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Selection of Silk Fibre as a Filler Material for PLA-Based Bio Composite Filament in FDM: A Systematic Review

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Abstract

Fused Deposition Modelling (FDM) has gained widespread adoption for producing functional components across industries such as healthcare, automotive, aerospace, electronics, art, and education, primarily due to its affordability in terms of operational and material expenses. Despite its advantages, FDM-printed parts using popular thermoplastics like Polylactic Acid (PLA) often suffer from drawbacks such as limited mechanical strength, dimensional inaccuracies, and insufficient interlayer bonding. To broaden the scope of FDM applications, extensive research efforts are being directed towards improving the mechanical performance of PLA-printed materials. Previous studies have demonstrated that reinforcing PLA with plant-based natural fibres and synthetic additives can significantly enhance its structural properties. However, limited research has focused on the reinforcement of PLA with animal-derived natural fibres. Notably, experimental studies indicate that silkworm silk fibres can serve as effective reinforcements, enhancing the mechanical performance of polymer composites. The integration of such natural fibres into PLA-based filaments not only boosts material performance but also promotes sustainable manufacturing practices. This paper presents a systematic review evaluating the potential of silk fibre as a reinforcement material in PLA biocomposite filaments for FDM. Based on its favourable mechanical, chemical, and physical attributes and promising applications in biomedical and industrial sectors, silk fibre emerges as a viable and eco-friendly alternative for improving PLA-based filaments in additive manufacturing.

Major Findings: *Silk fibre significantly enhances the mechanical, thermal, and dimensional stability of PLA-based filaments used in FDM. Optimal reinforcement is achieved with 2–7 wt % silk fibre of 2–5 mm length, ensuring good printability and strength. PLA-silk composites show high potential for eco-friendly and biomedical applications due to their biocompatibility and biodegradability.*

Keywords: *3d Printing, Fused Deposition Modelling (FDM), PLA-Silk Filament, Polylactic Acid (PLA), Silk Fibre*

1.0 Introduction

After 30 years of advancements, Additive Manufacturing (AM) has become a widely adopted manufacturing method. AM is a prototyping process that creates polymer, ceramic, metal, and composite structures layer by layer from a digital design file, without requiring moulds, dies, or lithographic masks[1,2]. The primary difference between this approach and other manufacturing methods is its "additive" nature, as opposed to a "subtractive"

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approach. AM technologies enable the construction of a wide variety of models or functional components using complex geometrical structures that would be difficult or impossible to produce with traditional methods. AM can reduce cycle time and production costs compared to traditional methods, thereby increasing competitiveness[3]. Polymer 3d printing encompasses various AM techniques, including Fused Deposition Modelling (FDM), Digital Light Processing (DLP), Stereolithography (SLA), Laminated Object Manufacturing (LOM), and Selective Laser Sintering (SLS). These technologies are continuously upgraded to attain the intended geometrical qualities of the finished product and optimise the manufacturing process[4,5]. Beyond rapid prototyping, the range of uses for 3d printed parts has greatly grown to include everything from space applications to medicinal applications[4].

Fused Filament Fabrication (FFF), also known as FDM, is the widely used technique for producing thermoplastic polymers and their composites in 3d printing[6]. Originally invented by Stratasys Company in the 1990s, FDM has gained attention in diverse sectors such as electronics, tissue engineering, biomedical engineering, pharmaceuticals, automotive, and aerospace industries in recent years. In the FDM process, a continuous filament of material is placed layer by layer after being fed via a hot nozzle to create 3d printed objects[5,7,8].

The extruder of the 3d printer moves along the x-y axis, while the platform travels on the z-axis upwards as shown in Figure 1. This coordinated movement allows for the precise layering of material to build the desired shape of the final product[5]. Numerous crucial factors that influence the FDM 3d printing process are filament type, infill patterns, infill density, flow rate, nozzle temperature, raster angle, print speed, layer thickness, overlap and fan speed[9-13]. Recently used filament materials, such as Polylactic Acid (PLA), are widely used but often lack the mechanical strength, thermal resistance, and qualities of materials needed for engineering applications. To overcome these limitations, incorporating filler materials into these materials to create composite filaments has emerged as an effective solution. Addressing these limitations is crucial for further enhancing the capabilities and reliability of FDM-based 3d printing technology[5].

