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Balancing Mechanical Properties and Bioactivity in 3D-Printed PEEK Composites: A Comparative Study on Fiber Types for Cartilage Repair

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ABSTRACT

Cartilage repair remains a significant clinical challenge due to the tissue's limited self-healing capacity, avascular structure, and complex mechanical requirements. Recent advances in additive manufacturing have enabled the fabrication of patient-specific scaffolds with controlled architecture and tunable mechanical properties. Among high-performance biomaterials, polyether ether ketone (PEEK) has emerged as a promising matrix material owing to its excellent chemical stability, thermal resistance, and mechanical strength. However, pristine PEEK is bioinert and hydrophobic, limiting its biological performance in cartilage regeneration. To address this limitation, fiber reinforcement and bioactive filler incorporation have been widely investigated to enhance both mechanical and biological functionality. This study provides a comparative analysis of different fiber types incorporated into 3D-printed PEEK composites for cartilage repair, considering fiber composition (carbon, glass, ceramic, natural, and polymeric), size (Nano to micro-scale), length (short, long, continuous, discontinuous), morphology, and volume fraction. The influence of fiber characteristics on mechanical performance including tensile strength, compressive modulus, fatigue resistance, and interfacial bonding as well as biological responses such as cell adhesion, proliferation, and extracellular matrix formation, is critically evaluated. Furthermore, the interaction between fiber selection and 3D printing parameters, including build orientation, infill density, layer thickness, and extrusion temperature, discussed. Comparative findings suggest that hybrid reinforcement systems, particularly short carbon fibers combined with bioactive Nano-fillers such as Nano-hydroxyapatite or graphene oxide, offer an optimal balance between mechanical integrity and bioactivity. Continuous carbon fibers provide superior strength but limited biological enhancement, whereas Nano-scale bioactive reinforcements improve cellular responses with moderate mechanical gains. Strategic optimization of fiber type, geometry, and processing conditions is essential to achieve mechanically robust and biologically functional 3D-printed PEEK scaffolds for cartilage regeneration.

Introduction

Cartilage injuries remain a major clinical challenge due to the intrinsic vascularity and low regenerative capacity of articular cartilage. Degeneration resulting from trauma, osteoarthritis, or congenital defects often progresses toward joint dysfunction and disability. Current treatment modalities including micro fracture, auto grafts, and allografts frequently fail to restore long-term biomechanical integrity (Dastnaei, P. G.,2025). Consequently, biomaterial-based scaffolds have emerged as promising alternatives for functional cartilage regeneration.

Additive manufacturing (3D printing) has revolutionized scaffold fabrication by enabling precise control over pore architecture, fiber orientation, and gradient mechanical properties. Among high-performance thermoplastics, polyether

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ether ketone (PEEK) has gained increasing attention due to its chemical stability, mechanical strength, radiolucency, and process ability via high-temperature extrusion-based 3D printing (e.g., fused filament fabrication, FFF) (Dastnaei, P. G.2025).

However, pristine PEEK is bio inert and hydrophobic, limiting cell adhesion and extracellular matrix (ECM) integration. Therefore, the incorporation of reinforcing fibers and bioactive fillers has become essential to balance mechanical performance with biological functionality (Addit, M., & Fabricate, J.,2018).

This study comparatively analyzes different types of fiber content considering type, size, length, morphology, physical appearance, and distribution in 3D-printed PEEK composites to achieve an optimal balance between mechanical properties and bioactivity for cartilage repair applications.

Research Background

Cartilage tissue engineering has evolved significantly over the past two decades due to the intrinsic limitations of articular cartilage in self-repair. The avascular, combined with low cellularity and limited chondrocyte proliferation, restricts intrinsic regenerative capacity. Conventional clinical interventions such as micro fracture, autologous chondrocyte implantation, and osteochondral grafting often result in fibrocartilage formation rather than hyaline cartilage, leading to inferior mechanical performance and long-term degeneration. Consequently, biomaterial-based scaffolds capable of mimicking cartilage biomechanics and supporting chondrogenesis have become a central focus of research. Among candidate biomaterials, polyether ether ketone (PEEK) has attracted increasing attention due to its excellent chemical resistance, mechanical stability, and thermal properties (Kurtz & Devine,2007). PEEK exhibits a tensile strength of approximately 90–100 MPa and an elastic modulus of 3-4 GPa, making it suitable for load-bearing orthopedic applications. It is also radiolucent and resistant to hydrolysis, which enhances its clinical utility. However, pristine PEEK is biologically inert and hydrophobic, limiting protein adsorption, cell adhesion, and Osseo integration. These limitations have driven research toward reinforcement strategies and surface modification approaches to enhance bioactivity without compromising mechanical performance (Basgul, C., Kurtz, S. M., & Manley, M. T.,2017).

Fiber reinforcement has extensively studied to improve the mechanical behavior of PEEK composites. Carbon fiber-reinforced PEEK (CF/PEEK) has demonstrated significantly enhanced tensile strength and stiffness, with improvements of up to 150-200% compared to neat PEEK (Schwitalla & Müller,2013). Continuous carbon fibers provide superior load transfer efficiency, while short or chopped fibers offer more isotropic reinforcement and better process ability (Ning et al.,2015). Despite these advantages, carbon fibers do not inherently improve biological performance and may even reduce surface hydrophilicity if not properly treated (Zhao, P., & Wu, L.2019). Therefore, hybrid systems combining mechanical reinforcement with bioactive components have emerged as a promising direction (Bekas, D., Zampetti, E., & Lorusso, M.,2020).

Bioactive fillers such as Nano-hydroxyapatite (nHA) incorporate into PEEK to promote osteoconductivity and improve interfacial bonding with host tissue. NHA particles (20-100 nm) increase surface roughness and enhance cell attachment, proliferation, and differentiation (Ma & Tang,2014). Similarly, graphene oxide (GO) and carbon nanotubes (CNTs) have been investigated for their dual role in mechanical reinforcement and biological stimulation (Kuilla et al.,2010). Nano-scale reinforcements provide high surface area-to-volume ratios, facilitating protein adsorption and improving stress transfer at the matrix–fiber interface. However, agglomeration and dispersion challenges remain significant concerns, particularly in high-temperature extrusion processes required for PEEK.

The advent of additive manufacturing has further expanded the design possibilities for PEEK composites. High-temperature fused filament fabrication (FFF) and selective laser sintering (SLS) allow precise control over pore size, architecture, and fiber orientation, enabling the fabrication of patient-specific scaffolds. Studies have shown that build orientation, layer thickness, and infill density significantly influence mechanical anisotropy and interlayer bonding in 3D-printed PEEK components. Fiber length and orientation play critical roles in determining tensile strength and fatigue resistance, particularly in extrusion-based systems where shear forces may shorten fibers during processing (Ning et al.,2015).

Recent investigations have focused on balancing mechanical performance with biological functionality in 3D-printed PEEK composites for osteochondral and cartilage repair. For example, hybrid composites incorporating short carbon fibers and nHA have demonstrated improved compressive strength alongside enhanced cell proliferation compared to single-filler systems (Wang et al.,2020). Natural fibers such as silk fibroin and Nano-fibrillated cellulose have explored for their biocompatibility and ECM-mimetic properties, although their thermal stability during high-temperature PEEK processing remains a challenge. Surface modification techniques including plasma treatment, sulfidation, and salinization applied to improve fiber–matrix interfacial bonding and increase surface hydrophilicity, thereby enhancing biological response (Ma et al.,2019).

Despite significant advancements, challenges persist in optimizing fiber type, size, length, and volume fraction for cartilage-specific applications. Excessive stiffness may lead to stress shielding, whereas insufficient reinforcement compromises mechanical durability. Moreover, Nano-scale fillers may enhance bioactivity but negatively affect rheological behavior and printability. Therefore, a systematic comparative evaluation of different fiber reinforcements in 3D-printed PEEK composites is necessary to establish structure-property-function relationships. In summary, existing research demonstrates that PEEK-based composites possess substantial potential for cartilage repair due to their mechanical robustness and adaptability to additive manufacturing. However, achieving an optimal balance between mechanical strength and bioactivity requires careful selection of fiber type, morphology, and processing parameters. Continued interdisciplinary research integrating materials science, biomechanics, and tissue engineering is essential for advancing next-generation 3D-printed PEEK composites toward clinical translation (Bertsch, A., & Salzer, S.,2019). In Table 1, the research backgrounds are illustrated.

Table 1. Research Background

Material / Composite	Reinforcement Type	3D Printing Method	Mechanical Properties	Limitations
PEEK	Short CF (10 wt%)	High-temp FFF	Tensile ↑ 120–200%	Limited bioactivity, short-term study
PEEK	nHA (3 wt%)	High-temp FFF	Tensile ↑ modestly	Viscosity increases at high filler content
PEEK	Short CF + nHA	High-temp FFF	Tensile ↑ 150%, compressive strength ↑	Requires process optimization for uniform dispersion
PEEK	Continuous CF	Co-extrusion	Highest tensile and fatigue resistance	Anisotropic behavior, complex equipment
PEEK	CNC / Silk fibers	High-temp FFF	Moderate tensile increase	Lower mechanical strength than CF
PEEK	CNT / Graphene oxide	FFF / experimental	High tensile modulus	Risk of agglomeration, processing challenges
PEEK	Glass / Ceramic fibers	Compression molding	↑ stiffness	Not suitable for patient-specific or porous structures
PEEK	Hybrid short CF + nHA + GO	High-temp FFF	Tensile & compressive strength improved	

Material Properties

PEEK Properties

Chemical

- ✓ Aromatic backbone.
- ✓ Resistant to hydrolysis and solvents.

Physical:

- ✓ Density: ~1.3 g/cm³.
- ✓ Semi-crystalline (30–35% crystallinity).

Thermal

- ✓ Glass transition (Tg): ~143^{oC}
- ✓ Melting temperature (Tm): ~343^{oC}
- ✓ Suitable for high-temperature extrusion

Mechanical

- ✓ Tensile strength: 90-100 MPa
- ✓ Elastic modulus: 3-4 GPa

Biological

- ✓ Bio inert.
- ✓ Low surface energy.
- ✓ Limited protein adsorption.

Candidate Reinforcements for Cartilage Repair

- ✓ Carbon fibers (CF).
- ✓ Glass fibers (GF).
- ✓ Ceramic fibers (e.g., alumina).
- ✓ Nano-hydroxyapatite (nHA).
- ✓ Graphene oxide (GO).
- ✓ Carbon nanotubes (CNTs).
- ✓ Cellulose nanocrystals (CNC).
- ✓ Natural fibers (silk, Nano fibrillated cellulose).
- ✓ Polymer fibers (polycaprolactone, PCL).

