FDM Based 3D Printing of Short Fiber Composites: A Comparative Review of Synthetic and Natural Fiber Composites

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Abstract

Short fiber-reinforced composites produced through fused deposition modeling (FDM) have emerged as promising materials for improving the performance of additively manufactured polymer components. While conventional thermoplastics offer design flexibility and processability, their relatively low stiffness, weak interlayer bonding, and anisotropic behavior limit their use in demanding applications. Incorporating short fibers into thermoplastic matrices has therefore gained attention as an effective strategy to enhance the mechanical, thermal, and functional properties of FDM-printed parts. This review provides a comprehensive comparative analysis of natural and synthetic short fiber-reinforced composites used in FDM-based additive manufacturing. It examines how fiber characteristics including type, morphology, aspect ratio, and fiber matrix interactions influence mechanical performance, thermal stability, and chemical resistance. Key processing challenges such as changes in melt rheology, fiber breakage during extrusion, anisotropy, interlayer adhesion limitations, porosity formation, and dimensional accuracy are also discussed. Environmental aspects including life cycle impacts, recyclability, moisture sensitivity, and durability are considered. Natural fibers offer advantages in renewability, lower density, and reduced embodied energy, while synthetic fibers such as carbon and glass provide superior mechanical performance and thermal stability for structural applications. Hybrid reinforcement strategies combining natural and synthetic fibers are also highlighted as a promising approach to balance performance and sustainability. Finally, key research gaps and future directions are identified to support the development of more reliable and sustainable FDM composite systems. This integrated perspective aims to guide material selection and process optimization for next-generation fiber-reinforced additive manufacturing.

1 Introduction

Additive manufacturing, particularly fused deposition modeling (FDM), has significantly transformed the way polymer components are designed and fabricated. By enabling the production of geometrically complex, lightweight, and customizable structures, FDM allows designs that are difficult or impossible to achieve using conventional manufacturing methods [1]. Despite these advantages, the mechanical performance of printed thermoplastic parts is still limited by several inherent factors, including low stiffness, weak interlayer bonding, and anisotropic properties resulting from the layer-by-layer deposition process. To overcome these limitations, the incorporation of short fiber reinforcements into thermoplastic matrices has emerged as one of the most effective strategies for improving the structural, thermal, and functional properties of FDM-printed components [2, 3].

Short fiber composites used in FDM can generally be divided into natural fiber and synthetic fiber systems, each presenting distinct advantages and processing challenges. Natural fibers such as jute, flax, hemp, curauá, and other plant-derived microfibers have attracted increasing attention because of their biodegradability, low density, renewability, and reduced environmental impact [4, 5]. These characteristics align with the growing global emphasis on sustainable manufacturing. However, natural fibers also present several challenges, including hydrophilicity, heterogeneous morphology, thermal sensitivity, and relatively weak interfacial bonding with polymer matrices, which can complicate melt processing and limit their reinforcement efficiency in extrusion-based additive manufacturing. In contrast, synthetic fibers such as carbon, glass, and aramid are widely used when higher mechanical strength, dimensional stability, and thermal resistance are required [6]. These fibers generally exhibit uniform geometry, strong fiber–matrix interactions, and predictable performance, making them well suited for engineering and functional applications. However, synthetic fibers are associated with environmental drawbacks, including high embodied energy during production and challenges related to end-of-life management.

Although the integration of both natural and synthetic fibers has expanded the functional capabilities of FDM composites, the process introduces a complex interaction of factors that influence printability and final material performance. Parameters such as fiber length and attrition, fiber orientation, dispersion within the matrix, melt rheology, interlayer adhesion, porosity, thermal gradients, and nozzle wear all play important roles in determining the quality of printed parts [7]. These interactions are further complicated by the choice of polymer matrix. Thermoplastics commonly used in FDM such as PLA, PP, PA, PETG, and PEEK exhibit different melting behavior, viscosity characteristics, degradation thresholds, and compatibility with specific fiber types [8]. Despite the rapid growth of research in this field, existing studies often report fragmented or inconsistent findings. Variations in fiber loading, compounding methods, surface treatments, printer configurations, raster strategies, and testing protocols make it difficult to directly compare results across studies. Consequently, a clear and systematic understanding of how natural and synthetic short fiber systems behave within the unique thermal and mechanical environment of FDM is still lacking.

This review provides a comprehensive comparative analysis of natural and synthetic short fiber-reinforced composites used in FDM. As research in this area has expanded rapidly, findings across literature remain fragmented due to differences in fiber types, matrix systems, processing conditions, and testing methods. This review therefore integrates existing studies to clarify how material selection and processing parameters influence the performance and sustainability of fiber-reinforced FDM composites. Specifically, the review synthesizes current knowledge on

how fiber type, morphology, aspect ratio, interfacial characteristics, and matrix selection influence the mechanical, thermal, and chemical behavior of printed composites. It also examines key processing challenges, including rheological changes, fiber breakage during extrusion, anisotropy, interlayer bonding limitations, porosity formation, nozzle clogging, and dimensional accuracy.

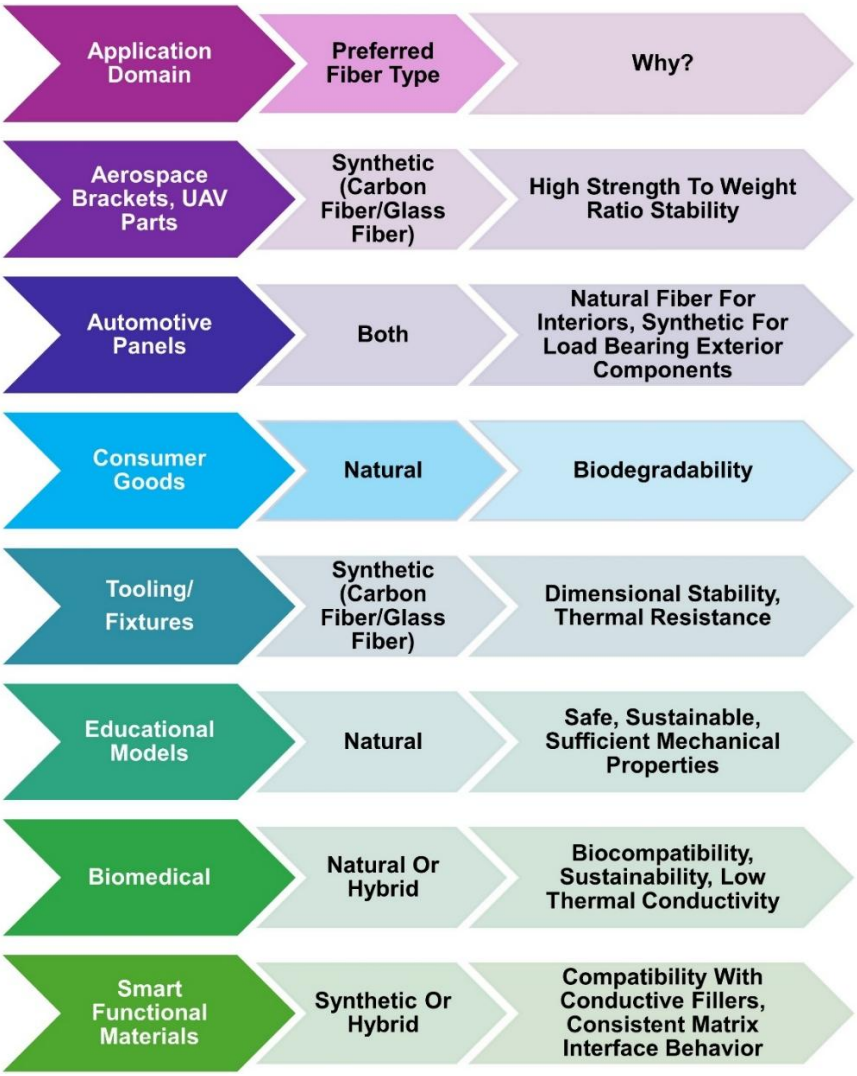

Figure 1. Schematic overview of FDM-based short fiber composite systems, illustrating natural and synthetic fiber pathways, processing steps, and representative application domains.

In addition, the review evaluates the environmental and sustainability aspects of these materials, considering life-cycle impacts, recyclability, moisture sensitivity, and long-term durability. Major application domains are discussed, ranging from high-performance engineering components to consumer products and sustainable materials, while highlighting the growing importance of hybrid reinforcement systems that combine natural and synthetic fibers. Finally, the review identifies key research gaps and future directions in materials development, interface engineering, and process optimization. By linking material selection, processing behavior, microstructural evolution, and final performance, this work provides a framework for advancing

short fiber–reinforced FDM composites from prototyping materials toward reliable and sustainable solutions in additive manufacturing. An overview of the FDM-based short fiber composite landscape is presented in **Fig. 1**, which illustrates the classification of natural and synthetic fiber reinforcements, the key processing steps involved in composite fabrication, and the broad range of application areas enabled by these materials. The schematic highlights the interconnected relationships among material selection, processing, structure, and performance that underpin the development of advanced fiber-reinforced FDM composites.

2 Materials Selection and Design Considerations for FDM Composites

The development of short fiber-reinforced composites for FDM is governed by a combination of material selection and processing design considerations. In particular, the choice of reinforcing fibers (natural or synthetic), the selection of an appropriate polymer matrix, and the methods used for filament fabrication and printing collectively determine the mechanical performance, processability, dimensional accuracy, and environmental impact of the final printed components. These factors are highly interdependent, and their interactions define the overall behavior of fiber-reinforced FDM systems. Accordingly, this section examines the key material and processing aspects that underpin FDM composite performance. It begins with fiber selection and characterization, followed by matrix selection considerations, and then discusses filament fabrication strategies and printing parameters that ultimately govern part quality and performance.

2.1 Fiber Selection and Characterization

In FDM-based short fiber composites, fiber selection is guided less by conventional material classifications and more by the functional requirements of the intended application and the constraints of extrusion-based processing. The reinforcing phase in FDM plays a crucial role in regulating melt rheology, interlayer adhesion, and load-transfer mechanisms, all of which directly influence the structural integrity and performance of the printed component [9]. Synthetic fibers are typically chosen for applications that require predictable reinforcement, thermal stability, and dimensional accuracy, particularly in structural, aerospace, and tooling environments. Their uniform geometry and high thermal tolerance promote consistent flow during extrusion and facilitate reliable interlayer fusion, which is essential for components subjected to cyclic loading or elevated temperatures.

Natural fibers, in contrast, are often selected for applications emphasizing biodegradability, lightweighting, and cost efficiency, such as consumer products, automotive interiors, and sustainable packaging. However, their inherent variability and moisture sensitivity introduce several processing challenges in FDM, including inconsistent melt flow, reduced interfacial bonding, and increased porosity. These challenges often require careful preprocessing, surface treatments, and controlled fiber sizing to achieve consistent reinforcement [10]. Compared with natural fibers, synthetic fibers generally provide more uniform reinforcement efficiency. Natural fibers exhibit greater variability due to differences in plant origin, lumen structure, and irregular cross-sectional geometry. Such variability frequently necessitates chemical or enzymatic surface treatments to improve compatibility with polymer matrices. Another critical factor is the fiber aspect ratio, which strongly influences stress-transfer efficiency, melt viscosity, and the likelihood of nozzle clogging. While higher aspect ratios enhance reinforcement potential, they also increase shear stresses during extrusion, which may destabilize melt flow and affect deposition consistency [11].