This study aims to systematically review and evaluate the suitability of silk fibre as a natural reinforcement material in PLA-based biocomposite filaments for Fused Deposition Modelling (FDM), with a focus on enhancing

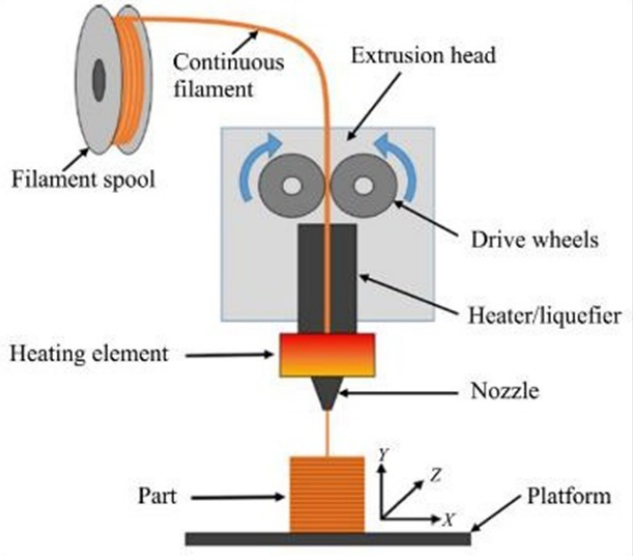


Figure 1. Fused Deposition Modeling (FDM) process[5].

mechanical, thermal, and biodegradable properties for sustainable and biomedical applications.

1.1 FDM Filament Material Selection

1.1.1 PLA as a Promising Matrix Material for The FDM Filament

PLA outperformed conventional polymers, including polypropylene, polystyrene, and polyethene in terms of mechanical characteristics such as tensile, impact, and shear properties[14,15]. The two most commonly utilised materials in FDM 3d printing are PLA and Acrylonitrile Butadiene Styrene (ABS) due to their distinct properties that serve a range of purposes. PLA has excellent mechanical strength and rigidity, while ABS offers superior impact resistance and thermal stability. Polylactic Acid exhibits several mechanical properties (Table 2) that contribute to its superiority over Acrylonitrile Butadiene Styrene in Fused Deposition Modelling applications. These properties include higher tensile strength, better rigidity, enhanced interlayer bonding, better thermal stability, and reduced warping during the printing process, which is critical for producing durable and reliable 3d printed parts[16]. Mechanical and thermal property comparison of PLA and ABS is given in Table 1.

PLA takes the place of petroleum-based thermoplastics in tissue engineering and biomedical applications[17,18]. PLA is the most widely used bioplastic globally, second only to cellulose acetate[14]. It is one of the most popular biodegradable polymers and is employed in over 30 %

Table 1. Thermal and Mechanical Property Comparison of ABS and PLA Material[16]

Material	Mass Density (kg/m³)	Poisson's Ratio	Elastic Modulus (MPa)	Shear Modulus (MPa)	Tensile Strength (MPa)	Thermal Conductivity (W/m.K)	Specific Heat (J/kg.K)
ABS	1020	0.394	2000	2000	30	0.2256	1386
PLA	1240	0.33	3500	2400	60	0.13	1800

of all applications in FFF[14,15]. The morphological and mechanical qualities of PLA and ABS material scaffolds were compared to check their feasibility as biomaterials and to check the effect of printing process parameters on them. PLA scaffolds demonstrate higher yield strength, superior pore definition, smoother surfaces, higher and readily available biomaterial, making them a favourable choice for tissue engineering and biomedical applications[16,19,20]. By considering the mechanical and thermal features of PLA, Biodegradability, suitability, availability for FDM application and cost consideration, PLA is preferred as the material for FDM filament.

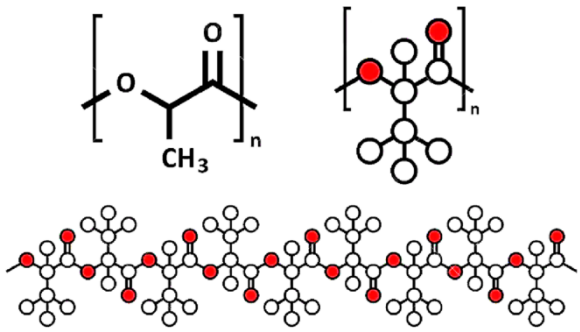


Figure 2. Chemical Structure of PLA[15].

2.0 Chemical Structure of PLA

To create PLA (Figure 2), aliphatic polyester, starch derived from renewable vegetable sources, like maize and potatoes, is converted to glucose turns into lactic acid during fermentation and undergoes additional polymerisation. PLA melts at 180 °C and has a glass transition temperature of 55 °C. PLA is completely biodegradable, strong, and has exceptional biocompatibility. After decomposition, carbon dioxide and water are the end products. As a result, it is non-toxic and does not pollute the environment. PLA is quite strong and has good integral characteristics, although it is not very rigid[15].