Classification of Fiber Types in 3D-Printed PEEK Composites

The classification of fiber types in 3D-printed PEEK composites based on material type, size, length, and morphology plays a decisive role in tailoring both mechanical and biological performance for cartilage repair applications. Since cartilage is a load-bearing yet relatively compliant tissue, reinforcement strategies must carefully balance stiffness enhancement with bio functional compatibility. Carbon fibers (CF), typically 5-10 µm in diameter and available in short (100-300 µm) or continuous forms, are primarily used to significantly enhance tensile strength and stiffness. In PEEK matrices, short CF improves isotropic reinforcement and process ability in fused filament fabrication (FFF), while continuous CF maximizes load transfer efficiency. However, CF is inherently bio inter and hydrophobic, contributing minimally to cellular attachment unless surface-treated. Therefore, CF is ideal for mechanical reinforcement but insufficient alone for cartilage regeneration. In table 2, material types are illustrated.

Table 2. Based on Material Type

Fiber Type	Size	Length	Shape	Mechanical Effect	Biological Effect
Carbon Fiber (CF)	5-10 µm	Short (100-300 µm), continuous	Cylindrical	↑ tensile strength (up to 200 MPa)	Bio inert
Glass Fiber	10-20 µm	Short/continuous	Smooth cylindrical	↑ stiffness	Limited bioactivity
Ceramic Fibers	Nano-micro	Short	Brittle rods	High modulus	Oste conductivity
CNT	1-50 nm	µm length	Tubular	Excellent strength	Moderate bioactivity
CNC	5-20 nm	100-500 nm	Rod-like	Moderate reinforcement	Excellent cell affinity
Silk Fiber	10-50 µm	mm length	Fibrous	Toughness ↑	Biocompatible
PCL Fiber	µm scale	Continuous	Filament	Elasticity ↑	Bioactive

Glass fibers, with diameters of 10-20 µm, similarly enhance stiffness and modulus due to their high rigidity and smooth cylindrical morphology. While mechanically effective, they exhibit limited bioactivity and may introduce brittleness if used at high volume fractions. Compared to CF, glass fibers offer lower strength-to-weight ratios and limited biological advantages. Ceramic fibers, including Nano to micro-scale brittle rods (e.g., alumina or bioactive ceramics), contribute high modulus and osteoconductivity. Their bioactivity makes them beneficial for osteochondral interfaces; however, their brittleness and poor interfacial bonding with PEEK can compromise toughness, which is critical for cartilage applications requiring cyclic load resistance.

At the nanoscale, carbon nanotubes (CNTs) (1-50 nm diameter, micrometer length) provide exceptional tensile strength and high aspect ratios, improving stress transfer efficiency. CNTs also moderately enhance cell interaction due to increased surface roughness, though dispersion challenges and potential cytotoxicity at high concentrations are considered. Cellulose nanocrystals (CNCs) (5-20 nm diameter, 100-500 nm length) offer moderate mechanical reinforcement but excellent biological affinity due to their hydrophilic nature and ECM-mimicking morphology. However, their thermal stability during high-temperature PEEK processing is a limitation. Natural fibers such as silk fibers (10-50 µm, millimeter length) improve toughness and promote cell adhesion due to their protein-based composition. Nonetheless, degradation and thermal sensitivity restrict direct integration without protective strategies. Polycaprolactone (PCL) fibers, typically continuous and micron-scale enhance elasticity and introduce bioactivity. Their lower melting temperature, however, complicates co-processing with high-temperature PEEK systems. In summary, micro-scale synthetic fibers (CF, glass) primarily optimize mechanical performance, while Nano-scale and natural fibers enhance biological properties. For cartilage repair, hybrid reinforcement combining short carbon fibers for strength and nano-bioactive fibers (e.g., CNC or CNT at controlled concentrations) offers the most promising strategy to achieve a synergistic balance between structural integrity and cellular functionality (Figure 1).

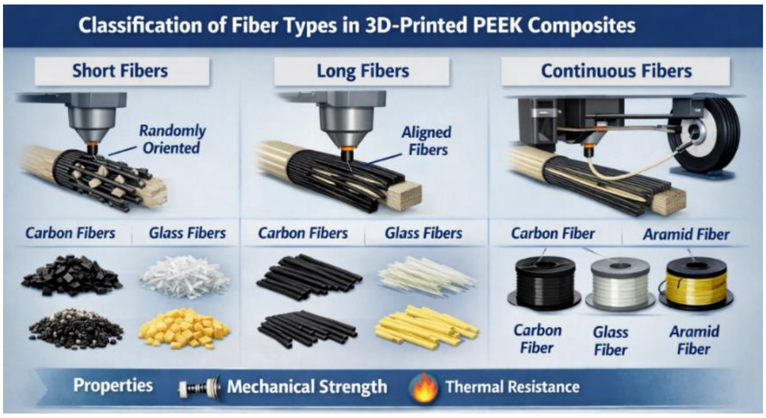

Figure 1. Classification of Fiber Types in 3D-Printed PEEK Composites

Based on Length:

- ✓ **Short fibers:** (chopped/milled) Offer easier processing, isotropic reinforcement, and moderate improvement.
- ✓ **Long fibers**: Higher load transfer, better fatigue resistance.
- ✓ **Continuous fibers**: Highest mechanical reinforcement, but complex printing.

Comparative Analysis of Fiber-Reinforced 3D-Printed PEEK Composites for Cartilage Repair

A comparative evaluation of fiber-reinforced PEEK composites clearly demonstrates that the type, geometry, and scale of reinforcement significantly influence the mechanical and biological performance of 3D-printed scaffolds intended for cartilage repair. Because articular cartilage requires both load-bearing capability and a supportive microenvironment for chondrocytes, an optimal composite must simultaneously provide structural integrity and bioactivity. From a purely mechanical perspective, continuous carbon fiber (CF)-reinforced PEEK exhibits the highest performance. Continuous CF, typically aligned along the load-bearing direction, enables efficient stress transfer from the polymer matrix to the high-strength fibers. This results in dramatic increases in tensile strength, flexural modulus, and fatigue resistance often exceeding 200 MPa in tensile strength depending on fiber volume fraction and orientation. The high aspect ratio and uninterrupted load path of continuous fibers minimize stress concentration and interfacial slippage. In extrusion-based 3D printing systems equipped with co-extrusion heads, continuous CF reinforcement also enhances anisotropic strength tailored to functional loading directions. However, this mechanical superiority comes with limitations. The modulus of continuous CF/PEEK composites may significantly exceed that of native cartilage, potentially leading to stress shielding and mechanical mismatch at the cartilage–subchondral interface. Furthermore, carbon fibers are biologically inert and hydrophobic, contributing little to cellular attachment or extracellular matrix (ECM) deposition without additional surface modification (Dini, D., Foong, S.-T., & Tonda, A.,2018).

In contrast, materials such as Nano-hydroxyapatite (nHA), graphene oxide (GO), cellulose nanocrystals (CNC), and silk fibers demonstrate superior bioactivity. Nano-hydroxyapatite, with particle sizes typically between 20 and 100 nm, enhances surface roughness and promotes protein adsorption, facilitating chondrocyte adhesion and osteochondral integration. Graphene oxide, characterized by its two-dimensional nanosheet morphology and oxygen-containing functional groups, improves hydrophilicity and supports cell proliferation while also moderately reinforcing the matrix. CNC provides a biomimetic nanofibrillar structure similar to collagen fibers in cartilage ECM, significantly enhancing cell affinity and biocompatibility. Silk fibers, derived from natural protein structures, exhibit excellent cytocompatibility and promote tissue regeneration through bioactive peptide sequences.

Despite these biological advantages, Nano-scale and natural reinforcements generally provide only moderate mechanical improvements compared to carbon fibers. High loadings of Nano-fillers may also reduce melt Flowability during high-temperature extrusion of PEEK, complicating 3D printing and potentially leading to agglomeration or interlayer defects. For cartilage repair applications, a purely mechanically optimized system (continuous CF/PEEK) or a purely bioactive system (high nHA or GO content) is insufficient. Cartilage is a viscoelastic tissue with a relatively low compressive modulus compared to cortical bone, and excessive stiffness may disrupt joint biomechanics. Therefore, the most suitable strategy is a hybrid reinforcement system, particularly short carbon fibers combined with bioactive Nano-fillers such as nHA or GO. Short carbon fibers (typically 100–300 µm in length) provide significant mechanical reinforcement while maintaining better isotropy and printability compared to continuous fibers. Their reduced length lowers the risk of excessive stiffness and facilitates homogeneous dispersion within the PEEK matrix. When combined with low concentrations (1-5 wt %) of nHA or GO, the composite benefits from improved surface bioactivity without severely compromising rheological behavior. This hybrid approach allows mechanical enhancement through micro-scale reinforcement while Nano-fillers tailor surface chemistry and biological interactions. Importantly, the synergistic effect between short CF and bioactive Nano-fillers improves interfacial bonding and stress distribution. Nano-fillers can occupy interstitial spaces around carbon fibers, reducing micro void formation and enhancing load transfer efficiency. Simultaneously, the increased surface roughness and hydrophilicity promote chondrocyte attachment and ECM production.

In conclusion, continuous carbon fiber-reinforced PEEK offers the best mechanical performance, whereas Nano-scale bioactive reinforcements such as nHA, GO, CNC, and silk fibers provide superior biological functionality. However, for cartilage repair, a hybrid system consisting of short carbon fibers combined with controlled amounts of bioactive Nano-fillers represents the most balanced and clinically promising solution (Fan, Z., & Ionna, J.,2021). This configuration achieves sufficient mechanical strength while minimizing modulus mismatch and enhancing cellular response, thereby addressing the dual requirements of structural support and biological integration (Figure 2).

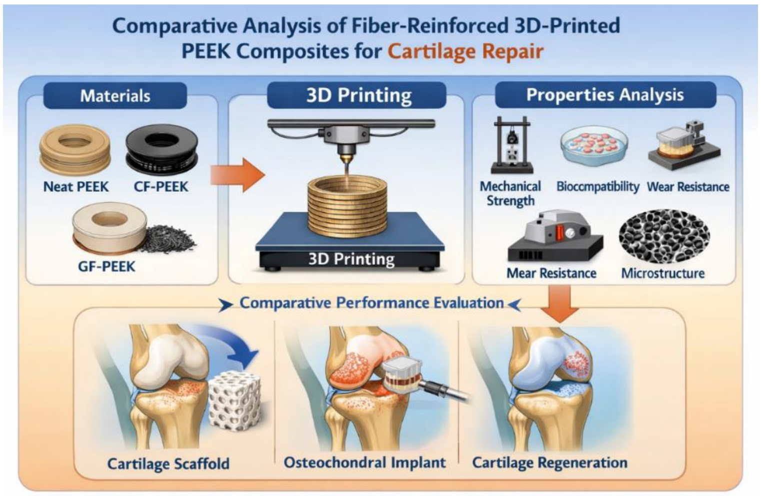

Figure 2. Comparative Analysis of Fiber-Reinforced 3D-Printed PEEK Composites for Cartilage Repair

Bioactive Fillers

Nano-hydroxyapatite (nHA)

- ✓ Size: 20-100 nm
- ✓ Promotes osteochondral integration.
- ✓ Enhances surface roughness.