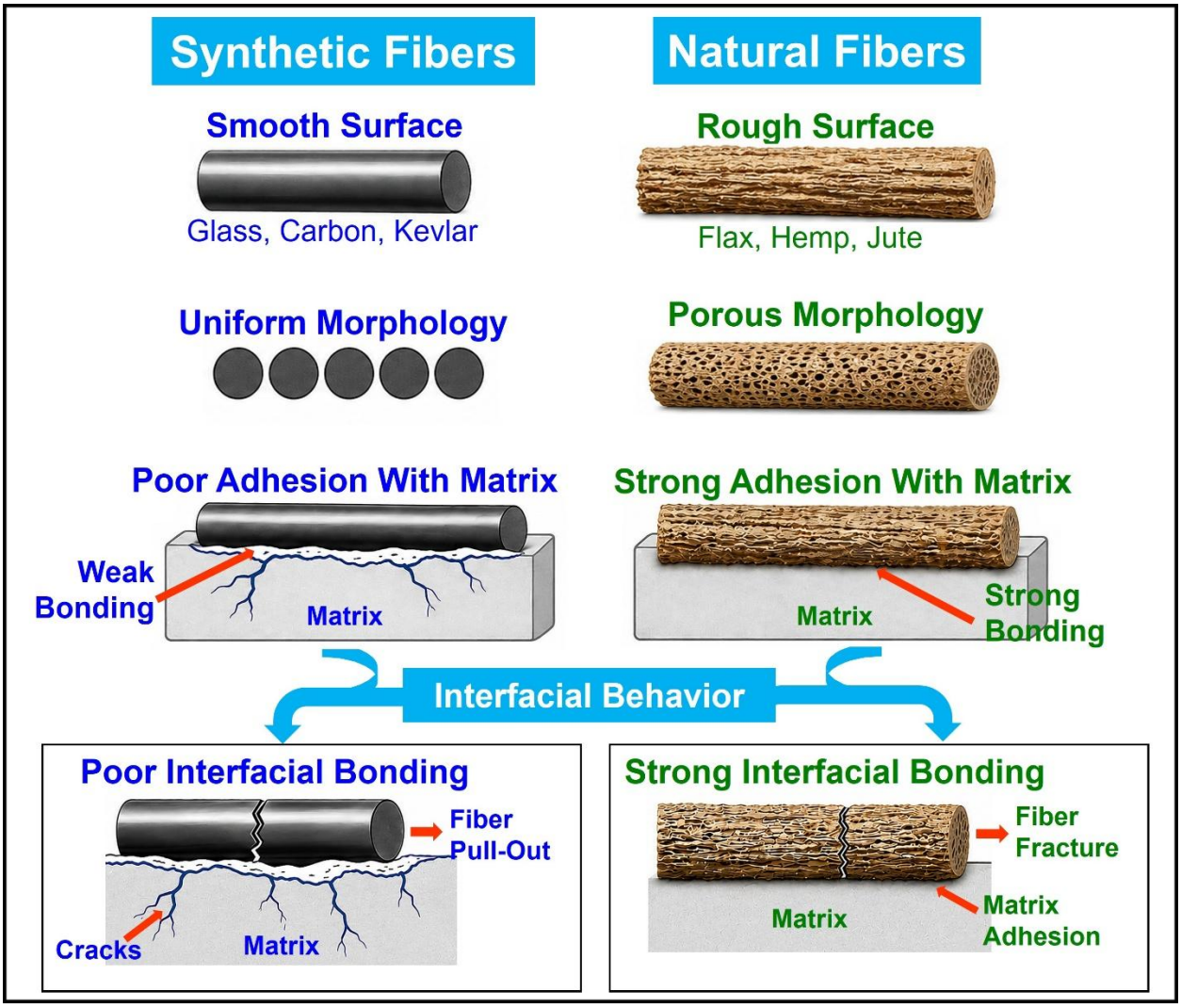

Figure 2. Comparison of natural and synthetic fibers used in FDM, highlighting differences in morphology, surface characteristics, and interfacial behavior.

Overall, fiber selection depends on the complex interplay between fiber–matrix compatibility, interfacial adhesion, thermomechanical stability, moisture behavior, and rheological characteristics during processing. These combined factors determine whether synthetic, natural, or hybrid fiber systems are best suited to meet application-specific performance requirements within the thermal and mechanical constraints of FDM [12]. **Figure 2** presents a schematic comparison of natural and synthetic fibers in FDM, highlighting differences in morphology, surface characteristics, and interfacial behavior.

2.2 Rationale Behind Matrix Selection for FDM Composites

The polymer matrix plays a critical role in determining the performance and processability of natural fiber composites (NFCs). Because natural fibers are susceptible to thermal and environmental degradation, selecting a compatible matrix is essential to ensure stable processing and adequate composite performance. Matrix selection depends on factors such as interfacial bonding, biodegradability, weather resistance, mechanical strength, and thermal stability.

Thermoplastic polymers are predominantly used in FDM because they provide suitable processability, thermal control, and compatibility with both natural and synthetic fibers. Common matrices include nylon (PA), polypropylene (PP), polylactic acid (PLA), and polyethylene terephthalate glycol (PETG) [11, 13]. Among these materials, PLA remains one of the most widely used matrices for both natural and synthetic fiber composites due to its relatively low processing temperature and biodegradability. However, PLA has limitations, including brittleness and relatively slow crystallization behavior, which can affect mechanical performance [14]. PLA is a bio-based aliphatic polyester synthesized from renewable agricultural resources such as corn, cassava, or sugar beet. It is widely considered a promising matrix for environmentally friendly composites because of its low greenhouse gas emissions, non-toxic degradation products, and wide availability [15]. The polymer typically exhibits a tensile strength of approximately 49 MPa and a tensile modulus of about 3.2 GPa, along with good stiffness and optical clarity [16]. However, its relatively low elongation at break and glass transition temperature between 50 °C and 75 °C restrict its use in high-temperature or dynamically loaded applications.

Table 1. Common thermoplastic matrices used in FDM composites with key properties (Tg, Tm, processing temperature, advantages, and limitations).

Matrix	Type	T_g / T_m (°C)	Processing Temp. (°C)	Key Advantages	Limitations	Fiber Suitability
PLA	Bio-based polyester	T_g: 50-75 Tm: 150-180	180-220	Biodegradable; low processing temperature; good stiffness; widely available	Brittle; low thermal resistance; slow crystallization	Natural + Synthetic
PP	Thermoplastic polyolefin	T_g: -10 to 0 T_m: 160-170	200-240	Excellent chemical resistance; good fatigue behavior; low density	Poor adhesion with polar fibers; requires compatibilizers	Natural + Synthetic
PA / Nylon	Engineering thermoplastic	T_g: 40-70 T_m: 210-260	230-270	High toughness; good wear resistance; thermal stability	Hygroscopic; dimensional instability under moisture	Synthetic preferred
PETG	Copolyester	T_g: 75-85 T_m: ~230	220-260	Good chemical resistance; ductility; easy processing	Moderate stiffness; lower heat resistance than PA	Natural + Synthetic
ABS	Engineering thermoplastic	T_g: ~105 T_m: amorphous	220-260	Good impact resistance; dimensional stability	Warping; moderate chemical resistance	Synthetic preferred
PEEK	High-performance polymer	T_g: ~143 T_m: ~343	350-400	Excellent thermal stability; high strength; chemical resistance	Very high processing temperature; expensive	Synthetic only
PBS	Biodegradable polyester	T_g: -30 to -10 T_m: 110–120	180–220	Flexible; biodegradable; improved toughness vs PLA	Lower stiffness and strength	Natural
PHA	Biopolymer	T_g: -10 to 10 T_m: 150-180	170-210	Biodegradable; biocompatible	Processing instability; cost	Natural

PLA: Polylactic Acid, PP: Polypropylene, PA: Polyamide/Nylon, PETG: Polyethylene Terephthalate Glycol, ABS: Acrylonitrile Butadiene Styrene, PEEK: Polyether Ether Ketone, PBS: Polybutylene Succinate, PHA: Polyhydroxyalkanoates.

Various chemical and physical modifications have been explored to improve PLA performance. For example, copolymerization with biodegradable polymers such as

polycaprolactone (PCL) or polyethylene glycol (PEG) can enhance flexibility and impact resistance. Adjusting the ratio of L-lactide to D-lactide through stereocomplex formation can regulate crystallinity and thereby influence thermal and mechanical properties. In addition, the incorporation of plasticizers, chain extenders, and nucleating agents can improve toughness, processing behavior, and crystallization kinetics [15, 17]. High-molecular-weight PLA suitable for FDM is typically synthesized through ring-opening polymerization (ROP) of lactide using catalytic systems, producing polymers with the melt flow and mechanical properties required for extrusion-based manufacturing [16]. Other thermoplastics, including polypropylene (PP) and polyamide (PA or nylon), are widely used in synthetic fiber composites due to their excellent impact resistance, thermal stability, and long-term durability [18]. Polypropylene, for example, offers strong chemical resistance and fatigue performance due to its nonpolar and hydrophobic molecular structure. However, this same nonpolarity can limit interfacial bonding with polar fibers, particularly natural fibers. To overcome this limitation, compatibilizing agents are often introduced to improve adhesion between the fiber and matrix phases. Common thermoplastic matrices used in FDM composites with key properties (Tg, Tm, processing temperature, advantages, limitations) are presented in **Table 1**.

Recent studies have also explored hybrid polymer matrices, combining PLA with other biodegradable polymers such as polybutylene succinate (PBS), thermoplastic starch, or polyhydroxyalkanoates (PHA) [16]. These polymer blends aim to overcome the limitations of PLA while preserving its environmental advantages, resulting in composites with improved toughness, thermal stability, and biodegradability. Overall, matrix selection and modification are central to optimizing both the mechanical performance and processing behavior of fiber-reinforced composites. A well-designed matrix not only governs the interaction between fibers and the polymer phase but also influences crystallization behavior, thermal stability, melt flow characteristics, and the environmental profile of the final material [19].

2.3 Filament Fabrication and Preparation

Two primary methods are commonly used to incorporate short fibers into FDM filaments. The first is direct melt compounding, in which fibers are blended with the thermoplastic matrix in an extruder to form a homogeneous mixture that is subsequently extruded into filament form. This method enables relatively uniform fiber dispersion; however, it may lead to fiber breakage and loss of orientation, particularly when natural fibers are used [20]. The second approach is solvent- or masterbatch-assisted blending, where the matrix polymer is dissolved or a masterbatch is used to pre-disperse the fibers before the final extrusion step. This method can improve fiber dispersion and help minimize fiber degradation. However, it is less commonly employed due to its processing complexity and concerns related to solvent recovery. In practice, both natural and synthetic fiber-reinforced filaments are typically produced with diameters of 1.75 mm or 2.85 mm, with fiber loadings generally ranging from 5 to 40 wt% [21]. The optimal fiber content depends on achieving a balance between mechanical reinforcement and printability. While higher fiber loadings can enhance strength, they may also increase brittleness and the likelihood of nozzle clogging during printing [22, 23].

2.4 Printing Parameters and Specimen Preparation

Specimens are typically fabricated using either open-source or commercial FDM systems (e.g., MakerBot, Markforged, or custom-built platforms), with printing parameters carefully adjusted to match the rheological behavior of the composite material [24]. Nozzle temperatures

generally range from 190 °C to 260 °C, depending on the type of polymer matrix, while layer heights are typically maintained between 0.1 and 0.3 mm [25]. To reduce internal porosity and ensure reliable mechanical testing, an infill density of 100% is commonly used. Mechanical characterization of these printed specimens is usually conducted following established ASTM standards, including ASTM D638 for tensile properties, ASTM D790 for flexural performance, and ASTM D256 for impact resistance. However, variations in specimen preparation such as print orientation, raster angle, and post-processing conditions can lead to significant variability in the reported mechanical properties [26]. These factors highlight the importance of developing more standardized and reproducible testing protocols for FDM composite research.

3 Mechanical Properties

The mechanical behavior of short fiber–reinforced FDM composites is primarily governed by two main classes of reinforcement materials: synthetic fibers and natural fibers. Synthetic fibers generally provide higher and more predictable mechanical performance, whereas natural fibers offer sustainability advantages but often exhibit lower and more variable mechanical properties. Synthetic reinforcements such as carbon fiber (CF), glass fiber (GF), and aramid fibers are widely used because they provide strong interfacial load transfer, high stiffness, and significant strength enhancement in printed composites [27, 28]. In contrast, natural fibers including flax, hemp, curauá, wood, and basalt fibers are attractive due to their biodegradability, lower density, and reduced material cost. However, their hydrophilic nature, lower thermal stability, and inherent variability in fiber morphology can limit reinforcement efficiency and introduce greater variability in printing and mechanical performance [29]. As a result, the mechanical performance of FDM composites often reflects a fundamental trade-off: synthetic fibers maximize mechanical strength and structural reliability, whereas natural fibers enhance sustainability but may struggle to achieve the same level of structural reinforcement provided by synthetic alternatives [22, 30].

