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Mechanical Performance Assessment of Polylactic Acid (PLA) Based Bio-composite Filaments Incorporating Natural Fiber Reinforcements for Sustainable Additive Manufacturing

Lukkitha M C R, Ashlyn Janet A K
Department of Aeronautical Engineering, School of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai-600119, India

Abstract:

AM (Additive Manufacturing) has opened up new possibilities for the use of bio-based polymers, with PLA (Polylactic Acid) standing out as one of the most promising sustainable materials in FDM (Fusion Deposition Method). Yet, despite its popularity, pure PLA often falls short in toughness and thermal resistance, limiting its range of applications. One of the most widely explored solutions to this issue is reinforcing PLA with natural fibres, which not only improves material performance but also aligns with sustainability goals. This review brings together insights from studies on PLA composites strengthened with hemp and agave fibres, with particular attention to their mechanical behaviour, thermal response, and printability. Alongside existing research, the paper also discusses a planned fabrication process involving two extrusion trials: the first with PLA blended with 5% hemp and 5% agave fibre, and the second with 10% of each fibre. Before extrusion, the fibres are treated with alkali, dried, and ground to ensure better bonding with the polymer matrix. By linking literature findings with this experimental framework, the review highlights both the advantages and challenges of fibre reinforcement such as dispersion, bonding quality, and processing conditions. Ultimately, the study emphasizes the potential of hemp–agave reinforced PLA as a sustainable filament for 3D printing, while pointing out areas where further research is needed to refine fibre combinations and optimize processing techniques.

Keywords: Additive Manufacturing; PLA-Filaments; FDM; natural fibre-based filaments; mechanical properties; hemp fibre; agave fibre

1. Introduction:

PLA has become one of the most widely explored biopolymers in recent years, mainly because it is renewable, biodegradable, and offers mechanical properties that make it suitable for sustainable applications in manufacturing and healthcare [1]. Unlike petroleum-based plastics, PLA is produced from natural resources such as corn or sugarcane, which significantly lowers its carbon footprint and ties in with global efforts to reduce environmental impact [2]. Its biodegradability and ability to compost under controlled conditions make it especially attractive for packaging and single-use products, where the environmental burden of conventional plastics is greatest[3] . At the same time, PLA offers competitive tensile strength and stiffness, giving it the potential to move beyond disposables into more structural applications [4]. With its relatively low melting point and ease of processing, PLA has also become a natural fit for fused FDM, one of the most common techniques in 3D printing [5]. Researchers have been working on enhancing PLA's properties by blending it with fillers or chemically modifying it, steps that address weaknesses such as brittleness and poor thermal resistance [6]. Studies into its flow and crystallization behaviour are also helping fine-tune how it performs during printing and post-processing [7]. In figure 1, the image shows the working principle of an FDM 3D printer, where filament from a spool is heated and extruded layer by layer onto a print bed to create a part. It highlights both the schematic process and its practical application in an actual printer.

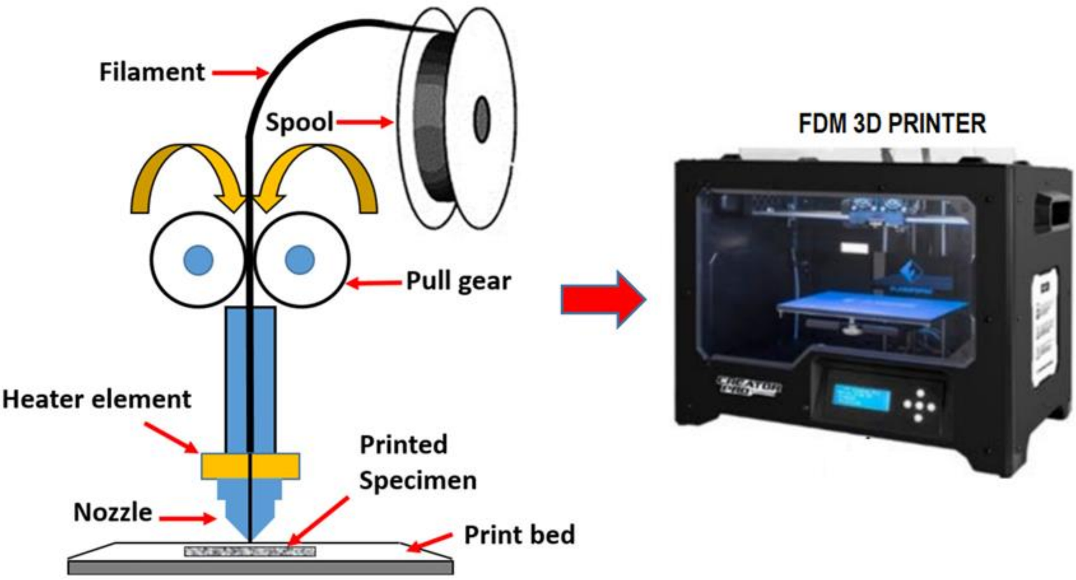

Figure 1: Schematic illustration of a FDM 3D printing [8]

In medicine, its biocompatibility and FDA (Food and Drug Administration) approval have opened doors to applications like tissue engineering scaffolds, drug delivery systems, and implantable devices [9]. The material is also gaining attention in recycling and circular economy initiatives, with new methods being explored to recover and reuse PLA [10]. Still, challenges remain its limited heat resistance and slow breakdown in natural conditions are key concerns but ongoing research into composites and copolymers shows promising ways to overcome these limitations [11]. In figure 2, the image explains additive manufacturing as a layer-by-layer process, with 3D printing technology enabling object creation from digital designs. It also distinguishes the 3D printer as the tool that executes this process using methods like FDM, SLA (Stereo Lithography), and SLS (Selective Laser Sintering).

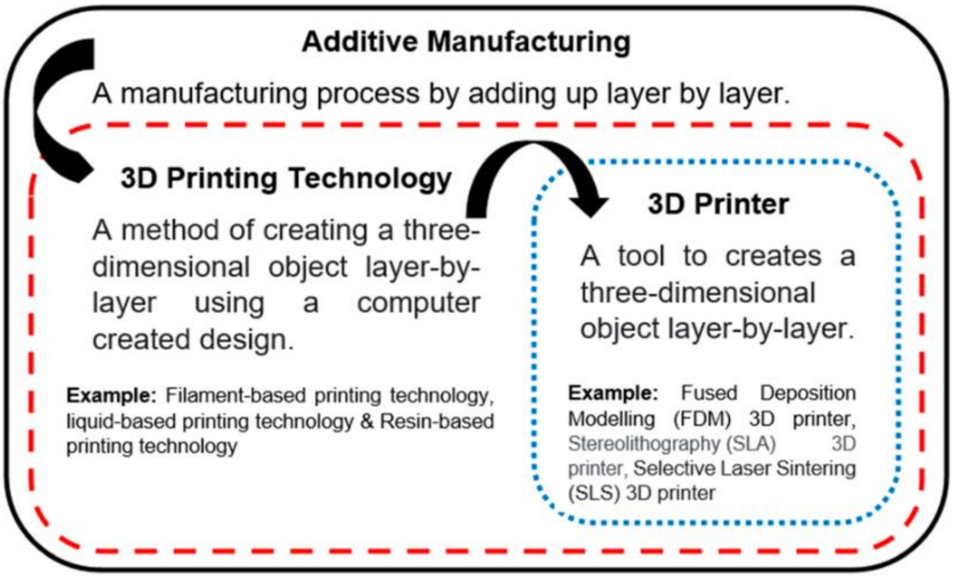

Figure 2: Important terms in additive manufacturing [12].