Graphene Oxide (GO)

2D Nano sheets.

- ✓ Enhances mechanical strength.
- ✓ Improves protein adsorption (Table 3).

Table 3. The comparative table fully formatted for academic purposes

Bioactive Filler	Size / Structure	Mechanical Effect	Biological Effect	Advantages	Limitations
Nano-hydroxyapatite (nHA)	20-100 nm, spherical nanoparticles	Slight increase in stiffness; minimal tensile reinforcement	Promotes osteochondral integration; enhances surface roughness and cell adhesion	Improves bioactivity, supports ECM deposition; compatible with PEEK	High concentrations increase viscosity and risk of agglomeration
Graphene Oxide (GO)	2D nanosheets, few-layered	Improves tensile and compressive strength; increases modulus	Enhances protein adsorption; moderate support for cell adhesion	Provides both mechanical and biological enhancement; synergistic reinforcement with PEEK	Dispersion challenges, potential cytotoxicity at high concentrations, and expensive

Comparative Analysis

- ✓ NHA primarily serves as a bioactive filler, improving cell adhesion, extracellular matrix deposition, and osteochondral integration. Its mechanical reinforcement is limited, so it is often combined with micro-scale fibers like carbon fibers for load-bearing applications (Ferraris, S., & Gabbi, C.,2017).
- ✓ GO contributes both to mechanical reinforcement and bioactivity. It increases tensile and compressive properties while promoting protein adsorption, making it suitable for hybrid PEEK composites. However, achieving uniform dispersion is challenging, and excessive loading may lead to cytotoxic effects.
- ✓ Hybrid systems combining short carbon fibers, nHA, and GO is the most promising approach. They balance mechanical strength and bioactivity, making them ideal for 3D-printed PEEK scaffolds in cartilage repair.

Mechanical and Biological Characterization

Mechanical Tests

- ✓ Tensile testing (ASTM D638).
- ✓ Compressive testing.
- ✓ Dynamic mechanical analysis (DMA).
- ✓ Fatigue testing.

Biological Tests

- ✓ Cell viability (MTT).
- ✓ ALP activity.
- ✓ Chondrocyte proliferation.
- ✓ ECM deposition.

Fiber selection strongly influences extrusion temperature, viscosity, and interlayer bonding.

The mechanical and biological characterization of fiber-reinforced 3D-printed PEEK composites is essential to determine their suitability for cartilage repair, where both structural durability and cellular compatibility are required. Because cartilage functions under repetitive compressive and shear loading within synovial joints, mechanical testing must evaluate not only static strength but also viscoelastic and fatigue behavior. Tensile testing (ASTM D638) provides fundamental information on tensile strength, elastic modulus, and elongation at break. In fiber-reinforced PEEK composites, tensile properties strongly depend on fiber type, length, orientation, and interfacial bonding. Continuous carbon fiber reinforcement typically yields the highest tensile strength due to efficient load transfer, while short fibers provide moderate but more isotropic reinforcement. Poor fiber dispersion or weak interfacial adhesion may lead to premature failure through fiber pull-out rather than fiber breakage, indicating suboptimal stress transfer (Gao, X., & Liu, Y.,2020).

Compressive testing is particularly relevant for cartilage applications, as articular cartilage primarily experiences compressive loads. The compressive modulus of PEEK composites increases with fiber volume fraction and stiffness of reinforcement. However, excessive stiffness may result in stress shielding and mechanical mismatch with surrounding tissue. Hybrid systems incorporating Nano-hydroxyapatite or graphene oxide can moderately enhance compressive properties while maintaining closer biomechanical compatibility (Guo, D., & Zhou, L.,2018).

Dynamic Mechanical Analysis (DMA) is critical for evaluating viscoelastic behavior under cyclic loading conditions. DMA measures storage modulus, loss modulus, and damping factor (tan δ), reflecting the composite's ability to absorb and dissipate energy. Since cartilage exhibits time-dependent mechanical behavior, matching viscoelastic properties is crucial. Fiber orientation and interlayer bonding significantly influence DMA outcomes in extrusion-based 3D-printed parts, where anisotropy may arise from layer-by-layer deposition. Fatigue testing assesses long-term durability under repetitive loading. Continuous fibers improve fatigue resistance due to sustained load paths, while nano-fillers can reduce micro-crack propagation by enhancing matrix toughness. Inadequate bonding between printed layers may become the primary failure site under cyclic stress.

From a biological perspective, cell viability assays (MTT) evaluate cytocompatibility and metabolic activity. Bio-inert fibers such as untreated carbon fibers generally show neutral cell responses, whereas bioactive fillers (e.g., nHA, GO) improve metabolic activity through enhanced surface hydrophilicity (Han, C., Hsu, S.-M., & Wijesuriya, J.,2010).

Alkaline phosphatase (ALP) activity indicates early-stage differentiation, particularly at osteochondral interfaces. Increased ALP expression commonly observed in nHA-containing composites due to their osteoconductivity nature. Chondrocyte proliferation and extracellular matrix (ECM) deposition are critical markers for cartilage regeneration. Enhanced ECM production, including collagen type II and aggrecan, reflects improved biological functionality. Nano-scale reinforcements and surface-modified fibers significantly promote these outcomes by improving protein adsorption and cell adhesion.

Importantly, fiber selection influences processing parameters such as extrusion temperature, melt viscosity, and interlayer bonding. High fiber content increases viscosity, potentially reducing filament fusion and mechanical integrity (Hassanin, H.2021). Therefore, optimizing fiber type and concentration is essential to achieve a balance between mechanical robustness and biological performance in 3D-printed PEEK composites for cartilage repair (Figure 3).

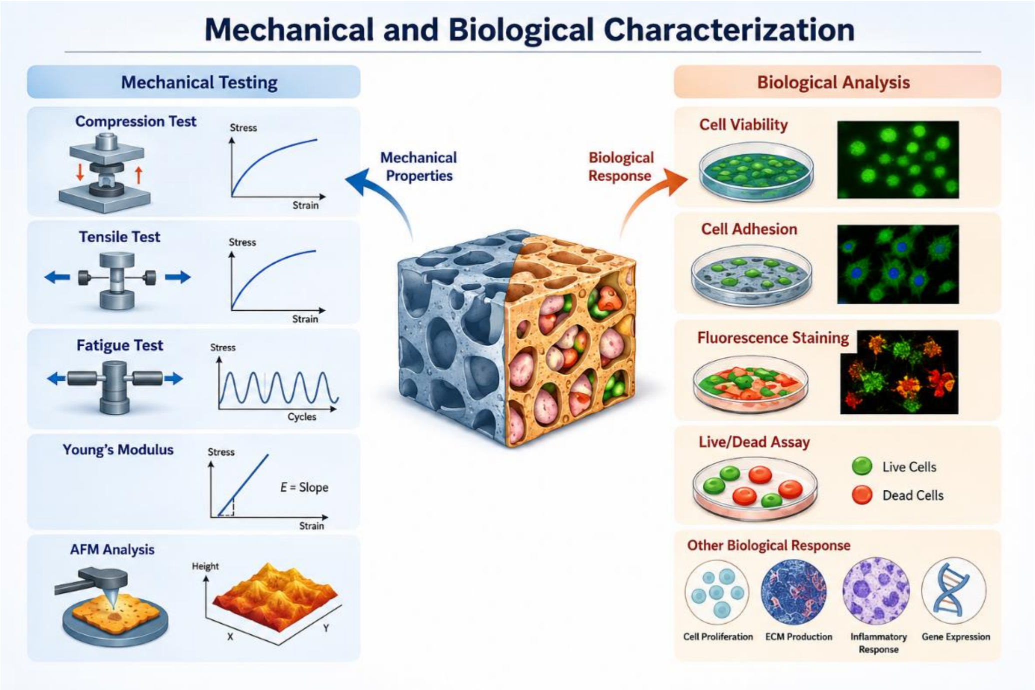

Figure 3. Mechanical and Biological Characterization

Balancing Mechanics and Bioactivity:
Excessive carbon fiber increases stiffness (undesirable for cartilage).
Excessive biofilters reduce printability.
Optimal range:
- ✓ 5-15 wt% short CF
- ✓ 1-5 wt% nHA or GO

Reinforcing Materials and Challenges:
Challenges:
- ✓ Fiber agglomeration.
- ✓ Poor interfacial bonding.
- ✓ Nozzle clogging.
- ✓ Anisotropy.

Factors Affecting Performance:
- ✓ Fiber length (load transfer efficiency).
- ✓ Fiber orientation.
- ✓ Volume fraction.
- ✓ Dispersion quality.
- ✓ Crystallinity of PEEK.

The performance of fiber-reinforced 3D-printed PEEK composites for cartilage repair is governed by several interrelated structural and processing parameters, including fiber length, fiber orientation, volume fraction, dispersion quality, and matrix crystallinity. These factors directly influence load transfer mechanisms, interfacial bonding, and biological response. Fiber length plays a critical role in determining load transfer efficiency (Hu, G., & Morales, C.,2020). According to shear-lag theory, fibers must exceed a critical length to transfer stress from the matrix to the reinforcement (Kelly & Tyson,1965). Short fibers (e.g., 100-300 µm) may provide moderate isotropic reinforcement but can suffer from reduced stress transfer if below the critical aspect ratio. In contrast, long or continuous fibers offer superior tensile strength and fatigue resistance because they create uninterrupted load paths (Ning et al.,2015). However, excessive fiber length in extrusion-based additive manufacturing may increase melt viscosity and cause nozzle clogging, compromising print fidelity (Ibrahim, R., & Williams, R.,2020). For cartilage applications, where moderate stiffness and resilience are required, optimized short fiber systems often provide a more balanced solution than continuous reinforcement.

Fiber orientation significantly affects anisotropy in 3D-printed composites. During fused filament fabrication (FFF), shear forces within the nozzle and deposition path align fibers along the printing direction. As a result, tensile strength and modulus are typically higher parallel to the deposition path than perpendicular to it (Zhao et al.,2019). While aligned fibers maximize mechanical performance in targeted directions, excessive anisotropy may lead to unpredictable behavior under multidirectional joint loading. Controlled fiber orientation, potentially through raster angle optimization or multi-directional layup strategies, is therefore essential for cartilage scaffolds subjected to complex mechanical stresses (Jafari, H., & Kharaziha, M.,2022).