3.1 Tensile Strength

Across the reported systems, synthetic fibers consistently produce the highest tensile strengths, primarily due to their high intrinsic modulus and the strong fiber orientation achieved during extrusion. For example, PA6 reinforced with 25 wt% carbon fiber (CF) exhibits tensile strengths of approximately 98 MPa in the as-printed condition, which can exceed 160 MPa after optimized heat treatment [31]. Similarly, CF-reinforced ABS printed with fibers aligned at 0° orientation reaches tensile strengths of 51-70 MPa [2], while CF-PLA and CF-nylon composites have reported even higher values under highly optimized processing conditions [27].

In contrast, natural fiber–reinforced composites rarely surpass the tensile strength of neat PLA or ABS, and in many cases the strength decreases as fiber loading increases. For instance, curauá-reinforced PLA reaches peak tensile strengths of 54–58 MPa at approximately 2 wt% fiber loading, but higher concentrations often lead to reduced strength due to fiber agglomeration and increased porosity [32]. Flax-PLA composites can achieve tensile strengths of around 50 MPa under optimized printing conditions, whereas hemp-PLA systems typically show a gradual decline in strength with increasing fiber content [33]. Wood fiber–reinforced PLA generally exhibits the lowest performance (approximately 19–20 MPa), as wood particles tend to act more as fillers that disrupt matrix continuity rather than as effective reinforcing phases [34, 35]. Among natural reinforcements, basalt fiber demonstrates comparatively better performance and

is often considered the only natural fiber capable of partially bridging the tensile performance gap between natural and synthetic reinforcements [36].

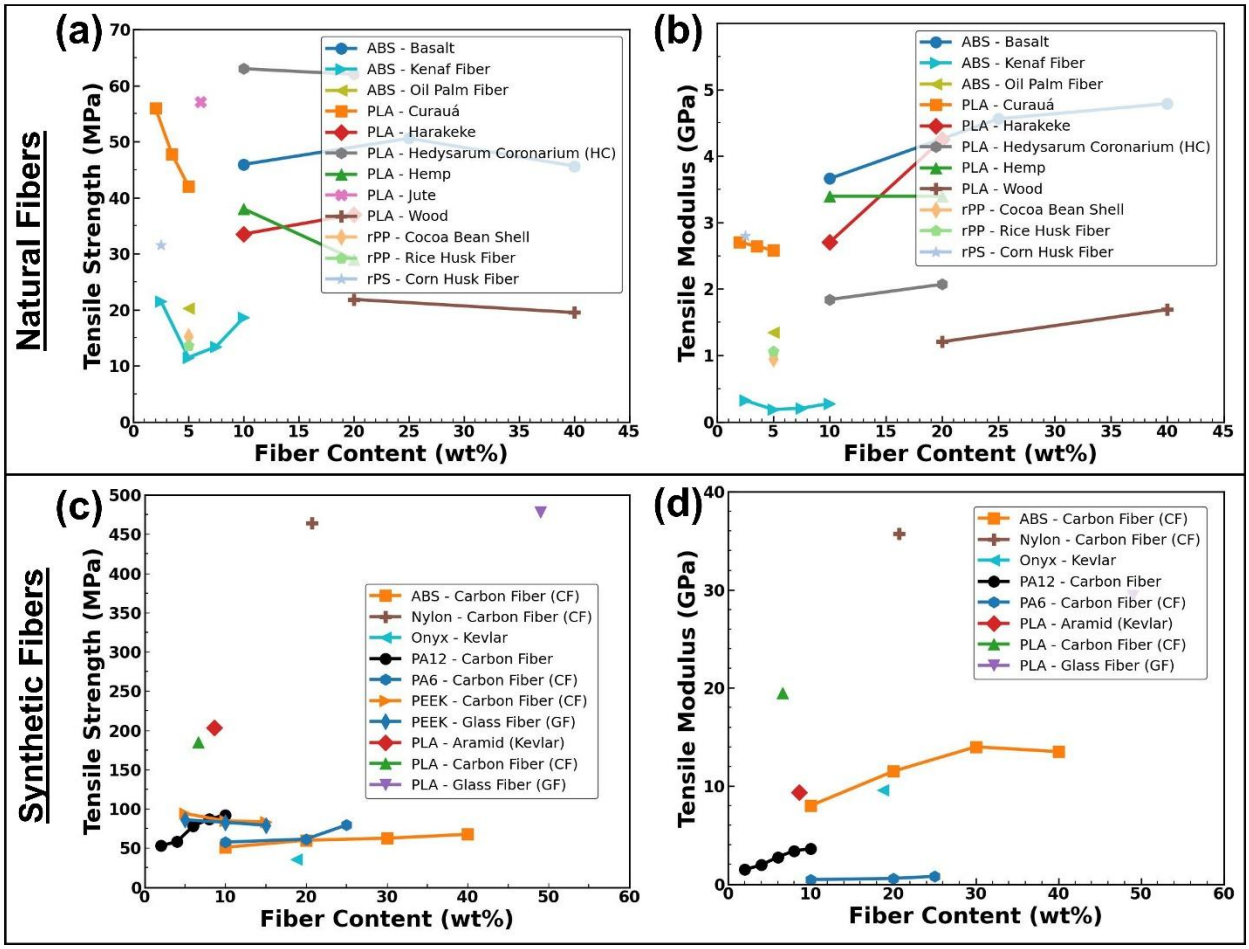

Figure 3. Tensile properties of natural and synthetic fiber-reinforced FDM composites as a function of fiber content: (a) Tensile strength versus fiber content for natural fiber-reinforced composites, (b) Tensile modulus versus fiber content for natural fiber-reinforced composites, (c) Tensile strength versus fiber content for synthetic fiber-reinforced composites, and (d) Tensile modulus versus fiber content for synthetic fiber-reinforced composites. The figures summarize tensile performance trends reported in the literature [2, 27, 31-49] for FDM-printed fiber-reinforced composites.

Tensile behavior in FDM composites is also strongly influenced by fiber length reduction during compounding and printing, as well as fiber orientation within the printed layers. While controlled fiber alignment significantly enhances mechanical performance in synthetic fiber systems, this effect is less pronounced in hydrophilic natural fibers due to their relatively weaker interfacial bonding with polymer matrices [50, 51]. Data reported across the literature [2, 27, 31-49] were compiled and analyzed in **Fig. 3** to compare the effects of fiber type and fiber content on the tensile strength and tensile modulus of natural and synthetic fiber-reinforced FDM composites.Natural fiber composites generally exhibited tensile strengths below 65 MPa and tensile moduli below 5 GPa, with basalt, curauá, and Hedysarum coronarium fibers providing the

greatest improvements. In contrast, synthetic fiber composites achieved substantially higher tensile performance, with tensile strengths exceeding 450 MPa and tensile moduli approaching 36 GPa in carbon fiber- and glass fiber-reinforced systems. Carbon fiber was the most effective reinforcement for improving stiffness, whereas glass fiber and aramid fibers produced the highest tensile strengths in selected polymer matrices. Overall, the results demonstrate the superior reinforcing efficiency of synthetic fibers relative to natural fibers, although natural fibers offer a more sustainable alternative with moderate mechanical enhancement.

3.2 Flexural Strength

Flexural performance in FDM composites generally follows trends similar to those observed for tensile behavior, with synthetic fiber–reinforced systems providing the most significant improvements in mechanical properties. For example, heat-treated PA6–carbon fiber (CF) composites can achieve flexural strengths of up to 175 MPa, while glass fiber (GF)-reinforced ABS demonstrates 30–37% improvements compared with neat ABS [31, 52]. These enhancements are primarily attributed to strong fiber–matrix interfacial adhesion, efficient stress transfer, and the high degree of fiber alignment along the printed filament paths [53]. In contrast, natural fiber–reinforced composites typically exhibit more variable and generally lower flexural

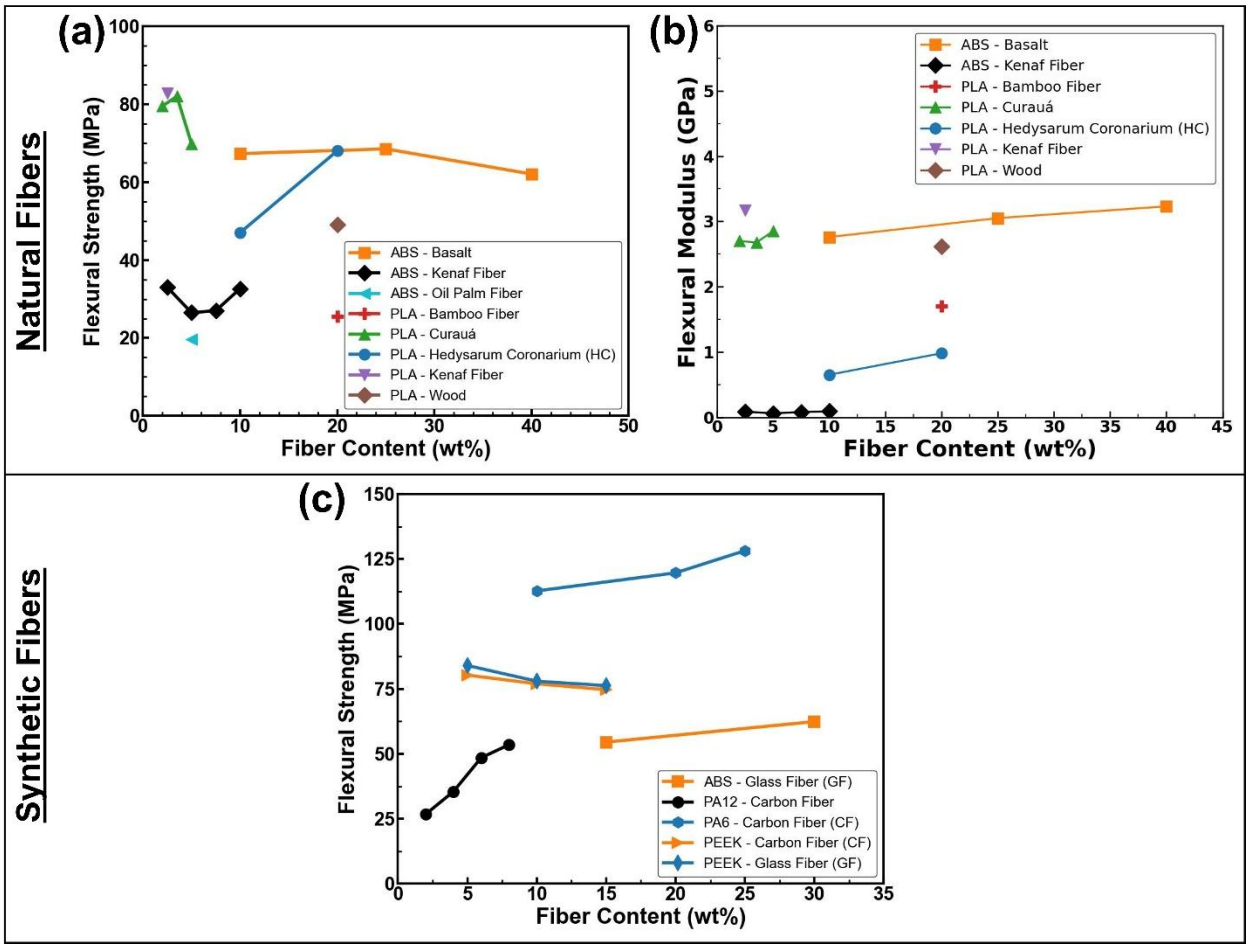

Figure 4. Flexural properties of natural and synthetic fiber-reinforced FDM composites as a function of fiber content: (a) Flexural strength versus fiber content for natural fiber-reinforced

composites, (b) Flexural modulus versus fiber content for natural fiber-reinforced composites, and (c) Flexural strength versus fiber content for synthetic fiber-reinforced composites. The figures summarize flexural performance trends reported in the literature [31-36, 40-42, 44-46, 52, 54-58] for FDM-printed fiber-reinforced composites. A corresponding plot of flexural modulus versus fiber content for synthetic fiber-reinforced composites is not presented because insufficient flexural modulus data are currently available in the literature to enable a meaningful comparison across different synthetic fiber systems.

performance. For instance, curauá–PLA composites show improved flexural strength at 2–3.5 wt% fiber loading, reaching approximately 75–89 MPa, but the strength declines at 5 wt% due to challenges related to fiber dispersion and increased defects [32]. Similarly, flax–PLA composites can reach flexural strengths of around 73 MPa, whereas wood fiber–PLA systems remain comparatively limited, typically ranging between 32 and 52 MPa [34, 35]. In some configurations, basalt/silk-reinforced PLA exhibits flexural strengths as low as 18 MPa, which likely reflects processing limitations rather than the intrinsic capability of the fibers themselves [59]. Flexural properties are also highly sensitive to printing architecture in FDM composites [53]. Parameters such as infill pattern, raster orientation, and contour count can significantly influence bending performance. For example, concentric infill patterns and increased contour layers can shift the region of maximum stress inward and substantially enhance flexural strength, in some cases having a greater impact than the choice of fiber reinforcement itself [60].

