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Enhancing the Mechanical Properties and Printability of Natural Fiber-Reinforced Filaments for Fused Deposition Modelling through Optimized Fiber Processing and Polymer Matrix Selection

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Abstract
Natural fiber composites are a more environmentally friendly substitute for petroleum-based products. Natural fibers are not only renewable and biodegradable, but also natural fibers, which are produced from plants and animals, have a large number of advantages, such as reduced emissions of greenhouse gases and more fire resistance. However, Natural fiber composites have certain drawbacks as well. They might have poor moisture absorption and have weak interfacial adhesion. These issues were the focus of research, and in recent years, a lot of progress has been made. The most common filler reinforcements used in fused deposition modelling (FDM) are synthetic and carbon fibers, but these fibers are damaging the environment. To solve the problem, the researchers have recommended using natural fibers as filler reinforcements. This paper has included the most recent findings in the field of natural fiber composites, including the advantages of using natural fibers, the difficulties we still need to overcome, and the advancements achieved thus far. In addition, we also provide a general review of the many natural fiber types that can be used in composites and the many resins that can be used to join them.

Keywords- Surface modification techniques, Sustainability, Biodegradable materials, Natural fiber composites, Fiber processing optimization.

1. Introduction

Conventional manufacturing often uses subtractive techniques to manufacture shapes as required by removing the excess material. In comparison, additive manufacturing makes an object by adding material layer by layer. Without layer-by-layer assembly, to design complicated components, it is impossible (Ning et al., 2015). As compared to traditional methods, additive manufacturing (AM) can reduce the time between design and manufacturing, which reduces cost and enhances competitiveness (Hague et al., 2003a).

The advancement of techniques, processes, and modelling has helped AM to expand its applications in many industries over the last thirty years, such as Aerospace, Automobile, and medical fields (Hague et al., 2003b).

The FDM technology offers great flexibility and seamless integration with computer-aided design (CAD) software packages. However, since it operates as a thermally controlled process, it requires the melting of thermoplastic filament before the deposition phase, leading to certain limitations on the types of materials that can be utilized in FDM. Only some materials, such as polylactic acid (PLA) and acrylonitrile–butadiene styrene (ABS), have the appropriate rheological properties (Melt Flow Index-MFI) and thermal characteristics (Glass transition temperature, Melting point, etc.) that help them to be easily processed by these technologies (Masood & Song, 2004).

Petroleum-derived polymers are a well-known source of emitting greenhouse gases during manufacturing, and they are based on non-renewable resources for product production (Gholampour & Ozbakkaloglu, 2020). Recently, the trend of using eco-friendly green materials has been boosted. Since they are recyclable, biodegradable, and renewable, they can help to reduce environmental footprints due to petroleum-based materials (Alix et al., 2014). Fully green composites are a specific category of bio-composites created by blending renewable agricultural and forestry feedstock-derived biofibers with resins. These composites do not harm the environment, as they can be safely managed and composted once their life cycle is complete (Campilho, 2015).

Biofibers have gained significant usage as both reinforcers and fillers in composite materials. These fibers originate from biological sources and can be categorized into two types: non-wood fibers, also known as natural fibers, and wood fibers. Natural fibres have superior physical and mechanical properties, and are lighter in weight as compared to wood fibres due to their higher cellulose content and crystallinity (Campilho, 2015). Natural fibers are recognized for their biodegradable qualities, aligning with the principles of eco-friendly materials. However, a significant issue that requires attention when using these composites is the adhesion bonding between the reinforced natural fibers and the polymer matrix, which can result in costly consequences, including wetting problems, swelling, and dimensional instability. This problem directly affects the composite's mechanical and physical properties (Obada et al., 2020).

Governments are now enforcing the adoption of recyclable and reusable green materials. With the declining significance of petroleum resources, societies have come to recognize the importance of preserving renewable sources for future generations, while industrialists are grasping the concept of sustainable manufacturing. At the moment, researchers are tirelessly working on developing base composites utilizing natural fiber-reinforced biodegradable polymer matrices, aiming to create the first biodegradable and sustainable products. As an example, Japan has successfully developed multiple products using kenaf fiber-reinforced polylactic acid (Netravali, 2005). Biopolymers are increasingly being explored as a viable alternative to conventional fossil fuel-based polymers. Among the extensively studied biopolymers, Polylactic Acid (PLA) has already found applications in plastic bottles and biodegradable medical devices. Moreover, Polylactic Acid (PLA) has been widely used as a matrix material in the production of composites reinforced with natural fibers (Siakeng et al., 2019).

Bio composites are eco-friendly, sustainable alternatives to conventional materials, combining renewable natural fibers with biodegradable polymers. These materials reduce dependency on non-renewable resources, lower environmental impact, and offer advantages like biodegradability, reduced weight, improved mechanical properties, and lower carbon footprint. Applications include automotive, construction, and consumer goods (Campilho, 2015). Natural fiber composites, which are also known as bio composites, are widely used in the construction and automotive industries. Within the automotive industry, they are prominently utilized for crafting interior components of vehicles. Studies have demonstrated that bio-composites offer favorable strength properties and improved fire resistance, making them a reliable choice for these industries. Significantly, the adoption of natural fiber composites enables a remarkable 20% reduction in weight and manufacturing costs for vehicles. Notably, this specific sector of the automotive industry represented more than 30% of the total revenue share in 2015. Furthermore, the demand for natural fiber composites is expected to increase by 15% to 20% in the automobile applications, and by 50% or more in selected building applications. In 2021, the construction industry accounted for 56% of the total market volume (Ahmad et al., 2015).

The objective of the review is to critically examine the latest advance in natural fiber-reinforced filaments in fused deposition modelling (FDM) especially in terms of fiber properties, methods of surface modification, choice of polymer matrix, processing pathways, and printability issues. The paper also aims at creating and defining connections between material choice, processing guidelines, and mechanical competencies in order to offer a clear-cut outline of sustainable and high-performance composite filaments.

1.1 Natural Fibers for FDM: Requirements and Constraints

Owing to concerns about the environment, including global warming, pollution, health risks, dwindling fossil resources, and diminishing economic advantages, eco-conscious materials that are renewable and biodegradable have been introduced into the production market. The aim of these eco-friendly materials is to enhance both human health and environmental sustainability (Singh et al., 2017). Scientists have started incorporating plant fibers into Bioplastics/Thermoplastics to create diverse composite filaments for Fused Deposition Modeling (FDM). This approach of using natural fibers as fillers in biopolymeric materials for FDM offers several benefits, such as cost reduction and enhanced degradability of the filaments. Moreover, it imparts a natural wood-like texture to the additive manufacturing (AM) parts. Through effective marketing, one can establish the perception that AM products are derived from renewable resources and have visually appealing designs (Siakeng et al., 2019).

The evolution of composite materials represents a contemporary advancement in response to the ever-increasing requirements of technological and industrial advancements. The enhancement of mechanical properties is a direct outcome of the unique combination achieved within these composites (Tholibon et al., 2019). Sustainability in the environment is one of the key advantages of adopting natural fiber reinforcements. Renewability, biodegradability, and a smaller carbon impact are some of these advantages. Despite the fact that these advantages are crucial, potential users may not readily understand and value them. Other clearly visible direct advantages exist, nevertheless, such as low weight, high specific characteristics, effective thermal insulation, and vibration dampening (Dicker et al., 2014).

1.2 Types of Natural Fibers

Natural fibers are made from sources that are based on plants, animals, and minerals. Tropical regions and crops are filled with fibrous plants (Campilho, 2015). Both plants and animals can serve as sources of natural fibers. They are frequently treated and turned into yarn before being turned into a final product. Natural fabrics like cotton, which tend to be soft and lightweight due to their physical properties, are preferred for use in clothing. Because of this, they are a very sought-after type of textile (Kicińska-Jakubowska et al., 2012). The strongest component of plants, cellulose, is used to make fibers from plants or vegetables, whereas proteins, such as those found in hair, silk, and wool, are typically obtained from animals (Akil et al., 2011).

The majority of natural fibers are well known for their superior capacity to efficiently absorb sweat and other liquids. To generate a range of textures, different natural fibers can be mixed with other natural fibers, or they can be used separately to make a single texture. For instance, cotton fabrics are made from cotton fibers, which are natural fibers obtained from the cotton plant and have a pleasant texture and a relatively low weight (Jawaid & Khalil, 2011). The ability to weave cotton fiber into garments in a variety of sizes and hues is another benefit of cotton. Most individuals prefer wearing clothing made of natural fibers (like cotton) over clothing made of synthetic fibers, especially those who live in hot, humid climates. In addition to being utilized in textiles, natural fibers are also commonly used in non-textile applications. On the other hand, it should be mentioned that natural fibers are thinner and less strong than synthetic fibers (John & Thomas, 2008). **Table 1** shows the types of natural fibers and their sources. **Table 1** categorizes natural fibers according to their source. Of these types, the most applicable in the context of FDM is plant-based fibers as it has a low density, biodegradable, and can be integrated with thermoplastic matrices. Animal and mineral fibers in contrast are mostly used in textile and insulation and are less applicable to extrusion-based 3D printing. Thus, the recent FDM studies revolve around plant-based fibers, like flax, hemp, jute, bamboo, and agricultural byproducts.

Table 1. Types of natural sources and their source (Akil et al., 2011; John & Thomas, 2008; Kicińska-Jakubowska et al., 2012).

Type	Source	Properties	Applications	Name of natural fibers
Plant fibers	Plants	Strong, durable, versatile	Textiles, paper, composites	Cotton, flax, hemp, jute, ramie, bamboo, sisal, kapok, coir
Animal fibers	Animals	Warm, comfortable	Clothing, bedding	Wool, silk, mohair, cashmere, alpaca, llama, vicuña
Mineral fibers	Minerals	Heat-resistant, non-flammable	Insulation, filtration	Asbestos, mica, talc

Table 1 shows the categorization of natural fibers according to their source *i.e.* plant fibers, animal fibers and mineral fibers and their sources, properties and uses. The plant, animal, and mineral natural fibers have unique structural fabric and physical properties that determine their appropriateness in diverse industrial works. Plant fibers belong to such categories, and they are the most used in composite materials because they have high amounts of cellulose, low densities, biodegradability, and are renewable. Cotton, flax, hemp, jute, bamboo, sisal, and coir are examples of these fibers that are characterized by positive mechanical properties and are usually utilized in textiles, paper production and polymer composites. Cellulose, hemicellulose, and lignin are the main components of plant fibers, they make them strong and stiff. Plant fibers contain high cellulose content which gives them structural reinforcement and increases their load bearing capacity in composite materials. Other researchers have reported that other benefits of these fibers include low density, affordability, and environmental friendliness, which, in turn, make them an excellent substitute to synthetic fibers in most engineering processes (Akil et al., 2011). Animal fibers such as wool, silk, mohair, cashmere and alpaca are primarily protein-based structures and are typically utilized in textile and clothing-related applications because of their flexibility, thermal insulation capabilities as well as fuzzy feel. Their comparative low level of stiffness and structural strength to plant fibers however limits their application as reinforcement in composite reinforcement applications (Kicińska-Jakubowska et al., 2012). Mineral fibers like asbestos, mica and talc are obtained by extracting minerals that naturally occur and they are mostly described as having a high heat rating and being able to withstand flames and that is why they can be used in insulating and as filters. Although such merits are present, the polymer composite reinforcement with mineral fibers is less widely used in comparison with plant fibers because some mineral-based materials have certain health and environmental issues. Generally speaking, **Table 1** shows that even though there is a wide range of natural fibers sources, plant-based fibers are the most applicable to composite production and additive manufacturing processes. They have good mechanical characteristics,

are renewable, and biodegradable, thus they will be ideal reinforcement materials in developing sustainable natural fiber-reinforced composite filaments that are applied in fused deposition modelling processes.

1.2.1 Compatibility

The hydrophilic character of natural fiber reinforcements renders them incompatible with the current hydrophobic resin systems employed in the industry, which is where they fall short. Additionally, their limited thermal resistance prevents them from being compatible with thermoplastic matrices that melt at high temperatures. Additionally, their compatibility with the quality requirements established by some industries, such as aerospace, is limited by the considerable variability in their mechanical, chemical, and physical properties and the absence of standardization (Gurunathan et al., 2015). They are additionally challenging to spin on current spinning lines due of their coarse texture, and they are challenging to transform into woven preforms. Because of this, nonwoven materials are employed most often as natural fiber reinforcements.

1.2.2 Trialability

While most manufacturers of composites are found in the United States, western Europe, and Japan, natural fiber reinforcements are primarily produced from plants growing in developing nations like China, Bangladesh, India, and Sri Lanka. Additionally, the widespread prohibition on hemp cultivation in some nations severely restricts its potential for experimentation. Flax is an exception because it is mostly farmed in France and Belgium, which are countries with a large concentration of composites manufacturers (Palanisamy et al., 2024). In fact, flax is now the most extensively utilized natural fiber reinforcement in these areas due to the simple and quick availability to it. The benefits and drawbacks of totally green composites compared to conventional composites are outlined in **Table 2** (Rohan et al., 2018). **Table 2** presents the advantages of fully green composites in terms of the environment and limitations in use. Even though those materials provide benefits related to sustainability, as they are biodegradable and have less carbon footprint, such obstacles as fluctuating mechanical characteristics, greater prices, and processing constraints may influence their usability in producing FDM filaments. Thus, the key to the stable 3D printing performance is the acquisition of material optimization.