2. Types of Bio-Composite Filaments:

Bio-composite filaments span a wide spectrum from simple blends of PLA with wood flour or plant fibres for improved sustainability, to engineered blends that target specific mechanical and thermal improvements for FDM printing [13]. Several studies show how natural fibres (cellulose, hemp, bamboo, etc.) act as low-cost, renewable fillers that can reduce weight and environmental impact while requiring careful surface treatment and compatibilizers to avoid poor interfacial adhesion [14]. Others demonstrate that combining thermoplastics with micron- or nano-sized plant fillers improves stiffness and can tune biodegradation rates, although excessive filler loading often harms ductility and printability [15]. There's also a growing body of work on hybrid filaments that mix biopolymers with inorganic fillers for example hydroxyapatite or bioactive ceramics opening routes for biomedical scaffolds with enhanced bioactivity and load-bearing capacity [16]. Work on processing and filament fabrication highlights how twin-screw extrusion parameters, drying, and pellet quality critically affect filament diameter stability and eventual print mechanical reliability small changes at the filament stage cascade to large differences in printed parts [17]. In table 1, the table compares the mechanical properties of various natural fibres, highlighting differences in density, tensile strength, tensile modulus, and elongation at break. It shows that fibres like flax, pineapple, and hemp exhibit high strength and stiffness, making them promising candidates for composite applications.

Research further explores recycled and partially bio-based matrices blended with natural fibres as a circular-economy strategy, showing promising trade-offs between sustainability and retained performance when recycling routes are well controlled [19]. Advances in coupling agents, surface treatments, and sizing for fibres help reduce voids and improve interfacial load transfer, which is key for achieving repeatable mechanical properties in printed composites[20]. Some studies focus on functionally graded or continuous-fibre approaches (using short vs continuous reinforcement) to move beyond particulate fillers toward higher strength-to-weight printed components [21].

Fibre	Density (g/cm^3)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Elongation Break (%)
Sugar Palm	1.30	15.5-290	0.5-3.4	5.7-28
Sisal	1.50	400-700	9.0-38.0	2.0-14.0
Oil Palm	1.55	400	9.0	18.0
Jute	1.60	393-800	10.0-30.0	1.2-1.8
Kenaf	1.45	930	53.0	1.6
Hemp	1.48	550-900	70.0	1.6-4.0
Cotton	1.60	287-800	5.5-12.6	2.0-10.0
Bamboo	1.25	290	17.0	-
Flax	1.50	345-1500	27.6	1.2-3.2
Pineapple	1.44	413-1627	60.0-82.0	14.5
Banana	1.35	579-914	27.0-32.0	5.9

Table 1: Mechanical properties of Various Types of Bio-Composite Materials [18]

Others investigate material families and print parameter interactions crystallization behaviour, rheology, and nozzle temperature windows which collectively determine printability, layer bonding and final anisotropic properties of bio-composite filaments [22]. Altogether, the literature maps a clear path: starting from simple, eco-friendly filler blends and moving toward engineered, multifunctional bio-composite filaments that balance sustainability, printability, and application-specific performance [23]. In figure 3, the diagram classifies natural fibres into three main categories: plant-based, animal-based, and mineral-based. Each category is further divided into subtypes, showing the wide diversity of natural fibres used in different applications.

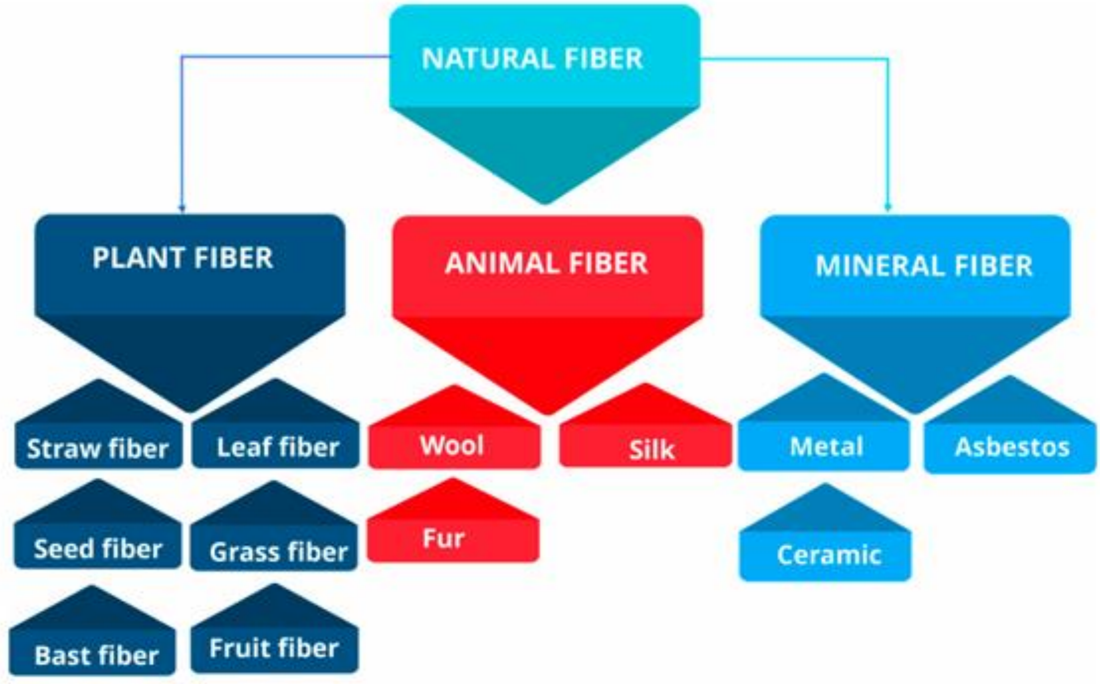

Figure 3: Classification of natural Fibres [24]

2.1 Types of Bio-Composite Materials in PLA

Polylactic acid (PLA) is increasingly blended with natural plant fibres like wood, flax, hemp, and lignocellulosic residues to produce lightweight, biodegradable composites, with fibre choice heavily influencing mechanical strength and adhesion quality [25]. Recent studies showcase the rise of nanocomposite systems, where nanofillers such as biochar or carbon-based particles enhance thermal stability, stiffness, and biodegradation control when evenly distributed [26]. Research also highlights natural waste-derived fillers, such as walnut shells or eggshell powders, which not only valorise by-products but also boost hardness and structural integrity in PLA matrices [27]. Innovations in metal-filler blends, such as PLA infused with zinc particles or magnesium fibres, have shown potential for biomedical scaffolds, improving printability, mechanical performance, and sometimes bioactivity [28]. Other advanced formats include shape-memory PLA composites reinforced with bio-derived materials, unlocking new possibilities for stimuli-responsive (4D) printing applications [29]. In figure 4, the image shows different natural fibre-based filaments prepared for 3D printing, each coiled into spools ready for processing. These variations demonstrate the adaptability of natural fibres in filament form for additive manufacturing applications.

