus replacement device represents an example of unfilled PEEK application in spinal arthroplasty, though current FDA clearance is limited to cervical disc replacement applications.

(3) Cranial implants

PEEK has gained significant traction in cranial reconstruction applications, where its combination of mechanical properties and ability to be manufactured into patient-specific geometries offers distinct advantages. The material's thermal and electrical insulation properties provide additional benefits for cranial applications, improving patient comfort compared to metallic implants. Studies have shown that PEEK's modulus of elasticity (3 – 4 GPa) closely matches that of cortical bone (7 – 30 GPa), making it biomechanically more compatible than traditional materials like titanium (102 – 110 GPa) [124]. The ability to create precise anatomical matches through computer-aided design and manufacturing (CAD/CAM) has led to improved aesthetic outcomes and reduced operative times. Clinical studies have demonstrated that PEEK cranial implants can achieve excellent cosmetic results, with satisfaction rates reaching 94.7 % in some series [125]. The material's radiolucency and compatibility with various imaging modalities, including MRI and CT, make it particularly valuable for post-operative monitoring and long-term follow-up [126].

Large-scale clinical studies have validated the efficacy and safety of PEEK cranial implants. A comprehensive review of 22 studies involving 620 patients revealed a success rate of 93.7 % and a complication rate of 15.4 %, with infection being the most common complication at 6.3 % [124]. Comparative studies have shown that PEEK performs favorably against traditional materials – it demonstrates superior outcomes compared to titanium mesh in terms of both cosmetic satisfaction and brain function improvement [125]. The material has also shown advantages over autologous bone, which has a reported resorption rate of 17.4 % [127, 128]. Recent developments in PEEK surface modification and composite formulations have further enhanced its performance. For instance, incorporating bioactive materials such as hydroxyapatite or titanium dioxide has improved osseointegration properties [129], while surface treatments with silver nanoparticles have enhanced antimicrobial properties [130]. These advancements, combined with PEEK's established mechanical reliability and biocompatibility, have made it an increasingly preferred choice for complex cranial reconstruction cases, particularly in situations requiring large defect repair or when long-term stability is crucial.

VI. Future Perspectives and Challenges

Despite the significant progress in PEEK-based orthopedic implants, several challenges remain to be addressed while new opportunities continue to emerge. Understanding these limitations and future directions is crucial for advancing the field and improving clinical outcomes. Fig. 8 illustrates the current challenges and future directions in PEEK-based orthopedic implant development. The diagram is structured into four sections: existing limitations, recent advancements, areas requiring further research, and anticipated future innovations. Arrows connect these segments, highlighting the interdependencies between technological limitations, research needs, and innovation potential. This visual representation underscores the multifaceted approach required to enhance the clinical performance and versatility of PEEK implants. The primary challenge in PEEK implant technology remains its limited biological activity and osseointegration capability. While various surface modification strategies and composite formulations have shown promise, achieving consistent and reliable bone integration remains problematic. The intrinsic hydrophobicity and bioinert nature of PEEK continue to present obstacles in achieving optimal tissue-implant interfaces. Additionally, the mechanical properties of PEEK, while advantageous in many applications, may still be insufficient for certain high-load bearing situations, particularly in large joint replacements. Manufacturing challenges persist, especially in additive manufacturing processes. The high processing temperatures required for PEEK, combined with its significant shrinkage upon cooling, can lead to dimensional accuracy issues and internal stress development. The optimization of process parameters to achieve consistent material properties while maintaining geometric precision remains an ongoing challenge. Quality control and validation procedures for additively manufactured PEEK implants also require further development and standardization.