2.1 Natural Fibres as Reinforcement in Biocomposites

One form of a renewable resource, a new generation of reinforcements and additives for polymer materials, is natural fibre. In a nutshell, natural fibres can be categorised according to their origins and the types of plants, animals, and minerals they are derived from, as shown in Figure 3. The following three categories can be used to further categorise natural fibres[21]:

1. Vegetable Fibres: It includes sisal, cotton, hemp, linen, jute, coir, kapok, pina and ramie.
2. Animal Fibres: These include wool, silk, and hair.
3. Mineral Fibres: The only mineral fibre that occurs naturally is asbestos.

For a variety of engineering applications, these renewable fibres have been used in place of glass fibre and other synthetic polymer fibres. The commercial and research potential of natural fibres is enhanced by their notable advantages over typical inorganic man-made fillers. Since natural fibres are typically a plentiful renewable resource, their price is lower than that of synthetic fibres. Natural fibres are biodegradable, which can help with the issue of large-scale solid waste production and ease the strain on landfills when environmental consciousness is taken into account[22-25].

3.0 Criteria for Selection of Natural Fibres

The selection of natural fibres as composite materials for Fused Deposition Modelling filament involves several critical criteria that ensure optimal performance and sustainability. Standards for choosing natural fibre as composite filament material for FDM include general properties (production rate and raw cost), mechanical characteristics (Young's modulus, elongation at break, density, and glass transition temperature), chemical characteristics (cellulose, hemicellulose, lignin, and moisture content), and physical characteristics (density, thermal conductivity, and glass transition temperature)[19]. The integration of natural fibres into polylactic acid

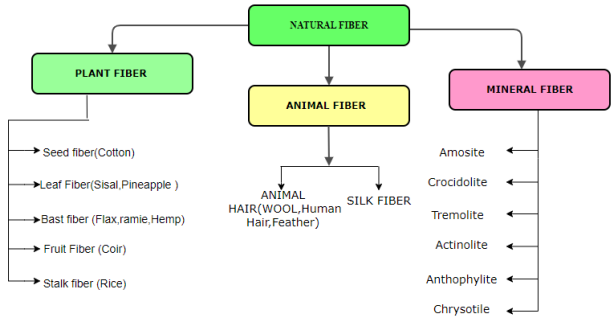


Figure 3. Classification of natural fibre[26].

(PLA) for biocomposite production in FDM 3d printing has shown promising potential to enhance mechanical properties. Various fibres, including wood particles[27-29] banana[30], rice straw[31], lemongrass fibre[32], jute, kenaf, sisal[22-24], silk[33-37], hemp[38,39] and Harakeke[38], biocarbon[30], etc. have been explored, each contributing unique benefits to the composite's performance. A summary of properties that play a crucial part in choosing natural fibre as a filler material in biocomposite formation for FDM printing is highlighted in Tables 2 and 3. Summarises the mechanical, chemical and Physical properties of natural fibres.

Along with mechanical properties, the physical and chemical properties of natural fibres play an important role in the selection of natural fibres as a biocomposite substitute. When we compared the density of silk fibre, it is 1300 kg/m^{3,} which is less than most fibres used, such as flax, kenaf, hemp, banana, and sisal fibres. The Glass transition temperature of silk fibre is 150 °C - 243°C, which is close to PLA as compared to other alternatives studied. Silk fibre has a moisture level of 8.7 %, which is lower than that of the other materials under study and one of the key selection criteria. The silk fibre is an animal-based fibre that is made from protein and increases the potential of this material in biomedical applications. Thus, by comparison of the chemical and physical properties of silk fibres, we found that silk fibre will be a promising alternative as an additive material for PLA-based filament material[19,21,37, 40]

4.0 Silk as Potential Fibre Reinforcement In PLA

4.1 Silk Fibre Sources and Structure

Spiders and silkworms are the two main sources of silk, in general. Spider silk has not been used because of its low

Table 2. Mechanical properties of natural fibre

Fibre Name	Density (g/cm^3)	Strength (MPa)	Tensile Modulus (GPa)	Elongation at break (%)	References
Cotton	1.5–1.6	45.5-1000	5.5-12.6	3.00-10.00	22, 23, 24, 37
Bamboo	0.6-11	140–441	11–35.9	9.5	
Silk	1.17-1.33	248 - 972	9.4-22	15-34	
Rice husk	1.4	19–135	0.3–2.6	2.5-3	
Alfa	1.4	188 - 308	18 - 25	1.5 - 2.4	
Kenaf	0.6 - 1.5	215 - 1191	2.86 - 60	1.5- 6.9	
Sisal	1.3 - 1.5	80 - 840	9 - 38	2 - 2.5	
Jute	1.3 - 1.5	385 - 850	10 - 55	1.16 - 8	