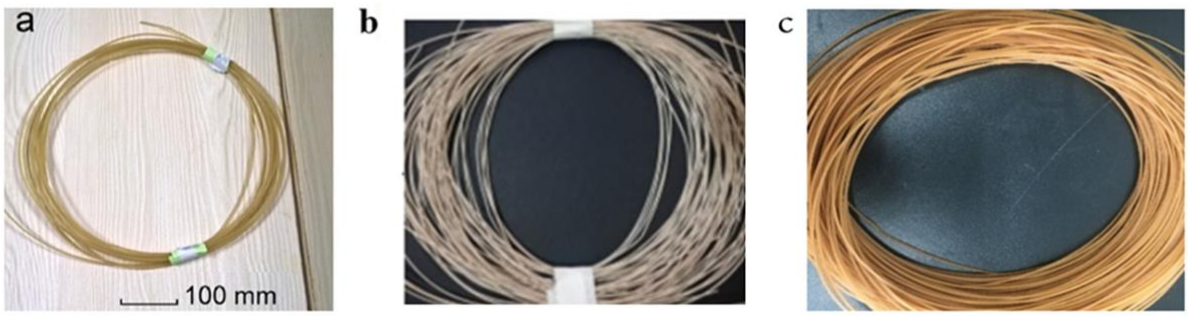

Figure 4: Extruded natural fibre composite filament (a) wood/PLA, (b) Kenaf/A, and (c) astragalus/PLA [30].

Processing techniques like twin-screw extrusion and controlled fibre particle sizing have been shown essential to ensuring filament diameter stability and preserving mechanical reliability during printing [31]. Several reviews emphasize plant-fibre composites with pretreatments chemical or physical alongside coupling agents, to improve interface bonding and mechanical fidelity at low fibre loadings [32]. PLA blends with other biodegradable polymers (e.g., starch, PHA) are being explored to combine complementary properties like toughness, flexibility, or cost-efficiency [33]. Cutting-edge studies are investigating micro- or nano-structured PLA composites, employing techniques like laser writing to create controlled topographies and enhanced surface features for scaffolds and tailored interfaces [34]. Lastly, the field is also embracing mycelium-infused bio-composites, which leverage fungal networks for lightweight, eco-friendly materials with unique hyphal reinforcement properties [35].

2.2 Types of Bio-Composite Materials in ABS

ABS (Acrylonitrile Butadiene Styrene) is increasingly being modified with natural waste-derived fibres like banana peel, orange peel, cinnamon bark, and neem leaves these eloquently sustainable fillers not only reduce viscosity during filament extrusion but also significantly enhance shape-memory behaviour, with ABS/orange peel blends showing particularly strong mechanical performance [36]. Beyond fruit waste, researchers are exploring natural fibre-reinforced ABS composites, aligning with broader efforts in additive manufacturing to marry eco-friendliness with performance through NFRPCs (Natural Fibre-Reinforced Polymer Composites) that bring affordability, biodegradability, and strength to the table [37]. For those managing PLA–ABS blends, mechanistic models (like rule-of-mixtures and series or percolation models) guide how fibre loading impacts tensile, flexural, and impact properties allowing engineers to tailor performance metrics such as flexural strength to around 60 MPa or more with suitable compatibilizers [38]. On the practical side, filament stability often lies in the processing: twin-screw extrusion, correct fibre sizing, and controlled drying ensure uniform diameter and reliable print performance across composite ABS filaments [39]. Researchers are also experimenting with hybrid ABS composites for instance, combining ABS with natural fillers plus inorganic bioactive particles to push ABS into realms like 4D printing and biomedical scaffold fabrication, without sacrificing mechanical or print-quality norms [40].

2.3 Types of Bio-Composite Materials in PETG

When it comes to PETG (Polyethylene Terephthalate Glycol) based bio-composites, researchers have explored a wide range of natural and synthetic reinforcements to enhance both printability and performance. For example, combining recycled PETG with expanded graphite and carbon fibres has been shown to boost strength and reduce thermal expansion, while still remaining highly compatible with FDM printing [41]. Beyond synthetic fillers, natural materials are also making their way into PETG blends silk, for instance, has been used to create PETG silk composites that not only improve stiffness and thermal stability but also demonstrate excellent biocompatibility, making them suitable for biomedical scaffolds [42]. Similarly, hemp and jute fibres have been studied as reinforcements for PETG, with jute-reinforced blends reaching tensile strengths of over 60 MPa; however, challenges with interlayer bonding highlight the importance of optimizing print parameters [43]. On the commercial side, fibre-reinforced PETG filaments such as PETG-CF (Carbon Fibre) and PETG-GF (Glass Fibre) are now widely available, offering higher rigidity, wear resistance, and dimensional stability, which makes them attractive for industrial-grade parts and tooling applications [44]. Taking this a step further, researchers are also experimenting with PETG in 4D printing, where flax fibres are combined with PLA and PETG to produce shape-memory composites striking a balance between sustainability, toughness, and functionality [45].

3. Role of Natural Fibres in FDM

FDM has emerged as one of the most widely used additive manufacturing techniques due to its accessibility, design flexibility, and cost effectiveness. In recent years, there has been growing interest in incorporating natural fibres into FDM filaments, motivated by sustainability goals, environmental awareness, and the need for improved mechanical performance[46] . Natural fibres such as flax, hemp, jute, bamboo, and other plant-based fillers have been increasingly studied as reinforcements in thermoplastic matrices, including PLA, ABS, and PETG, to produce eco-friendly, high-performance composites [47]. These fibres are renewable, low-cost, and biodegradable, offering a sustainable alternative to synthetic fillers, while also contributing to weight reduction and enhanced stiffness in printed parts [48]. One of the major advantages of using natural fibres in FDM is their ability to improve mechanical properties. Studies have shown that fibre reinforced filaments exhibit higher tensile strength, flexural modulus, and impact resistance compared to pure polymer filaments [49]. The fibres act as load-bearing elements within the polymer matrix, distributing stress more efficiently and reducing the occurrence of brittle failure in printed components. However, this enhancement is highly dependent on fibre dispersion, orientation, and interfacial adhesion between the fibre and the polymer. Poor dispersion or weak bonding can create voids and stress concentrations, compromising the part's structural integrity [50]. In figure 5, the diagram illustrates the 3D printing process using biomass fillers, where natural fibres are mixed with polymer pellets, extruded into filaments, and then printed into test samples. It highlights the full workflow from material selection and filament preparation to printing and evaluating mechanical properties.