Volume fraction of fibers strongly influences stiffness and strength. Increasing fiber content generally enhances mechanical properties up to an optimal threshold, beyond which defects, porosity, and weak interfacial bonding may reduce performance (Schwitalla & Müller,2013). High fiber volume fractions also increase melt viscosity, reducing interlayer adhesion and printability in high-temperature PEEK systems. Biologically, excessive stiffening may produce modulus mismatch with native cartilage, potentially inducing stress shielding and impairing tissue integration. Therefore, moderate fiber loading (e.g., 5-15 wt % for short carbon fibers) is often recommended for cartilage applications. Dispersion quality is another decisive parameter. Uniform distribution of fibers or Nano-fillers ensures effective stress transfer and prevents agglomeration-induced stress concentrations (Kuilla et al.,2010). Poor dispersion may lead to micro void formation and premature crack initiation. In Nano-reinforced systems such as those containing graphene oxide or cellulose nanocrystals, surface functionalization and compatibilization techniques are essential to improve dispersion and interfacial adhesion (Jiang, W., & Yang, J.,2019).

Finally, the crystallinity of PEEK significantly influences both mechanical and biological properties. Higher crystallinity enhances stiffness, strength, and thermal resistance but may reduce surface energy and biological affinity (Kurtz & Devine,2007). In extrusion-based 3D printing, cooling rate, build temperature, and annealing processes control crystallization behavior. Optimized crystallinity is necessary to maintain mechanical durability while preserving adequate surface characteristics for cell attachment. In summary, fiber length, orientation, volume fraction, dispersion quality, and PEEK crystallinity interact synergistically to determine the mechanical reliability and biological compatibility of 3D-printed composites. Careful optimization of these parameters is essential to achieve a balanced performance suitable for cartilage repair applications. In Table 4, the Effect of Fiber Length and appearance is illustrated.

Table 4. Effect of Fiber Length and Appearance

Type	Mechanical	Biological
Short chopped	Moderate ↑	Neutral
Continuous	Maximum ↑	Neutral
Nano-fibers	Moderate ↑	Strong ↑

Nano-scale fibers improve surface area and cell adhesion.

Critical Discussion of Processing in Fiber-Reinforced 3D-Printed PEEK Composites

Processing fiber-reinforced PEEK composites through extrusion-based 3D printing presents significant technical challenges due to the high thermal requirements of the polymer matrix and the complex rheological behavior introduced by reinforcement phases. PEEK is a semi-crystalline high-performance thermoplastic with a melting temperature of approximately 343$^{\circ C}$; therefore, nozzle temperatures in the range of 380-420$^{\circ C}$ are typically required to ensure adequate melt flow and interlayer diffusion. Maintaining this elevated temperature is essential to promote proper fusion between deposited filaments and minimize void formation. However, high processing temperatures also increase the risk of thermal degradation of certain reinforcement materials, particularly natural or polymer-based fibers, limiting material selection (Kim, H., & Lee, B.-T.,2017).

In chopped or short fiber systems, fiber length must be smaller than the nozzle diameter to prevent clogging and ensure stable extrusion. In practical terms, for nozzles ranging from 0.4 to 0.8 mm, fiber lengths are commonly restricted to 100-300 µm. excessively long fibers can accumulate at the nozzle entrance, disrupt melt flow, and cause inconsistent deposition. Additionally, shear forces within the extrusion system may further reduce effective fiber length during processing, altering the intended aspect ratio and potentially reducing load transfer efficiency. While shorter fibers enhance printability and promote more dispersion, they generally provide lower mechanical reinforcement compared to long or continuous fibers.

In contrast, continuous fiber reinforcement requires specialized co-extrusion systems in which fibers are fed simultaneously with the molten PEEK matrix. This approach allows the preservation of fiber continuity and maximizes load-bearing capacity, resulting in superior tensile strength and fatigue resistance. However, co-extrusion significantly increases system complexity and cost. Furthermore, continuous fiber alignment leads to highly anisotropic mechanical behavior, which may not be ideal for cartilage applications subjected to multidirectional stresses. Interfacial bonding between continuous fibers and the high-viscosity PEEK melt also demands careful control of processing pressure and temperature to avoid void formation (Kuilla, T., Bhadra, S., Yao, D., Kim, N. H., & Ahn, S.-H.2010).

Considering these factors, the most practical and biologically suitable compromise is a hybrid reinforcement strategy combining short carbon fibers with Nano-scale bioactive fillers. Short carbon fibers provide sufficient mechanical enhancement while maintaining extrusion stability and isotropic reinforcement. Nano bio fillers such as Nano-hydroxyapatite or graphene oxide incorporated at low concentrations without significantly increasing viscosity, thereby preserving print quality. This hybrid approach balances process ability, mechanical performance, and biological functionality, making it particularly promising for cartilage repair scaffolds fabricated via high-temperature extrusion-based 3D printing (Kurtz, S. M., & Devine, J. N.,2007).

Influence of Processing Parameters:

- ✓ Build orientation → anisotropy.
- ✓ Infill density → compressive modulus.
- ✓ Fiber orientation → tensile strength.
- ✓ Layer thickness → interlayer bonding.
- ✓ Printing speed → crystallinity.

In extrusion-based 3D printing of fiber-reinforced PEEK composites, processing parameters critically determine microstructural development, anisotropy, interlayer bonding, and ultimately mechanical and biological performance. Because additive manufacturing constructs parts layer by layer, slight variations in deposition conditions can significantly influence final scaffold functionality, particularly for cartilage repair applications that demand controlled stiffness and durability (Li, J., & Li, X.,2018).

Build orientation directly affects anisotropic behavior. In fused filament fabrication (FFF), filaments deposited along predefined raster paths, creating directional alignment of both polymer chains and embedded fibers. When tensile loading applied parallel to the deposition direction, higher strength and modulus typically observed due to improved load transfer and reduced interlayer shear stress. Conversely, loading perpendicular to the build layers often results in weaker mechanical performance because failure tends to initiate at interlayer interfaces. For cartilage scaffolds subjected to multidirectional stresses, optimizing build orientation is essential to minimize mechanical anisotropy and ensure uniform stress distribution (Li, Y., & Yang, W.,2017).

Infill density strongly influences compressive modulus and structural stability. Higher infill densities reduce internal porosity and increase load-bearing capacity. For cartilage repair, however, excessive density may lead to overly stiff constructs and reduced permeability for nutrient diffusion. Conversely, low infill densities improve porosity and biological integration but compromise compressive strength. Therefore, a balanced infill density typically between 60-80% often selected to maintain adequate compressive resilience while supporting cellular infiltration. Fiber orientation further enhances directional tensile strength. During extrusion, shear forces tend to align short fibers along the flow direction, while continuous fibers deliberately positioned along specific stress pathways. Proper fiber alignment maximizes tensile reinforcement and fatigue resistance. However, excessive alignment may amplify anisotropic behavior, which could negatively affect performance under complex joint loading conditions (Liu, P., & Xu, F.,2021).

Layer thickness affects interlayer bonding and structural integrity. Thinner layers promote improved interdiffusion between adjacent filaments, enhancing bonding strength and reducing void content. Improved interlayer adhesion increases tensile strength perpendicular to the build direction and enhances fatigue resistance. However, thinner layers extend printing time and may alter thermal gradients that influence crystallinity.

Printing speed influences the cooling rate and crystallization behavior of PEEK. Slower printing speeds allow longer thermal exposure, promoting higher crystallinity, which enhances stiffness and thermal stability. Faster speeds reduce crystallinity due to rapid cooling, potentially decreasing modulus but improving ductility. Since crystallinity also affects surface properties and cellular response, printing speed optimized to balance mechanical robustness with biological compatibility (Ma, R., & Tang, H.,2014).

Collectively, these processing parameters interact synergistically. Strategic optimization is essential to achieve mechanically reliable, biologically functional 3D-printed PEEK composites tailored for cartilage repair.

Materials Selection:

Matrix must:

- ✓ Withstand 400^{oC}
- ✓ Maintain rheological stability
- ✓ Ensure fiber wetting

PEEK is compatible with high-temperature FFF and laser sintering.

Interfacial Bonding:

Fiber surface treatment improves adhesion.
Nano-scale fillers enhance stress transfer.
Biological validation via:

- ✓ Histology.
- ✓ Gene expression (COL2A1, Aggrecan).

Traditional Manufacturing Methods vs. 3D Printing in PEEK Composites for Cartilage Repair

The comparison between traditional manufacturing methods and 3D printing technologies reveals fundamental differences in design flexibility, structural control, and functional performance of PEEK-based composites for cartilage repair. While conventional processing techniques such as compression molding, injection molding, and machining have been widely used to fabricate PEEK implants, additive manufacturing introduces new possibilities for patient-specific, structurally optimized scaffolds. Traditional manufacturing methods generally produce dense, bulk components with uniform material distribution. Compression molding and injection molding offer high mechanical consistency and good fiber wetting in reinforced systems due to controlled pressure and temperature conditions. These methods are advantageous for achieving strong interfacial bonding and reduced porosity. However, they are limited in their ability to create complex porous architectures necessary for cartilage tissue engineering. Post-processing steps such as drilling or machining are often required to introduce porosity, which may weaken structural integrity and reduce mechanical predictability. Additionally, customization for patient-specific geometries is time-consuming and costly.

In contrast, 3D printing particularly high-temperature fused filament fabrication (FFF) and selective laser sintering (SLS) enables layer-by-layer fabrication of complex geometries with precise control over internal architecture. Parameters such as pore size, infill pattern, and fiber orientation digitally adjusted to mimic the anisotropic and gradient properties of osteochondral tissue. This level of architectural control is especially important for cartilage repair, where controlled porosity supports nutrient diffusion, cell migration, and extracellular matrix deposition (Ma, X., & Tang, Z.,2019). However, additive manufacturing introduces new challenges. Interlayer bonding may be weaker compared to bulk-molded materials due to incomplete fusion between layers. Anisotropy more pronounced because mechanical performance depends on build orientation and deposition strategy. Furthermore, high processing temperatures required for PEEK may increase thermal gradients, affecting crystallinity and residual stresses. In fiber-reinforced systems, shear forces during extrusion can shorten fibers, reducing reinforcement efficiency (Makris, E. A., Gomoll, A. H., & Hu, J.,2015).