The literature-reported flexural property data [31-36, 40-42, 44-46, 52, 54-58] compiled in Fig. 4 demonstrate that both fiber type and fiber loading strongly influence the flexural performance of FDM composites. Natural fiber-reinforced composites generally exhibited flexural strengths below 85 MPa and flexural moduli below 3.5 GPa, with curauá, basalt, and Hedysarum coronarium fibers providing the greatest improvements. In contrast, synthetic fiber-reinforced composites achieved substantially higher flexural strengths, exceeding 125 MPa in some carbon fiber-reinforced systems. These results highlight the superior reinforcement efficiency of synthetic fibers for enhancing flexural performance, while natural fibers offer a sustainable alternative with moderate mechanical improvements. A direct comparison of flexural modulus trends for synthetic fibers was not possible because of the limited availability of flexural modulus data in the current literature.

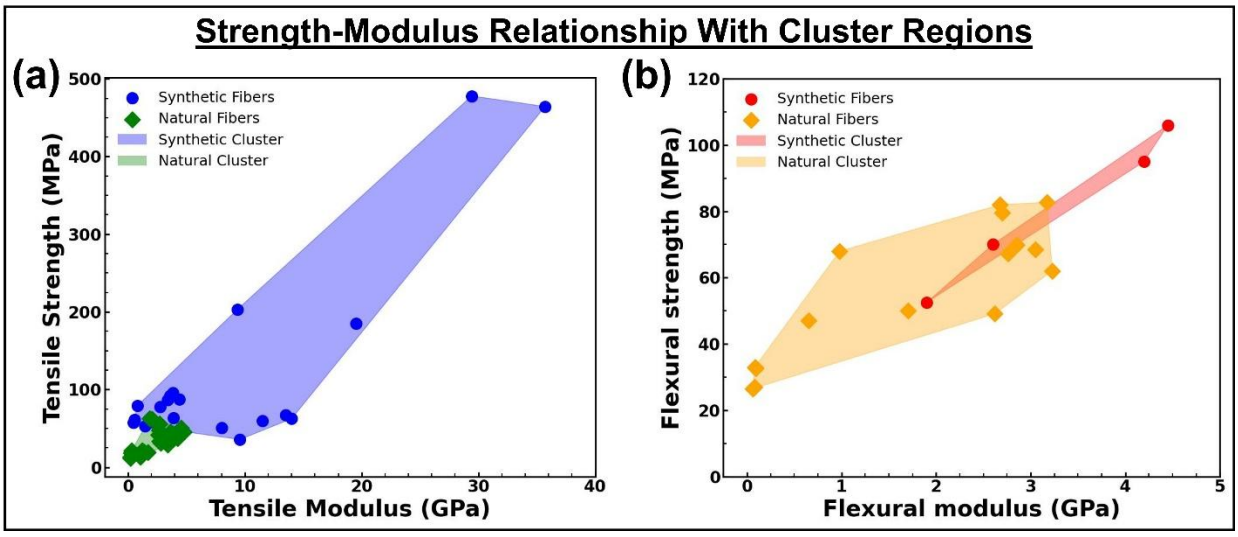

Figure 5. Strength-modulus relationships of natural and synthetic fiber-reinforced FDM composites: (a) Tensile strength as a function of tensile modulus for natural and synthetic fiber-reinforced composites, and (b) Flexural strength as a function of flexural modulus for natural and synthetic fiber-reinforced composites. Data points were compiled from the literature-reported tensile and flexural property datasets summarized in Figs. 3 and 4 [2, 27, 31-49, 52, 54-58]. Shaded regions represent cluster envelopes generated from the compiled experimental data and highlight the characteristic property domains occupied by natural and synthetic fiber-reinforced FDM composites.

The strength-modulus relationships for natural and synthetic fiber-reinforced FDM composites, compiled from the literature datasets presented in **Figs. 3 and 4**, are compared in **Fig. 5**. Distinct clustering behavior is observed between the two fiber classes. Synthetic fiber composites occupy a substantially larger and higher-performance property space, characterized by simultaneously high strength and stiffness, reflecting the superior load-transfer efficiency and intrinsic mechanical properties of carbon, glass, and aramid fibers. In contrast, natural fiber composites are concentrated within a narrower region at lower strength and modulus values, indicating more moderate reinforcement effects. Nevertheless, the clustering of natural fiber composites demonstrates their ability to provide meaningful mechanical enhancement while maintaining advantages in sustainability, low density, and renewability. The clear separation between the cluster envelopes highlights the fundamental performance gap between natural and synthetic reinforcements and provides a useful framework for selecting fiber systems based on application-specific mechanical requirements.

3.3 Impact Resistance

Impact resistance reveals one of the most pronounced mechanical differences between synthetic and natural fiber–reinforced FDM composites. Carbon fiber (CF) typically increases stiffness but may reduce toughness, often resulting in more brittle failure when fiber–matrix interfacial bonding is insufficient. In contrast, glass fiber (GF) can significantly enhance toughness due to its ability to dissipate energy during fracture [40]. For example, GF-reinforced ABS exhibits increases in impact strength of approximately 42% and 54% at fiber loadings of 15 wt% and 30 wt%, respectively[52]. Similarly, PA6 reinforced with 25 wt% CF (PA6–CF25) shows improved impact resistance with increasing fiber content, reaching 26.1 kJ/m² [31]. Among synthetic reinforcements, Kevlar fibers provide some of the highest impact resilience because of their exceptional energy absorption capacity and crack-arresting mechanisms [40].

Natural fiber composites, however, exhibit highly system-dependent impact behavior. For instance, basalt/silk-reinforced PLA can achieve impact strengths of 36.8 kJ/m², suggesting that mineral-based natural fibers may approach the toughness levels of some synthetic systems [59]. In addition, TPU-modified flax–PLA composites demonstrate a 120% increase in toughness, highlighting the significant role of matrix modification in improving energy absorption [61]. Conversely, systems such as wood–PLA and basalt-ABS composites often show reduced impact resistance, primarily due to increased brittleness and weaker fiber-matrix interfacial bonding [36, 62, 63]. Overall, the impact performance of FDM composites is governed by a combination of factors, including fiber stiffness mismatch, matrix ductility, interfacial adhesion, and void morphology, which collectively influence energy dissipation during fracture. These factors often create distinct differences in toughness behavior between synthetic fiber systems and plant-based natural fiber composites [55]. **Table 2** presents impact resistance data of short fiber-reinforced FDM composites.

Table 2. Impact resistance of short fiber-reinforced FDM composites [31, 36, 41, 42, 45, 52, 54, 55, 58, 62-64].

Matrix Material	Fiber Type	Fiber Content (wt%)	Impact Resistance
PA6	CF	10%	9.2-13.1 kJ/m²
PA6	CF	20%	12.1-15.2 kJ/m²
PA6	CF	25%	15.1-26.1 kJ/m²
ABS	GF	15%	2.22 J/mm²
ABS	GF	30%	2.86 J/mm²
ABS	CF	2.9 vol%	0.046 kJ/m²
ABS	BF	10%	60.69 J/m
ABS	BF	25%	53.41 J/m
ABS	BF	40%	41.42 J/m
PLA	CF	Not reported	3.27-4.04 kJ/m²
PLA	Wood	Not reported	44.76 J/m
PLA	HC	10%	2.65 MJ/m³
PLA	HC	20%	3.83 MJ/m³
PLA	Bamboo	20%	9.1±0.2 kJ/m²
PLA	Wood	30%	9.4±0.9 kJ/m²
GFRP + CA	Hemp	Not reported	400 J/m
PEEK	GF	15%	21.2±1.7
PEEK	CF	5%	24.9±2.1
PEEK	CF	10%	22±1
PEEK	CF	15%	18.3±1.3
PA12	CF	2%	12±1
PA12	CF	4%	12.5±0.5
PA12	CF	6%	18.25±2
PA12	CF	8%	19±2.5
PA12	CF	10%	25±2

CF = carbon fiber; GF = glass fiber; BF = basalt fiber; HC = Hedysarum Coronarium

3.4 Influence of Fiber Characteristics on Mechanical Performance

The mechanical performance of short fiber-reinforced composites fabricated through FDM is strongly governed by the characteristics of reinforcing fibers. In contrast to neat polymers, where properties are primarily dictated by the matrix, fiber-reinforced systems depend on a combination of fiber type, geometry, and orientation to achieve effective load transfer and structural reinforcement. These fiber-related parameters influence not only strength and stiffness but also toughness, anisotropy, and overall reliability of printed components. In FDM, the role of fiber characteristics becomes even more critical due to processing-induced effects such as shear-driven alignment, fiber breakage during extrusion, and variability in fiber dispersion. As a result, the reinforcing efficiency of fibers is not solely determined by their intrinsic properties but also by how they evolve during filament fabrication and printing.

Accordingly, the discussion is organized around three key aspects that collectively define the mechanical behavior of fiber-reinforced FDM composites: the type of fiber used (natural versus synthetic), the fiber length and aspect ratio relative to critical load transfer requirements, and the degree of fiber alignment induced during extrusion and deposition. Together, these factors establish the extent of reinforcement, govern anisotropic behavior, and determine the balance between mechanical performance and processability in FDM printed composites.

3.4.1 Fiber Type

The mechanical performance of FDM-printed short fiber composites is strongly influenced by the intrinsic properties of the reinforcing fibers, including their stiffness, strength, toughness, density, and compatibility with the thermoplastic matrix [29]. While the polymer matrix establishes the baseline mechanical behavior, the choice of fiber ultimately determines the upper limits of reinforcement and defines the trade-offs among stiffness, strength, impact resistance, processing complexity, and sustainability [27, 32]. Among synthetic reinforcements, carbon fiber (CF) is widely used due to its exceptionally high Young's modulus and tensile strength combined with low density, enabling significant stiffness enhancement in lightweight structures [27]. These attributes make CF particularly attractive for load-bearing applications. However, its brittle nature can reduce impact resistance, and its abrasive characteristics can accelerate nozzle wear during FDM processing [65]. In addition, the relatively high cost of carbon fiber can limit its adoption in cost-sensitive applications. Glass fiber (GF) offers a more economical alternative, providing a balanced combination of strength and stiffness that is often comparable to basalt fibers [27]. Glass fibers are electrically insulating, less abrasive than carbon fibers, and can improve impact performance in certain composite systems, making them suitable for a wide range of functional components [52].

Aramid fibers, such as Kevlar®, are distinguished by their exceptional toughness and high tensile strength-to-weight ratio. These fibers primarily contribute to improved impact resistance rather than significant stiffness enhancement [66]. However, their relatively low compressive strength and tendency to fibrillate during processing can present challenges for FDM manufacturing. As a result, their reinforcement efficiency under compression-dominated loading is typically lower than that of carbon or glass fibers. In addition to synthetic reinforcements, natural and mineral fibers provide alternative strategies with reduced environmental impact. Basalt fiber occupies a unique position between synthetic and natural reinforcements, offering strength and stiffness comparable to E-glass fiber while providing superior thermal resistance, chemical stability, and acoustic damping [36]. Its production also requires fewer additives than conventional glass fiber, contributing to an improved environmental profile [67]. Among plant-based fibers, flax and hemp are widely studied due to their favorable specific mechanical properties, low density, renewability, and biodegradability [68]. However, their mechanical performance can vary significantly depending on plant origin, growth conditions, and processing history. Their hydrophilic nature and limited thermal stability can also restrict processing conditions and long-term durability [69].