The advantages and limitations of full green composites are summarized in **Table 2** and are developed by normally incorporating natural fibers within the bio-based polymer or biodegradable polymer matrices. Green benefits of these composites are one of the largest benefits since such materials are made of renewable resources, and they help save reliance on petroleum-based composites. The natural fiber-reinforced composites are also part of the lower carbon footprint, lower greenhouse gas emission, and enhanced biodegradability, which makes them eligible in the application of sustainable manufacturing processes (Campilho, 2015). Also, natural fibers present the advantage of being low density, cost effective and consuming less energy to produce, which once again increases their applicability in the development of environmentally friendly composite.

Biodegradability and a low environmental impact of green composites is another outstanding benefit as mentioned in **Table 2**. Both the reinforcement and the matrix material could be made using renewable biological materials and therefore, at the end of their life cycle, the composites could be safely discarded or even composted. Earlier research has indicated that bio-based materials have a massive impact on the reduction of waste in the manufacturing sector and that circular material systems are created (Ahmad et al., 2015). Although these are some of the environmental advantages associated with the use of fully green composites, there are a number of limitations that influence the popular use of green composites. Diverse mechanical properties of natural fibers can be one of the major issues because they may depend on the differences in the plant species, plant growth conditions, and methods of harvesting the fibers. This variability can cause inconsistency in the performance of composite and could be a limiting factor in their use in high-performance engineering structures. Moreover, natural fibers are hydrophilic in nature, i.e. they absorb moisture and this is likely to loosen interfacial bond between the fiber and polymer matrix and it has adverse consequences on the mechanical and dimensional stability of composite.

Table 2 also indicates another limitation that is the processing and economic challenges of green composites. Bio-based materials could be associated with the costs of increased production initial costs, reduced availability of raw materials, and less optimized production processes than synthetic composites. Moreover, the absence of standardized techniques of processing as well as methods of testing may become a source of challenges in the attainment of consistent material performance in various industrial applications. However, current research endeavors are geared towards perfection of fiber surface modification methods, compatibilizers and processing technology to eliminate such constraints and optimize the mechanical and environmental performance of natural fiber composites. More recent studies have gone further to state that the recent developments in bio-based polymer matrices, hybrid fiber systems, and better surface treatment are contributing towards many of these problems by incorporating better fiber-matrix compatibilities and mechanical performance. Such advances suggest that a full-fledged green composite is highly capable of being used in sustainable engineering processes such as the creation of natural fiber-reinforced filaments in fused deposition modelling (FDM) additive manufacturing where lightweight, biodegradable, and non-environmentally damaging materials are becoming more and more desired.

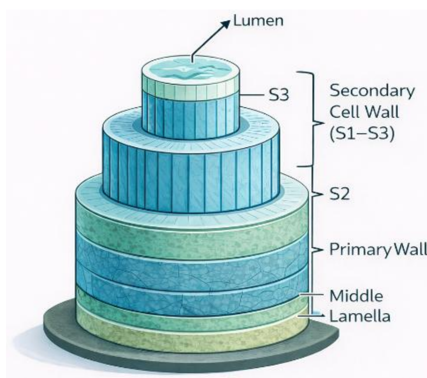

Figure 1. Structure of plant fiber (Pereira et al., 2015).

A natural fiber cell wall's structural organisation is seen in **Figure 1** (Pereira et al., 2015). **Figure 1** shows the structure of a cell wall of a natural plant fiber as a hierarchy, which is made up of various layers that are used to give the fiber its mechanical characteristics. The structure has middle lamella, primary wall, secondary wall layers (S1, S2, S3) and the central lumen. Middle lamella serves to bond the neighboring plant cells whereas the primary wall gives the wall its flexibility in that it is a composition of cellulose, hemicellulose and lignin. The thickest part is the secondary wall with the S1, S2 and S3 layers and mainly defines the strength and stiffness of the fiber due to high content of cellulose microfibrils. The lumen is a hollow space in the cell located in the middle of the fiber. Generally, the figure demonstrates the effect of chemical composition (cellulose, hemicellulose, and lignin) and stratified architecture of plant fibers on their mechanical performance, which is needed to use them as a reinforcement material in natural fiber-reinforced composite filaments in FDM additive manufacture. Animal hair, avian fibers, and silk fibers are the three main types of animal fibers. Wool and other fibers made from animal hair are obtained from furry mammals and creatures including sheep, goats, alpacas, and horses. Desiccated insect saliva used in the construction of their cocoons is the source of silk fibers. Bird feathers are used to create avian fibers (Khalil et al., 2012; Pereira et al., 2015).

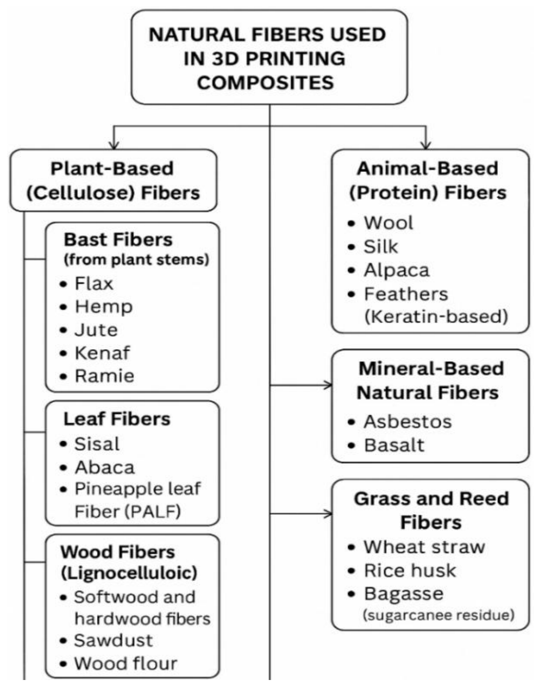

Figure 2. Classification and subclassification of fibers.

Table 2. Summary of advantages and disadvantages of green composites (Ahmad et al., 2015; Campilho, 2015; Gurunathan et al., 2015).

Aspect	Advantages of fully green composites	Disadvantages of fully green composites
Environmental Impact	Lower carbon footprint	Limited material availability
	Renewable and sustainable sources	Production processes may be less optimized
	Reduced reliance on non-renewable resources	Initial higher production costs
Biodegradability	Biodegradable and compostable	Potential for faster degradation
	Reduced waste accumulation	Limited durability
Health and Safety	Reduced emission of harmful VOCs	Variable mechanical properties
	Lower risk of toxic exposure	Limited fire resistance
Market and Perception	Attractive to environmentally conscious consumers	Lower familiarity among industries
	Compliance with eco-friendly regulations	Limited supply chain integration
Innovation and Research	Driving innovation in sustainable materials	Limited standardized testing methods
	Encouraging development of new technologies	Longer research-to-market timelines
Resource Dependence	Decreased reliance on finite petrochemicals	Potential for competition with food sources

A few scholars have experimentally investigated the performance of thermoplastic composite reinforced with natural fibers in the additive manufacturing applications. To provide an example, Ermeydan (2024) dealt with the study of flax-reinforced PLA FDM filament and reported on the enhanced stiffness but lower interlayer bonding with higher loading rates of fibers because of the poor behavior of melt flow. On the same note, Tao et al. (2017) investigated the topic of short carbon and natural fiber composites in FDM and showed that fiber content and raster orientation have significant effects on tensile strength and anisotropy. Ahmad et al. (2022) conducted a review of natural fiber composites and highlighted that the interfacial adhesion is increased by chemical treatment, including alkali and silane modification, which leads to better mechanical properties. Moreover, Lendvai et al. (2023) also examined the mechanical characteristics of natural fiber biocomposites and emphasized that the dispersion of fibers and processing criteria influence the final composite characteristics. All these studies affirm that though natural fibers enhance sustainability and stiffness optimization of fiber loading, surface treatment, and processing conditions are needed to obtain reliable FDM performance.

1.3 Physical, Mechanical, and Thermal Properties of Natural Fibers

Natural fibers provide a number of beneficial properties, including low energy consumption, low density, non-abrasiveness, affordability, renewability, and biodegradability. They are also widely available and abundant. Plant fibers, which are typically hard, do not fracture during processing, in contrast to brittle synthetic fibers. Similar to glass fibers, plant fibers have similar specific strength and stiffness characteristics (Mohanty et al., 2005). The majority of natural fibers have various chemical characteristics. Each fiber's chemical makeup consists mostly of substances like cellulose, hemicellulose, and lignin (Akil et al., 2011).

In addition to lignin and sugar-based polymers (such as cellulose and hemicellulose), dried plant fibers also contain minor amounts of other substances like starch, extractives, protein, and inorganics in their cell walls. Cellulose is one of the crucial elements in plants. Hydrogen bonds in cellulose give plants their stability and strength. Hemicellulose, a different molecule found in plants, is in charge of absorbing moisture and water. Under natural circumstances, cellulosic fibers have a hydrophilic character (capable of absorbing moisture) (Akil et al., 2011). The mechanical behaviour of composites made of natural fibers may be adversely affected by the moisture content of the fibers. Due to its cross-linking structure, lignin or pectin is also in charge of thermal stability and UV resistance (Campilho, 2015). **Figure 2** shows the classification and sub-classification of natural fibers (Siakeng et al., 2019). **Figure 2** shows how the natural fibers can be classified according to their origin and there are three major categories: plant fibers, animal fibers, and mineral fibers. The most common of these used in composite materials are plant fibers including flax, hemp, jute, and bamboo as they are low density, of good mechanical strength, biodegradable and renewable. Protein based fibers such as wool and silk are animal fibers and are mostly used in the textile industry, whereas mineral fibers, asbestos and mica are mostly used in insulation since they are effective in resisting heat. In general, the figure underlines the fact that plant-based fibers are the most appropriate reinforcement material in natural fiber-reinforced composites and FDM filament manufacturing, as the selected material has positive mechanical characteristics and is environmentally friendly.

Table 3. Tensile strength (MPa), Young's modulus (GPa), elongation (%), and density (g/cm^3) typical characteristics for fibers (Akil et al., 2011; Gholampour & Ozbakkaloglu, 2020; Siakeng et al., 2019; Tholibon et al., 2019).

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Density (g/cm^3)
Cotton	250-400	1-10	1-2	1.54
Flax	300-700	17-25	1-5	1.5
Hemp	250-600	25-60	1-5	1.5
Jute	200-400	1-9	1-3	1.45
Ramie	500-800	40-70	1-3	1.45
Sisal	300-600	30-60	1-5	1.5
Wool	150-300	1-10	15-30	1.32-1.34
Silk	500-800	40-70	15-30	1.3
Cashmere	150-250	1-10	30-40	0.9
Mohair	200-300	1-10	15-25	1.25

Table 3 is a summary of the mechanical properties of different natural fibers with their tensile strength, Youngs modulus, elongation of break, and density. These are the parameters needed to assess the applicability of natural fibers in polymer composites and fused deposition modelling (FDM) filaments as a reinforcement material. These values represent the data in the table that the tensile strength and stiffness of plant-based fibers, including flax, hemp, ramie, and sisal, tend to be higher than that of most animal fibers, meaning that they should be used as structural reinforcement. The cellulosic composition and microfibril structure of these fibers in the cell wall are the main factors that affect the mechanical performance of these fibers and lead to their load-bearing capacity.

Past research has pointed out that the advantage of plant fibres is that they have good strength-to-weight ratio because of their high content in cellulose and crystalline structure. In one example, Akil et al. (2011) found that cellulose microfibrils in the fiber structure offer a large tensile strength and stiffness which are very crucial in composite materials reinforcement. Likewise, Jawaid & Khalil (2011) highlighted the fact that flax and hemp which are plant-based fibers are capable of having their mechanical properties match some of the synthetic fibers on a normalized density basis rendering them a potential lightweight composite applicant.

The tensile strength values in **Table 3** indicate that tensile strength of fibers like ramie and flax have quite large strength ranges, and on the other hand, fibers like cotton and jute have moderate strength values. Gurunathan et al. (2015) state that these differences in mechanical properties are caused by the changes in the methods of fiber extraction, environmental growth conditions, maturity of plants, and chemical composition. The percentage of cellulose, hemicellulose, and lignin in the fiber structure is highly important in determining the mechanical behavior and durability of natural fibers employed in the composite systems.

The values of modulus of young provided in **Table 3** also suggest that a number of plant fibers have relatively higher stiffness in them, and this is useful in reinforcing composites. As, Dicker et al. (2014) indicated, the orientation and crystallinity of cellulose microfibrils in the secondary cell wall determine the stiffness of natural fibers and enhances the resistance to mechanical loading deformation. The properties are especially beneficial in polymer composite projects where the stiffness of reinforcement is the key factor in the mechanical performance of the finished part.

On the contrary, animal fibers including wool, silk, and cashmere exhibit greater values of elongation and thus they are more flexible and ductile than plant fibers. John & Thomas (2008) posit that the fibers composed of proteins are more likely to be more extensible because of their molecular structure but are usually less stiff than the plant fibers. Due to this reason, these fibers are normally employed in textile works and not structural composite reinforcement. Density is another significant parameter in **Table 3** with the majority of natural fibers having rather low-density values (between 1.2 to 1.5 g/cm^3). This is one of the most significant benefits of natural fibers in composite construction because it allows obtaining lightweight materials with reasonable mechanical properties. Moderate tensile strength, adequate stiffness and low density also give natural fibers a desirable strength to weight ratio, which is especially attractive in applications like automotive parts, building materials, and additive manufacturing, among others, as argued by Campilho (2015).