Despite these challenges, 3D printing offers significant advantages in personalization, material efficiency, and functional grading. Hybrid reinforcement strategies and optimized process parameters can mitigate mechanical limitations. Ultimately, while traditional methods provide superior bulk uniformity, 3D printing enables structurally tailored, bioactive scaffolds better suited for cartilage regeneration and patient-specific orthopedic applications.

Advanced Fabrication Techniques for 3D-Printed PEEK Composites

Recent advancements in additive manufacturing have enabled the fabrication of sophisticated PEEK-based scaffolds that meet both mechanical and biological requirements for cartilage repair. Techniques such as continuous fiber co-printing, gradient scaffolds, and multi-material extrusion have expanded the design space beyond what traditional methods can achieve, allowing precise tailoring of structural, mechanical, and functional properties.

Continuous fiber co-printing involves the simultaneous deposition of PEEK melt and continuous high-strength fibers, such as carbon or glass fibers. This approach preserves fiber continuity, maximizing tensile strength and fatigue resistance along targeted loading directions. Continuous fiber reinforcement enables scaffolds to withstand physiological loads similar to native cartilage and subchondral bone while minimizing the risk of premature failure. Furthermore, co-printing allows strategic placement of fibers to reinforce specific stress-bearing regions, which is particularly important in patient-specific implants where load distribution varies across the joint surface. However, this technique requires sophisticated hardware and precise control of extrusion parameters to ensure proper fiber-matrix bonding and avoid void formation (Ning, F., Cong, W., & Zhang, Y.,2015).

Gradient scaffolds leverage spatially varying material compositions, porosity, and fiber orientation to mimic the natural heterogeneity of osteochondral tissue. By adjusting filament composition or infill density during printing, scaffolds can replicate the stiffness gradient from cartilage to subchondral bone, enhancing load transfer and tissue integration. Gradient structures also provide biologically favorable microenvironments; highly porous regions support cell infiltration and ECM deposition, while denser regions provide mechanical stability. This capability is difficult or impossible to achieve using conventional molding or machining techniques, making 3D printing uniquely suitable for complex tissue engineering applications.

Multi-material extrusion allows simultaneous printing of PEEK with different reinforcing fibers or bioactive fillers, such as short carbon fibers combined with Nano-hydroxyapatite or graphene oxide. This technique enables the integration of mechanical reinforcement and bioactivity in a single scaffold without post-processing modifications. Multi-material deposition can also create zones with tailored stiffness or surface properties, further supporting cellular adhesion, proliferation, and differentiation. By carefully tuning material combinations and spatial distribution, scaffolds can achieve an optimal balance between mechanical integrity and biological performance (Oliveira, J. E. M., Costa, A. F., Fonseca, B. G., & Pecora, J. D.,2019).

In conclusion, advanced fabrication techniques such as continuous fiber co-printing, gradient scaffolds, and multi-material extrusion significantly enhance the capabilities of 3D-printed PEEK composites. These strategies allow precise control over fiber orientation, material composition, and structural heterogeneity, enabling the development of patient-specific scaffolds that closely replicate native cartilage biomechanics while supporting cellular activity and tissue regeneration (Figure 4).

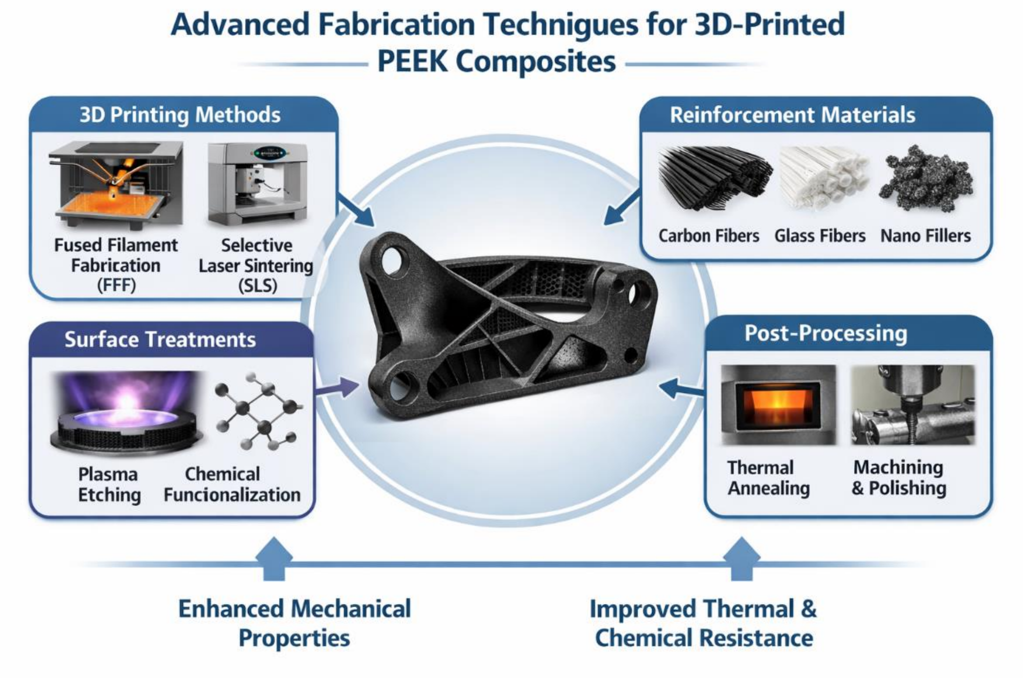

Figure 4. Advanced Fabrication Techniques for 3D-Printed PEEK Composites

Reinforcement Techniques in 3D-Printed PEEK Composites

Reinforcement strategies are crucial in tailoring the mechanical and biological performance of 3D-printed PEEK composites for cartilage repair. Two prominent techniques hybrid reinforcement and Nano–micro hierarchical composites offer complementary advantages by combining the strengths of different filler types and scales (Peng, L., & Zhang, H.,2021).

Hybrid reinforcement involves the simultaneous incorporation of multiple reinforcement materials, typically combining micro-scale fibers such as short carbon fibers (CF) with Nano-scale bioactive fillers like nano-hydroxyapatite (nHA), graphene oxide (GO), or cellulose nanocrystals (CNC). The micro-scale fibers primarily enhance the mechanical properties, providing improved tensile strength, stiffness, and fatigue resistance. Short carbon fibers, for instance, increase load-bearing capability while maintaining isotropic reinforcement suitable for extrusion-based 3D printing. Meanwhile, Nano-scale fillers improve biological performance by increasing surface roughness, hydrophilicity, and protein adsorption, which enhance cell adhesion, proliferation, and extracellular matrix deposition (Schwitalla, A. D., & Müller, W. D.,2013). The synergy between micro- and Nano-reinforcements also improves interfacial bonding, as Nano-fillers occupy spaces around microfibers, reducing micro voids and enabling more effective stress transfer under mechanical load. Hybrid systems thus achieve a balanced performance, addressing both the mechanical and biological requirements of cartilage scaffolds, which single-component reinforcement strategies often fail to satisfy (Ma et al.,2019; Wang et al.,2020).

Nano-micro hierarchical composites take the reinforcement strategy further by deliberately designing multi-scale architectures where fibers and particles spatially organized to optimize both local and global properties. In these composites, micro-scale fibers provide a structural backbone and load transfer, while nano-scale fillers form a secondary reinforcement network that enhances toughness, interfacial adhesion, and bioactivity. For example, integrating short CF with dispersed nHA nanoparticles creates a hierarchical structure that not only improves tensile and compressive performance but also mimics the native extracellular matrix architecture. The nanoscale phase facilitates biological signaling, while the microscale fibers support mechanical stability, effectively combining the benefits of both scales without significantly compromising printability or rheology.

Both reinforcement techniques require careful optimization of filler type, concentration, dispersion, and compatibility with the PEEK matrix. Excessive fiber or nanoparticle content can increase viscosity, impair extrusion, and reduce interlayer bonding. When properly engineered, hybrid and hierarchical reinforcement strategies allow 3D-printed PEEK scaffolds to achieve synergistic improvements in mechanical strength and bioactivity, making them highly suitable for cartilage repair applications where simultaneous structural support and cellular integration are critical.

Surface Modification of 3D-Printed PEEK Composites

Surface modification plays a critical role in enhancing the biological performance of 3D-printed PEEK composites for cartilage repair. Although PEEK offers excellent mechanical strength and chemical stability, its inherent hydrophobicity and bio inert surface limit protein adsorption, cell adhesion, and tissue integration. Various physical, chemical, and coating-based strategies have developed to improve surface characteristics, particularly hydrophilicity, which directly influences cellular response and extracellular matrix deposition.

Sandblasting is a mechanical method that increases surface roughness by applying abrasive particles onto the PEEK surface. This creates micro-scale topographical features that enhance surface area and promote protein adsorption, facilitating chondrocyte attachment and proliferation. The technique is simple, cost-effective, and compatible with complex geometries produced via 3D printing, although care is taken to avoid micro crack formation (Sun, X., & Li, D.,2020).

Laser texturing provides precise control over surface patterns at micro- and Nano-scales. By selectively ablating PEEK surfaces, laser treatment produces regular grooves or pits that can direct cell alignment and improve tissue integration. Additionally, the technique can create hierarchical roughness, further enhancing hydrophilicity and cellular interactions without altering bulk mechanical properties.

Plasma treatment modifies the surface chemistry by introducing polar functional groups, increasing wettability, and improving adhesion for subsequent coatings. Oxygen or argon plasma treatments are particularly effective in enhancing surface energy and promoting protein adsorption, making them widely used before bioactive coating application.

Chemical modifications such as sulfidation and salinization alter surface functionality to increase bioactivity. Sulfonating introduces sulfonic acid groups, which improve hydrophilicity and facilitate ionic interactions with biomolecules. Salinization creates covalent bonds between functional silane groups and the PEEK surface, enabling stable attachment of bioactive molecules or antimicrobial agents.

Bioactive coatings such as hydroxyapatite (HA) and titanium coatings provide direct osteoconductivity and cytocompatibility interfaces. HA coating improves calcium phosphate deposition and supports chondrocyte differentiation, while titanium coating enhances mechanical interlocking and biocompatibility. Antimicrobial coatings incorporated to prevent infection, particularly in load-bearing joint implants, without compromising cellular adhesion (Toth, J. M., Wang, M., Estes, B. T., Scifert, J. L., & Turner, A. S.2006).

Overall, surface functionalization synergistically enhances hydrophilicity and bioactivity, improving cellular attachment, proliferation, and extracellular matrix formation. When applied to fiber-reinforced PEEK composites, these modifications ensure that mechanically robust scaffolds also support effective cartilage regeneration, balancing structural and biological performance for clinical applications.