Table 3. Physical and Chemical Properties of Natural Fibre

Properties	Sugar palm	Coir	Flax	Kenaf	Hemp	Sisal	Banana	SILK	References
Density (kg/m^3)	1260	1200	1500	1400	1500	1500	1350	1300	19, 21,37,40
Thermal conductivity (W/m°C)	–	0.05	0.3	0.35	0.3	0.35	0.66	0.54	
Glass transition temperature (°C)	–	209	130	390	100	390	–	157-243	
Cellulose (%)	50.3	43	71	70.2	68	65	67.6	-	
Hemicellulose (%)	13.3	0.25	20.6	20.3	15	12	19	-	
Lignin (%)	31.5	0.25	2.2	20.3	10	9.9	5	-	
Moisture content (%)	7.4	8	12	12	12	10	8.7	-	
Fibroin	-	-	-	-	-	-	-	70-80 %	
sericin	–	–	–	–	–	–	–	20-30 %	

production level, and even though spiders are predators, whereas silkworm silk has been commercialised and employed in biomedical applications[41]. In the evaluation of different silk fibres, Mei-Po Ho *et al.*[23] looked at the mechanical characteristics of several silkworm silk fibres, such as Bombyx mori, twisted Bombyx mori, and Tussah silk fibres. A test for uniaxial tensile strength was performed on a single fibre to calculate its ultimate tensile strength, elongation at break, and Young's modulus. According to their research, the greatest choice for a biocomposite material will be Bombyx mori silk fibre[23]. The silk, which is made from a pure protein, consists of two types of proteins- sericin (20-30 %) and fibroin (70-80 %) and other components such as carbohydrates, waxes and ash (1-2 %). Sericin ($C_{15}H_{25}N_5O_8$) is a hydrophilic protein made up of 18 amino acids with strong polar side groups and high levels of serine, aspartic acid, and glycine[21].

4.2 Properties of Silk Fibre as Biocomposite Reinforcement

Because of its mechanical, biocompatible, and bioresorbable qualities, silkworm silk fibre is a well-known animal fibre for use in biomedical engineering and surgical procedures[23]. Silk fibres are stronger and have a higher modulus than some natural fibres. The mechanical, chemical and physical properties of silk, as mentioned in Table 2 and Table 3, show its potential to be used as a filament for FDM as a biocomposite material. Most biocomposites are composed of biopolymers reinforced by natural fibres, which can be derived from either plants or animals. It may be possible to use silkworm silk in structural composites, and it has several medical applications, including biomedical scaffolds and wound sutures. Silk-based fibre-reinforced polymeric composites have lately become popular for altering the mechanical and thermal characteristics of biodegradable polymers[42].

According to several studies, the mechanical properties of PLA were improved by adding natural fibres derived from plants and conventional synthetic fibres as reinforcements. Nevertheless, relatively few studies have attempted to reinforce this biodegradable polymer using animal-derived natural fibres. The mechanical properties of polymeric materials can be enhanced by adding silkworm silk strands as reinforcements, according to experimental evidence from earlier investigations. Prior studies focused on the creation of completely biodegradable biocomposites and examined the effects of silk threads on polymeric polymers[37]. Silk's exceptional mechanical qualities, adjustable biodegradability, and adaptable processing capabilities have prompted the creation of biomaterials based on silk proteins for several biological purposes, transforming silk from a conventional textile material to a premium protein biopolymer[33-37]. Silk in the form of particles or fibres at the micro or nano scale has shown promising results as the reinforcing filler in the creation of composite scaffolds for tissue engineering applications due to its exceptional capacity for reinforcement, favourable biological effects in promoting tissue regeneration, and flexibility in building bio-scaffolds. Apart from that, several studies have demonstrated that silk particles can transport bioactive substances like growth factors and promote tissue regeneration by acting as a bioresorbable vehicle[33]. There are several ways to process silk, including scaffolds, films, and hydrogels, enabling tailored applications in regenerative medicine[43-45]. Silk is inherently biocompatible, promoting cell adhesion and proliferation, which is essential for effective incorporation into biological systems[44]. Its biodegradability allows for gradual absorption by the body, reducing the need for surgical removal of implants[45]. Literature studied earlier shows promising mechanical properties. The elasticity of silk allows it to stretch without breaking, making it ideal for dynamic environments within the body, such as blood vessels and skin[43]. Silk has superior mechanical qualities, including high tensile strength, toughness, and elasticity, making it suitable for biocomposite materials in biomedical applications. The tensile strength of silk fibres is great, comparable to steel, which is crucial for load-bearing applications in tissue engineering[45].