Fibers made of plant material, including hemp, ramie, sisal, and flax, are stronger in terms of tensile strength and modulus than animal fibers and are therefore considered more appropriate in reinforcing the FDM filament's structure. Their comparatively low density also favors the lightweight composite development. These features are the reasons why plant-based fibers are chosen most to use in extrusion-based 3D printing. The method used to harvest the fibers from the plants is an additional important factor when comparing the qualities of natural fibers. There have been several reported extraction methods, including mechanical, chemical, and combinations of both. Some of these methods are crude, and there is no scientific consensus or set of standards permitting a reliable comparison. In order to boost their wettability and dimensional stability and, consequently, their adhesion to hydrophobic matrix, natural fibers must also have their surface physio-chemistry and roughness modified (Ramesh et al., 2017).

Natural fibers often have a low density, 1.5 g/cm^3, which is significantly less than that of synthetic fibers. They are therefore perfect for uses in the automotive and aerospace industries where weight is a key factor. Natural fibers have a high specific strength and stiffness and are very robust and rigid. They qualify well for usage in composites because they have a high strength-to-weight or stiffness-to-weight ratio (Huang et al., 2025).

Altogether, **Table 3** proves that mechanical properties of natural fibers can differ in accordance with their origin, chemical structure, and structure, yet the plant-based fibers tend to offer the most reasonable ratio of strength, stiffness, and low density. These characteristics render them potential reinforcement materials to form sustainable composite filament to be employed in FDM additive manufacturing system.

Recent research has also measured the physical, mechanical, and thermal properties of new and traditional natural fibers, which justifies their use in composites. Ahmad et al. (2025) also surveyed the mechanical, thermal, and physical characteristics of natural fiber-reinforced thermoplastic composites with FDM-based 3D printing, detailing that the composition of the fibers and the choice of the matrix were the main factors to consider in order to fulfill the desirable performance in printing processes. Uddin et al. (2025) demonstrated that natural fiber hybridization with synthetic reinforcement was a successful way to increase mechanical and thermal properties of the composite due to an increase in stress transfer and structural synergy. These newly discovered insights support the previous evidence on cellulose, hemicellulose and lignin impact on fiber performance and also broaden the fiber and composite formula portfolio available to sustainable engineering implementation.

1.4 Matrix Selection for FDM Filaments

In composites, the matrices held the reinforcing components together by surface bonding. In addition, matrices help to make a composite stronger, visually appealing, and resistant to environmental factors. Since there is a limited amount of fossil fuel, and there are a lot of negative effects of petroleum-based matrices, many recent studies focus on finding sustainable alternatives. A matrix's primary role as a reinforcement binder is to give a firm grip to boost the composite's strength and serve as a load transfer (Campilho, 2015). Unsaturated epoxy, polypropylene, and polyesters are primarily produced using three different types of matrices: metallic, ceramic, and polymeric. A chemical product made from petroleum, which is made from fossil fuels like coal and natural gas, is known as a petrochemical-based matrix. There are two categories of polymeric materials: thermosets and thermoplastics. The characteristics and chemical structures of these thermosets and thermoplastics differ from each other, as shown in **Table 4** (Kabir et al., 2012).

Because thermoplastics can withstand larger energy impacts than thermosets, their strength is often higher. When the thermoplastic polymer is heated, the bonds between hydrogen molecules and Van der Waals forces are momentarily dissolved, which allows the molecules to migrate. The polymers have similar properties to metals (Peças et al., 2018). When a polymer is heated to its melting point, it melts and can be reshaped into new products. As the thermoplastics are recyclable, this process can be repeated several times (Sreenivasan et al., 2013). **Table 4** is the comparison of thermoset and thermoplastic polymers.

Thermoplastics are desirable since FDM is an extrusion process, which needs repeating solidifying and melting, so it is best used in the melt process and recycling.

Table 4 has compared thermoset and thermoplastic polymers concerning properties like chemical structure, strength, heat resistance, recyclability and processing factors. The thermoset polymers develop cross-linked molecular networks permanently during curing to give it high stiffness, strength and thermal stability. But, after being treated, they cannot be melted and remodeled, which reduces their recyclability and processing capabilities. Due to this non-lament cross-linking structure, thermosets are usually utilized in and around the use of adhesives, laminates, and electrical components where dimensional stability and resistance to heat are needed (Kabir et al., 2012). Thermoplastic polymers on the other hand are a linear or branched molecular chain which does not form permanent cross-links and thus can melt when heated and solidify on cooling. This melting and solidifying behavior is reversible, and thus, thermoplastics could be reshaped and recycled numerous times. As it has been reported in earlier studies done on polymer materials, intermolecular forces within thermoplastics are weakened, on a temporary basis, during heating enabling the molecular mobility and therefore permitting melt processing (Peças et al., 2018). This is a characteristic that renders thermoplastics especially fitting in the manufacturing processes that make use of extrusion. In the case of additive manufacturing technologies like fused deposition modelling (FDM), thermoplastics have been the most popular mother materials since the additive manufacturing technology needs to melt and harden filament before depositing a layer upon the previous layer. It has been revealed that thermoplastic polymers can be easily processed into filaments and extruded through the printing nozzle and can be used repeatedly in thermal cycles and still be structurally intact (Sreenivasan et al., 2013). As a result, polylastic acid (PLA), acrylonitrile-butadiene-styrene (ABS), and polypropylene are typical thermoplastic materials employed in the development of composite in FDM. They can be melted and flow and hardened over and over again to enable the incorporation of natural fibers easily to create sustainable composite filaments. Thus, thermoplastics tend to be better than thermosets when developing natural fiber-reinforced filaments to be used in additive manufacturing.

Table 4. Difference between thermoset and thermoplastic polymers (Kabir et al., 2012; Peças et al., 2018; Sreenivasan et al., 2013).

Property	**Thermoset**	**Thermoplastic**
Chemical composition	Forms cross-linked bonds between polymer chains	Does not form cross-linked bonds between polymer chains
Curability	Cured once and cannot be reshaped	Can be melted and reshaped multiple times
Strength	Stronger	Weaker
Stiffness	Stiffer	Less stiff
Heat resistance	More heat resistant	Less heat resistant
Impact resistance	Less impact resistant	More impact resistant
Cost	More expensive	Less expensive
Recyclability	Not recyclable	Recyclable
Applications	Electrical components, cookware, adhesives, laminates	Packaging, bottles, toys, furniture

All polymers that are derived from renewable resources are known as "bio-based resins. Based on their physical characteristics, bio-based polymers can be divided into three categories: fully biodegradable, such as polyhydroxyalkanoates (PHA) and starch; partially biodegradable, such as cellulose and PLA; and partially biodegradable, but not biodegradable, such as bio-polyethylene terephthalate, bio-polyethylene, and biopolypropylene. The advantages and disadvantages of bio-based resins are tabulated below. **Table 5** is a comparative analysis of bio-based resins that are usually used in developing sustainable composite. Of these, PLA is the most commonly used in FDM because of its good melt-processability as well as moderate mechanical behaviour. Whenever extrusion of filament is involved, however, there are limitations that include brittleness, sensitivity to moisture and the capability to operate within a limited processing range that should be well considered. Other biodegradable polymers like PHA, PBAT and starch-based resins have similar benefits to bio-based polymers but they may need additional modification to be printable and maintain mechanical stability in FDM applications.

The benefits and drawbacks of some of the most common bio-based resins that are typically utilized to develop sustainable composites are compared in **Table 5**, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene adipate terephthalate (PBAT), cellulose acetate (CA), and starch-based polymers. These resources emerge out of renewable sources like agricultural biomass or fermentation by micro-organisms and they are widely regarded as potentially beneficial alternatives to petroleum-based polymers. One of the significant benefits of these resins is that these resins are biodegradable and can be renewed, which contributes to minimizing environmental impact and reliance on fossil resources. As demonstrated in the past, bio-based polymers have a high potential to reduce carbon emissions and help to achieve sustainable manufacturing processes, such that they can be considered attractive matrix material of natural fiber composites and other products that are environmentally friendly (Campilho, 2015).

PLA is one of the most common bio-based polymers and has received much popularity among other materials because of its high processability, average mechanical strength, and additive manufacturing process compatibility. It is usually made using renewable resources like corn or sugarcane and can also be processed easily by extrusion-based technologies like fused deposition modelling (FDM). As emphasized, natural fibers-reinforced PLA-based composites may be used to enhance the stiffness without negatively affecting biodegradability, thus, they are applicable to sustainable composite applications (Siakeng et al., 2019). Recent researches have also established that PLA is still among the most dominant biodegradable polymers due to its desirable mechanical properties, crystallinity, and processing in nature (Mou et al., 2025).

The other bio-based resins that are in the list also included in the **Table 5**. PHA and PBAT also avail promising characteristics in the development of sustainable composite. Indicatively, PHA-based materials are biodegradable and thermally stable, whereas PBAT has been known to be flexible and tough. Recent studies have also indicated that the combination of biodegradable polymers like PLA, PHA and PBAT can work synergistically in enhancing the mechanical performance and processability through their complementary characteristics. As an example, PLA positively affects the body and rigidity whereas PBAT enhances elongation and impact resistance which makes it possible to create balanced systems of biodegradable polymers (Olonisakin et al., 2025).

Although these are the benefits of bio-based resins, **Table 5** also shows that there are a number of limitations that are linked to bio-based resins. A large portion of these materials are sensitive to processing temperature and moisture that may result in thermal degradation or less mechanical performance during processing. Furthermore, certain biodegradable polymers are brittle, have a low barrier or are comparatively expensive to manufacture when compared to traditional polymers. Other challenges that have become highlighted in the recent reviews on bio-based polymers include inconsistencies in mechanical properties, processing, and compatibility of blending biopolymers with natural fibers (Jiang et al., 2024).

However, current research studies are aimed at enhancing the performance of bio-based polymers by the means of polymer blending, nanofiller reinforcement, and optimization of fiber-matrix compatibility. It has been shown that bio-based polymers can be used together with natural fibers or other biodegradable polymers to increase the stiffness, toughness and thermal stability without compromising the sustainability of the environment. These trends suggest that bio-based resins can be used effectively in the context of sustainable engineering materials such as fabricating natural fiber-reinforced filaments utilized in FDM additive manufacturing where biodegradable and renewable materials are becoming more demanded. On the whole, **Table 5** shows that bio-based resins have some drawbacks in terms of processing and mechanical behavior, however, their renewable nature, biodegradability, and the ability to interact with natural fiber reinforcers precondition the future usage of bio-based resins as promising matrix materials in the creation of environment-friendly composite filaments and stable additive manufacturing technology.

Table 5. Advantages and disadvantages of bio-based resins (Mukhopadhyay & Fangueiro, 2009).

Property	**PLA**	**PHA**	**PBAT**	**CA**	**Starch-based resins**
Advantages					
Biodegradability	Yes	Yes	Yes	Yes	Yes
Renewable Source	Yes (from corn or sugarcane)	Yes (from microbial fermentation)	Yes (from renewable resources)	Yes (from cellulose)	Yes (from corn, potatoes, etc.)
Mechanical properties	Good	Varies	Good	Moderate	Varies
Transparency	Transparent and translucent	Varies	Transparent	Transparent	Varies
Versatility	Suitable for rigid and flexible applications	Varies	Suitable for various applications	Varies	Wide range of applications
Disadvantages					
High cost	Relatively high cost	Higher cost than traditional plastics	Higher cost	Higher cost	Cost can be an issue
Processing requirements	Sensitive to high temperatures, limited processing conditions	Limited processing conditions	Limited processing conditions	Sensitive to processing conditions	Limited processing conditions
Brittleness	Can be brittle	Varies	Varies	Less brittle	Varies
Barrier properties	Limited barrier properties	Varies	Varies	Moderate barrier	Limited barrier
Moisture sensitivity	Sensitive to moisture	Varies	Varies	Sensitive to moisture	Highly sensitive

The literature reveals that even with the recent rise in interest in natural fibers, the properties of natural fibers are highly varied because of the variation in the producer plant, the methods used in extraction, and the environmental factors. John & Thomas (2008) and Kicinska-Jakubowska et al. (2012) stated that mechanical performance is controlled by fiber composition, especially cellulose and lignin level, but Faruk et al. (2012) and Palanisamy et al. (2024) pointed out that even fibers of the same type may behave differently in geographic conditions and various methods. In addition, although an increase in the amount of cellulose tends to increase the stiffness, Mukhopadhyay & Fangueiro (2009) and Manickararaj et al. (2024) reported that an increase in cellulose content can also make materials brittle and less impact resistant. These opposite results suggest that the selection of natural fibers should take into account the variability and compatibility of processing and not be based only on nominal mechanical properties.

1.5 Fiber Surface Modification for Printability

The mechanical behavior of composites depends critically on interfacial adhesion across the phase boundary. Weak properties might result from poor bonding. The main issue with natural fiber composites is their excessive absorption of moisture, which results in a weak compatibility between the fibers and matrix. Both the fiber surfaces and the matrix must be altered to increase the natural fiber's adherence to the matrix in order to increase strength and stiffness. The performance and compatibility of the natural fiber composites with synthetic polymers can be improved by modifications, using methods like chemical, biological, and physical techniques. By physical means, the topology of the fiber surface can be changed, by chemical means, functional groups can be added, and by biological means eco eco-friendly surface modifications can be done. These methods broaden the uses of natural fibers in the packaging, construction, and automotive sectors by overcoming their limitations, such as weak interfacial adhesion and low moisture resistance (Faruk et al., 2012). As illustrated in **Figure 3,** there are two routes in the natural fiber surface modifications: the physical route by means of plasma etching, UV irradiation, and corona treatment, and the chemical route through alkaline treatment, silane treatment, or maleated coupling agents. In either case, the adhesions are created between fiber–matrix interface, resulting in better consistency of the filament and improved printability and mechanical properties in FDM.