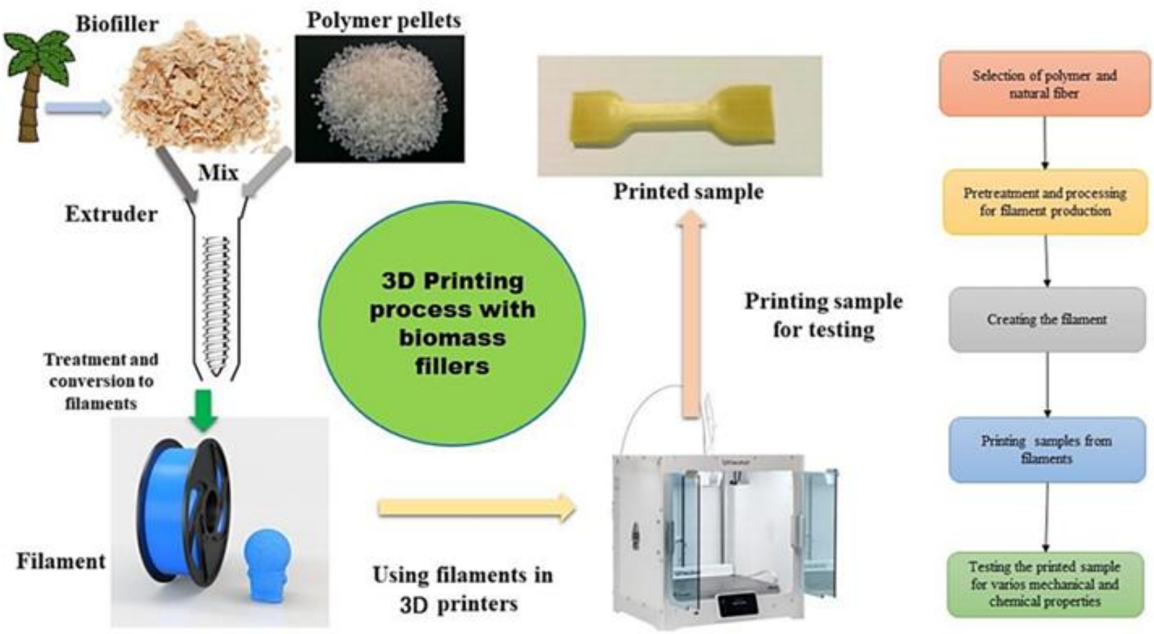

Figure 5: Process of making the natural fibre filament for FDM and printed sample [51].

Another key factor is fibre-matrix compatibility and moisture sensitivity. Natural fibres tend to absorb moisture from the environment, which can lead to swelling, poor interlayer adhesion, and reduced dimensional stability during printing [52]. To overcome these issues, researchers have explored pre-treatment techniques such as chemical modification, silane coupling, or alkali treatment to improve fibre surface properties, enhance interfacial bonding, and reduce water uptake [53]. Fiber particle size and aspect ratio also play a critical role in printability, as larger fibres may cause nozzle clogging, while smaller particles can lead to more uniform extrusion and smoother printed surfaces [54]. Processing techniques have evolved to accommodate these fibre-reinforced filaments. Twin-screw extrusion, controlled drying, and precise temperature management ensure consistent filament diameter, homogeneous fibre distribution, and reduced defects during printing [55]. Advances in extrusion parameters, such as screw speed, nozzle temperature, and layer height, have enabled the production of natural fibre composites that maintain printability while delivering enhanced mechanical performance. These developments are crucial for scaling FDM applications beyond prototyping to functional and structural components in industries such as automotive, consumer products, and biomedical devices. In addition to mechanical improvements, natural fibres also influence thermal properties and sustainability. In figure 6, the image depicts the hierarchical structure of natural fibres, showing cellulose microfibrils embedded in a matrix of hemicellulose and lignin. This composition provides strength, flexibility, and stability, making natural fibres suitable for composite reinforcement.

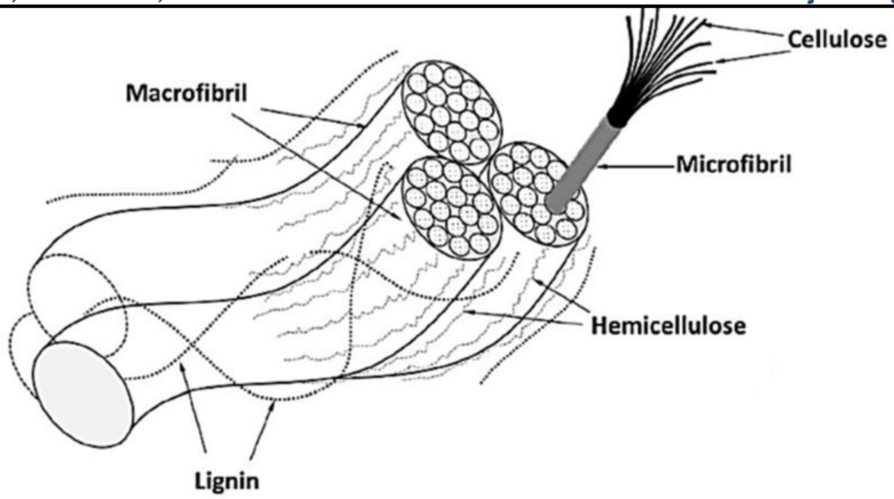

Figure 6: Graphical Image of natural fibre composition [56].

Fiber inclusion can modify the heat deflection temperature, thermal conductivity, and crystallization behaviour of the polymer matrix, impacting both the printing process and the final part performance [57]. Moreover, the use of biodegradable natural fibres aligns with the growing emphasis on circular economy principles, reducing environmental impact and enabling partial composability of printed parts. This combination of sustainability and performance makes natural fibre-reinforced FDM filaments particularly attractive for green manufacturing initiatives. Researchers are also exploring hybrid strategies, combining natural fibres with other fillers or polymers to tailor properties for specific applications. For instance, blending fibres with bioactive ceramics or other biodegradable polymers can enhance stiffness, thermal stability, or even biomedical functionality while maintaining eco-friendly characteristics. Such hybrid composites broaden the applicability of FDM, including in medical scaffolds, lightweight structural components, and functional prototypes. In summary, the integration of natural fibres in FDM filaments represents a promising avenue for sustainable, high-performance 3D printing. By carefully selecting fibre type, size, surface treatment, and processing parameters, it is possible to achieve a balance between mechanical strength, printability, and environmental responsibility. Current research demonstrates that while challenges remain such as moisture management, interfacial adhesion, and uniform fibre dispersion continuous innovation in material science and processing techniques is steadily addressing these limitations. The role of natural fibres in FDM is therefore pivotal, not only in enhancing material performance but also in driving the broader adoption of sustainable additive manufacturing practices[58].

Types of Natural Fibre	Enhancement Development	Challenges
Short Hemp and Harakeke Fibre	Tensile Strength improvement	Sample surface appeared less glossy and coarser. Pores forming due to insufficient fusion of the layers during printing process
Short Hemp Fibre	Storage modulus and Elastic modulus enhancement	A reduction of viscosity due to pectin degradation during melt mixing stage
Short Bamboo Fibre	Reinforcement in thermal and strength properties achieved by adding nano clay	High brittle of specimen due to the nano clay insertion. Degradation of polymer found during mixing
Long Flax yarn	4.5 times of tensile strength and modulus enhancement	The filaments produced in non-perfect circular shape due to immature fabrication process. Poor impregnation of yarn filament creates porosity and microstructures. Overlapping printing found at the corner spot. Low performance at transverse direction.