The following characteristics of silk such as Biocompatibility, Biodegradability, Controlled degradation, Mechanical strength, Thermal stability, and antibacterial properties as reported in the literature, make it an attractive material for reinforcement in biocomposites for a range of applications.

4.3 Application of Silk Material

Silk fibres have a diverse range of applications across various fields, particularly in biomedical engineering, food technology, and advanced materials. Below are key applications of silk fibres:

4.3.1 Biomedical Applications

- Tissue Engineering: Silk fibroin scaffolds mimic the extracellular matrix, encouraging the adherence of cells and tissue regeneration for bone, cartilage, and nerve tissues[45].
- Surgical Devices: Silk fibroin is utilized in osteo fixation devices like screws and plates, enhancing bone healing and offering tunable degradation rates[10].
- Wound Healing: Silk's biocompatibility supports its use in sutures and artificial veins, facilitating effective healing processes[46].
- Drug delivery: Silk fibroin is used in drug delivery systems because it can enhance the stability of active ingredients. Silk fibroin solutions can be transformed into various formats, including hydrogels, films, and nanoparticles[44].
- Cartilage regeneration: Silk fibroin-based scaffolds are used to regenerate cartilage due to their biocompatibility and controlled degradation rate[43].
- Ligament and tendon Regeneration: Silk-based scaffolds are used for the healing of ligaments due to their biocompatibility, slow degradability, and mechanical strength[43].
- Nerve tissue regeneration: Spider silk is used in regenerative medicine to help damaged nerve or muscle cells grow[43].

4.3.2 Food Technology

- Packaging Solutions: Silk fibroin can form films and coatings that improve barrier properties and control the release of food preservatives[46].
- Quality Detection: Its sensitivity and stability make silk suitable for detecting food quality parameters, enhancing food safety[46].

4.3.3 Nanotechnology Integration

The mechanical qualities of silk are improved by the use of nanoparticles in its manufacture and introducing functionalities like antibacterial effects, broadening its industrial uses[47].

4.4 PLA-Silk Composite as Budding Material for FDM Filament

4.4.1 Importance of PLA-Silk as a Biocomposite for Biomedical Applications

Over time, polymers like PLA have been created to break down in a regulated way and may also offer the right amount of mechanical strength for implant applications. Even though these polymers have been suggested as an alternative to metals for orthopaedic fixators, bones have better mechanical qualities. Consequently, attempts are being undertaken to enhance these qualities through reinforcement. The outcomes of several scholars' studies on mechanical properties are compared in Table 4. It demonstrates that, compared to other PLA-based composites, PLA-Silk composite exhibits superior mechanical qualities and thermal stability[22,23,33-35,42,48-50].

4.4.2 Mechanical and Thermal Properties Enhancement

The mechanical properties of PLA and PLA-silk composites were compared as shown in Table 5. PLA-silk composite is reported to exhibit enhanced flexural and tensile characteristics, including stiffness and elongation, when compared with pure PLA. Comparing silk fibre to other natural fibres examined in previous research, the % elongation is found noteworthy[22,23, 33-35,37,42,50,68].

The addition of silk fibre, which may function as a nucleating agent, can improve PLA crystallisation ability, according to the thermal characteristics of PLA-silk biocomposites listed in Table 6. The degree of crystallinity (X) is significantly influenced by the chain structure and molecular chemistry. This is because cross-linking and side branches impair chain mobility. PLA is glassy and has applications in the biomedical field because its glass transition temperature (Tg) is higher than 37°C (physiological body temperature). With a 7 % increase from the neat to the composite sample, the Tg of pure PLA and PLA/5 weight per cent silk composite were found to be 60.2 °C and 64.4 °C, respectively[22]. According to the findings of the researchers' thermal analysis, the PLA-Silk composite exhibits enhanced biodegradability and thermal stability. Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) studies revealed that PLA and silk materials are unquestionably outstanding biodegradable, sustainable, lightweight, and environmentally friendly materials with a lot of potential for use in textile and medicinal applications[37].