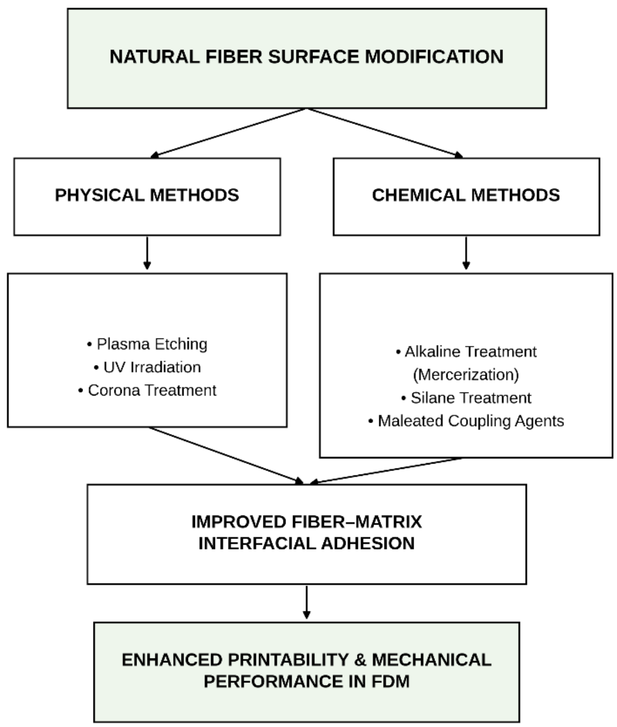

Figure 3. Physical and chemical surface modification pathways for natural fibers and their resulting effect on fiber–matrix adhesion and FDM printability.

1.5.1 Physical Modification

With the help of Physical modification methods, such as plasma etching, UV irradiation, and corona treatment, without any chemical alteration, the strength and durability of natural fiber composites can be improved. These methods strengthen the link between the fibers and matrix material and produce composites that are tougher, powerful, and rigid. In addition, they provide fiber with more thermal stability and less moisture absorption. It increases the flexibility and eco-friendliness of these compounds. While plasma treatment regulates gas type, velocity, pressure, and concentration, corona treatment modifies the surface energy of cellulose fibers (Mukhopadhyay & Fangueiro, 2009).

1.5.2 Chemical Modification

Natural fiber composites provide a sustainable substitute for conventional materials, but they are limited by their weak interfacial adhesion and moisture sensitivity. With the help of chemical treatment, wear resistance, mechanical strength, and fiber-matrix bonding can all be improved. Acetylation can lower water absorption and increase thermal stability, whereas alkaline treatments can eliminate waxy surfaces, reveal hydroxyl groups in cellulose, and produce cohesive materials. The full potential of natural fiber composites may be realized with these chemical treatments, opening the door for high-performance, environmentally friendly materials in a variety of sectors (Singh et al., 1996).

1.5.3 Alkaline Treatment

In alkaline treatment, impurities and some non-cellulosic components, like hemicellulose, lignin, and waxes, are removed by soaking the fiber in sodium hydroxide (NaOH) solution. It results in the pure cellulose core, which has enhanced interfacial adhesion. Additionally, it has increased strength, flexibility, and moisture resistance. On the other hand, excessive concentration of NaOH or too long treatment time can damage the cellulose. So, it is important to determine the ideal concentration and duration of the treatment. Because of the increased surface area and aspect ratio, an ideal alkali concentration promotes fiber adhesion and inhibits excessive delignification (Walker, 2006).

1.5.4 Silane Treatment

Silane treatment helps to improve and fill the gap between natural fiber and composite matrix. It involves the attachment of silanes, containing a hydroxyl group, to organic polymers and natural fibers. This treatment overall increases the tensile strength, moisture resistance, fire performance, and thermal stability of the composites. It makes the natural composites more competitive than untreated or just alkali-treated ones. When compared to alkali treatment, it improves tensile strength by establishing molecular continuity across the composite surface (Kalia et al., 2011).

1.5.5 Maleated Coupling Agents

Maleated coupling agents help to make a bridge between the fiber and the composite matrix, which leads to improved interfacial adhesion and increased mechanical strength, stiffness, and durability of natural fiber composites. They also decrease the moisture absorption and increase the overall performance of the composites. Long-chain polymers are applied to the fiber surfaces to lessen their hydrophilic inclination and provide a bridge interface that facilitates effective interlocking between the fiber and matrix.

There are more investigations done after 2023 that reinforce the significance of surface modification in enhancing printability and mechanical performance of natural fiber-reinforced composites. Ahmad et al. (2022) indicated that tensile strength and the interlayer bonding of PLA-based FDM filaments using alkali-treated flax and hemp fibers was much greater than the use of untreated fibers mostly because of better fiber-matrix compatibility and the reduced porosity caused by moisture. In a similar study, Khan et al. (2023) have stated that silane-treated natural fibers were characterized by enhanced thermal stability and less water uptake in thermal plastic composites, which resulted in enhanced dimensional stability upon extrusion-based 3D printing. Besides this, recent research on maleic anhydride grafted polypropylene (MAPP) and maleated PLA coupling agents have demonstrated significant increases in interfacial shear strength and impact resistance particularly in wood-plastic composite that is used in additive manufacturing. These results underscore the fact that surface modification of these materials can be controlled in order to enhance mechanical properties as well as provide a stable filament extrusion, nozzle clogging and a uniform adhesion of the layers in FDM processes.

Surface modification methods are commonly used to enhance the bond between fibers and matrix, but the methods are not very effective across the board, depending on the conditions of the treatment and type of fibers. Kabir et al. (2012) have illustrated that alkali treatment improves interfacial bonding by making the surface rougher, and Singh et al. (2017) have provided evidence that a high level of chemical treatment is detrimental to the fiber structure and strength. Likewise, Alonso-Montemayor et al. (2022), Li et al. (2025), and Shakir & Singh (2025) pointed out the efficiency of silane and plasma treatments, whereas recent works like Ermeydan (2024) and Keymanesh et al. (2024) showed that more sophisticated treatments enhance the interaction between the interfaces but add more complexity and cost to the processing. Moreover, Chahar et al. (2025) noted that mechanical properties may be destroyed by not using the appropriate parameters of treatment. Such observations indicate that treatment conditions optimization is of paramount importance since there is no universal way of ensuring enhanced composite performance.

Table 6 is a summary of some of the post-processing and surface modification methods employed to improve the mechanical performance of natural fiber composites. The majority of the treatments are used to enhance the interfacial adhesion and decrease void formation to lead to the improvement of tensile, flexural and impact properties. Nevertheless, though these methods demonstrate obvious mechanical advantages, their practical use in the context of FDM is determined by the possibility to adapt to the conditions of filament extrusion and continuous operation in terms of scalability. Hence, both material adjustment and printing settings should be optimized to ensure the reliability of the performance in FDM-printed parts.

Table 6. Summary of existing studies on mechanical properties of natural fiber composites (Alonso-Montemayor et al., 2022; Chahar et al., 2025; Keymanesh et al., 2024).

Post-processing technique	Natural fiber	Matrix	Mechanical property studied	Effect	Reference
Thermal Treatment	Flax	Epoxy	Tensile Strength, Flexural Strength, Interfacial Shear Strength	Increased tensile and flexural strength, improved interfacial adhesion	Ermeydan (2024)
Mercerization (NaOH Treatment)	Kenaf	Polyester	Tensile Strength, Young's Modulus, Impact Strength	Increased tensile strength, Young's modulus, and impact strength due to improved fiber-matrix adhesion and crystallinity	Shakir & Singh (2025)
Plasma Treatment	Sisal	Polypropylene	Tensile Strength, Interfacial Shear Strength, Surface Wettability	Improved tensile strength, interfacial shear strength, and surface wettability, leading to better fiber-matrix bonding	Alonso-Montemayor et al. (2022)
Microwave Irradiation	Jute	Polyester	Tensile Strength, Flexural Strength, Impact Strength	Improved tensile, flexural, and impact strength due to enhanced fiber-matrix interaction and reduced void formation	Mahmud et al. (2023)
Ultrasonic Treatment	Banana	Epoxy	Tensile Strength, Interfacial Shear Strength, Interlaminar Shear Strength	Increased tensile strength, interfacial shear strength, and interlaminar shear strength due to improved fiber alignment and matrix consolidation	Keymanesh et al. (2024)
Corona Treatment	Coir	Polyurethane	Tensile Strength, Flexural Strength, Water Absorption	Increased tensile and flexural strength, reduced water absorption due to surface modification and improved fiber wettability	Malik et al. (2024)
High Pressure Impregnation	Hemp	Polylactic Acid	Tensile Strength, Flexural Strength, Impact Strength	Enhanced tensile, flexural, and impact strength due to better fiber wetting and reduced void formation	Tao et al. (2024)
Surface Sizing	Bamboo	Epoxy	Flexural Strength, Interfacial Shear Strength	Improved flexural strength and interfacial shear strength due to enhanced fiber-matrix adhesion and reduced fiber pull-out	Trivedi (2024)
Cryogenic Treatment	Abaca	Polyester	Tensile Strength, Impact Strength	Increased tensile strength and impact strength due to improved fiber alignment and crystallinity	Chahar et al. (2025)

Table 6 presents some of the post-processing and surface modification methodologies that have been applied to improve the mechanical performance of the natural fiber-reinforced composites. Those methods are thermal, mercerization (alkali), plasma, microwave, ultrasonic, corona, high-pressure impregnation,

surface sizing, and cryogenic, all of which are supposed to enhance fiber-matrix interfacial bonding and composite strength. It has been demonstrated by numerous studies that the mechanical properties of natural fiber composites are highly sensitive to the quality of fiber-matrix interface since weak bonding may result in fiber pull-out and void formation, as well as, inefficient load transfer. The most common approach to surface modification of natural fibers is the alkali treatment (mercerization), which is among the listed methods. This process eliminates the surface impurities of the fiber like waxes, hemicellulose, lignin thus raising the surface roughness and enhancing the adhesion with the polymer matrix. A number of studies have indicated that alkali treatment is majorly important in increasing tensile strength, Youngs modulus and impact resistance of natural fiber composites, because of the bonding between the fibers and the matrix is improved (Shakir & Singh, 2025). Plasma and corona treatments, similarly, alter the energy levels of the surface of fibers, making them more wetted and strongly adhering to the reinforcement and the matrix material.

1.6 Processing Routes for Filament Extrusion

Weaving, extraction, and refining are steps in the creation of natural fiber composites. Valuable fibers are separated from plant stems using methods like retting, and then they are bound together with a thermoset or thermoplastic glue. The performance, sustainability, and composition of the composite are influenced by the fibers' length, aspect ratio, and chemical makeup. Other factors include pultrusion, manual lay-up, pressure molding, and processing temperature. Ultimately, finishing and machining turn raw materials into high-performing composites that will last for a long time (Campilho, 2015). When temperatures rise over a particular point, natural fiber composites may experience mechanical, chemical, and/or physical alterations that lead to deterioration, shrinking, and poor performance. Compression molding, extrusion molding, injection molding, and resin transfer molding are important production techniques. Surface treatments increase material adhesion, change the hydrophilic character, and decrease moisture absorption (Yildiz et al., 2006).

The process of creating thermoplastic natural fiber composites is called compression molding. It entails filling a heated mold with a polymer and natural fiber combination, applying regulated pressure and heat, and letting the composite flow and take on the shape of the mold. This method is beneficial for small production runs, as it produces little waste and high-fiber-volume products with superior polish. To get the best strength and quality, pressure, temperature, and fiber orientation must all be optimized (Araújo et al., 2008). In the extrusion molding process of producing bespoke thermoplastic composites, heat, pressure, and natural fibers are used. In this technique, the melted polymer is integrated with natural fiber to create a composite mix. This composite mix is passed through a die to give it a desired shape. This method allows the excellent fiber dispersion, continuous manufacturing, and allows one to add the desired chemical for improved qualities. Since extrusion molding offers excellent rigidity and strength, it is frequently utilized in the production of natural fiber composites (Campilho, 2015). The injection method is used to shape thermoplastic natural fiber composites. It allows them to increase strength and have an appealing shape, which produces lightweight, durable, and sustainable products such as car dashboards, interior panels, and eco-friendly furniture. The most popular technique for creating composites in large quantities is injection molding, which guarantees excellent dispersion and impact resistance (Turyahabwe et al., 2025). In **Table 6**, the author compares traditional composite processing methods with additive manufacturing methods. Although compression molding and resin transfer molding are traditional processes that are very efficient in their production, they are not as flexible to design as FDM.

Table 7 presents a comparison of some of the manufacturing methods applied in the production of natural fiber-reinforced composites and their benefits and drawbacks. Traditional processing methods that were used in the fabrication of fiber-reinforced composite materials include: hand lay-up, compression molding, pultrusion, vacuum bag molding, resin transfer molding (RTM), and thermoforming. Among these methods, the hand lay-up is one of the easiest and least costly methods of manufacturing since it needs few equipments and installation. The process is however, very labor intensive and time consuming and the quality of final products may differ with the skill of operators and processing conditions (Yildiz et al., 2006). Thermoplastic natural fiber composites Compression molding is a popular method of producing thermoplastic composites due to the ability to consolidate fibers and polymer matrices under high temperature and pressure. Composites with fairly good surface finish, better fiber wetting and higher fiber volume fractions can be made using this process. Compression molding, however, has special molds and increased tooling costs thus limiting its versatility in creating complex geometries (Araújo et al., 2008). Most structural composite items such as pultrusion and resin transfer molding (RTM) are commonly used to create structural composite components that have enhanced fiber alignment and mechanical performance. Pultrusion facilitates uninterrupted manufacture of high strength and stiffness fiber-reinforced profiles whereas RTM can be used to obtain enhanced part consolidation and better wetting of fibers and their matrix. Although they have these advantages, these methods demand intense mould design and a greater initial investment cost which has the potential to make a production process more expensive and decrease the flexibility in the manufacturing process (Turyahabwe et al., 2025).