Commercial wood	Better printing formability than ceramic, aluminium and copper-based PLA filament	Weak interlayer bonding was observed contributed to low strength performance
Wood Short fibre	Initial deformation resistance has enhanced	Poor interfacial bonding between wood fibre and PLA polymer reduced the strength values. Lower thermal stability wood fibre reduced the overall thermal performance
Wood flour	Better interfacial bonding with coupling agent	Unflavoured colour changes on the filament. Rougher fracture surface with localized plastic deformations. Crystalline hindrance in filament produces more amorphous regions. Higher water uptake. Print nozzle was clogged due to agglomeration of wood flour
Silk Fibre	Retain antibacterial properties for scaffold printing	-

Table 2: Enhancement development and difficulties for natural fibre-reinforced PLA composite filament in FDM 3D printing [65].

PLA reinforced with natural fibres has become a widely studied bio-composite in additive manufacturing, particularly in FDM, because it combines sustainability with enhanced material performance [59]. Natural fibres such as flax, hemp, jute, kenaf, and bamboo are increasingly used as reinforcements in PLA, improving tensile strength, stiffness, and impact resistance compared to pure PLA [60]. These fibres are renewable, biodegradable, and lightweight, making them an attractive option for environmentally friendly 3D printing applications [61]. The mechanical performance of PLA-natural fibre composites depends strongly on fibre type, length, orientation, and surface treatment [62]. Proper dispersion of fibres within the PLA matrix ensures better load transfer, while poor interfacial adhesion can lead to weak points and reduced mechanical properties [63]. To address this, surface modifications such as chemical treatments or coupling agents are often applied to improve bonding between fibres and the PLA matrix [64]. In table 2, it shows an overview of advancements, challenges, and future prospects of natural fibre-reinforced PLA composites in FDM 3D printing. Processing techniques also play a crucial role in the quality of these composites [66]. Filament extrusion must be carefully controlled to achieve uniform fibre distribution, prevent agglomeration, and maintain consistent filament diameter [67]. Printing parameters, including nozzle temperature, layer height, and print speed, must also be optimized to accommodate the presence of natural fibres without compromising print quality [68]. Beyond mechanical enhancements, PLA-natural fibre composites contribute significantly to sustainability in 3D printing [69]. By partially replacing petroleum-based polymers with renewable fibres, these bio-composites reduce environmental impact while retaining the biodegradability of PLA. This makes them suitable for applications where ecological responsibility and performance are both priorities.

Overall, PLA reinforced with natural fibres offers a promising combination of strength, printability, and sustainability. Through careful selection of fibre types, pre-treatment methods, and processing parameters, these composites can be tailored for a wide range of applications from consumer products and automotive parts to biomedical scaffolds highlighting their potential to expand the scope of FDM in environmentally conscious manufacturing [70].

4. Concept of Micro Tomography (MT) in bio-sourced 3D printed structures

Microcomputed tomography (micro-CT) is a high-resolution, non-destructive imaging technique that allows researchers to explore the internal microstructure of biological and synthetic materials in three dimensions, without the need for sample sectioning or destructive preparation [71]. It has become a cornerstone in bioengineering, materials science, and additive manufacturing because it enables detailed visualization and quantitative analysis of complex structures, including bone, cartilage, soft tissues, and engineered scaffolds [72]. By providing a volumetric view of samples, Micro CT (Computed Tomography) surpasses traditional 2D imaging methods, revealing intricate internal architectures that are critical for understanding material performance and biological function [73]. The working principle of micro-CT relies on acquiring multiple 2D X-ray projections at different angles around the specimen, which are then reconstructed computationally into a 3D model using specialized algorithms [74].

This approach allows researchers to accurately assess important structural parameters such as porosity, pore connectivity, pore size distribution, and surface area. Such measurements are vital in tissue engineering, where scaffold architecture directly influences cell migration, nutrient transport, and overall tissue regeneration [75]. One of the major advantages of micro-CT is its ability to perform in situ imaging, meaning that samples can be studied in their natural or operational state, without chemical staining or mechanical alteration [76]. This capability is particularly important for longitudinal studies that track changes over time, such as bone remodelling, tissue growth, or the integration and degradation of implants in vivo [77].

In these contexts, micro-CT allows repeated imaging of the same sample, providing dynamic insights into structural evolution and material behaviour under physiological conditions. In addition to biological applications, micro-CT is highly relevant in additive manufacturing and polymer/composite research. It enables the evaluation of 3D-printed scaffolds and complex polymeric structures, ensuring that internal geometries meet design specifications for mechanical performance, permeability, and biocompatibility [78]. For instance, micro-CT analysis can identify voids, fibre distribution, or layer inconsistencies that might compromise the strength or functionality of printed constructs [79]. In figure 7, it shows cross-sectional SEM (Scanning Electron Microscopy) images of wood-PLA filament showing its internal morphology at two different scales where subdivision (a) shows 500 µm magnification highlighting the overall structure, and subdivision (b) shows 50 µm magnification revealing finer microstructural details.

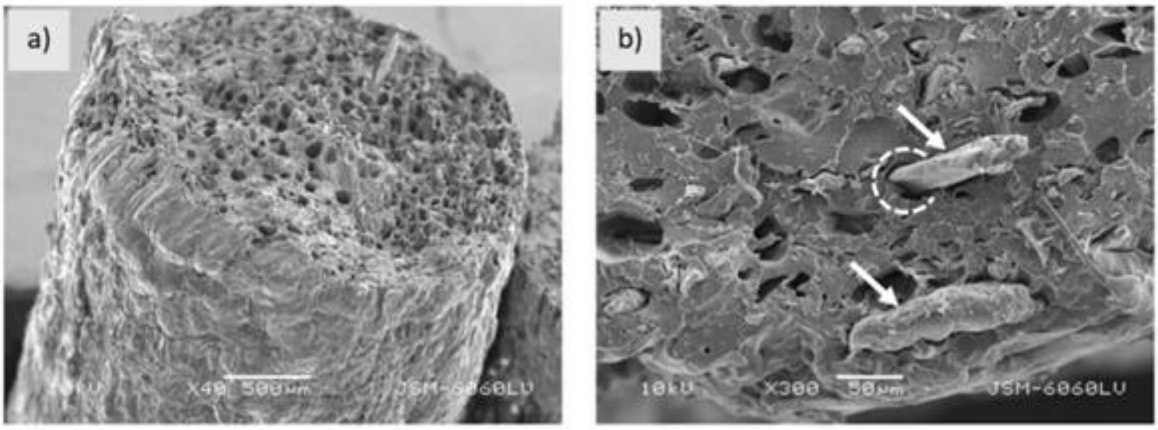

Figure 7: SEM Images (Cross sectional view) of wood PLA filament (a) magnification 500 µm and (b) magnification 50 µm [80].