Wood fibers and wood flour, although abundant and low-cost, generally function more as fillers than true reinforcements in FDM composites [68]. While they may increase stiffness, they often reduce tensile and flexural strength [35]. Curauá fiber, a high-cellulose leaf fiber, has attracted attention because it offers relatively high mechanical performance among natural fiber reinforcements [32]. Overall, natural fibers offer several advantages, including lower density, reduced cost, renewability, lower tool wear during processing, and partial carbon neutrality during plant growth. However, these benefits are often offset by challenges such as moisture sensitivity, lower processing temperatures, interfacial compatibility issues, and greater variability in material properties [29]. To address these limitations, hybrid reinforcement strategies such as combining natural and synthetic fibers or blending different natural fibers have emerged as promising approaches to balance mechanical performance, manufacturability, and sustainability in FDM-printed short fiber composites [22].

3.4.2 Fiber Length and Aspect Ratio

The reinforcing efficiency of short fibers in FDM composites is strongly influenced by fiber length relative to the critical fiber length required for effective stress transfer. Fibers shorter than this threshold cannot fully develop tensile stress through interfacial shear, which limits their contribution to load bearing within the composite [16, 45]. When the fiber length exceeds the critical value, improvements in tensile strength, stiffness, and, in some cases, impact resistance are typically observed. Longer fibers enable more efficient stress transfer between the fiber and matrix and provide enhanced crack-bridging capability [44]. For example, experimental studies on carbon fiber–reinforced polypropylene have demonstrated clear correlations between average fiber length and improved mechanical performance, confirming the theoretical advantages of longer reinforcing fibers [46, 47].

In practical applications, however, the benefits of longer fibers are often constrained by processing-induced fiber attrition. Significant fiber breakage occurs during melt compounding and is further intensified during FDM extrusion due to high shear stresses within the nozzle and fiber–fiber interactions. Consequently, the final fiber length distribution in printed parts is frequently much shorter than the nominal length of the feedstock fibers, with many fibers falling below the critical length required for efficient reinforcement [2]. This reduction can limit the achievable mechanical enhancement and, in some cases, causes processing conditions to have a greater influence on mechanical performance than the initial fiber length itself.

Moreover, at higher fiber loadings, increasing fiber length may negatively affect processability by hindering dispersion, promoting fiber entanglement, and introducing defects, which can ultimately reduce stiffness and strength [70]. Similar trends have also been observed in natural fiber systems, where increasing the initial fiber length does not necessarily translate into improved mechanical performance when interfacial adhesion or processing quality is inadequate [32]. These findings highlight that fiber length, aspect ratio, and processing parameters must be optimized collectively rather than independently in order to achieve effective reinforcement in FDM short fiber composites.

3.4.3 Fiber alignment

Shear forces generated during extrusion strongly align short fibers along the printing path. While this alignment enhances reinforcement in the extrusion direction, it simultaneously weakens properties in the transverse direction and increases the contrast between in-plane and out-of-plane mechanical responses [2]. Stiff fibers, particularly carbon and glass fibers, can further intensify these discontinuities across printed layers and raster lines, amplifying the anisotropic behavior of the material [31]. As a result, FDM-printed composites typically exhibit pronounced directional dependence in mechanical performance. Tensile and flexural strengths are generally highest along the raster direction within the X–Y plane, while the lowest strengths occur in the Z-direction, where failure is primarily governed by interlayer bonding [27]. Strength reductions of 50–75% in the Z-direction relative to in-plane properties are commonly reported, and in fiber-reinforced systems this disparity can exceed 80–90% [71]. Even within the X–Y plane, mechanical properties may differ between directions parallel and perpendicular to the raster orientation, reflecting the influence of fiber alignment on local stiffness and load transfer [65].

Reported levels of anisotropy vary widely in the literature, ranging from 26–88% in ABS-based systems to values exceeding 160% in PLA composites, highlighting the strong sensitivity of mechanical performance to printing parameters, material selection, and fiber characteristics

[72]. Synthetic fibers, due to their high stiffness and strong alignment during extrusion, often enhance in-plane reinforcement but also amplify directional contrasts in mechanical properties. In comparison, natural fibers typically exhibit lower stiffness and less uniform geometry, which may reduce the degree of in-plane strengthening but can sometimes result in slightly lower overall anisotropy. Compared with other additive manufacturing techniques such as Selective Laser Sintering (SLS) which generally exhibits lower anisotropy levels of approximately 15-20% or conventional molded composites that possess more homogeneous microstructures, FDM remains significantly more direction-dependent [72]. Consequently, reducing anisotropy through improved interlayer fusion, reduced porosity, and better control of fiber orientation remains a critical challenge for advancing FDM short fiber composites toward reliable load-bearing structural applications.

3.5 Mechanical Anisotropy

Mechanical anisotropy is a defining characteristic of FDM-printed fiber-reinforced composites and remains one of the major limitations for their use in structural applications. This directional behavior arises from the inherent architecture of the printing process and is further amplified by the alignment and behavior of short fibers during extrusion [2]. Several mechanisms collectively contribute to this anisotropic mechanical response. FDM components are fabricated through a layer-by-layer deposition process, where successive filaments are stacked to form the final structure. This manufacturing approach inherently creates planar interfaces between layers, which act as mechanical boundaries and contribute to directional differences in material performance. In addition, when molten material is deposited onto previously printed layers that have partially cooled, polymer chain diffusion across the interface is limited [73]. This results in incomplete bonding between adjacent layers and rasters, leading to weak interfacial regions within the printed structure. These weak interfaces often become the dominant sites of failure, particularly under tensile or shear loading in the Z-direction, where cracks can propagate along poorly fused planes [74]. Another contributing factor is the formation of voids within the printed structure. The geometry of deposited filaments naturally produces voids, often triangular or rhombus-shaped, between adjacent filaments [75]. These voids reduce the effective load-bearing cross-sectional area and act as stress concentrators that can initiate crack formation. In fiber-reinforced systems, porosity may increase further due to disrupted melt flow, fiber agglomeration, or insufficient wetting of fibers by the polymer matrix, which can further compromise the mechanical integrity of the composite [2, 76].

4 Thermal and Chemical properties

The thermal and chemical behavior of short fiber-reinforced composites plays a central role in defining both their processability during FDM and their durability under service conditions. In extrusion-based additive manufacturing, materials are exposed to elevated temperatures, shear stresses, and environmental conditions that can significantly alter their structural integrity and long-term performance. As a result, thermal stability, chemical resistance, and environmental durability become critical factors in determining the suitability of a given fiber–matrix system for practical applications. These properties are strongly influenced by the combined effects of fiber type, polymer matrix, and processing conditions. Notably, important distinctions arise between natural and synthetic fiber systems due to differences in intrinsic thermal resistance, chemical stability, moisture sensitivity, and susceptibility to environmental degradation [77].

In this context, this section is structured around key aspects including thermal stability during processing, the influence of matrix selection and printing parameters, and the chemical resistance and environmental durability of the resulting materials. Particular emphasis is placed on moisture-driven degradation mechanisms in natural fiber systems, which remain a key limitation in their broader adoption.

4.1 Thermal Stability of FDM Fiber Composites

Thermal stability is a key factor in FDM processing because filaments must tolerate the high temperatures of the printer liquefier, which typically range from 180 °C to more than 300 °C, depending on the polymer matrix [78]. Any thermal degradation that occurs during extrusion, whether in the matrix or the reinforcing fibers, can reduce molecular weight, weaken mechanical performance, and introduce processing defects such as voids or nozzle blockage [79]. Natural fibers generally exhibit lower thermal stability than synthetic reinforcements. Their primary components-hemicellulose, cellulose, and lignin-decompose sequentially as temperature increases, placing clear limitations on their compatibility with high-temperature thermoplastics. Thermal degradation often begins near 200–220 °C, with hemicellulose decomposing first, followed by cellulose at higher temperatures[78]. These temperatures are close to, or sometimes below, the processing temperatures required for engineering polymers such as polyamide, polycarbonate, ABS, and PEEK. Consequently, natural fiber–reinforced FDM composites are typically processed using lower-melting polymers such as PLA or polypropylene [74, 80, 81]. Chemical treatments can partially improve the thermal stability of natural fibers. Alkaline and silane surface modifications are commonly used to remove thermally unstable components and enhance fiber–matrix adhesion. These treatments have been reported to increase the onset of degradation by approximately 20-50 °C in systems such as flax/PLA, hemp/PLA, and PALF/PLA composites [82].

Table 3. Thermal Properties of Selected FDM Short Fiber Composites [81-85].

Fiber Type	Matrix	Treatment / Additive	Fiber wt%	T_{onset} (°C) (TGA)	T_{max} (°C) (TGA/DTG)	T_g (°C) (DSC)	T_m (°C) (DSC)
Flax	**PLA**	Untreated	10	257	301.7	59.15	158.21
Hemp	**PLA**	Untreated	10	280	319.3	56.97	152.06
PALF	**PLA**	Untreated	10	267	309.2	54.67	152.9
Flax	**PLA**	Alkali Treated	10	291	351.9	57.25	154.05
Hemp	**PLA**	Alkali Treated	10	306	334.6	58.81	150.81
PALF	**PLA**	Alkali Treated	10	295	327	57.18	153.88
SPF	**PLA**	Untreated	2.5	118.9	379.7	54	155
SPF	**PLA**	NaOH + Silane	2.5	133.6	375.2	58.9	154.3
Hemp	**PP**	Not reported	Not reported	302.8	337.5	Not reported	Not reported
Flax	**PP**	Not reported	Not reported	317.5	356.6	Not reported	Not reported
Flax	**PLA**	Untreated	Not reported	Not reported	Not reported	63 ± 2	178 ± 1
Flax	**PLA**	Plasma Treated	Not reported	Not reported	Not reported	64 ± 3	178 ± 2
GF	**PLA**	Not reported	Not reported	309.5-312.5	369.2-373.2	63.8-65.7	173.5-180.8

GF = glass fiber; PALF = pineapple leaf fiber; SPF = sugar palm fiber

In contrast, synthetic fibers are well suited for high-temperature printing and enable the use of high-performance thermoplastic matrices. Carbon and glass fibers exhibit excellent thermal stability and low coefficients of thermal expansion, contributing to improved dimensional stability during both printing and service conditions [86]. For example, in carbon

fiber–reinforced PA6 composites, the presence of carbon fibers can enhance the thermal resistance of the polymer matrix [87]. Similarly, glass fiber reinforcement in PLA or ABS increases the onset of thermal degradation and produces more gradual mass-loss behavior compared with unreinforced polymers [83, 88, 89]. Aramid fibers also tolerate elevated temperatures and are widely used in applications requiring high thermal durability [86]. Because this review contrasts natural and synthetic reinforcement systems, **Table 3** summarizes representative thermal stability values reported for short fiber-reinforced FDM composites.

4.2 Influence of Matrix and Processing Parameters

Beyond fiber selection, the polymer matrix and FDM processing conditions play a decisive role in determining the thermal behavior and overall printability of short-fiber composites. The matrix establishes the baseline thermal characteristics of the system, including the glass transition temperature, melting temperature, crystallinity, and degradation profile, which together define the allowable processing window [77]. Polymers such as PLA and polypropylene (PP) are widely used for natural fiber composites because their extrusion temperatures remain below the degradation thresholds of cellulose-based reinforcements [80, 81]. In contrast, engineering thermoplastics such as nylon, PEEK, PEI, and PPS offer superior service temperatures and thermal resistance, but their higher processing temperatures generally restrict their use to synthetic fiber reinforcements that can tolerate elevated thermal conditions [74].

Among processing parameters, extrusion temperature is particularly critical. It must be sufficiently high to ensure proper melting, flow, and interlayer bonding, yet low enough to prevent thermal degradation of the matrix or the reinforcing fibers [78]. Achieving this balance is especially challenging in natural fiber systems, where required printing temperatures may approach the onset of fiber degradation [82]. Consequently, many studies focus on identifying a narrow processing window that preserves fiber integrity while maintaining adequate print quality.

Additional printing parameters also influence the thermal history of the deposited material. Factors such as print speed, layer height, and infill density affect cooling rates, void formation, and the quality of interlayer fusion [79]. These microstructural differences can in turn influence thermal stability. For instance, glass fiber–reinforced PLA composites have shown slightly higher degradation onset and completion temperatures when printed at higher infill densities, likely due to improved thermal uniformity and reduced internal defects [83].