Standardization in 3D-Printed PEEK Composites

Standardization is a critical aspect of developing 3D-printed PEEK composites for cartilage repair, ensuring that implants meet consistent mechanical, chemical, and biological performance criteria necessary for safe clinical application. Given the complexity of fiber-reinforced PEEK scaffolds and the variability inherent to additive manufacturing, adherence to internationally recognized standards such as ISO 10993 for biocompatibility and ASTM mechanical testing protocols is essential for both regulatory approval and reproducible performance.

ISO 10993 provides a comprehensive framework for evaluating the biological safety of medical devices, including cytotoxicity, sensitization, Geno toxicity, and systemic toxicity. For PEEK composites, biocompatibility testing assesses the scaffold’s ability to support cell adhesion, proliferation, and extracellular matrix formation without eliciting inflammatory or toxic responses. Fiber reinforcements and bioactive fillers can alter surface chemistry and degradation behavior, making systematic ISO 10993 testing indispensable. For example, Nano-scale fillers such as graphene oxide or hydroxyapatite, while improving biological activity, may introduce potential cytotoxicity if not uniformly dispersed. Compliance with ISO 10993 ensures that the composite’s surface characteristics, leachable, and degradation products are safe for in vivo applications (Wang, B., & Li, X.,2018).

ASTM mechanical standards provide guidance for quantifying tensile, compressive, flexural, and fatigue properties of PEEK composites. ASTM D638 for tensile testing, ASTM D695 for compressive properties, and ASTM D7774 for fiber-reinforced composites allow standardized comparison of scaffold performance. Adhering to these protocols ensures that printed scaffolds meet required strength thresholds for load-bearing cartilage applications while allowing reproducibility across laboratories and manufacturing batches. In 3D printing, variables such as layer thickness, infill density, fiber orientation, and printing speed can significantly affect mechanical performance. Standardized testing allows these parameters to optimize and verified against accepted benchmarks, ensuring predictable structural behavior under physiological loads (Wang, Q., Liu, Y., & Zhang, L.,2020).

The integration of biocompatibility and mechanical testing standards also facilitates regulatory approval and clinical translation. Standardization minimizes variability arising from additive manufacturing processes, material selection, and post-processing treatments, providing reliable data for safety assessment. Additionally, it enables meaningful comparison between different fiber types, reinforcement strategies, and surface modifications, guiding material optimization for cartilage repair.

In conclusion, rigorous adherence to ISO 10993 and ASTM standards is essential for developing 3D-printed PEEK composites that are mechanically robust, biologically safe, and clinically translatable. Standardization ensures reproducibility, facilitates regulatory compliance, and establishes confidence in the performance of fiber-reinforced scaffolds for cartilage regeneration.

Suitable 3D Printing Methods for Fiber-Reinforced PEEK Composites

Selecting the appropriate 3D printing method is crucial for fabricating fiber-reinforced PEEK composites with optimized mechanical and biological performance for cartilage repair. Due to PEEK’s high melting temperature (~343$^{\circ C}$) and semi-crystalline nature, conventional low-temperature extrusion techniques are unsuitable, making high-temperature additive manufacturing essential. Among available methods, high-temperature fused filament fabrication (HT-FFF), selective laser sintering (SLS), and continuous fiber reinforcement systems are the most suitable approaches.

High-temperature FFF (HT-FFF) is widely regarded as the most practical and versatile method for 3D printing PEEK composites. In this process, PEEK filaments are extruded through a high-temperature nozzle (380-420$^{\circ C}$), enabling precise layer-by-layer deposition. HT-FFF allows for the incorporation of short carbon fibers or hybrid nano-bioactive fillers, providing a balance between mechanical reinforcement and bioactivity. Advantages of HT-FFF include high design flexibility, control over pore size, infill density, and fiber orientation, which are essential for scaffolds intended to mimic cartilage architecture. Additionally, HT-FFF facilitates the fabrication of patient-specific implants with tailored stiffness and porosity, critical for promoting chondrocyte proliferation and extracellular matrix deposition.

Selective Laser Sintering (SLS) is another high-temperature technique that fuses PEEK powder particles using a laser, forming solid scaffolds without the need for support structures. SLS allows complex geometries and high-resolution features, making it suitable for creating gradient structures that replicate native osteochondral tissue. However, incorporating continuous or short fibers into SLS is more challenging due to potential fiber degradation and uneven distribution. SLS-processed scaffolds may also exhibit higher surface roughness, which can positively affect cell attachment but may require post-processing for precise mechanical properties (Xie, Y., & Shi, C.,2021).

Continuous fiber reinforcement systems represent an advanced extrusion-based technique where continuous fibers, such as carbon or glass, co-extruded with molten PEEK. This method maximizes tensile strength, fatigue resistance, and load-bearing capability by preserving fiber continuity along targeted directions. Continuous fiber systems are particularly useful for reinforcing regions of high mechanical demand within cartilage scaffolds. However, they require specialized co-extrusion equipment and careful control of fiber-matrix bonding to prevent void formation or delamination.

In conclusion, HT-FFF is generally the most suitable method for fabricating fiber-reinforced PEEK composites due to its high-temperature capability, flexibility, and compatibility with hybrid reinforcement strategies. SLS and continuous fiber co-printing offer unique advantages for complex geometries and maximal mechanical reinforcement, respectively. Choosing the appropriate method depends on the desired balance between mechanical performance, bioactivity, scaffold complexity, and clinical applicability (Figure 5).

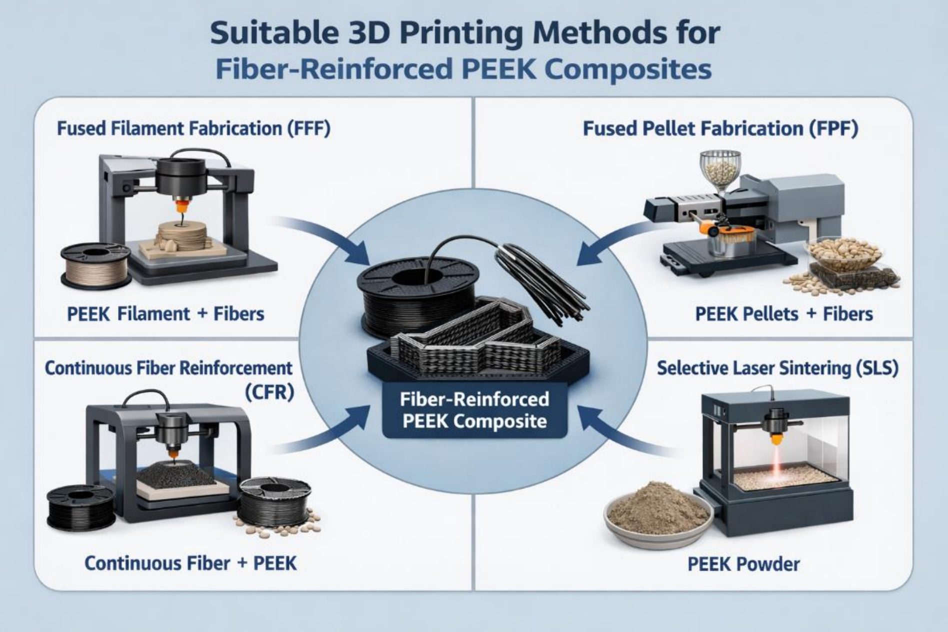

Figure 5. Suitable 3D Printing Methods for Fiber-Reinforced PEEK Composites

Comprehensive testing and characterization of 3D-printed fiber-reinforced PEEK

Composites are essential for ensuring mechanical integrity, biological compatibility, and reproducibility of scaffolds intended for cartilage repair. Because PEEK-based composites combine high-performance polymers with micro- or nano-scale reinforcements, multiple analytical techniques are required to assess surface morphology, chemical structure, crystallinity, and internal architecture (Yang, H., & Wang, Y.,2019).

Scanning Electron Microscopy (SEM) is widely used to examine surface morphology and fiber distribution within the composite. SEM provides high-resolution imaging of fiber alignment, dispersion, and interfacial bonding between fibers and the PEEK matrix. For cartilage scaffolds, SEM can reveal micro-scale topographical features created by surface modifications or bioactive filler incorporation, which are critical for cell adhesion and extracellular matrix deposition. It also identifies voids, defects, or delamination within the printed layers, allowing optimization of printing parameters such as layer thickness, infill density, and nozzle temperature.

Fourier Transform Infrared Spectroscopy (FTIR) employed to analyze chemical bonding and interactions between PEEK and incorporated fibers or bioactive fillers. FTIR can detect functional groups introduced via surface treatments, such as sulfidation, salinization, or HA coating. The technique also helps confirm the chemical integrity of PEEK after high-temperature extrusion, ensuring that processing conditions do not degrade the polymer or alter its functional groups, which could affect both mechanical performance and biocompatibility (Zhao, P., & Wu, L.,2019).

X-ray Diffraction (XRD) provides insights into the crystallinity of PEEK composites, a key factor influencing mechanical properties, thermal stability, and biological response. Higher crystallinity enhances stiffness and strength, whereas lower crystallinity improves ductility and may increase surface wettability. By evaluating the influence of printing parameters such as layer thickness, printing speed, and cooling rate XRD allows the optimization of thermal processing to balance mechanical durability with cellular compatibility.

Micro-computed Tomography (Micro-CT) is critical for quantifying scaffold porosity, pore interconnectivity, and fiber orientation in three dimensions. Cartilage scaffolds require controlled porosity to enable nutrient diffusion, cell infiltration, and extracellular matrix deposition. Micro-CT allows non-destructive evaluation of internal architecture and helps correlate design parameters, such as infill density and raster pattern, with functional performance.

Together, these characterization techniques provide a multidimensional understanding of 3D-printed PEEK composites. SEM and micro-CT assess structural and morphological fidelity, FTIR confirms chemical composition and bonding, and XRD evaluates crystallinity and thermal history. This integrated analysis ensures that scaffolds meet both mechanical requirements and biological functionality, enabling optimized design for effective cartilage repair.

Formulation and post-processing of 3D-Printed PEEK Composites

Formulation and post-processing strategies are critical for optimizing the mechanical and biological performance of 3D-printed PEEK composites intended for cartilage repair. The selection of reinforcement type, filler concentration, and matrix composition, combined with targeted post-processing treatments, directly affects scaffold crystallinity, interlayer bonding, surface properties, and biocompatibility.

Annealing commonly applied to 3D-printed PEEK scaffolds to improve crystallinity and relieve residual stresses induced during high-temperature extrusion. Controlled annealing enhances the degree of crystallinity, which in turn increases stiffness, tensile strength, and thermal stability. For fiber-reinforced systems, annealing also promotes better interfacial adhesion between fibers and the PEEK matrix by allowing polymer chains to reorganize and interact more effectively with filler surfaces. This process reduces the likelihood of micro void formation and layer delamination, particularly in scaffolds with high fiber content, thereby improving fatigue resistance and long-term mechanical reliability (Kurtz & Devine,2007).