There has also been the emergence of additive manufacturing technologies especially fused deposition modelling (FDM) in recent years as an option in the production of natural fiber composites. In contrast to conventional manufacturing, FDM is a layer-by-layer printing process of components based on thermoplastic filaments, which allows manufacturing complex geometries with minimal waste materials. Research has demonstrated that FDM has a lot of benefits including design flexibility, less tooling needs and customization ability (Ning et al., 2015). Nonetheless, issues like the adhesion between layers, formation of voids and distribution of fibers may influence the mechanical performance of printed composite parts. Some recent works have also highlighted that mechanical properties and printability of fiber reinforced filaments made of natural fibers can be improved with better fiber surface modification, extrusion processing and optimization of printing parameters. On the whole, **Table 6** indicates that although the conventional composite processing strategy offers desirable structural performance, additive manufacturing technologies, including FDM, are more flexible, more efficient in terms of material utilization, and can be customized. Thus, optimized processing methods along with natural fiber reinforcements can be used to develop sustainable composite materials that can be used in contemporary manufacturing processes.

Table 7. Advantages and disadvantages of processing techniques of natural fiber composites.

Technique	Advantages	Disadvantages
Hand Lay-up	- Simple and low-cost setup	- Time-consuming and labor-intensive
Compression Molding	- Faster than hand lay-up	- Higher tooling costs
Pultrusion	- Continuous production of long, profile shapes	- High initial investment costs
Vacuum Bag Molding	- Excellent surface finish and compaction	- Requires complex tooling and bagging materials
Resin Transfer Molding (RTM)	- Good fiber-matrix wetting and part consolidation	- Complex mold design and injection system
Thermoforming	- Suitable for thermoplastic matrices with low melting points	- Limited thickness control
3D Printing (FDM)	- Highly customizable designs with complex geometries	- Relatively slow printing speeds

Microwave irradiation and ultrasonic treatment are also other physical modification methods that have been reported to improve the performance of the composites by increasing the distribution of the fibers and minimizing the inner defects like voids. These reactions are used to enhance mechanical qualities like tensile strength, flexural strength and impact strength by increasing the alignment of the fibers and consolidation of the matrix. Also, high pressure impregnated and surface sizing methods enhance the permeation of the polymer matrices within the fiber structures, which results in enhanced interfacial bonding as well as enhanced structural integrity of the composite material. Recent research has further pointed out that optimization of these modification methods is important in enhancing the performance of natural fiber composites in the additive manufacturing processes.

These results suggest that structural reliability and durability of natural fiber-reinforced composites applied in the modern technologies can be improved through the combination of chemical modification techniques with the improvement of processing conditions. Generally, as noted in **Table 7**, post-processing and surface modification methods are very important in enhancing the mechanical performance of natural fiber composites. These techniques help to increase tensile, flexural and impact performance, by increasing fiber-matrix adhesion and minimizing structural defects, so that natural fiber composites become more appropriate in high-technology engineering, such as sustainable composite filaments in fused deposition modelling (FDM).

Composites of natural fibre reinforced (processed via fused deposition modelling (FDM)) present a number of material and process related issues. The possibility of using FDM in composite fabrication was first mentioned by Masood & Song (2004), though Daver et al. (2018) and Tao et al. (2017) explained that the addition of natural fibers change the melt flow characteristics resulting in the clogging of nozzles and low extrusion stability. Conversely, Giani et al. (2024) and Niang et al. (2022) have shown that, optimized processing parameters and controlled filler dispersion could have a significant impact on improving print quality and mechanical performance. Moreover, most of the recent research, including Arivendan et al. (2026) and Goh et al. (2024) suggests that there is a transition to large-scale and continuous additive manufacturing of fiber, rendering the integration of processes and materials more significant. The comparing results indicate that the performance of FDM is very sensitive to the material formulations and processing conditions, and that it needs to be optimized in a systematic way.

1.7 Mechanical and Physical Performance of Printed Parts

1.7.1 Physical Properties of Printed Parts

In fused deposition modelling (FDM), tiny gaps known as voids impact the mechanical strength and quality of natural fiber composites. There are several factors that generate the voids, which include natural porosity in the material, weak bonding between fibers and the matrix, or poor fiber dispersion. To reduce these void formations the techniques like fiber modification, chemical treatments, and optimized printing parameters can be used. Additionally, voids may develop during melt-flow processing or compounding, which could result in abrupt failure and poor mechanical qualities. The potential of natural fiber-reinforced FDM composites can be realized with the right processing and fiber selection. Graphite fiber/polyimide and glass fiber/polystyrene composites with high void content have low fatigue resistance (Shi et al., 2024). Voids can be reshaped and their content reduced by hot-drawing; they increase thermal conductivity, decrease dimensional stability, affect surface finish, decrease tensile strength, and degrade flexural strength; they disrupt the uniform distribution of stress, making the composite more vulnerable to impact damage; they also impair fatigue resistance, accelerating crack initiation and propagation under cyclic loading; these effects can be mitigated by post-extrusion hot-drawing techniques.

From **Table 8** it can be concluded that Cellulose-based fibers like wood, cotton, and bamboo have moderate strength and flexibility, making them suitable for lightweight applications. Protein-based fibers like silk and wool have higher strengths but lower Young's modulus, making them flexible. Other natural fibers like hemp, jute, kenaf, and flax have similar mechanical properties and low density. The physical and mechanical properties of the selected natural fibers are shown in **Table 8**. Hemp, jute, kenaf, flax and bamboo are plant-based fibers with moderate strength-weigh ratios and high biodegradability, which seems to be good candidates of reinforcement in FDM filaments. Their comparatively greater ability to absorb moisture, however, may adversely impact interfacial bonding, dimensional stability and extrusion performance.

Table 8. Physical properties of selected natural fibers (Akil et al., 2011; Bhardwaj & Sharma, 2025; Dicker et al., 2014; Jawaid & Khalil, 2011).

Fiber type	Tensile strength (MPa)	Flexural strength (MPa)	Young's modulus (GPa)	Density (g/cm³)	Thermal conductivity (W/mK)	Moisture absorption (%)	Biodegradability
Wood	80	45	15	0.8	0.15	10	High
Cotton	30	15	8	1.6	0.05	7	High
Bamboo	45	30	12	0.8	0.15	10	High
Silk	60	40	15	1.3	0.05	11	Moderate
Wool	30	15	8	1.4	0.04	18	High
Hemp	30	18	7	1.2	0.15	10	High
Jute	24	20	11	1.5	0.15	12	High
Kenaf	30	24	12	1.8	0.15	12	High
Flax	34	20	8	2.2	0.15	12	High

Table 8 shows the physical characteristics of some of the natural fibers, such as tensile strength, flexural strength, young modulus, density, thermal conductivity, moisture absorption and biodegradability. They are properties that are critical in deciding the appropriateness of natural fibers as a reinforcement material in polymer composites and additive manufacturing. The figures included in this table demonstrate that natural fibers tend to have moderate mechanical strength, moderate level of density, and high biodegradability, which makes them rather appealing materials in the development of sustainable composite systems. It has been reported in the past that wood, bamboo, hemp, jute, kenaf and flax are cellulose-based plant fibers that have good mechanical performance with lightweight properties, which are useful especially when it is used in applications where high strength-weight ratios are needed (Akil et al., 2011).

Of the fibers in **Table 8**, plant-based fibers, including bamboo, hemp, jute, kenaf, and flax exhibit moderate tensile and flexural strength and have a density of about 0.8-2.2 g/cm^3. This is a relatively low density when compared to the synthetic fibers and this is a factor that leads to production of lightweight composite materials. The study done in the past has reiterated that high cellulose content fibers are more likely to be stronger and stiffer due to the structural reinforcement and load-bearing capacity of cellulose microfibrils in the fiber cell wall (Jawaid & Khalil, 2011). Further, the crystalline structure of cellulose adds to the increase in the values of the Youngs modulus, which increases the stiffness of the composite materials reinforced with natural fibers (Dicker et al., 2014). The other notable point that **Table 8** points out is the ability of natural fibers to absorb water, and this fact can be mostly explained by the hydrophilic character of cellulose and hemicellulose. Natural fibers are able to imbibe moisture in the surrounding environment, and this could have an impact on the dimensional stability of natural fibers and the bonding between the fibers and polymer matrices. Taking into account the previous studies, a high moisture absorption can result in swelling, decreased fiber-matrix bonding, and deterioration of mechanical characteristics in composite material (Campilho, 2015). Thus, a surface modification method, including alkali treatment and silane treatment is commonly used to enhance fiber compatibility with hydrophobic polymer matrices, and minimize moisture sensitivity.

Another significant property that is presented in **Table 8** is the thermal conductivity. The majority of natural fibers have rather low values of thermal conductivity, and that is why they can be used in the industries where thermal insulation needs to be performed and the materials that are energy efficient. Past studies have indicated that porous nature of natural fibers is associated with the low thermal conductivity and lightweight properties, and can therefore be used in the construction material and insulating composite panel (Ahmad et al., 2015). Some mechanical and physical properties are also not the only ones: **Table 8** also points out the fact that natural fibers are biodegradable, and it is one of the key benefits of this type of reinforcement materials in comparison with other synthetic ones. Natural fibers are biodegradable and are able to decompose in the environmental conditions, which means that the long-term impact on the environment is minimal and sustainable material development is encouraged.

These studies also mention that natural fibers and biodegradable polymers like PLA can be combined to come up with sustainable composite materials that have better mechanical properties and less environmental footprint. In general, all the data in **Table 8** shows that natural fibers provide a balanced combination of moderate mechanical strength, low density and good thermal insulation, and biodegradability, and thus they are reasonable candidates in terms of reinforcement in polymer composites. Nevertheless, issues like moisture uptake, and inconsistency in fiber characteristics should be resolved by proper treatment of fiber and optimization of fiber processing. Natural fibers are therefore still potential reinforcement materials in making sustainable composite filaments applied during the fused deposition modelling (FDM) technique and other modern technology manufacturing processes.

Polymer matrix choice is another factor that has a great impact on the performance of natural fiber-reinforced composite but the literature reports differing results in the best material systems. According to Siakeng et al. (2019) the benefits of using PLA are associated with its biodegradability and ease of processing but Bijarimi et al. (2020) indicated that the composites made using PLA tend to be brittle and lack impact resistance. In the recent research, such as that of Mou et al. (2025) and Olonisakin et al. (2025), attention has been drawn to the creation of bio-based polymer blends to eliminate these constraints. Moreover, Jha et al. (2024) and Jiang et al. (2024) focused their attention on the increased role of biodegradable polymers in sustainable use. Nevertheless, hybrid systems, even though they enhance toughness, could deal a blow to environmental gains. The results suggest that the choice of the matrix involves paying attention to mechanical performance, processability, and sustainability.

1.7.2 Mechanical Properties of Printed Parts

Compared to synthetic fibers, natural fiber composites have poorer mechanical qualities, though they can be enhanced with the right adjustments. Properties and structure are influenced by variables such as age, fiber source, and testing parameters. By adding reinforcement, natural fibers can enhance printed parts and filaments. The mechanical properties of the composite are improved by fiber alignment and pretreatments, which increase contact with the polymer matrix. When fibers are added to a polymer matrix, the performance of the composite is greatly improved.

The interfacial adhesion between the fibers and resin affects the tensile characteristics of natural fiber composites. These qualities can be improved by modifications. The tensile strength of other natural fibers, such as flax, kenaf, hemp, and jute, is also moderate. The source of the fiber, the processing methods, and the degree of reinforcement can all affect the unique qualities of natural fibers. The fiber volume fraction in the matrix resin determines the tensile characteristics of natural fibers. Brittle fiber fractures and a composite failure owing to low tensile strength can result from an increased fiber volume fraction. Uneven trends can be brought on by things like incompatibility, fiber deterioration, and improper manufacturing techniques. Composite tensile strength typically improves as the fiber volume fraction rises because of the increased load-bearing capacity. Nevertheless, poor interfacial bonding brought on by an excessive fiber volume can reduce overall tensile strength (Alhijazi et al., 2022).

Composite resistance against bending deformation is measured by flexural stiffness. The volume fraction, fiber type, and orientation all affect the compressive characteristics of natural fiber-reinforced composites. When paired with a robust polymer matrix, natural fibers can still offer sufficient strength even though their compressive strength is lower than that of synthetic fibers. Fiber volume fraction, interfacial bonding strength, and matrix characteristics all affect fracture toughness in natural fiber composites. While too much fiber can result in porosity and poor bonding, fiber orientation and volume fraction increase compressive strength. Fiber pullout during crack propagation affects energy dissipation (Manickaraj et al., 2024). The degree of bonding between the fiber and matrix influences the impact behaviour of natural fiber composites, which impacts their service life. Although these qualities can be enhanced by modification techniques, the inherent brittleness and potential weaknesses of natural fibers may result in a lower impact strength when compared to synthetic composites. The factors that are affecting the impact strength of the composites are level of adhesion, strength of bonding, energy absorption, and fiber pullout.