Fiber loading is another important variable. Increasing fiber content raises melt viscosity, which can hinder material flow, weaken interlayer bonding, and increase the risk of nozzle clogging. Although the influence of fiber loading on degradation temperature is generally modest, processability becomes the main constraint at high reinforcement levels. Maintaining an appropriate balance between reinforcement level and printing reliability is therefore essential for practical FDM composite manufacturing [79]. In summary, the matrix selection, extrusion temperature, printing parameters, and fiber loading collectively define the practical thermal-processing window for FDM composites. Effective processing requires optimizing these factors simultaneously rather than considering them independently.

4.3 Chemical Resistance

The chemical resistance of FDM fiber-reinforced composites is governed primarily by the polymer matrix, which determines whether the material can withstand exposure to solvents, acids, bases, oils, or cleaning agents without swelling, softening, or losing structural integrity

[74]. Among commonly used thermoplastics, PLA exhibits relatively limited solvent resistance. Although it remains stable in water, it is susceptible to organic solvents such as acetone, MEK, toluene, and dichloromethane, which can cause dissolution or interlayer delamination. ABS provides improved thermal and chemical stability but is also vulnerable to ketones and certain esters. Nylon demonstrates strong resistance to oils and greases but can degrade in the presence of strong acids; its hygroscopic nature also affects performance under humid conditions. PETG offers broader chemical resistance and good temperature tolerance, making it suitable for applications involving detergents or mild solvents [74]. Polypropylene (PP) similarly exhibits excellent chemical stability and is often selected for natural fiber composites due to its compatibility with lower processing temperatures [81]. High-performance matrices such as PEEK provide exceptional resistance to a wide range of solvents and corrosive environments [74].

Reinforcement fibers also contribute to the chemical behavior of the composite. Natural fibers, composed primarily of cellulose, hemicellulose, and lignin, are less chemically inert than synthetic fibers and can undergo hydrolysis in acidic or alkaline environments. Their polysaccharide structure makes them more susceptible to molecular degradation under harsh chemical conditions [90]. Chemical treatments, such as alkaline or silane modification, are frequently used to remove unstable components and improve fiber–matrix adhesion [84]. However, even with these treatments, natural fiber composites generally exhibit lower chemical durability than those reinforced with synthetic fibers [91].

Synthetic fibers, in contrast, provide greater chemical stability. Carbon fiber is largely inert and resistant to corrosion, contributing to improved composite stability in chemically aggressive environments, although galvanic interactions may occur when in contact with certain metals [87]. Glass fiber also exhibits strong resistance to many solvents and corrosive agents, maintaining structural integrity across a wide range of chemical exposures [83]. Aramid fibers, including Kevlar®, similarly demonstrate good resistance to chemical degradation and are frequently used in applications requiring durability in chemically demanding environments [92].

4.4 Environmental Durability

Environmental durability describes the ability of FDM composites to maintain structural integrity and mechanical performance under prolonged exposure to ultraviolet (UV) radiation, moisture, temperature fluctuations, and freeze–thaw cycling [93]. These environmental factors are particularly important for applications requiring long-term service or outdoor exposure. Natural fiber composites generally show limited environmental durability. Both plant-based fibers and commonly paired matrices such as PLA are susceptible to UV-induced degradation [93]. Lignin, a major component of natural fibers, undergoes photochemical degradation when exposed to UV radiation, leading to discoloration, surface embrittlement, microcracking, and progressive loss of mechanical properties [91]. Moisture exposure further accelerates this deterioration. Because natural fibers are inherently hydrophilic, they readily absorb water, which leads to fiber swelling, interfacial debonding, hydrolytic degradation of fiber constituents, and plasticization of the surrounding polymer matrix [90]. These processes reduce stiffness and strength, particularly during cyclic wetting–drying or freeze–thaw exposure. Comparative studies have shown that 3D-printed bio-based composites degrade more severely under moisture and freeze–thaw conditions than synthetic fiber composites such as CF/ABS systems [93]. Although biodegradability is desirable from a sustainability perspective, it can limit long-term durability in

humid or biologically active environments, restricting the use of natural fiber composites in outdoor applications [94].

Synthetic fiber composites generally exhibit superior environmental durability, although performance still depends on matrix selection. Carbon and glass fibers are inherently resistant to UV radiation and moisture and therefore do not undergo photochemical or hydrolytic degradation [80]. When combined with weather-resistant polymers such as ASA, PETG, PP, or high-performance thermoplastics, these composites maintain stable mechanical performance under extended environmental exposure [74]. Even in PLA-based systems, glass fiber reinforcement has been shown to significantly improve resistance to accelerated weathering, with PLA/GF composites retaining substantially higher tensile strength than neat PLA after prolonged UV and moisture cycling [95]. Moisture sensitivity in synthetic fiber composites is generally low, although exceptions may occur in systems containing hygroscopic matrices such as nylon or moisture-absorbing reinforcements such as aramid fibers [74]. Outside of these cases, synthetic fiber composites exhibit considerably greater resistance to environmental degradation than natural fiber counterparts.

4.5 Moisture Effects on Natural Fiber Composites

Moisture sensitivity represents one of the most critical limitations of natural fiber–reinforced FDM composites. Environmental durability reflects a material's ability to maintain mechanical integrity when exposed to moisture, UV radiation, temperature fluctuations, and freeze–thaw cycles, and these conditions disproportionately affect plant-based fiber systems [74]. Natural fibers readily absorb moisture due to their hydrophilic cellulose-based structure. Water uptake can lower the glass transition temperature of the polymer matrix, accelerate thermal degradation during heating, and weaken fiber–matrix interfacial bonding, ultimately reducing load transfer efficiency and mechanical strength [96]. Prolonged moisture exposure also promotes fiber swelling, hydrolysis of fiber components, and plasticization of both fiber and matrix phases [79, 90, 96]. These mechanisms are intensified during cyclic environmental conditions such as repeated wetting–drying or freeze–thaw exposure, leading to progressive reductions in stiffness and strength [90]. **Fig. 6** shows a schematic representation of moisture absorption and degradation mechanisms in natural fiber composites.

In contrast, synthetic fiber composites generally exhibit much lower moisture sensitivity. Carbon and glass fibers are resistant to moisture and UV radiation and therefore maintain structural stability during long-term environmental exposure [97]. When combined with durable matrices such as ASA, PETG, PP, or other engineering polymers, these systems retain their mechanical properties under accelerated aging conditions. Even in PLA-based composites, glass fiber reinforcement significantly improves resistance to UV–moisture degradation, enabling greater strength retention compared with unreinforced PLA. Moisture sensitivity in synthetic systems is generally low, with notable exceptions involving hygroscopic matrices such as Nylon or moisture-absorbing reinforcements such as aramid fibers [74, 92].

Various strategies have been proposed to mitigate moisture-related degradation in natural fiber composites. These include fiber surface treatments, matrix modification, hybrid reinforcement with synthetic fibers, protective coatings, and careful filament drying prior to

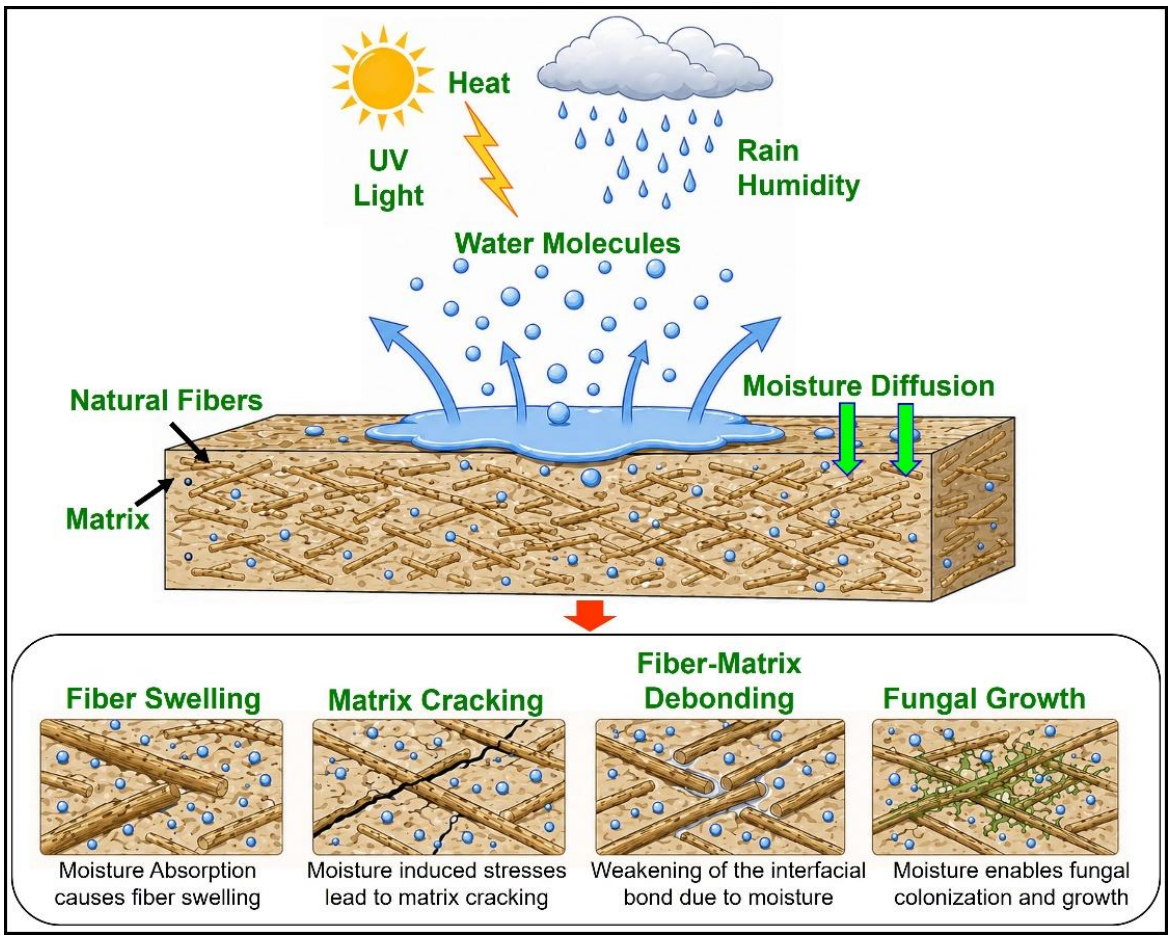

Figure 6. Moisture absorption and degradation mechanisms in natural fiber composites.

printing [89, 90, 96, 98]. Despite these approaches, moisture-induced degradation remains the primary factor limiting the long-term durability of natural fiber composites compared with carbon- and glass-fiber-reinforced systems, and it continues to constrain their use in demanding structural and outdoor applications [98].

5 Printability and Processability

The incorporation of short fibers into thermoplastic matrices introduces complex rheological, thermal, and interfacial interactions that directly govern the printability and processing efficiency of FDM-based composite systems [24]. Unlike neat polymers, fiber-reinforced materials exhibit altered melt behavior, flow characteristics, and interlayer bonding dynamics, which collectively influence extrusion stability, dimensional accuracy, and defect formation during printing. These processing responses are highly dependent on fiber type, fiber loading, and fiber–matrix compatibility, leading to distinct differences between natural and synthetic fiber systems. Synthetic fibers generally enable more stable and predictable processing due to their uniform geometry and thermal stability, whereas natural fibers introduce additional variability associated with moisture sensitivity, heterogeneous morphology, and lower thermal resistance. As a result, achieving reliable and defect-free printing requires careful coordination of material formulation, processing parameters, and printer design.

In this context, printability is governed by several interrelated factors, including melt rheology and flow behavior during extrusion, interlayer adhesion and interfacial quality, dimensional accuracy and surface finish, and the influence of printer architecture and toolpath strategies. Together, these aspects define the process-structure-property relationships that ultimately determine the manufacturability and performance of short fiber-reinforced FDM composites.