This feedback loop allows researchers and engineers to optimize fabrication parameters, resulting in more reliable and reproducible outcomes. Micro CT also plays a crucial role in material characterization, allowing scientists to link microstructural features to mechanical, thermal, and biological performance [81]. Its non-destructive nature ensures that samples remain intact for further testing or implantation, providing a comprehensive view of material properties without compromising subsequent analyses. Across disciplines from biomaterials and tissue engineering to polymers and composite research micro-CT stands out as a versatile, indispensable tool that bridges imaging, quantification, and functional evaluation. Overall, micro-CT combines high-resolution imaging, non-destructive analysis, and quantitative 3D reconstruction, making it a pivotal technology for both fundamental research and applied studies in bioengineering and material science [82]. Its ability to reveal internal features, monitor changes over time, and support design optimization underscores its value in advancing sustainable and high-performance material development. In figure 8, it shows the microscopic comparison of neat PLA and pine/PLA composite filaments extruded at varying speeds.

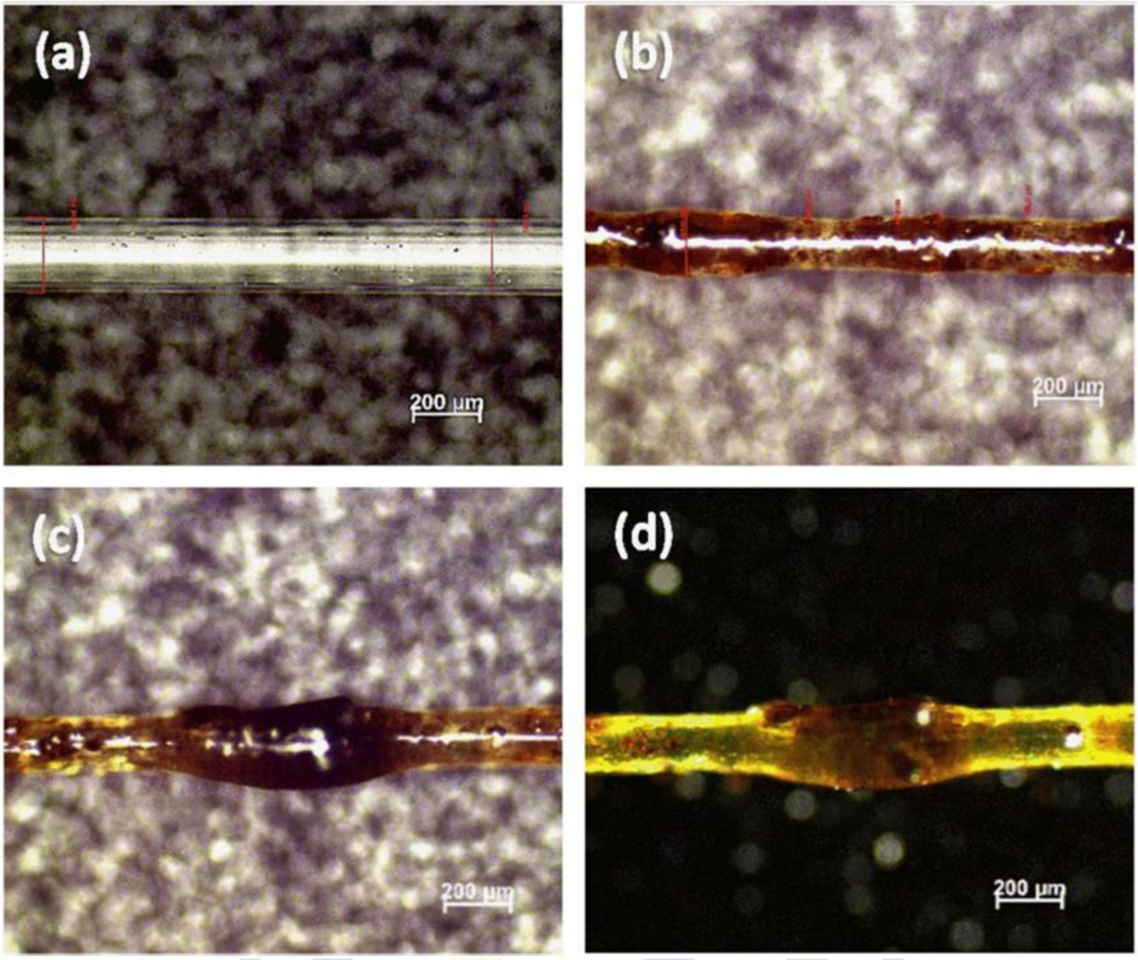

Figure 8: Microscopic Images of extrudate filaments (a) neat PLA and (b-d) wt% of pine/PLA with different speed of extrusion [83]

5. Testings' done on the printed Composite materials

When researchers evaluate bio-composite parts produced by FDM, they usually start with basic mechanical tests tensile, flexural and impact testing to measure strength, stiffness, ductility and toughness under standard loading conditions. [84] Layer bonding and anisotropy are then probed by printing specimens in different orientations and performing interlaminar shear or peel tests so we can see how the printing direction weakens or strengthens parts in real use. [85]Because printed bio composites often include brittle natural fillers, many studies include fracture toughness and fatigue tests to understand crack initiation and propagation during repeated loading or accidental overloads. [86] Thermal characterization is also routine: DSC (Differential Scanning Calorimetry) and TGA (Thermogravimetric Analysis) tell us about crystallinity, glass-transition, melting behaviour, and decomposition temperatures information that links processing windows to end-use performance. [87] Rheological measurements and melt-flow studies performed on the filament or melt help predict printability, nozzle pressure, and the risk of nozzle clogging when natural fibres or particulates are present. [88]. In table 3, it shows the mechanical (wire pull), density, and porosity results highlighting performance of natural fibre–based filaments for FDM.

Matrix	Filler	Wire Pull Test/UTM	Density/Porosity Test	Results
ABS	Oil Palm Fibre	Shimadzu Autograph (AGSX), ASTM638	Archimedes principle (ASTM D3800)	Tensile strength was increased by 60% by going from 0.15 to 0.4 MPa of fibre loading. After that, the Young's modulus increased by 22.8% from 16.1 to 18.3 MPa. As the fibre loading was increased from 3to 7 wt% the density of extruded filament decreased and the percentage of porosity rose.
ABS	Nutshell	-	Archimedes principle	The two nutshell composite samples densities are much lower than those of pure polymer filaments and commercial wood fill. It is clear that when 29% nutshell is added, the density is reduced by more than 27.4% compared with pure ABS.

Table 3: Result of wire pull test, density, and porosity of natural fibre-based filament for FDM.[89]

Microstructural and morphological analysis via SEM reveals fibre dispersion, interfacial bonding, voids, and failure modes these images often explain why a sample failed mechanically. [90] Porosity and internal architecture are increasingly quantified with micro-CT (X-ray microcomputed tomography) to non-destructively visualize internal defects, fibre distribution, and pore connectivity in 3D. [91] Because bio-composites interact with water, water absorption and swelling tests are common; these show how moisture affects dimensional stability and long-term mechanical retention. [92] For biomedical or food-contact candidates, researchers add cytotoxicity, bioactivity and bacterial colonization assays to ensure the materials are safe and, where required, promote cell attachment and growth. [93] Wear, abrasion and tribological tests are used for applications involving sliding contact or repeated friction, helping to predict lifespan in real operational conditions. [94]

Researchers evaluate printed bio-composites using a wide variety of structural tests to understand how the parts will behave in real use; most studies begin with fundamental tensile tests to measure ultimate strength, modulus, and elongation at break, which reveal how fibre content and print orientation change load bearing capacity [95]. Compression testing is commonly used for parts expected to support loads (blocks, lattice cores, or scaffold struts), helping quantify buckling behaviour and compressive modulus under steadily increasing load [96]. Flexural (three-point and four-point bending) tests probe bending stiffness and strength these are especially informative for beam-like printed parts and show how layer bonding and fibre alignment affect performance [97]. In figure 9, it shows the tensile test specimen and fibre pullout in FFF (Fused Filament Fabrication) jute/PLA composites, alongside microstructures of PLA–PHA(Polyhydroxyalkanoates)–wood fibre composites at different processing stages and print widths.