PLA-Silk biocomposite will be a promising alternative to other PLA-based composites given the predictable disadvantages of biomedical engineering with metallic materials, The increasing need for and possible applications of biodegradable and bioresorbable polymers

Table 4. Mechanical Properties of PLA Composites

Biocomposite material	Strength at peak (MPa)	Strength at break (MPa)	Peak strain	Break strain	Young's modulus (GPa)	Flexural strength (MPa)	GTT (°C)	Impact strength (KJ/M2)	Elongation at breakpoint	Compression Strength	References
PLA with Synthetic fibres											
PLA	55				3.5						51
PLA	≥ 60					31.5			*4.4-6 %*		52
PLA	40.272	-	-	-	2.53	-	-	-	-	-	53
ABS	38.31	34.48	0.056	0.056	0.684	-	-				19
PLA-HAP-CS (90-8-2)	45.45	-	0.0252	0.042	-	40.91	-	--	-	-	36
ABS- GF	44.95	40.45	0.0525	0.056	0.856	-	-				54
PLA -GF	171.66	-	-	-	-	148					55
NYLON-GF (65-70 &25-30)	-	62.8	-	-	4.261	72	70				56
PA6-CF (80-20)	-	63	-	-	3.8	84	70				57
PLA-CF	-	48	-	-	4.95	89	60				58
PLA-SHORT CARBON FIBRE (85 %-15 %)	41					62	56	38			51,59
TOUGH PLA (80-20)		53			2.275	98					60
PLA with Natural fibres											
PLA-SILK(1*7WT %)	62.08			10.29 %	4.994		64.4				37
fish scale powder-PLA (80-20 %)	51.68					91.26		14.03			10
PLA-BBB (97-3 %)		33.6			1.9	58.7		5.2J			54
TPU	52	-	-	-	-	-	-	-			11
AL2O3-PLA (60-40 %)		45-50				332±21					61
PLA-CHITOSAN (99-1 %)	44.56	-	-	-	-	156.96	-	-	-	47.15	62
PLA-AL POWDER (80-20 %)	39.13	35.22							5		63
PLA-Crab shell particles (0, 1, 5, 7, and 10 %)	62	-	-	-	-	-	-	1.3	-	217	57
PLA-HEMP (10,20,30 %)	37-38	-	-	-	3.2-3.6	-	-	-	-	-	37
PLA -HERAKEKE(10,20,30 %)	37-38	-	-		4-5	-	-	-	-	-	37
PLA-HEMP (20 %)	33.6			3.50	4.42						39
PLA-WEED (20 %)	19.5			8.80	2.287						39
PLA-RISE STRAW (15 %)	20-23				0.2-0.3	40-45	58-59.6				31
PLA-LEMONGRASS FIBRE (0-10 %)	48.8 ± 1.5					87.8 ± 1.8(at2.5 %)		2.4 ± 0.1(AT 5 %)			64
PLA-LEMONGRASS FIBRE-PLA -gMAH (0-20 %) with 5wt % of LF invariable	54.0 ± 0.9					97.4 ± 0.9(at 2 %)		2.5 ± 0.2 (at 5 %)			64

Table 4. (Continued)

Biocomposite material	Strength at peak (MPa)	Strength at break (MPa)	Peak strain	Break strain	Young's modulus (GPa)	Flexural strength (MPa)	GTT (°C)	Impact strength (KJ/M2)	Elongation at breakpoint	Compression Strength	References
PLA/PBSeT/PLA-g-MAH blends. 25 %PBSeT with PLA-g-MAH varying from 0-9 phr	30-34						59.2-60				32
PLA-WOOD (15-25 %)	30-33	-	-	-	-	-	-	6.8	-	65-70	65
PLA- OFI, POL (10 & 20 %)	54				2.780	76 +8		25.4	3.4		66
PLA-BAMBOO (70-30) fibre with LDA as coupling agent	29-45	-	-	-	2.666-2.946	-	-	-	5	-	42
PLA-CELLULOSE (0-25 %)	38.2				5				1.9		49
PLA-WP (25 %)	45.2				6				1.90		49
PLA-WF (25 %)	45.2				6.3				1.70		49
PLA-SILK (5 wt %	61.25	-	-	4.575	2.439	-	-	-		-	67
PLA-SILK (5 wt %)	70.6			3.8	4.08	97.41		110.7			23

Table 5. Mechanical properties comparison of PLA-Silk fibre composite with pure PLA[22]

Sample	Hardness (HV)	Tensile Properties			Flexural Properties		Impact Strength (MPa)
		Tensile Strength (MPa)	Elongation (%)	Stiffness (GPa)	Flexural Strength (MPa)	Stiffness (GPa)	
Pure PLA	17	70.73	6.73	3.75	109.4	3.58	-
5mm/5wt %silk/PLA	19	70.6	10.29	4.99	97.41	4.01	-

Table 6. Thermal properties of PLA and PLA/silk fibre biocomposites[22]

Sample	Tg	Tc	Tm	Δmc	Δmm	X (%)
Pure PLA	60.2	114	166.5	34.5	48	51.2
PLA/Silk (95/3)	59.6	112.5	163	39	40.9	-
PLA/Silk (95/5)	64.4	100.5	168.4	29.5	48.4	51.7

in the centuries to come, the increased environmental consciousness of the public in helping to reduce carbon footprints and non-naturally decomposed solid waste, and the thermal and mechanical properties of silk fibre and its suitability as a natural fibre filler material in biocomposites[43-47,69].