5.1 Rheological Behavior and Flow Characteristics

The addition of short fibers generally increases the melt viscosity of the polymer–fiber mixture, particularly at higher fiber loadings or when fibers are long or poorly dispersed. While increased viscosity can improve structural stiffness during deposition, it also raises the risk of nozzle clogging, incomplete extrusion, and reduced interlayer bonding, especially under the shear conditions typical of FDM printing [99]. Synthetic fibers such as milled carbon fiber and glass fiber typically exhibit more uniform geometry and higher thermal stability, allowing for higher reinforcement loadings and more consistent flow behavior. Studies by Ning et al. and Alarifi et al. show that carbon fiber– and glass fiber–reinforced PLA and PETG composites maintain acceptable flowability at fiber contents up to 30 wt%, although some reduction in dimensional precision may occur [100]. In contrast, natural fibers often introduce greater processing challenges. Their irregular geometry, moisture sensitivity, and lower thermal stability can complicate extrusion behavior [101]. Variations in particle size and the presence of lignocellulosic impurities may lead to inconsistent melt flow and localized thermal degradation during printing. To mitigate these issues, preprocessing steps such as fiber drying, surface modification, and controlled particle sizing (typically 100-200 μm) are commonly employed.

5.2 Layer Adhesion and Interfacial Quality

Successful deposition in FDM relies heavily on interlayer diffusion and adhesion, both of which are affected by the presence of reinforcing fibers [25]. Short fibers can restrict polymer chain mobility at the interface between layers, particularly when fibers are oriented perpendicular to the build direction. This can contribute to anisotropic mechanical behavior and potential interlayer delamination [26]. In synthetic fiber–reinforced composites, improved stiffness and strength often come at the cost of reduced interlayer bonding, especially at high fiber loadings. Maintaining sufficient melt flow and thermal diffusion during deposition is therefore essential to preserve layer fusion [18]. Researchers have explored modifications such as optimized nozzle geometries, oscillating infill paths, and elliptical extrusion dies to improve fiber alignment and promote more uniform bonding between printed layers.

Natural fiber composites tend to exhibit more pronounced interfacial compatibility issues, primarily due to the polarity mismatch between hydrophilic plant fibers and hydrophobic thermoplastic matrices. Poor adhesion can lead to microvoid formation, increased porosity, and rough surface finishes, particularly at higher fiber contents [102]. Surface modification techniques including alkaline treatment, enzymatic functionalization, and silane grafting have been shown to significantly improve fiber wettability and fiber–matrix adhesion [101]. By enhancing compatibility between fibers and the polymer matrix, these treatments improve both interlayer bonding and overall mechanical performance. Additionally, fiber pull-out during deposition is commonly observed in natural fiber composites and is frequently identified in scanning electron microscopy (SEM) images of fractured samples [101]. This phenomenon

indicates insufficient interfacial shear strength and incomplete wetting of fibers by the matrix at the microscale.

5.3 Dimensional Accuracy and Surface Quality

Fiber type, loading level, and printing parameters strongly influence the dimensional stability and surface finish of FDM-printed composites [13]. In synthetic fiber composites, the high stiffness and thermal stability of the reinforcing phase generally improve dimensional stability during cooling. However, increasing fiber content often leads to reduced surface quality. At fiber loadings exceeding approximately 20-30 wt%, fibers may protrude through the outer layers, producing surface striations, increased roughness, and irregular layer widths [103]. Natural fiber composites tend to introduce greater variability in dimensional accuracy. Because plant fibers absorb moisture from the environment, they may swell during extrusion and subsequently contract during cooling. This behavior can lead to warping, curling, and layer misalignment, particularly in open-frame desktop FDM printers that lack environmental control.

Differences in the coefficients of thermal expansion between fibers and the polymer matrix, especially when hygroscopic natural fibers are used, can generate residual stresses during cooling and crystallization. These stresses may cause internal strain and distortion, making dimensional accuracy more difficult to achieve compared with synthetic fiber systems [104]. Several strategies have been proposed to improve dimensional stability. These include the use of closed-chamber printers, controlled build environments, in situ thermal or UV curing, and optimized raster angles and infill densities to reduce internal stresses. Post-processing treatments such as annealing or controlled heating have also been investigated as methods for relaxing residual stresses and improving geometric fidelity.

5.4 Printer Design and Toolpath Strategies

Recent advances in FDM printer technology have improved the ability to process short fiber composites with greater reliability and precision. These developments include dual-feed extruders capable of co-depositing fibers and matrix materials, reinforced hot-end designs that tolerate abrasive fillers, and improved thermal management systems that minimize temperature gradients during printing. Toolpath design also plays a crucial role in controlling internal stress distribution and mechanical anisotropy in fiber-reinforced composites. Aligning the print path with anticipated load directions can significantly enhance the load-bearing performance of synthetic fiber composites, while alternating raster orientations (e.g., ± 45° patterns) helps distribute stresses more evenly and limit crack propagation [105].

Printing natural fiber composites typically requires lower layer heights, slower printing speeds, and carefully controlled deposition rates. These adjustments increase interlayer contact time and allow more effective thermal diffusion between layers, improving bonding and reducing defects such as voids, incomplete fusion, or weak interfacial regions [106, 107]. Researchers have also explored hybrid reinforcement strategies, combining natural and synthetic fibers within a single composite system to balance mechanical performance with environmental sustainability. In such systems, toolpath optimization becomes even more critical to ensure uniform reinforcement distribution and consistent thermal behavior across printed layers [108].

6 Environmental Impact and Sustainability

Environmental sustainability has become a critical consideration in the development and application of short fiber-reinforced composites for FDM. Beyond mechanical performance and

printability, the overall environmental footprint of these materials is influenced by a combination of factors, including raw material sourcing, energy consumption during processing, service life, and end-of-life management. The sustainability of fiber-reinforced systems is therefore not determined by a single parameter but by the cumulative effects of material selection, manufacturing processes, and long-term performance. Significant differences exist between natural and synthetic fiber systems due to their distinct production pathways, resource requirements, and environmental trade-offs. Natural fibers are typically associated with renewable sourcing and lower embodied energy, whereas synthetic fibers often require energy-intensive processing but offer enhanced durability and longer service life. As a result, a comprehensive evaluation framework is required to accurately assess their environmental performance.

In this context, sustainability considerations are addressed through life cycle analysis, which captures impacts from material extraction to end-of-life, as well as through an assessment of recyclability, degradation behavior, and disposal pathways. These aspects collectively determine the long-term environmental viability of FDM composite systems and provide insight into strategies for improving their sustainability.

6.1 Lifecycle and Environmental Considerations

Life Cycle Assessment (LCA) provides one of the most comprehensive frameworks for evaluating the environmental performance of FDM-based short fiber composites. According to ISO 14044:2006, LCA evaluates environmental impacts across the entire life cycle of a material, from raw material extraction and processing to filament production, printing, product use, and end-of-life management [109]. The methodology generally involves several key stages: defining the goal and scope of the assessment, establishing appropriate system boundaries, selecting a functional unit that allows meaningful comparison between materials or processes, compiling life-cycle inventory data on energy and material flows, and translating these data into environmental impact categories through the Life Cycle Impact Assessment stage[110]. For FDM composites, the choice of functional unit is particularly important when comparing natural and synthetic reinforcements. Evaluations based on equal material mass often favor natural fibers because of their lower density. However, when comparisons are based on equivalent mechanical performance or structural functionality, the results may favor synthetic fibers that provide higher strength and durability [110].

Applying LCA to emerging composite systems can present several challenges. Reliable data on novel materials, FDM-specific filament extrusion processes, and the energy requirements of additive manufacturing are often incomplete or inconsistent [111]. Furthermore, environmental outcomes may vary significantly depending on regional electricity mixes, agricultural practices associated with natural fiber production, and methodological decisions related to allocation rules or system boundaries [112]. For credible results, LCA studies must clearly document assumptions, rely on robust databases, and perform sensitivity analyses to account for uncertainties [113]. Transportation distances for raw fibers, particularly when natural fibers are imported across continents, can also significantly influence environmental outcomes and potentially offset some sustainability advantages [111].

Comparative LCA studies generally indicate that natural fibers such as flax, hemp, and jute exhibit lower cradle-to-gate energy demand and greenhouse gas emissions than synthetic fibers such as glass or carbon fiber [114]. Their renewable origin and the carbon sequestration that occurs during plant growth contribute to reduced global warming potential [115]. In contrast,

synthetic fibers are derived from non-renewable feedstocks and require energy-intensive manufacturing processes. For example, glass fiber production involves high-temperature melting, while carbon fiber manufacturing requires oxidation, carbonization, and graphitization processes often exceeding 1000 °C, resulting in substantially higher embodied energy and emissions [116].

However, the environmental advantages of natural fibers can be moderated by agricultural impacts. Cultivation may require land, irrigation water, fertilizers, and pesticides, which can contribute to eutrophication, ecotoxicity, and other environmental burdens [115, 117]. Some studies report that although flax performs favorably in energy and carbon metrics, it may exhibit higher impacts in categories such as aquatic toxicity or nutrient runoff when compared with glass fiber [111]. Conversely, synthetic fibers have higher production impacts but provide better mechanical performance and durability. These characteristics may reduce environmental burdens during the use phase, particularly in transportation-related applications where weight reduction leads to lower operational energy consumption [118]. In certain scenarios, these use-phase benefits can partially offset the higher production impacts associated with synthetic fiber manufacturing when evaluated across the full life cycle [114].

It is also important to note that LCA results derived from other sectors, such as textiles or traditional composite manufacturing, cannot be directly applied to FDM-based composite systems [117]. Additive manufacturing introduces unique factors, including filament compounding processes, fiber–matrix interface treatments, and the thermal and rheological constraints associated with extrusion-based printing [119]. These system-specific variables must be incorporated into dedicated LCA models. Therefore, while existing studies provide valuable insights into general environmental trends, accurate evaluation of FDM composites requires life-cycle models specifically tailored to additive manufacturing processes, material formulations, and printing conditions [111].

6.2 End-of-Life Pathways and Recyclability of FDM Composites

For thermoplastic-based natural fiber composites, recycling represents an important potential end-of-life pathway alongside biodegradation. Mechanical recycling, which typically involves shredding, washing, re-melting, and re-extruding the material, is the most accessible recycling route for PLA- or PP-based composites commonly used in FDM [120]. However, practical limitations often result in downcycling rather than full circular recovery. Repeated thermal and shear exposure during recycling can cause polymer chain scission, reduce molecular weight, and decrease tensile strength and toughness [120]. At the same time, fiber integrity deteriorates during grinding and extrusion, reducing fiber aspect ratio and diminishing reinforcement effectiveness.

Natural fibers also introduce additional challenges during recycling. Their limited thermal stability means that reprocessing temperatures above approximately 180 °C can accelerate degradation of lignocellulosic components and release volatile compounds, further compromising composite performance. In addition, moisture retained in hydrophilic fibers can trigger hydrolytic degradation of PLA during re-melting, leading to void formation and reduced processability. Interfacial adhesion between fiber and matrix may also decline with repeated processing cycles as fiber surfaces and coupling agents degrade, resulting in diminished load transfer and progressive property loss in recycled materials [120].

Synthetic fiber composites face a different set of end-of-life challenges. Carbon and glass fibers are not biodegradable, and thermoplastic composites reinforced with these materials often accumulate in landfills if effective recycling strategies are not implemented. Given their high

embodied energy, recycling is highly desirable, but recovery technologies remain technically demanding. Mechanical recycling methods usually preserve only a fraction of the original fiber performance, while thermal and chemical recovery processes can produce higher quality fibers

Table 4. Comparative environmental performance of natural vs synthetic fiber composites [86, 89, 115, 121, 122].

Feature / Lifecycle Stage	Natural Fiber Composites (e.g., Hemp/Flax/Jute in PLA)	Synthetic Fiber Composites (e.g., Carbon/Glass in PLA/PP/Nylon)
Resource Origin	Renewable (Biomass)	Non-renewable (Fossil fuels, Minerals)
Fiber Production Energy/GWP	Generally lower	High (especially carbon)
Agricultural Impacts	Significant (land, water, eutrophication, toxicity- varies by practice)	Not applicable (but chemical precursors have impacts)
Chemical Use in Production	Pesticides/fertilizers, retting, treatment chemicals	Solvents, acids, precursors
Performance/ Durability	Moderate and variable	High and consistent
Moisture Sensitivity	High due to hydrophilic fibers	Low due to hydrophobic fibers/matrix
Thermal Stability	Lower (degradation around 200-220 °C)	High
FDM Process Compatibility	Risk of thermal degradation and clogging	Generally good with suitable matrix temperatures
FDM Emissions	Matrix-dependent; fiber/additive contribution unclear	Matrix-dependent; fiber/additive contribution unclear
Biodegradability Potential	Yes, but conditional (often requires industrial composting)	No (persistent)
Recyclability Methods	Mechanical (thermoplastic); chemical (PLA matrix)	Mechanical (downcycling), thermal (fiber recovery), and chemical (fiber/monomer recovery)
Recycling Challenges	Property degradation (4-6 cycles max), fiber damage, moisture, collection issues	Energy intensive, costly, complex (chemical/thermal), fiber damage
Typical EoL Fate	Landfill, industrial composting, recycling	Landfill, incineration, limited recycling

EoL; End of lifecycle.

but are energy intensive and not yet widely used at industrial scale. [123]. These limitations highlight the importance of developing more effective recycling and recovery strategies for both natural and synthetic fiber composites as their use in additive manufacturing continues to

expand. **Table 4** summarizes key comparative considerations regarding the environmental performance and end-of-life pathways of these materials.