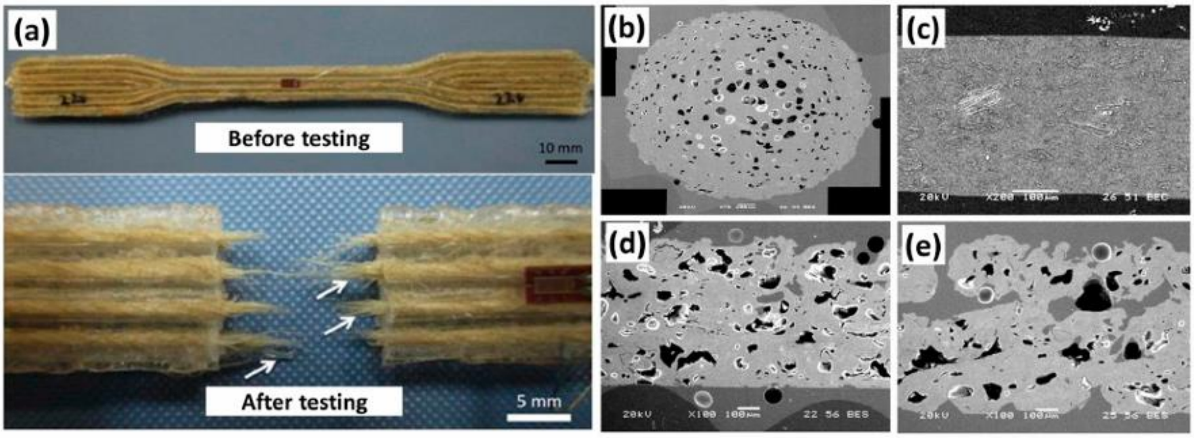

Figure 9: (a) Typical tensile test specimen of FFF processed jute fibre-reinforced PLA composites (top) and fibre pullouts after testing (below); Microstructures of PLA–PHA–wood fibre composites (b) as-received filament, (c) consolidated FFF Figure 5. (a) Typical tensile test specimen of FFF processed jute fibre-reinforced PLA composites (top) and fibre pullouts after testing (below); Microstructures of PLA–PHA–wood fibre composites (b) as-received filament, (c) consolidated FFF sample, (d) 100% print width, 300% print width [31]. sample, (d) 100% print width, 300% print width [98].

Interlaminar shear and short-beam shear tests target the weaker directions between printed layers, exposing anisotropy and the risk of delamination in layered FDM parts [99]. Impact and Charpy/Izod tests assess toughness and energy absorption, which matter for components that may experience accidental drops or shock loads in service [100]. Fatigue and cyclic loading experiments are used to study crack initiation and growth under repeated stresses, revealing life cycle limits for dynamic or vibrating applications [101]. Creep and long-term deformation tests examine how bio-composites slowly deform under sustained load and elevated temperature vital for parts that carry continual loads or operate near material softening points [102]. Modal, vibration and dynamic mechanical analyses DMA (Dynamic Mechanical Analysis) reveal damping, natural frequencies, and viscoelastic behaviour, helping designers avoid resonant failure in moving systems [103]. Environmental and hygrothermal conditioning followed by mechanical testing (wet aging, UV(Ultraviolet), temperature cycling) evaluate how moisture uptake and weathering degrade structural properties over time [104]. In table 4, it shows that the wire pull test evaluates the interfacial strength and mechanical reliability of PLA samples.

Matrix	Filler	Wire Pull Test/UTM	Density/Porosity Test	Results
PP	Wood dust	AI-7000-LAU Go-Tech, ISO 3341	ASTM D792-91	According to the results, treated silane has a filament strength that is higher than r-PP’s. The findings show that the silane pretreatment of the wood fibre improves the interaction between it and the recycled PP.
PLA	Kenaf	Instron 3382	Densimeter (Mettler Toledo)	The sample becomes less dense when the filler content rises from 3 to 7 wt%. Tensile strength starts to decline as fibre loading rises. That is as a result of the filler and matrix’s insufficient bonding.
PLA	Bamboo	Instron 5567	Computed Tomography (Phoenix Nano tom 180)	The compounded fibres length to diameter ratio had an effect on the filament’s modulus. Long bamboo fibres added to the PLA filament enhanced its stiffness by 215% compared with a 39% rise for the dust like fractions.

					Less porosities are present in every filament developed for this study compared with commercial filament. The porosities can be decreased to levels between 0 and 4% by anticipating appropriate drying.
PLA	Hemp	Instron 4484	-		The filaments initially act elastically up to 18-20 MPa, but as the test goes on, the filaments behave Visco elastically. Tensile modulus is between 1500 and 1575 MPa, and it breaks between 25 and 30 MPa.

Table 4: PLA Testings' using wire pull test in PLA [105]

Finally, combined and application-specific tests such as compression-after-impact, multi-axial loading, and full-scale structural trials provide the most realistic assessment, linking laboratory metrics to real-world performance and design safety factors [106].

6. Application of Bio-Composite Materials

Bio-composite materials are finding footholds across many industries because they blend lightweight performance with improved environmental credentials, making them attractive alternatives to conventional petroleum-based composites [107]. In automotive applications, bio-composites are being used for interior panels, seat backs, trim parts, and other non-structural components where weight savings and recyclability reduce fuel consumption and life-cycle impacts [108]. The construction sector benefits from these materials too they appear in wall panels, ceiling tiles, insulation boards, and temporary formworks where moisture resistance and thermal performance can be tuned via fibre choice and treatments. [109] In consumer products and furniture, designers leverage natural fibre reinforcements in PLA, HDPE (High-Density Polyethylene) or polypropylene matrices to produce attractive, durable goods that carry lower embodied carbon. [110] Packaging and single-use applications also profit: bio-composite trays, clamshells, and protective inserts can replace foams and virgin plastics while offering composability or easier recycling streams. [111] Biomedical and tissue-engineering fields use tailored bio-composite scaffolds (PLA/natural filler, hydroxyapatite blends) for bone repair and drug-delivery platforms because these materials can combine porosity, bioactivity, and gradual biodegradation. [112]

In the realm of civil engineering and infrastructure, researchers are exploring bio-composite laminates and boards for lightweight bridge components, cladding, and temporary structures where durability is balanced with cost and sustainability. [113] Sporting goods and leisure products bicycle helmets, racket handles, and surfboard cores exploit the favourable strength-to-weight ratios and damping behaviour of natural-fibre composites. [114] Agricultural uses include biodegradable mulch films, plant supports, and lightweight greenhouse panels that lower plastic waste and integrate into circular practices. [115] Finally, niche technical applications such as acoustic panels, thermal insulators, and prototype tooling demonstrate the versatility of bio-composites: by selecting appropriate fibres, matrices, and processing routes, manufacturers can tune mechanical, thermal, and acoustic properties for targeted end-uses. In figure 10, it shows the various applications of reinforced natural fibre composites in Industrial sectors.