4.4.3 Selection of Proportion of PLA-SILK (Percentage of Silk Fibre) Based on Literature

To find an optimum percentage of silk fibre in PLA-based composites, different researchers carried out experimentation using silk percentages up to 15 %. Results of previous work, which will provide recommendations for additional research in the same domain, are discussed ahead. When PLA and its composites were examined, it was discovered that the pristine PLA sample had a higher impact strength of 156.3 J/m than the PLA-5 weight per cent silk composite, which had an average impact strength of 110.7 J/m[30]. The impact strength decreased as a result of the silkworm silk fibres in the polymer matrix acting as stress concentrators and reducing the fracture initiation energy[48]. Adding 10 % of silk fibre to the composite increased the fragmented energy and energy loss by 70 %. However, adding more than 10 % of silk fibre to the composite resulted in a notable decrease in fracture energy, as illustrated in Figure 4. This was explained by the large volume percentage of fibre embedded in the matrix, which resulted in weak interfacial bonding[33].

Warping and other form changes can result from poor dimensional stability. Compared to pure PLA, the CTE of PLA-Silk composites with 1-7 % silk fibre loading is slightly lower, as illustrated in Figure 5. This suggests that the silk fibres in the PLA matrix reduce the amount of heat expansion. Consequently, adding silk fibre can lower CTE and provide the composites with a comparatively high degree of dimension stability. However, as the amount of silk fibre grows, so does the CTE of PLA-Silk composites with silk fibre loading. This implies that as silk fibre loading increases, there may be less interaction between the silk fibre and PLA matrix[50].

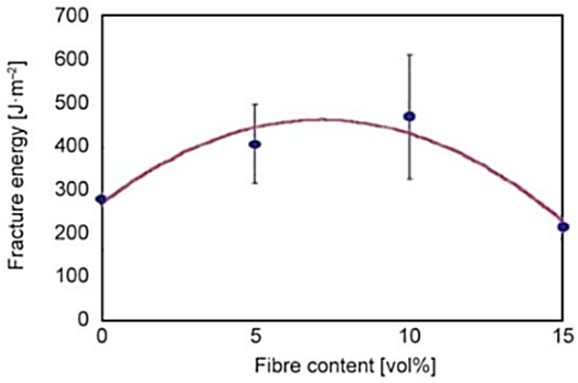


Figure 4. Fracture energy to the fibre content of 5–15 % vol PLA/silk fibre[22]

The hardness of pure PLA, as determined by averaging the observed findings, is 17 HV. Figure 6 plots the outcomes for biocomposite samples with different weight contents and fibre lengths. It was observed that the hardness increased in proportion to the fibre length, which increased from 3 mm to 5 mm. However, for every biocomposite sample with a different amount of fibre weight (from 1 weight per cent to 6 weight per cent), the hardness decreased when the fibre length exceeded 5 mm. An attempt was made to produce a sample with a 7 weight per cent fibre content, but it was discovered that the sample was brittle and barely demoulded[37].

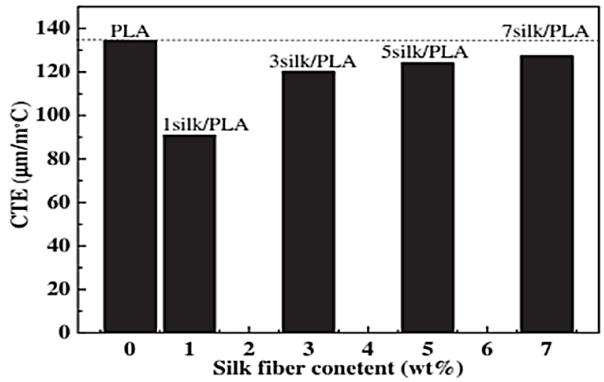


Figure 5. Effect of silk fibre content in silk/PLA composites on Coefficient Of Thermal Expansion (CTE)[50].