The various research from 2023 to 2026, meant that the recent findings are valid and the factors that govern the mechanical behavior of the natural fiber-based FDM printed components are void formation and interfacial adhesion. Chahar et al. (2025) and Khan et al. (2023) have stated that porosity in PLA-flax composites increases with agglomeration of fibers and poor interlayer diffusion, which severely affects tensile strength. Noted that the irregularity of the filament and deterioration of the mechanism by poor melt flow behaviour are observed at fiber loading of more than 20-25 wt%.

Though the research on natural fiber-reinforced composites and its use in additive manufacturing is vast, it can be also concluded that there are a few gaps and issues identified in the existing literature. As an example, Akil et al. (2011), and Siakeng et al. (2019) mentioned that natural fibers enhance the stiffness and specific strength of polymer composites much, because it has a high-cellulose content, but Gurunathan et al. (2015) also indicated that too much fiber loading and inadequate dispersion could cause agglomeration of the fibers and decreased mechanical properties. On the same note, Tao et al. (2017) have shown that the natural fibers increase the stiffness of the FDM-printed components whereas Ahmad et al. (2022) reported that an increase in the fiber content has a negative impact on the behavior of the melt flow and the interlayer adhesion leading to decreased quality of the prints. These contradicting results indicate that the behavior of natural fiber-reinforced filaments is very sensitive to such aspects as fiber treatment, dispersion, and processing conditions. Also, although the use of PLA-based systems has been well-researched because of the ease of processing and the biodegradability (Siakeng et al., 2019), weaknesses like brittleness and sensitivity to moisture also limit their use on a larger scale. The latest research, such as Lendvai et al. (2023), underlines the necessity of the optimization of fiber-matrix compatibility and control of processing parameters in order to find a balance between mechanical performance and printability. Thus, an integrated and systematic analysis of fiber properties, matrix choice, and processing conditions is the way to solve these issues and proceed towards creating high-performance sustainable FDM filaments.

Even though this natural fiber reinforcement is mostly linked with the enhanced mechanical properties, the reported findings are not consistent. Long et al. (2019) and Taborda-Rios et al. (2020) recorded the tensile strength and stiffness improvements, and Guo et al. (2018) and Yu et al. (2021) found that the mechanical performance was largely degraded with larger fiber loadings with poor dispersion and high porosity. Moreover, Morales et al. (2021) and Sun et al. (2022) noted that the mechanical behavior is the key factor of particle size, as well as distribution of fibers. More recent researches like Sharma et al. (2025a) and Uddin et al. (2025) indicate that further modeling and hybridizing reinforcement plans are capable of predicting and optimizing composite performance. These conflicting results show that mechanical performance cannot solely be determined by fiber content or interfacial bonding or processing conditions.

1.8 Printability Challenges and Filament Optimization in FDM of Natural Fiber Composites

1.8.1 Rheological Requirements for FDM Processing

Rheological behavior of the composite melt is crucial to successful printing of the natural fiber-reinforced composites in FDM. Addition of natural fibers in thermoplastic matrices changes the viscosity and flow properties of the melt in a large scale. Additionally, as a rule, the viscosity of the polymer melt is increased with the addition of fibers, and shear-thinning behavior occurs, and this may limit easy extrusion through the nozzle. Too much viscosity causes irregular flow of material, poorly formed beads and unsatisfactory finish. Hence, it is always imperative to keep the fiber loading and melt flow index (MFI) in good proportion. In the majority of cases of FDM applications, the short fiber contents of 5-20 wt% are perceived to be enough in order to preserve flowability and enhance the mechanical performance. The composite should have steady viscoelastic characteristics to make extrusion and inter-diffusion between neighboring layers steady to determine part strength and dimensional stability (Sun et al., 2022).

1.8.2 Filament Diameter Stability and Extrusion Control

One of the most important requirements of FDM printing is dimensional stability of filament because commercial printers normally use very tight tolerances of a filament diameter of 1.75 mm or 2.85 mm. Natural fibers can be introduced with alteration in the diameter of filaments, surface roughness, and internal porosity during extrusion. These inconsistencies interfere with feeding mechanisms causing under-extrusion or over-extrusion thus impacting adversely on part accuracy and mechanical properties. The risk of ovality and rough filament surfaces is also high in the light of heterogeneous nature of natural fibers. These challenges can be overcome by having strict control of extrusion temperature, screw speed, cooling rate and puller speed during the manufacturing of filament. Homogeneous fiber distribution and adequate compounding by use of twin-screw extrusion can largely boost filament uniformity (Niang et al., 2022).

1.8.3 Nozzle Clogging and Fiber Length Limitation

One of the most widespread and the most problematic aspects in the printing of natural fiber-reinforced composites is the nozzle clogging. The main cause of this issue is fiber agglomeration, fiber length excessive, poor dispersion, or swelling agglomeration of lignocellulosic particles, caused by moisture. FDM nozzles are usually 0.24 mm to 0.6 mm in diameter and therefore the length of the fibre has to be significantly shorter than the aperture size of the nozzle to maintain continuous flow. In practice, the length of fibers is usually not longer than a third of the nozzle diameter in order to reduce the risk of clogging. It is also necessary that the fibers should be properly dried before compounding since moisture can develop during extrusion, resulting in flow unsteadiness. Moreover, natural fibers have abrasive nature, which may hasten the wearing out of traditional brass nozzles, which influences the consistency of printing in the long-term. Consequently, this would result in the use of hardened steel or wear-resistant nozzle in continuous printing of fiber-reinforced filaments (Jha et al., 2024).

1.8.4 Thermal Stability and Degradation Behavior

Another major problem in FDM processing is the thermal stability of natural fibers. Lignocellulosic materials normally start to degrade under temperature of 200°C to 250°C as a result of hemicellulose and cellulose components. Nevertheless, most thermoplastic matrices (including PLA, ABS and polypropylene) are processed at a similar temperature. During degradation, the volatiles emitted and the mechanical properties can be reduced, discoloration can occur, and internal porosity can form. Thus, it is necessary to achieve a high optimization of extrusion and printing temperature to achieve total melting of the polymer and avoids a degradation of the fibers. Lower processing temperature biopolymers like PLA tend to be better affinity with natural fiber reinforcements and therefore are more likely to be used as matrices in developing sustainable FDM filaments (Giani et al., 2024).

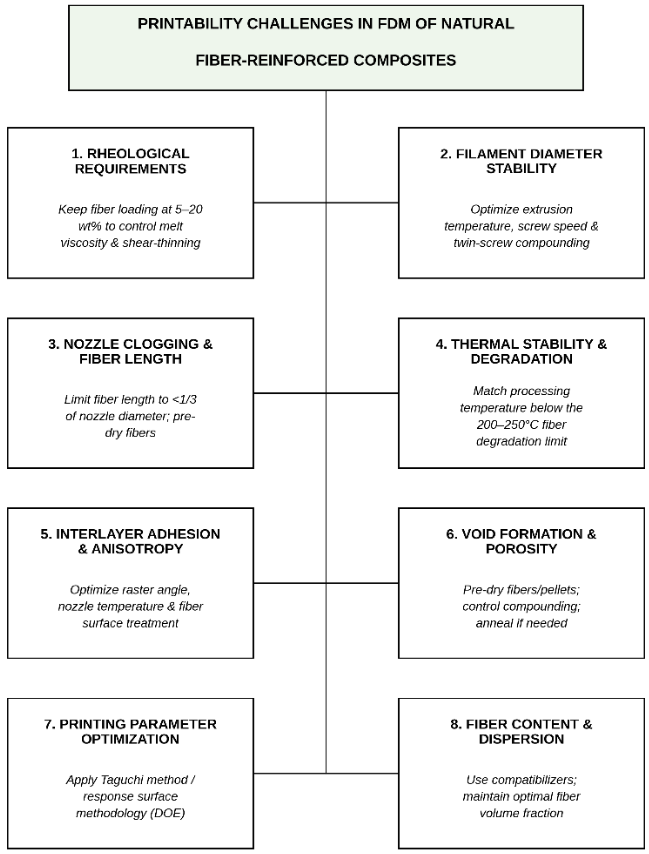

Figure 4. Key printability challenges in FDM processing of natural fiber-reinforced composites and their corresponding optimization strategies.

The main challenges of FDM processing of NF composites are summarized in **Figure 4**, which are rheological limitations, variations in fibre diameter, nozzle clogging, fibre degradation, interlayer adhesion/anisotropy, void formation and fibre dispersion. This is followed by an optimization strategy, which corresponds to each challenge, to ensure the printable and mechanically reliable filaments.

1.8.5 Interlayer Adhesion and Anisotropic Behavior

The components produced by FDM are inherently anisotropic with regard to their mechanical behavior since they are made by way of layer-by-layer. With natural fiber-reinforced composites, this anisotropy may be stronger since fibers are inclined towards the extrusion direction, which forms directional reinforcement. Poor lateral diffusion in diffusion of polymer chains between layers and poor wetting of the fibers further diminishes the interfacial adhesion. The mechanical performance, therefore, is quite different with regard to printing orientation and raster angle. Printing parameters should be optimized to enhance interlayer bonding, i.e. nozzle temperature, printing speed, layer height and raster overlap. Surface modification of fibers such as alkali treatment and silane treatment can be used to improve fiber-matrix compatibility and therefore, stress transfer and general structural integrity of the printed components (Sousa et al., 2025).

1.8.6 Void Formation and Porosity Control

The problem of void formation is a long-term problem in FDM-printed natural fiber composites and has a strong impact on the mechanical and physical performance. The cause of the voids can be entrapped air in the course of compounding, evaporation of moisture in the course of extrusion or a lack of complete fusion between beads that have been deposited. Voids decrease tensile strength, flexural strength, decrease fatigue resistance and decrease dimensional stability. Moreover, internal porosity has the potential to reduce the surface finish and encourage the formation of cracks at the time of cyclic loading. Porosity needs to be controlled through proper pre-drying of fibers and polymer pellets, optimum conditions during compounding and proper printing parameters. ost-processing to achieve increased density and mechanical properties (i.e. additional polymer diffusion) in some cases could involve annealing or hot pressing (Sharma et al., 2025b).

1.8.7 Printing Parameter Optimization

Printing parameters have a significant effect on the mechanical and physical properties of FDM-printed natural fiber composites. Nozzle temperature has direct impacts with melt viscosity and interlayer adhesion whereas printing speed has an impact on the stability of bead deposition and bonding quality. Increased nozzle temperatures are capable of enhancing fusion of the layers but should be well managed to prevent heat damage of fibers. Surface finish and bonding between layers is dependent on the layer height, whereas the raster angle and build orientation play an important role on anisotropic behavior. The Taguchi method and response surface methodology are some of the statistical techniques that have proved useful in establishing the best parameter combinations with regard to fiber-reinforced FDM composites (Kampeerapappun et al., 2024).

1.8.8 Fiber Content and Dispersion Optimization

Though greater reinforcement by adding fiber content usually results in greater stiffness and tensile strength, over reinforcement would have a negative impact on printability. The effects of high fiber loading are high viscosity of the melt, low flow stability, and porosity and brittleness. Moreover, the inadequate dispersion causes the locations of stress concentration causing structural lack of reliability. Thus, there should be an ideal fiber volume fraction that can be used to trade between mechanical performance and extrusion stability. Consistent dispersions gained by controlled dispersing methods of a uniform dispersion are essential in avoiding agglomeration and also in ensuring equal performance. The addition of compatibilizers and coupling agents only enhances dispersion and interfacial bonding, which add to the mechanical and thermal properties (Ahmad et al., 2025).

Although natural fiber reinforcement is generally associated with improved mechanical properties, the reported results are often inconsistent. Long et al. (2019) and Taborda-Rios et al. (2020) observed significant improvements in tensile strength and stiffness, whereas Guo et al. (2018) and Yu et al. (2021) reported a decline in mechanical performance at higher fiber loadings due to poor dispersion and increased porosity. Furthermore, Sun et al. (2022) highlighted that particle size and fiber distribution significantly influence mechanical behavior. Recent studies such as Sharma et al. (2025c) and Uddin et al. (2025) suggest that advanced modeling and hybrid reinforcement strategies can help predict and optimize composite performance. These contradictory findings indicate that mechanical performance depends not only on fiber content but also on interfacial bonding and processing conditions.

1.9 Future Perspectives in Sustainable FDM Filament Development

The future of filament engineering would see the printability of natural fiber reinforced composites become even greater. New developments are the introduction of compatibilizers, hybrid fiber systems, the use of micro- and nano-cellulose reinforcements, and the use of continuous natural fiber reinforcement in FDM systems. Real-time optimization of the process and in-line rheological monitoring of the extrusion of the filament can improve the consistency of the material. Further studies ought to incorporate rheological, thermal and mechanical testing to develop a holistic design principle to guide the development of sustainable FDM filament. This type of integrated strategies will facilitate the generation of high-performance environmental components that can be used in both structural and functional applications (Manickaraj et al., 2024).

The systematic research of the printability of natural fiber-reinforced FDM composites has been achieved recently (2023-2025). Ahmad et al. (2022) have stated that the viscosity of the melting point of PLA-based biocomposites increases sharply with the loading of the fibers after 20 wt% and results in unstable extrusion and interlayer bonding. On the same note, (Arivendan et al., 2026) found that changes in the diameter of filament and internal porosity are key factors that can lead to a decrease in tensile strength in flax-reinforced FDM components. Khan et al. (2023) emphasized that a lack of proper drying of fibers leads to the formation of bubbles with moisture during extrusion that enhances the content of voids and the risk of clogging the nozzle. In addition, Lendvai et al. (2023) established that anisotropic mechanical behavior in printed natural fiber composite is very sensitive to raster orientation and extrusion temperature. These new results establish the fact that the rheological control, the optimal dispersion of the fibers, moisture control, and printing parameters control are highly important in producing reliable and reproducible results in sustainable FDM filaments.