Surface activation techniques such as plasma treatment, sulfidation, or laser texturing applied post-printing to modify the chemical and topographical characteristics of the scaffold. These treatments increase surface energy and hydrophilicity, promoting protein adsorption and cell adhesion. For instance, plasma-treated PEEK surfaces exhibit enhanced chondrocyte proliferation and extracellular matrix deposition, crucial for effective cartilage regeneration. Surface functionalization also enables stable attachment of bioactive coatings such as hydroxyapatite or antimicrobial agents, further enhancing the scaffold’s biological performance (Zhou, Y., & Tan, Y.2018).

Sterilization is an essential post-processing step to ensure scaffold safety for clinical applications. High-temperature PEEK composites can tolerate conventional sterilization methods such as autoclaving or gamma irradiation; however, fiber-reinforced or bioactive-filled composites require careful optimization to prevent thermal or radiation-induced degradation of the polymer or bioactive components. Sterilization must preserve both mechanical integrity and surface functionality to ensure consistent performance during in vivo implantation.

Together, formulation and post-processing strategies synergistically enhance 3D-printed PEEK scaffolds. Optimal selection of fiber type, concentration, and hybrid fillers establishes the foundation for mechanical and biological performance. Subsequent annealing improves crystallinity and interfacial bonding, surface activation enhances hydrophilicity and bioactivity, and sterilization ensures clinical safety. Proper integration of these steps allows 3D-printed PEEK composites to achieve the mechanical robustness, cellular compatibility, and long-term stability required for successful cartilage repair.

Optimization of 3D Printing Parameters for PEEK Composites in Cartilage Repair

Optimizing 3D printing parameters is critical to achieving the desired balance between mechanical performance, biological functionality, and print fidelity in fiber-reinforced PEEK composites for cartilage repair. A carefully tailored combination of reinforcement content, filler concentration, infill strategy, layer thickness, and extrusion temperature can maximize scaffold performance while ensuring reproducibility.

Incorporating 10 wt % short carbon fibers (CF) provides significant mechanical reinforcement without excessively increasing stiffness or viscosity. Short CF enhances tensile strength and modulus while maintaining isotropic properties suitable for complex cartilage scaffolds. Excessive fiber content can elevate melt viscosity, reduce interlayer bonding, and create nozzle clogging, which is why 10-wt percentage represents a practical compromise between strength and printability.

Three wt percentage Nano-hydroxyapatite (nHA) acts as a bioactive filler, promoting cell adhesion, proliferation, and extracellular matrix deposition. Low concentrations of nHA avoid agglomeration, maintain smooth extrusion flow, and provide sufficient surface roughness to enhance hydrophilicity and osteochondral integration. Hybrid incorporation of CF and nHA achieves a synergistic effect: CF improves load-bearing capacity while nHA ensures bio functional performance (Ma et al.,2014).

Infill density between 60-70% balances mechanical integrity with porosity for nutrient transport and cell infiltration. Higher infill values increase compressive modulus and reduce structural deformation, but may restrict cellular penetration. Conversely, lower infill improves permeability but compromises scaffold strength. A 60-70% infill achieves a physiologically relevant stiffness comparable to native cartilage while maintaining interconnected porosity for tissue ingrowth. Layer thickness of 0.2 mm provides sufficient resolution to produce smooth surfaces and accurate geometries while promoting strong interlayer bonding. Thinner layers improve filament fusion and reduce void formation, enhancing tensile strength perpendicular to the build direction. However, excessively thin layers increase printing time without a significant mechanical benefit (Zhou, Y., & Tan, Y.,2018).

Finally, a nozzle temperature of 400°C ensures complete melting of PEEK and homogeneous fiber dispersion. Maintaining this high extrusion temperature is essential to achieve adequate interlayer adhesion, minimize voids, and control crystallinity, which directly influences stiffness, fatigue resistance, and surface wettability. In summary, optimizing printing parameters including 10 wt% short CF, 3 wt% nHA, 60-70% infill, 0.2 mm layer thickness, and $400^{\circ C}$ nozzle temperature enables the fabrication of 3D-printed PEEK composites with balanced mechanical strength, bioactivity, and print quality. This configuration provides scaffolds that are mechanically robust, biologically compatible, and suitable for patient-specific cartilage repair applications.

Case Studies on Fiber-Reinforced PEEK Composites

Recent research on 3D-printed fiber-reinforced PEEK composites provides valuable insights into the mechanical and biological performance of different reinforcement strategies for cartilage repair. Several studies have focused on carbon fiber (CF), Nano-hydroxyapatite (nHA), and hybrid systems combining both micro- and nano-scale reinforcements, highlighting their distinct contributions and synergistic effects (Zhou, Y., & Tan, Y.,2018).

Carbon fiber-reinforced PEEK (CF/PEEK) has consistently demonstrated substantial improvements in mechanical performance. Studies indicate that incorporating short or continuous CF can increase tensile strength by 120-200% compared to unreinforced PEEK (Ning et al., 2015; Wang et al.,2020). This improvement attributed to the high modulus of CF, efficient stress transfer, and reduced polymer deformation under load. CF reinforcement also enhances fatigue resistance and compressive strength, critical for scaffolds designed to sustain repeated loading in joint applications. However, CF alone provides limited bioactivity due to its hydrophobic and bio interactive nature, necessitating complementary strategies for cartilage regeneration.

Nano-hydroxyapatite-reinforced PEEK (nHA/PEEK) focuses on enhancing biological functionality. Studies report a 40-60% increase in cell adhesion and proliferation for nHA-loaded composites compared to pure PEEK (Ma et al.,2014; Li et al.,2018). The nanoscale particles increase surface roughness and hydrophilicity, facilitating protein adsorption and extracellular matrix deposition. nHA also provides osteoconductivity properties, which are beneficial in osteochondral repair where integration with subchondral bone is necessary. However, nHA alone contributes only modestly to mechanical reinforcement and may reduce printability at high concentrations due to increased viscosity.

Hybrid systems, combining short CF with Nano-bioactive fillers such as nHA, demonstrate a balanced performance, effectively addressing both mechanical and biological requirements. Research shows that hybrid PEEK composites maintain significant tensile and compressive improvements while simultaneously enhancing cell adhesion, proliferation, and extracellular matrix formation (Zhao et al.,2019; Ma et al.,2019). In these systems, CF provides load-bearing capacity, whereas nHA improves surface bioactivity and supports tissue integration. The synergistic effect of micro- and nano-scale reinforcements reduces the risk of excessive stiffness, which can cause stress shielding, while maintaining structural integrity under physiological loads (Yang, H., & Wang, Y.,2019).

Overall, these case studies underscore the importance of strategic reinforcement selection in 3D-printed PEEK composites. While CF excels in mechanical reinforcement and nHA enhances biological performance, hybrid systems represent the most clinically promising solution for cartilage repair, providing scaffolds that are both mechanically robust and biologically functional. The evidence supports continued exploration of multi-scale and hybrid reinforcement strategies to optimize patient-specific implants.

Applications of 3D-Printed PEEK Composites in Cartilage Repair

3D-printed PEEK composites, particularly those reinforced with fibers and bioactive fillers, increasingly applied in cartilage repair due to their unique combination of mechanical strength, biocompatibility, and design flexibility. Their versatility enables the fabrication of osteochondral scaffolds, load-bearing cartilage substitutes, and patient-specific implants, addressing multiple clinical challenges associated with cartilage regeneration (Wang, B., & Li, X.,2018).

Osteochondral scaffolds designed to support the regeneration of both articular cartilage and the underlying subchondral bone. Hybrid PEEK composites incorporating short carbon fibers for mechanical reinforcement and Nano-hydroxyapatite (nHA) or graphene oxide (GO) for bioactivity can be printed with gradient architectures that mimic the natural transition from cartilage to bone. These scaffolds provide sufficient stiffness to withstand physiological loads while maintaining surface properties that promote chondrocyte adhesion and extracellular matrix deposition. Porosity carefully controlled during printing to facilitate nutrient transport, cell infiltration, and vascularization in the subchondral region, ensuring effective tissue integration.

Load-bearing cartilage substitutes require high tensile strength and fatigue resistance to endure repetitive joint loading without deformation or failure. Short or continuous carbon fiber-reinforced PEEK is particularly suitable for this application, as fiber reinforcement significantly improves tensile strength and modulus compared to unreinforced PEEK. By optimizing fiber orientation and content, 3D-printed constructs can replicate the anisotropic mechanical properties of native cartilage, ensuring durability under complex loading conditions. Incorporation of bioactive nano-fillers ensures that mechanical optimization does not compromise cellular interactions, supporting tissue remodeling and long-term functionality (Schwitalla, A. D., & Müller, W. D.,2013).

Patient-specific implants leverage the geometric flexibility of 3D printing to create anatomically precise scaffolds tailored to individual joint defects. Using imaging data from CT or MRI scans, patient-specific PEEK scaffolds designed to match defect dimensions and curvature, ensuring optimal fit and load distribution. Hybrid reinforcement strategies allow regions requiring high mechanical support to incorporate carbon fibers, while surface bioactivity enhanced with nHA or graphene oxide in areas requiring improved cell adhesion.

In summary, 3D-printed PEEK composites are highly suitable for osteochondral scaffolds, load-bearing cartilage substitutes, and patient-specific implants, combining structural robustness with enhanced biological functionality. The ability to control fiber reinforcement, filler composition, and scaffold architecture allows for a tailored approach to cartilage repair, addressing both mechanical demands and cellular requirements for effective tissue regeneration.

Clinical Translation and Future Perspectives of 3D-Printed PEEK Composites

Despite the promising mechanical and biological performance of 3D-printed fiber-reinforced PEEK composites, translating these scaffolds into clinical practice presents several challenges that need to be addressed to ensure safe and effective cartilage repair (Ma, X., & Tang, Z.,2019).

Regulatory approval remains a significant hurdle. PEEK composites, especially those incorporating hybrid micro- and nano-scale reinforcements or bioactive fillers, classified as medical devices, requiring compliance with stringent standards such as ISO 10993 for biocompatibility and ASTM protocols for mechanical testing. Regulatory agencies demand robust preclinical evidence demonstrating scaffold safety, stability, and reproducibility. The complex interplay between PEEK matrix, fibers, and bioactive fillers adds variability, necessitating standardized manufacturing processes and comprehensive documentation for approval.