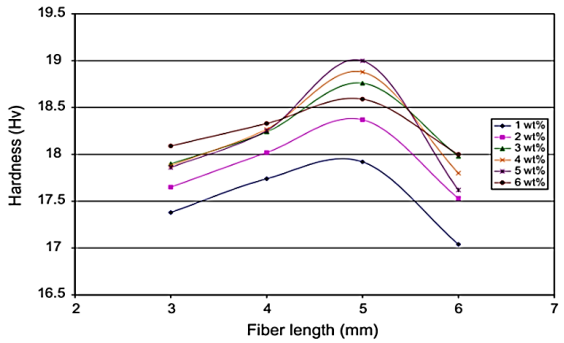


Figure 6. Results of micro hardness tests on silk fibre lengths and contents in Silk-PLA composite[37].

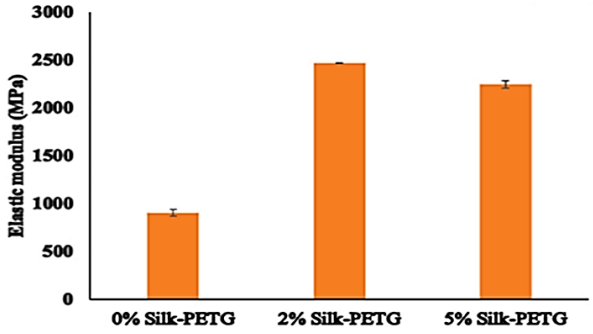


Figure 7. Elastic modulus of 3d printed composites with varying % of silk fibre[68].

Silk fibres were added in amounts of 2 %, 5 %, and 10 % (by weight) by Bonthu *et al*[68]. It was discovered that extruding silk fibres with a greater weight content (10 wt %) at 140 °C (used for other wt %) was difficult. Every material has demonstrated good printability, except 10 % silk-PETG. The structural, mechanical, and flexural characteristics of printed parts were found to be influenced by the fibre content. According to our findings, elastic modulus only rises to 2 % silk-PETG; beyond that, it falls (Figure 7). The development of fibre agglomerates on high filler content may be the cause of this modulus drop, leading to material discontinuity and the creation of high-stress concentration zones. The fibre addition considerably increased the material's elastic modulus, according to the results[68]. The best fibre length and weight content to create a stronger biocomposite, according to the literature, are 5 mm and 5 weight per cent, respectively. According to published research, it is feasible to create composite filament by adding 2, 5, and 7 wt % silk fibre to PLA granules.

5.0 Conclusion

The demand for sustainable and high-performance materials in additive manufacturing continues to rise, especially in the biomedical and engineering sectors. This study systematically explored the potential of silkworm silk fibres as reinforcement in PLA-based filaments for Fused Deposition Modelling (FDM). Through a comprehensive literature review and comparison with existing natural and synthetic fibre-reinforced PLA composites, silk fibre has emerged as a promising additive. Silk fibres demonstrate excellent mechanical, thermal, and biological properties, including high tensile strength, good elasticity, biocompatibility, and controlled biodegradability. Experimental results confirm that PLA-silk composites offer improved tensile and flexural properties, enhanced elongation, better crystallinity, and thermal stability compared to neat PLA. Moreover, the sustainable and biodegradable nature of both PLA and silk aligns well with the goals of eco-friendly manufacturing. Based on the findings, silk fibre is not only a viable reinforcement option but also an advantageous alternative to conventional fillers, especially for applications demanding mechanical strength and biocompatibility, such as tissue engineering, orthopaedic devices, and biodegradable implants. The study concludes that the optimal silk fibre content ranges between 2–7 wt % with fibre lengths of 2–5 mm to balance printability, mechanical performance, and structural integrity. Future work can focus on experimental validation, optimising processing parameters, and expanding the use of PLA-silk biocomposites in advanced 3d-printed applications.

6.0 Future Scope

Optimization of fibre parameters such as silk fibre length, orientation, and surface treatment could further enhance composite performance. Advanced material characterization techniques like SEM, FTIR, and TGA can be employed to better understand the interfacial bonding and structural integrity of the composites. Given the biocompatible nature of silk, in-depth biological studies including cytotoxicity and biodegradability assessments are required for medical applications such as implants, scaffolds, and sutures. Additionally, future research could focus on developing scalable and eco-friendly manufacturing processes for PLA-silk filaments, making them viable for commercial use. Exploring the use of these composites in multi-material 3d printing and the incorporation of functional agents could lead to the development of smart biocomposites. Long-term performance studies related to durability, biodegradation, and moisture resistance would be crucial for practical applications. Overall, PLA-silk composites hold great promise for advancing sustainable, high-performance materials in biomedical, packaging, and structural applications.

7.0 References

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