2. Critical Analysis of FDM Performance and Optimization Strategies

In addition to conventional analytical methods, this section also reviews machine learning and deep learning approaches that have emerged as powerful tools for pattern recognition, classification, and predictive analysis in the studied application domain.

2.1 Optimal Fiber Loadings for FDM Applications

There is a clear indication in the literature in the last few years that fiber loading is the conclusive factor in shaping mechanical reinforcement versus printability in natural fiber composite produced through FDM. Although addition of fiber material tends to increase stiffness and tensile modulus through better transfer of the load, too much fiber loading poses a major problem on the melt flow characteristics and extrusion stability. Majority of published studies indicate that there is an optimum range of 5-20 wt% fiber loading on short-fiber reinforced thermoplastic filaments. At concentrations below 5 wt, the reinforcement effect is negligible and not worth the complexity in processing that is added. But at composites melt content around 20 wt, the viscosity of the composite melt rapidly increases and results in inability to form filaments, nozzle blockage, uneven deposition of beads and high porosity of printed components. Surprisingly, tensile modulus is normally related to fibers fraction increment, yet tensile strength does not always correspond to the identical rate of linear enhancement with interfacial debonding and stress concentration that is related to fiber agglomeration. This shows that the best fiber blend in FDM systems cannot be defined with mechanical improvement but with a joint analysis of rheological performance, extrusion consistency and structural strength of the printed parts (Arivendan et al., 2026).

2.2 Trade-Off Between Mechanical Strength and Printability

Mechanical performance and printability of natural fiber-reinforced FDM composites have a basic trade-off. Increases in fiber content make it stiffer and more difficult to diffusion between layers as it melts, decreases the mobility of polymer chains and slows down polymerization. Furthermore, high fiber loading is likely to cause voids and micro-defects through an incomplete wetting and entrapment of air during compounding and negate tensile modulus enhancements. In some instances, when the stiffness is increased, there is also a rise in brittle qualities, decrease in impact resistance and reduced surface finish. Also, the melts of high viscosity demand more pressure to extrude and there is a higher chance of uneven flow and warpage. Thus, under maximum fiber reinforcement, optimum performance in FDM does not always result. The best recipes are the ones yielding moderate mechanical improvement and stable extrusion, cohesive layers and tolerable surface quality (Arivendan et al., 2026).

2.3 Limitations of Surface Treatments for Large-Scale Filament Production

Even though surface treatments like alkali modification, silane coupling and addition of compatibilizers are widely reported to increase the adhesion and mechanical performance between fibers and the matrix at the laboratory scale, their application in large-scale production of filaments faces a number of challenges. Silane treatments add new processing stages to the process, such as washing, drying, and solvent management, which add costs and complexity of production. Moreover, bulk chemical treatment has some environmental issues that are associated with wastewater treatment and disposal of the chemical. Continuous filament extrusion systems may make it hard to maintain the consistency of surface modification quality which may result in inconsistent mechanical performance. Therefore, although surface treatments enhance interfacial bonding when performed in controlled environments, their scalability, affordability and environmental friendliness are important constraints that need to be overcome before treated natural fiber FDM filaments can be widely used in industrial settings (Goh et al., 2024).

Table 9. Comparative evaluation of fiber type, matrix selection, FDM printability, and processing limitations in natural fiber–reinforced filaments.

Fiber type	Matrix material	Typical fiber loading (wt%)	FDM performance	Mechanical improvement	Printability issues	Key limitations
Rice Husk (Sun et al., 2022)	PLA	10–20	Stable extrusion at moderate loading; acceptable layer bonding	Increased tensile modulus and stiffness	Increased melt viscosity beyond 20%; intermittent nozzle clogging	Brittleness at high loading; moisture sensitivity
Hemp Fiber (Lendvai et al., 2023)	PLA / PBS	10–15	Good bead deposition with controlled fiber size	Improved tensile and flexural modulus	Reduced interlayer adhesion at higher fiber fraction	Thermal degradation risk; anisotropic behavior
Wood Flour (Dönitz et al., 2023)	PLA	5–15	Smooth filament formation at low content; aesthetic surface finish	Moderate strength enhancement	Flow instability and rough surface at high loading	Reduced impact strength; porosity formation
Oil Palm Fiber (Ahmad et al., 2015)	Thermoplastic Blend	10–20	Printable with optimized temperature and speed	Improved strength after parameter optimization	Sensitive to printing parameters; void formation	Fiber dispersion challenges; dimensional instability
Lignin (Zaidi et al., 2023)	PLA	5–10	Good filament stability at low addition	Slight stiffness increase; sustainability advantage	Reduced melt strength at high concentration	Compatibility concerns; lower impact resistance
Bamboo Fiber (Niang et al., 2022)	PLA / PP	10–15	Printable when fiber length is controlled	Enhanced flexural stiffness	Nozzle wear due to abrasive particles	Agglomeration risk; inconsistent surface texture
Kenaf Fiber (Tholibon et al., 2019)	PLA	10–20	Acceptable extrusion at moderate loadings	Increased modulus and dimensional stability	Elevated viscosity at higher loading	Weak bonding if untreated; moisture absorption
Jute Fiber (Mahmud et al., 2023)	PLA / PP	5–15	Moderate printability with pre-drying	Improved stiffness along raster direction	Poor layer fusion at high fiber percentage	Fiber pull-out; mechanical anisotropy

Recent studies by Khan et al. (2023) stated that the addition of natural fibers past 15-20 wt% in PLA led to a steep increase in melt viscosity and extrusion pressure, poor uniformity of beads, and internal porosity in FDM-printed components. In a similar manner, in the work by Sun et al. (2022), it was argued that even though stiffness increased with increased fiber loading, tensile strength was non-linear because of fiber agglomeration and weak diffusion between layers. In addition, Morales et al. (2021) noted that production of large-scale filaments has problems of reproducibility, with specific issues in fiber dispersion consistency and quality of surface treatment. All these studies support the fact that the ideal FDM behavior is determined by the balance between the fiber fraction and rheological stability and processing uniformity and not only by maximum reinforcement.

2.4 Research on Machine Learning Approaches for Predicting Mechanical Behavior of Composites

There are many publications in recent years, which use machine learning (ML) to predict and optimize the mechanical behavior of composite materials, which shows their high accuracy and practice applicability. A further overall assessment of ML application to aerospace composite design indicates that surrogate modeling and design space exploration are successful and enhances efficiency in predicting structural performance, design failure, and fatigue behavior. When applied to additive manufacturing, several ML algorithms have been used to forecast mechanical performance of FDM components, with high accuracy in all hardness, tensile and flexural performance indicators, allowing optimization of specific parameters to be performed in a short period (Sharma et al., 2025c). The use of explainable AI techniques, including SHAP, to interpret model predictions, and critical input features that affect mechanical predictions are also highlighted in the reviews and help in understanding structure-property relationships and materials design. Taken together, these studies validate the rising importance of ML in composite materials engineering, especially in terms of fastening the process of predicting performance, lowering the expenses of experiments, and aiding the optimization of formulations and processing parameter optimization based on the data.

Table 10. Comparison of ML model strengths and limitations in composite prediction (Song et al., 2023).

Algorithm	Strength	Limitation	Best use case
ANN	Captures nonlinear behavior	Needs large dataset	Complex multimodal data
Random Forest	Robust, interpretable	Less smooth predictions	Medium tabular datasets
GPR	Provides uncertainty	Computationally expensive	Small datasets
XGBoost	High accuracy	Hyperparameter tuning needed	Large datasets

Table 10 makes comparisons of various machine learning (ML) techniques employed in predicting mechanical behavior of composite materials such as Artificial Neural Networks (ANN), Random Forest (RF), Gaussian Process Regression (GPR), and Extreme Gradient Boosting (XGBoost). Such models are becoming more and more used in materials engineering to examine any complex correlation between material composition, processing parameters and the mechanical properties obtained. Recent research has established that the ML methods can drastically lessen experimental effort and enhance prediction accuracy in the composite design and additive manufacturing process (Sharma et al., 2025c).

Artificial Neural Networks (ANN) are one of such models that are popular because of their capability to model nonlinear relationships among the input parameters and the mechanical responses. Other researchers have also proved that ANN models can be successfully utilized to predict tensile strength, flexural strength and hardness of fiber-reinforced composites in cases when adequate experimental data is present. Contrarily, the Random Forest algorithms are regarded as strong and explainable models that have the capacity to determine how parameters like the fiber volume fraction, printing temperature, and the raster orientation affect the performance of the composites. Gaussian Process Regression (GPR) is especially appropriate when working with smaller datasets since it gives the results of the prediction tasks in addition to uncertainty determination, which enables researchers to determine the reliability of the models. Its computational complexity is however increased as it is applied on large datasets. Conversely, XGBoost has become popular due to its high accuracy in predictions and strong ability to scale large amount of data though it has hyperparameters that need to be effortlessly tuned to attain optimal model performance.

More current research since 2024 has also revealed the growing popularity of machine learning in the study of composite materials. To reflect on the example, it has been shown that the predictive models based on machine learning can be used to precisely determine the mechanical characteristics of fiber-reinforced polymer composites by examining material composition and manufacturing conditions. It is also demonstrated that the hybrid machine learning models that integrate neural networks with ensemble models can be used to improve the predictive accuracy of mechanical properties of 3D-printed composite materials. In general, **Table 10** demonstrates that machine learning methods, including ANN, Random Forest, GPR, and XGBoost, are potentially effective predictors and optimizers of the mechanical behavior of composite materials. Combining experimental studies and data-driven modeling, the techniques can help expedite the creation of natural fiber-reinforced composites and sustainable FDM printing materials and minimize experimental cost and wastage of materials.

3. Next-Generation Electrospun Nanofibers: Multidirectional Applications from Energy Systems to Precision Medicine

Electrospun nanofibers have found wide application in the area of energy storage as an electrode material in lithium-ion batteries, sodium-ion batteries, and supercapacitors. Carbonized electrospun polyacrylonitrile (PAN) fibers have been shown to have enhanced electrical conductivity and mechanical stability, and therefore they can be suitable as binder-free electrodes. It has also been reported that metal oxide-loaded electrospun fibers including MnO_2, TiO_2, and ZnO composites have been found to store charge better because of an increase in active surface area and the reduction in ion diffusion channels. Indicatively, it has been demonstrated in recent experimental studies that electrospun porous carbon nanofiber mats are more stable to cycling and retain high capacitance values than bulk electrode materials. Also, carbon nanofibers heteroatom doped (e.g. nitrogen or sulfur doped) have been reported to enhance electrochemical performance due to improved transport of electrons and active site density (Zhu et al., 2024).

Some of the recent researches indicate faster wound healing, and enhanced tissue regeneration with the use of electrospun mats made of biodegradable polymers, including polycaprolactone (PCL), polylactic acid (PLA), and chitosan blends. The use of silver nanoparticles and bioactive ceramics in nanofibers has also been studied to improve the antimicrobial effect and biocompatibility. In addition, it has been demonstrated that electrospun scaffolds with an aligned orientation of fibers can direct cell growth and differentiation, especially nerve tissue and musculoskeletal tissue engineering (Tsareva et al., 2025).

In addition to energy and medicine, electrospun nanofibers are slowly being used in sensing, filtration and environmental remediation. Electrospun fibers made of conductive polymers have also been applied in flexible strain and chemical sensors; in this case, the sensitivity of electrospun fibers is high due to the high surface area of interaction. Nanofiber membrane finds high efficiency in filtration process application by removing fine particulate matter and microorganisms with low pressure drop. New directions in the field of emergent research include the concomitant application of electrospinning and additive manufacturing methods to create hybrid constructions capable of merging nanoscale functionality and macroscale structural design (Bhattarai et al., 2019).

Even though there have been significant improvements, there are still a number of challenges. Numerous papers have various studies have limitations linked to scalability, solvent toxicity, fiber morphology reproducibility, and stability of the fibers under working conditions. It is noted on a regular basis that greener solvent systems, standardized protocols in performance evaluation and better methods of integrating device level application are required. However, the overall body of knowledge suggests that electrospun nanofibers can become a next generation material platform that can satisfy a wide range of technological needs as long as processing scalability are developed in an orderly manner (Alagulakshmi et al., 2025).

Nanofibers produced by electrospinning have become quite popular because of their multifunctional nature in energy storage and biomedical use, but their functioning is strongly related to the choice of the material and conditions of its processing. Zhu et al. (2024) found that the high surface area and porosity of nanofibers are the key factors in improving the performance of the energy system in terms of electrochemical and Tsareva et al. (2025) found their application in various biomedical applications including drug delivery and tissue engineering. In spite of these benefits, Bhattarai et al. (2019) observed that their implementation at scale, structural homogeneity, and reproducibility have challenges that limit their application on large scale. Such opposite results point to the fact that although the application of electrospun nanofibers has a wide range of opportunities, revision of the methods in making nanofibers is critical to maintaining performance consistency in other fields.