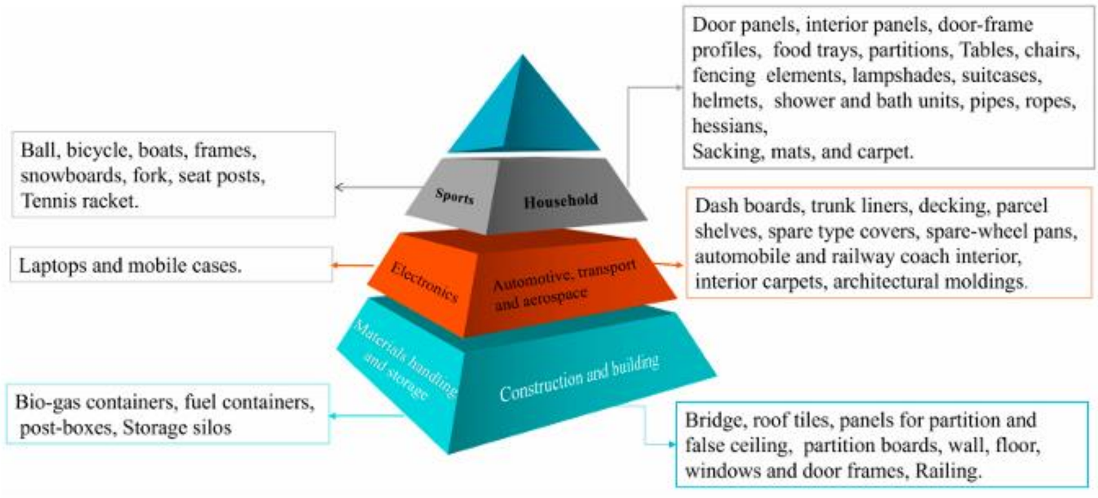

Figure 10: Applications of Reinforced Natural Fiber Composites in Industrial sectors

7. Conclusion

The exploration of bio-composites, particularly those reinforced with natural fibres and fabricated through AM, has emerged as a crucial step toward creating sustainable, high-performance materials. Across the literature, it is evident that PLA blended with natural reinforcements such as hemp, flax, jute, bamboo, and agricultural waste products can significantly improve the mechanical, thermal, and even environmental performance of 3D-printed components. The central motivation for these developments lies not only in replacing petroleum-based composites with eco-friendly alternatives but also in exploiting the unique structural and functional properties that natural fibres can provide. A recurring theme in the reviewed works is that the properties of bio-composites are highly dependent on processing and structure. Studies consistently show that factors such as fibre treatment, orientation, particle size, and distribution play a decisive role in determining tensile, flexural, and impact strength. For instance, alkali treatment (NaOH) of natural fibres improves adhesion with the PLA matrix, reducing porosity and enabling effective load transfer. Similarly, fibre alignment within the extruded filament or printed layer can drastically affect anisotropy, resulting in composites that can be tailored to specific performance requirements.

These findings indicate that while bio-composites are inherently variable due to the natural origin of reinforcements, careful processing and design strategies can harness their full potential. Another advancement is the integration of micro-computed tomography (micro-CT) into the characterization process. Micro-CT enables visualization and quantification of internal defects such as voids, porosity, and fibre pull-outs without destroying the sample. This non-invasive method provides insights into the correlation between internal architecture and mechanical behaviour. Researchers have emphasized that the presence of microstructural flaws, even at low volume fractions, can significantly reduce performance, underscoring the necessity of advanced characterization to optimize processing parameters. Such imaging technologies bridge the gap between experimental testing and predictive modelling, helping to refine bio-composite design. The diversity of mechanical, thermal, and biological tests performed across studies highlights the multi-functionality of bio-composites. Tensile and flexural tests remain the most common, evaluating stiffness and strength. Impact and fatigue testing provide insights into long-term durability under cyclic loading. TGA and DSC demonstrate that natural fibres enhance thermal stability, broadening the application range.

In biomedical contexts, biocompatibility and degradation studies reveal that PLA-natural fibre composites are safe and environmentally benign, offering an additional advantage over conventional composites. This wide range of testing emphasizes that bio-composites are not only mechanically capable but also adaptable to diverse operating environments. When it comes to types of structures tested, research spans from simple specimens such as dog-bone tensile bars to more complex geometries like lattice structures, sandwich panels, and scaffolds. The ability of additive manufacturing to fabricate intricate geometries has been particularly advantageous in this regard. Bio-composites have been tested under compression, bending, and torsional loads to evaluate their potential for real-world structural applications. Interestingly, results show that lightweight cellular and lattice designs printed with bio-composites can rival traditional materials in strength-to-weight ratios, making them attractive for aerospace and automotive industries where weight reduction is critical.

The applications of bio-composites are equally broad and impactful. Automotive sectors are increasingly adopting natural fibre composites for interior panels, dashboards, and lightweight body components, as they offer a balance of performance, cost reduction, and sustainability. In civil engineering, bio-composites are being evaluated for building materials, panels, and reinforcement structures, contributing to green construction initiatives. In biomedicine, PLA-natural fibre composites have shown promise for biodegradable implants, scaffolds for tissue engineering, and drug delivery systems due to their biocompatibility and tenable degradation rates. Even packaging industries are leveraging these materials for creating eco-friendly, biodegradable alternatives to plastics. This versatility demonstrates that bio-composites are not confined to niche applications but are steadily penetrating mainstream industries. Overall, the collective body of research reviewed demonstrates that bio-composites represent a practical, scalable, and sustainable alternative to conventional composites. The convergence of material science, processing technology, and advanced testing has elevated them from experimental curiosities to serious candidates for industrial adoption. However, challenges remain. Standardization of testing methods, consistency in natural fibre properties, and scalability of production are issues that must be resolved to ensure reliable large-scale use. Additionally, life-cycle assessments are needed to confirm that the environmental benefits of bio-composites extend across production, use, and disposal phases.

Conclusively, PLA-based bio-composites, reinforced with natural fibres and enhanced by modern testing and characterization techniques, offer a pathway toward sustainable material innovation. Their ability to combine mechanical robustness, thermal stability, biodegradability, and design flexibility positions them as a cornerstone in the transition to a circular economy. Future research should focus on optimizing fibre treatments, integrating machine learning with micro-CT data for predictive modelling, and exploring hybrid composites that blend natural and synthetic reinforcements. As industries increasingly prioritize sustainability, bio-composites are poised not only to complement but potentially to replace conventional petroleum-based composites across multiple sectors.

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