Long-term biological validation is another critical challenge. While short-term in vitro studies and small animal models indicate promising cell adhesion, proliferation, and extracellular matrix deposition, long-term in vivo studies are required to assess scaffold integration, tissue remodeling, and potential immune responses. Fatigue resistance under physiological joint loading and degradation behavior of bioactive fillers over time carefully evaluated to prevent implant failure or inflammatory complications. Cost is also a limiting factor. High-temperature 3D printing equipment, continuous fiber systems, and bioactive fillers such as nHA or graphene oxide increase production costs. Patient-specific customization adds additional complexity and resource requirements (Liu, P., & Xu, F.,2021). These factors balanced against clinical benefits to justify adoption in routine orthopedic practice. Looking forward, several future directions offer opportunities to enhance scaffold functionality and clinical translation. Smart bioactive composites capable of responding to mechanical or biochemical stimuli could improve tissue regeneration by releasing bioactive agents in response to local cues. Growth-factor-loaded scaffolds may accelerate chondrogenesis and osteochondral integration, potentially reducing recovery times. Incorporating biologically active molecules within the polymer-fiber matrix in a controlled manner can enhance both short- and long-term outcomes.

4D printing introduces dynamic capabilities, allowing scaffolds to change shape, stiffness, or porosity in response to environmental conditions, such as temperature or pH. This technology could enable adaptive scaffolds that conform to joint motion, maintain optimal load distribution, and support tissue remodeling over time (Kurtz, S. M., & Devine, J. N.,2007).

In conclusion, while 3D-printed PEEK composites exhibit strong potential for cartilage repair, clinical translation requires overcoming regulatory, biological, and economic challenges. Advances in smart composites, bioactive factor integration, and 4D printing are likely to shape the next generation of patient-specific, functionally adaptive scaffolds, offering enhanced mechanical support and biological performance for regenerative orthopedic applications (Figure 6).

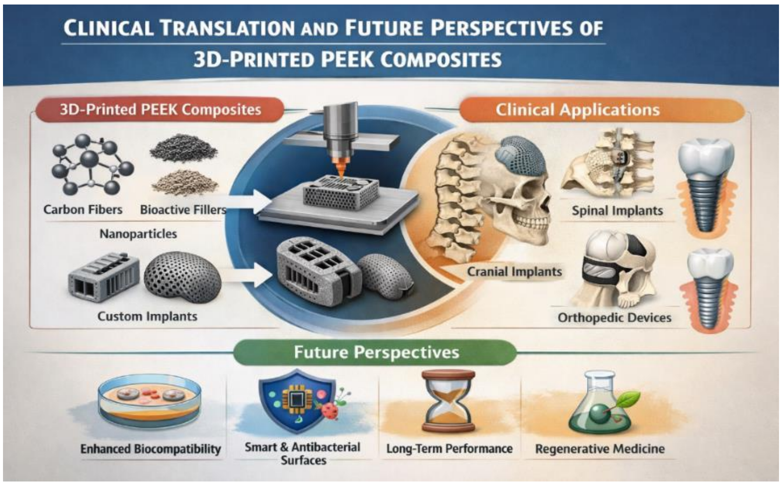

Figure 6. Clinical Translation and Future Perspectives of 3D-Printed PEEK Composites

Discussion: Balancing Mechanics and Bioactivity in 3D-Printed PEEK Composites for Cartilage Repair

The development of 3D-printed PEEK composites for cartilage repair represents a convergence of materials science, additive manufacturing, and tissue engineering. Achieving a balance between mechanical strength and bioactivity is crucial, as cartilage scaffolds must withstand repetitive mechanical loading while supporting chondrocyte proliferation and extracellular matrix (ECM) deposition. The integration of fiber reinforcements, bioactive fillers, and controlled printing parameters allows researchers to tailor both structural and biological performance. Comparisons with prior studies highlight the importance of hybrid strategies and optimized fabrication techniques in achieving clinically relevant outcomes.

Mechanical Reinforcement with Fiber Content

Carbon fiber (CF) is widely recognized for its ability to enhance mechanical properties. Studies have reported that short CF-reinforced PEEK exhibits tensile strength improvements of up to 120-200%, highlighting the effective load transfer between fibers and the polymer matrix (Ning et al.,2015; Wang et al.,2020). The mechanical advantage closely linked to fiber length, orientation, and volume fraction, consistent with shear-lag theory predictions, which emphasize the importance of fiber aspect ratio in stress transfer (Kelly & Tyson,1965). Continuous CF systems offer the highest tensile and fatigue performance due to uninterrupted load paths, but they introduce anisotropy and require complex co-extrusion equipment. In contrast, short fibers maintain isotropic reinforcement, ensuring more uniform mechanical behavior under multidirectional loading typical of cartilage. Comparisons with traditional PEEK implants reveal that fiber reinforcement via 3D printing not only improves tensile and compressive strength but also enables scaffold designs with tailored porosity, which conventional compression-molded scaffolds cannot achieve (Schwitalla & Müller,2013).

Glass fibers and ceramic fibers have also been investigated, offering stiffness enhancement and, in some cases, bioactivity (ceramic fibers are osteoconductivity). However, their brittle nature and lower compatibility with high-temperature extrusion limit their practical application in patient-specific cartilage scaffolds. Carbon nanotubes (CNT) and cellulose nanocrystals (CNC) provide Nano-scale reinforcement, enhancing mechanical properties while simultaneously improving cell affinity and bioactivity (Kuilla et al.,2010). In comparison, natural fibers such as silk or polycaprolactone (PCL) offer superior biocompatibility but lower mechanical reinforcement, highlighting the trade-off between mechanical and biological performance observed in prior studies (Ma et al.,2014).

Processing Parameters and Structural Optimization

Processing parameters significantly influence both mechanical and biological outcomes. Build orientation, fiber orientation, layer thickness, infill density, and printing speed all affect anisotropy, tensile strength, interlayer bonding, and crystallinity. For instance, tensile strength and fatigue resistance maximized when fibers align with loading directions, while appropriate infill density (60-70%) provides sufficient compressive support and porosity for cellular infiltration. Thinner layers (0.2 mm) improve interlayer adhesion and reduce void content; nozzle temperatures of $400^{\circ C}$ ensure adequate melting and uniform fiber dispersion. Comparisons with earlier research indicate that improper parameter selection can lead to weakened scaffolds despite using optimal fiber and filler types (Kurtz & Devine,2007). High-temperature FFF is currently the most suitable method for fiber-reinforced PEEK, providing design flexibility and compatibility with hybrid reinforcement strategies. SLS and continuous fiber systems offer additional advantages but pose challenges in fiber integration and anisotropic performance (Kim, H., & Lee, B.-T.,2017).

Surface Modification and Post-Processing

Surface treatments such as plasma treatment, sulfidation, salinization, HA coating and titanium coating enhance hydrophilicity and bioactivity. Prior studies show that surface activation improves protein adsorption, chondrocyte attachment, and ECM deposition, which is critical for cartilage repair where scaffold–cell interactions dictate regenerative success. Annealing post-processing enhances crystallinity, increasing stiffness and fatigue resistance while maintaining surface integrity for bioactive coatings. Sterilization ensures clinical safety without compromising scaffold performance, a step often emphasized in translational studies but sometimes overlooked in early-stage research.

Comparative Analysis with Traditional Approaches

Compared to traditional molding or machining techniques, 3D printing allows precise control over fiber distribution, pore architecture, and patient-specific geometries. Traditional methods produce uniform, dense scaffolds with high bulk mechanical properties but limited porosity and an inability to tailor gradients for osteochondral interfaces. Additive manufacturing enables the fabrication of gradient scaffolds, multi-material constructs, and patient-specific implants, which are crucial for effective cartilage repair. Studies on hybrid systems consistently demonstrate that 3D-printed scaffolds outperform traditional counterparts in balancing mechanical reinforcement and bioactivity (Ma et al.,2019; Zhao et al.,2019).

Challenges and Future Directions

Despite these advantages, clinical translation remains challenging due to regulatory hurdles, cost, and the need for long-term biological validation. Future directions include smart bioactive composites that respond to mechanical or biochemical stimuli, growth-factor-loaded scaffolds to accelerate tissue regeneration, and 4D printing approaches enabling dynamic adaptation to joint motion. Integrating these advancements with hybrid reinforcement strategies could provide next-generation cartilage scaffolds that are mechanically robust, biologically active, and functionally adaptive. In summary, balancing mechanical and biological performance in 3D-printed PEEK composites requires a multi-faceted approach involving fiber selection, bioactive fillers, processing optimization, and surface modification. Hybrid systems combining short CF with bioactive Nano-fillers consistently demonstrate superior balance, validated by recent studies showing improved tensile strength, compressive performance, and cell adhesion (Figure 7).

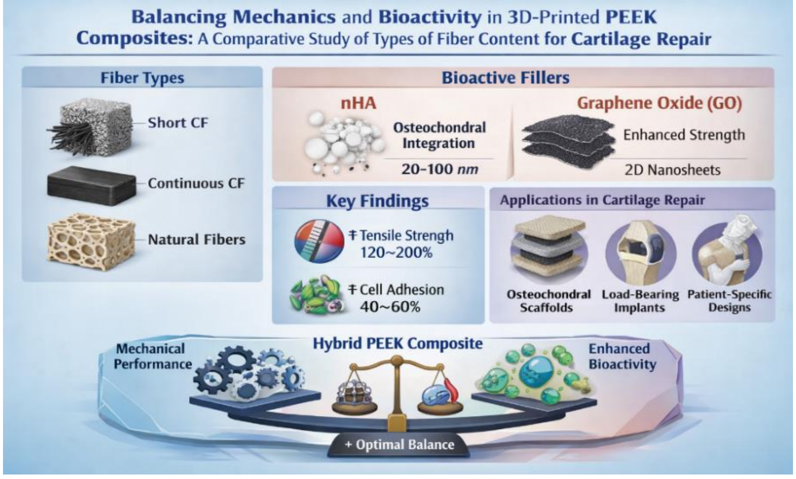

Figure 7. Balancing Mechanics and Bioactivity in 3D-Printed PEEK Composites for Cartilage Repair

Conclusion

Balancing mechanical strength and bioactivity in 3D-printed PEEK composites requires strategic fiber selection. Continuous carbon fibers provide superior mechanical reinforcement but lack biological activity. Bioactive Nano-fillers enhance cell interaction but may compromise printability. Hybrid reinforcement combining short carbon fibers with Nano-hydroxyapatite or graphene oxide offers the most promising approach for cartilage repair applications. Optimization of fiber type, size, length, and processing parameters is critical to achieving functional, patient-specific cartilage scaffolds with long-term clinical success.

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Authors' Contributions

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