4. Multi-Attribute Optimizations of Drilling Carbon-Innegra Fiber–Reinforced Composites using Entropy-TOPSIS

The multi-attribute decision-making (MADM) methods have become widespread in maximising machining parameters of fiber-reinforced composites since the methods enable multiple, and often conflicting, parameters of performance to be considered, including thrust force, torque, delamination (entry and exit), and surface roughness. Recently, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used to rank sets of machining parameters after assigning objective weights to each parameter using the Shannon entropy method and the Entropy-TOPSIS hybrid method was applied to the process of drilling Carbon-Innegra (CI) fiber-reinforced polymer composites. The authors conducted Taguchi-based drilling experiments at a factorial scope of the spindle speed (750-3000 rpm), feed (30-120 mm/rev) and a common carbide drill geometry and quantified five responses (thrust, torque, entrance and exit delaminations and surface finish). Entropy weighting was used to give an objective measure of the relative information content of each response and TOPSIS gave an overall ranking which gave the best compromise drilling conditions based on minimal damage and good surface quality (Ramachandran et al., 2025).

This Entropy-TOPSIS method of CI composites is consistent with the prior MADM research on composite drilling that indicates the approach to be useful in multi-response optimization. The common advice in these studies is to apply the objective weighting (entropy) approach in cases where there is no appropriate preference among the responses, and to complement the MADM results with physical examination of the delamination and tool wear in order to improve practical applicability.

This literature helps back two useful aspects. To start with, Entropy-TOPSIS is a suitable and ever-growing methodology to multi-objective optimization in machining of hybrid fiber composites, which offers an objective path of the trade-off between conflicting quality measures. Second, the particular CI drilling report illustrates the method on a new hybrid fiber system and gives the experimental ranges of parameters, experimental responses, and a prioritized solution that may be quoted as an example of best practice when developing drilling or post-processing recommendations to new composite filaments or printed parts (Tran et al., 2020).

Multi-attribute optimization models like Entropy-TOPSIS have been widely used to enhance the performance of drilling on the fiber-reinforced composites due to its simultaneous consideration of various conflicting factors. As evidenced by Ramachandran et al. (2025), Entropy-TOPSIS is a reliable methodology that can be used to determine the best drilling parameters to be used, balancing aspects of thrust force, roughness of the surface, and delamination. By contrast, Tran et al. (2020) used the same types of decision-making methods in the CFRP drilling and indicated better process reliability by the multi-criteria assessment. Nevertheless, Shukla et al. (2017) found that the effectiveness of those methods highly relies on the choice of parameters and weighting schemes. These results show that although Entropy-TOPSIS is an effective optimization tool its performance depends on the definition of criteria and quality of data.

Table 11 summaries of multi-attribute drilling optimization approaches applied to hybrid fiber composites, highlighting the integration of entropy weighting and TOPSIS ranking for simultaneous control of multiple machining quality indicators.

Table 11. Multi-response drilling optimization of CI-FRP using entropy-TOPSIS (Shukla et al., 2017).

Parameter type	Variables considered	Optimization goal
Input Variables	Spindle speed (rpm), Feed rate (mm/rev), Drill diameter	Identify stable machining window
Response Variables	Thrust force (N), Torque (Nm), Delamination factor (Fd), Surface roughness (Ra)	Minimize mechanical damage
Decision Method	Shannon Entropy (objective weight allocation)	Assign importance to responses
Ranking Method	TOPSIS	Select parameter combination closest to ideal solution

The problem is how the mechanical performance of composite materials depends on their composition and structure, and this is one of the main motifs of the recent polymer composite research. A 2025 systematic review points out that the reinforcing agent, matrix material, and production process have significant effects on tensile, flexural, hardness, elastic modulus, and impact behavior in polymer composites and, therefore, the microstructural morphology (i.e., fiber distribution, porosity, interfacial bonding) should be tightly controlled to attain desired behaviors in structural applications in biomedical, aerospace, and automotive industries (Sharma et al., 2025a). Experimental research also supports the fact that defects like voids, dry spots and bubbles which are usually formed during the fabrication of composites significantly reduce the mechanical performance since they serve as stress concentration zones and therefore lead to crack initiation and propagation. Studies of multi-component polymer systems also support the importance of morphology: attempts to enhance interfacial bonding and phase morphology in HDPE and hybrid polymer blends have found that particular microstructural structures result in increased stiffness and toughness because of increased interphase stress transfer. The body of nanocomposites research highlights that mechanical reinforcement is highly sensitive to the dispersion, shape and interfacial properties of nanoscale fillers like graphene and carbon nanotubes - well- dispersed nanofillers have the potential to enhance strength and stiffness, whereas agglomeration creates weak points which cancel any potential benefits (Kalova & Rusnakova, 2017).

The composition, microstructure and performance of polymer composites are important to understand in order to optimize the composites. As, Sharma et al. (2025b) pointed out, the mechanical behavior and failure mechanisms are directly dictated by the structural features of orientation of the fibers, dispersion and interfacial bonding. On the same note, Kalova & Rusnakova (2017) pointed out that microstructural uniformity is important in promoting strength and durability. On the contrary, current research by Uddin et al. (2025) states that the incorporation of data-driven models can enhance prediction of structure-property relations in composite systems further. These results indicate that it is necessary to combine the material design, control of structure, and advanced modeling in order to reach the optimum performance.

5. Future Perspectives and Research Gap

Although much has been done in the production of natural fiber-reinforced filaments to fused deposition modelling (FDM), some inherent problems and gaps in current research remain in the way to scaling the technology to large scales and commercial use. The main limitation of the existing literature is that no comprehensive and integrated solution is offered that concomitantly takes into account the fiber properties, surface modification, choice of polymer matrix, and processing conditions. The parameters have been examined separately in most of the studies, which has resulted in a scattered knowledge and gaps in the results. The future of additive manufacturing, as Arivendan et al. (2026), is the unification of material design with optimization of the process, but the systems based on natural fibers are yet to be developed in this regard.

Fiber dispersion and interfacial bonding is one of the biggest inconclusion problems that have direct impact on the mechanical properties and printability. Though surface treatments like alkali and silane have demonstrated to improve adhesion of the fibers and the matrix (Kabir et al., 2012), their efficacy is considerably different under different conditions and fiber type. The latest developments in interfacial engineering such as the application of plasma treatment and sophisticated chemical modification are promising alternatives, but their scalability, as well as cost-effectiveness is still questionable. Future studies must be aimed at coming up with controlled and scalable methods of surface modification that will keep dispersion uniform without compromising fiber integrity.

The other important knowledge gap is the rheological behavior and printability of composite filaments. Chemical additions of natural fibers tend to raise the viscosity, nozzle obstructing, and the adhesion of layers that all have an undesirable impact on the quality of printed components. Although the necessity of optimization of printing parameters is proven by studies, including Ahmad et al. (2025), there are no standard guidelines on the formulation and processing of filament. As proposed more recently by Giani et al. (2024) and Goh et al. (2024), better material-process compatibility is crucial to a uniform quality of the print. Future research, therefore, should seek to develop standard processing windows and design criteria of filament designs of various fiber-matrix systems.

Future research on the subject also has great opportunities in the choice and development of polymer matrices. Despite the fact that the most common matrix used is PLA because of its biodegradability, ease of processing (Siakeng et al., 2019), its brittle nature and susceptible to water restricts the use of the material in high performance parts. Recent studies in bio-based and hybrid polymer systems are pointing toward an increasing trend in the use of multifunctional materials that are sustainable and also have improved mechanical properties. Nonetheless, more efforts are needed in order to maximize the match-ability of these matrices with natural fibers, especially when it comes to the FDM processing.

Moreover, the mechanical behavior of the natural fiber reinforced composite is quite unpredictable because of: variability of fibers, lack of good dispersion, and defects brought about by the process. It has also been demonstrated that hybrid schemes of reinforcement and nano-scale filler can enhance the performance of composites, but at the expense of complicating the materials and being more expensive. Future studies should aim at the creation of cost-effective hybrid systems which compromise on performance, processability and sustainability.

The combination of machine learning and data-driven optimization methods in composite design and additive manufacturing is a promising direction, in general. The research conducted by Kumar et al. (2024) and Li et al. (2025) prove that predictive modeling can optimize processing parameters and mechanical performance. In the same fashion, Uddin et al. (2025) emphasized the importance of artificial intelligence in developing material design of polymer composites. Nevertheless, the use of these methods with natural fiber-reinforced FDM systems is not yet advanced. The next step in work should be the creation of intelligent structures that would create a combination of material selection, process optimization, and performance prediction.

In addition, the issue of the lack of standardization and reproducibility of experimental studies has to be tackled. The differences in fiber treatment, filament fabrication and printing conditions complicate the ability to compare the results of the different studies. The development of standardized testing procedures and reporting would be necessary to address the growth of the sphere and facilitate the use of it in the industry.

Lastly, the concept of sustainability should be enhanced further by integrating the concepts of life cycle assessment (LCA), recyclability, and a circular economy into the process of natural fiber composite development. They have environmental advantages as compared to natural fibers, and bio-based polymers, but no extensive comparison of their environmental impact on the whole lifecycle exists.

To conclude, the research that ought to be conducted in the future ought to aim at creating an integrated and multidisciplinary system in which material innovation, process optimization, and innovative modeling techniques will be combined. The solutions to these issues will be essential to not only harness the full potential of natural fiber-reinforced composites with FDM and allow their use in the highly sustainable and high-performance engineering practice.

6. Conclusions

Natural fiber-reinforced polymer composites have become a popular subject of study as green substitutes of traditional petroleum-based substances in additive manufacturing. This review has discussed natural fiber-reinforced filaments development in fused deposition modelling (FDM) and emphasized how the material selection, fiber processing, and optimization of printing can enhance the mechanical capability and printability. The increasing ecological anxieties of synthetic fibers and non-renewable polymers have spurred the quest to use renewable plant-based fibers and biodegradable matrices in sophisticated manufacturing processes. Natural fibers like flax, hemp, kenaf, jute, bamboo, sisal, and cotton have a number of benefits such as low density, biodegradability, renewability, and a relatively high specific strength, which makes them an excellent reinforcer in polymer composites that are applied in an additive manufacturing system.

The structural properties and mechanical properties of natural fibers were initially covered in the review. The tensile and stiffness and good strength to weight ratio were observed in plant-based fibers, mostly because of their high cellulose content and hierarchical cell wall structure. These characteristics ensure that they are especially reinforced in thermoplastic matrices in FDM processes. Nevertheless, natural fibers also present a number of challenges including moisture absorption, inconsistency of mechanical properties, as well as incompatibility with hydrophobic polymer matrices.

Selection of matrix was also found as one of the key areas in development of natural fiber composite filaments. Polymers or materials that are thermoplastic in nature (particularly, polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), and polypropylene) have been commonly utilized in FDM due to their ability to melt-process and the ability to recycle thermoplasts. Among them, the PLA has been identified as one of the most promising biodegradable matrices as it has good processability, middle mechanical characteristics, and is compatible with natural fibers. There is also a potential of developing sustainable filament using bio-based polymers including polyhydroxyalkanoates (PHA), polybutylene adipate terephthalate (PBAT) and starch-based polymers though the issues of processing stability and mechanical performance still prevail.

Modifying the surface of natural fibers is crucial in improving the compatibility between fibers and matrix and in the increase of composite performance. Alkali treatment, silane modification, plasma treatment and application of coupling agents have been reported to greatly enhance interfacial bond between fibers and polymer matrices. These methods enhance the surface roughness, eliminate impurities and add functional groups that enhance better bonding with the matrix. Natural fiber-reinforced composite systems have an opportunity to receive greater transfer of loads, have less sensitivity to moisture, and greater mechanical properties.

The way of processing and methods of production were also under scrutiny. Traditional composite fabrication approaches like compression molding, pultrusion and resin transfer molding exhibit good structural performance but not the designability of additive manufacturing. However, there are various issues that relate to the application of natural fiber composite in FDM. These are a high viscosity of the melt because of fiber loading, unstable filament diameter, clogging of the nozzles, agglomeration of fibers, creation of voids, and anisotropic mechanical behaviour because of layer-by-layer deposition. These variables may have a detrimental effect on the printability and mechanical performance of the end print components.

Such parameters as fiber loading fraction, extrusion temperature, nozzle temperature, printing speed, layer height and raster orientation play a vital role in interlayer adhesion and mechanical performance of printed components. Research indicates that it is better to keep fiber loading at moderate range (usually below 20 wt) to have the benefit of a stable melt flow yet maintain reinforcement. Also, fibers need to be dried properly, the dispersion of the fibers increased, and the extrusion conditions need to be regulated, which will reduce the amount of void and allow increasing the structural integrity.

Altogether, the concept of natural fibers and biodegradable thermoplastic matrix promises a viable direction in the enhancement of an environmentally friendly composite filament that can be additively manufactured. Although there are challenges in the material compatibility, process stability and mechanical reliability, the progress in fiber treatment procedures, polymer blending strategies and filament extrusion technologies, are slowly lowering these barriers.

Further studies are required to better the fiber-matrix compatibility by application of improved surface treatment, use of hybrid reinforcement schemes and even nano-scale reinforcements like nanocellulose to improve overall mechanical and thermal performance. Moreover, the process optimization and material design through artificial intelligence and machine learning might be of great help in enhancing the performance and uniformity of natural fiber composite filaments. As the state of art in materials science and additive manufacturing technologies continues to evolve, natural fiber-reinforced composites can become an important part of developing sustainable, lightweight, and high-performance materials that will be utilized in the next-generation engineering.

Conflicts of Interest

There is no conflict of interest to be declared by authors.

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Not Applicable

AI Disclosure

During the preparation of this work the author(s) used generative AI in order to improve the language of the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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