7 Applications

The application of short fiber-reinforced composites in FDM is governed by a balance between mechanical performance, processability, sustainability, and design flexibility. While FDM enables complex geometries and customized part design, the selection of reinforcement type ultimately determines whether a material can meet the functional demands of a given application. Synthetic fiber composites continue to dominate high-performance and load-bearing applications due to their superior strength, stiffness, and durability. In contrast, natural fiber composites are increasingly adopted in applications where environmental sustainability, cost efficiency, and reduced weight are prioritized [124]. At the same time, advances in material design and processing strategies are expanding the application space of both material classes. Hybrid reinforcement systems and functional composites are further bridging the gap between performance and sustainability. In this context, applications can be broadly categorized based on performance requirements, environmental considerations, and functional integration. This section highlights these application domains and the corresponding material strategies that enable them.

7.1 High-Performance Engineering and Structural Applications

Synthetic fiber composites, especially those reinforced with short carbon or glass fibers, are widely used in high performance sectors such as automotive engineering, aerospace components, tooling, and robotics. Their high tensile strength and stiffness, often exceeding 150 MPa in tensile strength and 10 GPa in elastic modulus, provide the structural reliability and dimensional accuracy required for demanding engineering applications [125]. Typical applications include brackets, housings, gears, and unmanned aerial vehicle (UAV) components, where high stiffness-to-weight ratios, fatigue resistance, and thermal stability are essential. For example, PETG and PLA composites reinforced with 20–30 wt% carbon fibers have been successfully used in drone arms, customized jigs, and protective equipment [103, 126]. Similarly, glass fiber–reinforced polypropylene (PP) and polyamide (PA) composites are commonly employed in under-hood automotive components, where enhanced heat resistance and fatigue durability are required [31].

Advancements in printing strategies, including optimized raster orientations and controlled fiber alignment, have further improved the performance of synthetic fiber composites in FDM. In some cases, these strategies allow printed components to achieve mechanical performance approaching that of traditional laminated composite structures. As a result, synthetic fiber FDM composites are increasingly used not only for functional prototyping but also for lightweight end-use components.

7.2 Sustainable Manufacturing and Consumer Applications

Natural fiber–reinforced composites are gaining popularity in applications where environmental sustainability, cost efficiency, and aesthetic qualities are important considerations. These materials are increasingly used in consumer goods, home appliances, educational tools, and interior automotive components. Their renewable origin, lower density, and biodegradability make them particularly attractive for non-critical load-bearing applications. Common examples

include PLA reinforced with jute, hemp, or bamboo fibers, which offer moderate mechanical performance while significantly reducing environmental impact [127].

Natural fiber composites are also being explored in applications such as sustainable packaging, acoustic panels, and decorative interior components. For instance, research by Sanjay et al. (2021) demonstrated that hybrid flax–jute fibers in a PLA matrix improved both structural rigidity and sound absorption properties, making these materials suitable for automotive dashboards, insulation panels, and interior furnishings [128].

Furthermore, natural fiber composites are finding increasing use in biodegradable wearables and temporary biomedical devices, where their low thermal conductivity, good skin compatibility, and environmentally friendly disposal characteristics are advantageous. Although challenges such as moisture absorption and dimensional instability remain, these issues can often be mitigated through fiber surface treatments, polymer blending, or hybrid reinforcement approaches.

7.3 Hybrid and Functional Applications

Beyond the exclusive use of natural or synthetic fibers, hybrid composite systems that combine both reinforcement types have emerged as an effective strategy for balancing mechanical performance with environmental sustainability. By integrating natural and synthetic fibers within a single matrix, hybrid composites can simultaneously improve tensile strength, fatigue resistance, and environmental durability, while also allowing tunable properties such as stiffness, damping, and thermal stability.

Importance of chemical surface treatments, including acetylation and silane modification, was highlighted in improving compatibility between natural and synthetic reinforcement phases within thermoset or semi-crystalline thermoplastic matrices [129]. When arranged in layered or interwoven configurations, hybrid composites often demonstrate improved impact resistance and structural reliability, making them suitable for applications such as protective enclosures, automotive fascia panels, and semi-structural frames. Hybrid fiber systems are also enabling emerging applications in smart devices, sensor-integrated components, soft robotics, and biomedical scaffolds. The incorporation of functional fillers such as carbon nanotubes or graphene oxide can further enhance electrical conductivity, sensing capability, or electromagnetic response, particularly in synthetic fiber-dominated hybrid systems. These multifunctional materials show promise for applications requiring self-sensing, electroactive, or responsive behaviors.

At the same time, bio-hybrid composites, which combine natural fibers with biodegradable polymers or functional additives, are gaining attention for flexible electronics, sustainable packaging, and environmentally friendly wearable devices [22]. Although challenges such as moisture sensitivity and interfacial compatibility remain, hybrid reinforcement provides a promising pathway to overcome these limitations while improving overall system performance. In this context, hybridization should not be viewed merely as a compromise between competing material properties, but rather as a deliberate design strategy that enables tailored performance across a wide range of applications.

7.4 Strategic Considerations and Application Mapping

The selection of natural, synthetic, or hybrid fiber reinforcements in FDM composites is ultimately driven by application-specific requirements, including mechanical performance targets, durability, cost constraints, environmental impact, and regulatory considerations [129].

Rather than a binary choice, material selection should be viewed as a design optimization problem in which trade-offs between performance, manufacturability, and sustainability must be carefully balanced. For high-load and structurally demanding applications, such as aerospace components or automotive parts, synthetic fibers are typically preferred due to their superior strength, stiffness, and long-term reliability. In contrast, natural fiber composites are more suitable for non-critical or semi-structural applications where reduced weight, lower cost, and environmental benefits are prioritized, such as consumer products, interior components, and packaging systems. Hybrid composites provide an intermediate solution, enabling tailored combinations of stiffness, toughness, and environmental performance for applications that require multifunctionality or balanced properties.

Table 5. Thermophysical and application-specific performance of representative FDM composites [31, 54, 100, 130-134].

Matrix	Fiber Type	Surface Modification / Pretreatment	Flexural Performance	Thermal Stability	Life Expectancy / Application Relevance
PLA	**SCF, 10-20 wt%**	Commercially sized CF; no extra treatment; optimized by printing parameters.	Neat PLA: 31.5 MPa; optimized parameters increased flexural strength by 28% to ~40 MPa.	CF increases crystallinity and melting temperature; degradation onset remains ~320-330 °C.	Good stiffness and dimensional stability for dry, moderate-temperature use; outdoor life limited by hydrolysis and low Tg.
PLA	**CF-MXene-GO**	CF surface functionalized with MXene-GO coating to improve interfacial adhesion.	MXene-GO coating markedly improves flexural strength and modulus compared with uncoated CF/PLA.	Higher onset decomposition temperature and char residue due to MXene-GO barrier effect.	Improved fatigue and creep resistance; interfacial reinforcement delays microcrack initiation.
PP	**SGF, ~20-30 wt%**	Silane-treated glass fibers; PP compatibilized with PP-g-MA.	Flexural strength typically 25-50 MPa; roughly up to two-fold higher than neat PP.	SGF and increased crystallinity improve heat-deflection temperature to ~110-130 °C.	Excellent multi-year durability for automotive interiors and technical parts; UV stabilization needed outdoors.
PA6	**SCF, 10-25 wt%**	Commercially sized CF; post-printing heat treatment at 120 °C improves crystallinity and interlayer diffusion.	At 25 wt% CF with optimized printing and heat treatment, flexural strength reaches ~175 MPa.	Heat treatment and CF increase crystallinity; decomposition temperature Td > 400 °C.	Suitable for long-life structural and automotive components if moisture uptake is controlled.
PETG	**SCF, 15 wt%**	Standard CF sizing; coupling agents may improve PETG-CF interfacial bonding.	CF increases flexural strength and modulus; reported strength increases of ~30-60%.	CF improves heat-deflection temperature and dimensional stability; degradation onset typically >380 °C.	Good medium- to long-term durability; less brittle than PLA and less moisture-sensitive than PA6.
ABS	**SCF, 10 wt%**	SCF introduced into ABS; interlayer bonding improved through optimized nozzle diameter and process parameters.	ABS/SCF shows 28% higher interlayer flexural adhesion; tensile strength and toughness also increase.	CF slightly raises Tg region and improves thermal conductivity; decomposition remains ~380-400 °C.	Useful for technical parts and housings; long indoor service life, but UV protection needed outdoors.

Application mapping frameworks can assist in guiding this selection process by correlating material systems with performance requirements, processing constraints, and lifecycle considerations. Such frameworks consider factors including load conditions, environmental exposure, required service life, and manufacturing limitations to identify optimal material configurations. In addition, increasing regulatory pressure toward sustainable materials and circular manufacturing is expected to further influence material selection, particularly in

industries such as automotive, construction, and consumer products. Overall, strategic material selection in FDM composites requires an integrated perspective that aligns material properties, processing capabilities, and application demands. Developing standardized application maps and decision-making tools will be essential for enabling broader adoption of fiber-reinforced FDM composites in both high-performance and sustainable manufacturing sectors. Thermophysical and application-specific performance of representative FDM composites are presented in **Table 5**.

8 Conclusion

Short fiber-reinforced composites fabricated through FDM represent an emerging class of materials that combine enhanced mechanical performance, processing flexibility, and sustainability considerations. The incorporation of short fibers significantly modifies the mechanical, thermal, chemical, and environmental behavior of printed parts. While fiber reinforcement improves stiffness, strength, and dimensional stability, it also intensifies inherent challenges of the FDM process, including anisotropy, void formation, and weak interlayer bonding. These outcomes depend on several interconnected factors such as fiber type, fiber content and morphology, matrix selection, interfacial adhesion, and processing conditions. A clear distinction exists between synthetic and natural fiber composites. Synthetic fibers such as carbon, glass, and aramid provide superior and more consistent mechanical performance, thermal stability, and durability, enabling their use in structural and high-performance applications. In contrast, natural fibers offer advantages in renewability, lower density, and reduced embodied energy, but their hydrophilicity, limited thermal stability, and variability restrict processing conditions and long-term durability. Consequently, natural fiber composites are generally better suited for applications where moderate performance and environmental sustainability are prioritized.

Thermal and chemical characteristics further define the processing boundaries of these materials. Synthetic fibers allow the use of high-temperature engineering polymers, whereas natural fibers require lower processing temperatures to avoid degradation. Although surface treatments and compatibilizers can improve interfacial bonding and stability, they cannot fully eliminate the intrinsic limitations of plant-based reinforcements. From a sustainability perspective, environmental performance must be assessed through full life-cycle analysis rather than fiber type alone. Natural fibers typically exhibit lower production energy and greenhouse gas emissions, while synthetic fibers often provide longer service life and better durability. These performance advantages can offset higher production impacts during the use phase.

Despite considerable progress, several challenges remain, including mechanical anisotropy, porosity, interlayer bonding limitations, and recycling difficulties. Future research should focus on integrated material-process optimization, including advanced fiber surface engineering, improved control of fiber orientation during printing, and hybrid reinforcement strategies combining natural and synthetic fibers. Standardized testing protocols and FDM-specific life-cycle assessments will also be essential for reliable comparison and informed material selection. Overall, short fiber-reinforced FDM composites offer significant potential for next-generation additive manufacturing. Continued advances in materials design, interface engineering, and processing strategies will be key to translating these materials from prototyping systems into reliable structural and sustainable manufacturing solutions.

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