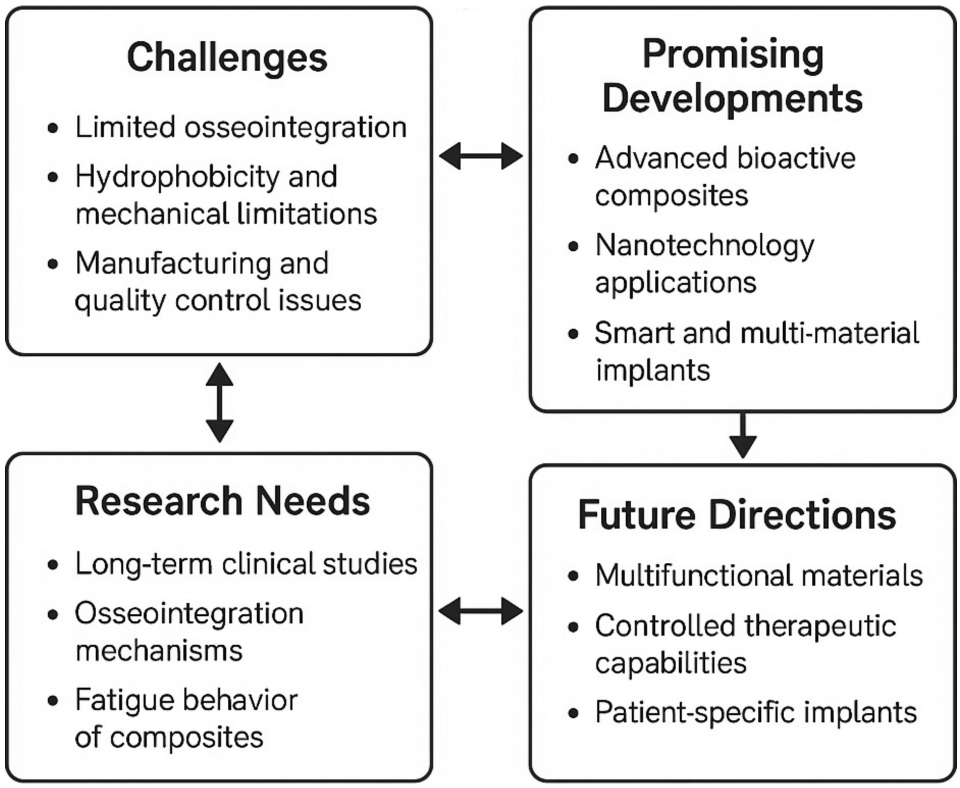

Fig. 8: Future perspectives and challenges in PEEK orthopedic implant technology. The diagram summarizes key limitations of current PEEK implants, recent advancements in material science and manufacturing, areas of ongoing research, and emerging directions such as smart composites and patient-specific implants.

The field of PEEK implant technology is witnessing several promising developments. Advanced composite formulations incorporating novel bioactive materials and reinforcing agents are being developed to enhance both mechanical and biological performance. The integration of nanotechnology, particularly in surface modification and composite development, offers new possibilities for controlling cell-material interactions at the molecular level. Smart PEEK composites capable of controlled drug delivery or stimuli-responsive behavior represent an emerging frontier in implant technology. The continued advancement of manufacturing technologies, particularly in additive manufacturing, is opening new possibilities for implant design and production. The development of multi-material printing capabilities and improved process control systems promises to enable the creation of functionally graded PEEK implants with optimized properties throughout their structure. These advances may allow for more sophisticated implant designs that better replicate the complex mechanical and biological properties of natural tissue.

Several areas require further investigation to advance PEEK implant technology. Long-term clinical studies comparing different surface modification strategies and composite formulations are needed to establish optimal approaches for specific applications. The mechanisms of osseointegration in modified PEEK surfaces and the factors influencing long-term stability require deeper understanding. Research into the fatigue behavior of PEEK composites, particularly under physiological conditions, remains crucial for expanding applications in load-bearing situations. The future development of PEEK implants is likely to focus on creating multifunctional materials that combine enhanced biological activity with improved mechanical performance. Integration of therapeutic capabilities, such as controlled release of growth factors or antibacterial agents, represents a promising direction. The development of patient-specific implants utilizing advanced manufacturing technologies and incorporating optimized mechanical and biological properties will continue to evolve.

VII. Conclusions

In summary, PEEK has emerged as a leading alternative to traditional metallic materials for orthopedic implants, owing to its bone-matching elastic modulus, radiolucency, chemical inertness, and excellent fatigue resistance. Despite its bioinert nature, recent advances in composite development and surface modification strategies – such as HA/PEEK, CF/PEEK, and ternary systems like CF/HA/PEEK – have significantly enhanced PEEK's osseointegration potential and mechanical performance. Innovations in additive manufacturing, especially FFF and SLS technologies, have enabled the creation of patient-specific implants with complex geometries and tailored porosity, improving both functional integration and load distribution. These technologies have also facilitated the incorporation of bioactive agents, carbon reinforcements, and smart functionalities, paving the way for multifunctional implants. Clinically, PEEK-based implants have shown excellent outcomes in spinal fusion, joint replacements, and cranial reconstruction, with high fusion success rates, improved imaging compatibility, and reduced stress shielding. Nonetheless, challenges remain, including limited intrinsic bioactivity, processing complexities in high-temperature additive manufacturing, and the need for standardized quality control protocols. Future developments are likely to focus on the integration of therapeutic functionalities, such as controlled drug release and electrical stimulation, as well as continued optimization of composite interfaces and microstructural design. Advances in surface engineering and nanotechnology are also expected to further enhance biological interactions and long-term implant stability. Overall, the convergence of materials science, manufacturing innovation, and clinical insight continues to expand the potential of PEEK-based implants, positioning them as a versatile and high-performance solution for next-generation orthopedic applications.

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