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Mechanical, thermal and physical properties of natural fiber reinforced composites for 3D printer - fused deposition modeling: A review

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ABSTRACT

Additive manufacturing (AM) or 3D printing technology is a method for building three-dimensional parts through the sequential addition of material layers according to a digital blueprint. It differs from subtractive manufacturing, which entails the removal of material to form an object. In the fields of research and manufacturing domains, fused deposition modeling (FDM) has received the greatest attention. The use of natural fibers as fillers for thermoplastic composites in 3D printing has drawn interest, which has led to a quest for more environmentally friendly production techniques. Careful techniques and a thorough understanding of the characteristics of natural fibers and their matrices are necessary for the fabrication of natural fiber reinforced thermoplastic composites for FDM. Thus, this paper reviews the properties of natural fiber reinforced thermoplastic composites for FDM based 3D printing. It covers the literature and findings on mechanical, thermal and physical properties of natural fiber reinforced thermoplastic composites for FDM based 3D printing. Finally, conclusions regarding required properties of natural fibers for FDM based 3D printing are also discussed. This review article provides readers with a complete understanding of the advantages and properties of natural fiber reinforced composites FDM based 3D printing. As the demand for sustainable materials continues to grow, the potential for these composites to contribute to eco-friendly manufacturing practices becomes significant.

1. Introduction

This paper reviews the characteristics of natural fiber reinforced thermoplastic composites specifically for Fused Deposition Modeling (FDM) or 3D printing. The main chapters of this review paper are shown in Fig. 1. This work encompasses the literature and findings regarding the mechanical, thermal, and physical properties of natural fiber reinforced thermoplastic composites specifically designed for FDM 3D printing. The article also discusses the comparison between the single and dual stage compounding processes. At the end, the necessary properties of natural fibers for FDM 3D printing are also examined.

Despite significant advancements in additive manufacturing, the development and application of natural fiber reinforced thermoplastic composites for Fused Deposition Modeling (FDM) remain limited. Most existing studies focus predominantly on synthetic fiber composites, leaving a gap in the comprehensive understanding of natural fiber behavior during the FDM process. Challenges persist in achieving uniform fiber dispersion, optimal fiber-matrix adhesion, and consistent filament quality. Additionally, the impact of fiber characteristics—such as aspect ratio, moisture content, and surface treatment on mechanical, thermal, and physical properties is still not fully understood. Variability in natural fiber properties due to their organic origin adds further complexity to standardizing material formulations for FDM. The dual-stage compounding process, while promising for enhancing fiber-matrix bonding, demands further investigation to optimize processing parameters and assess scalability. Moreover, existing literature seldom addresses the recyclability and environmental implications of using natural fibers in FDM filaments. Addressing these research gaps is essential to fully harness the sustainability potential of natural fiber reinforced composites in 3D printing. Overcoming these challenges will

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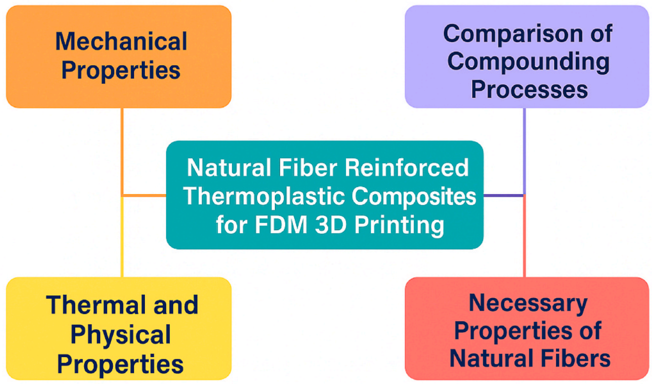

Fig. 1. The main chapters of the paper.

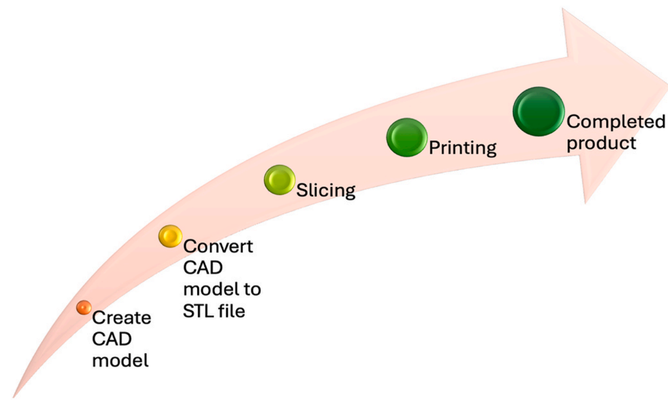

Fig. 2. The steps in the AM method.

contribute to developing eco-friendly, high-performance materials, supporting broader industrial adoption of sustainable FDM technologies.

This review also provide a focused examination of the current state-of-the-art in fused deposition modeling (FDM) of natural fiber–reinforced polymer composites, emphasizing the relationship between printing parameters, fiber characteristics, and composite performance. Unlike general reviews on additive manufacturing or biocomposites, this paper uniquely integrates both material and process perspectives to identify key challenges in fiber dispersion, interfacial bonding, and porosity formation during printing. The review further highlights emerging trends, research gaps, and potential strategies for improving the mechanical integrity and sustainability of natural fiber–based composites in additive manufacturing applications.

2. Overview of additive manufacturing

Today, additive manufacturing (AM) is the latest technology used to fabricate detailed and complex built parts for a multiple of applications. It is becoming well-known for its affordability and ease of customization in producing complex shapes. AM markedly decreases molding and machining time. Moreover, the manufactured parts frequently demonstrate a refined microstructure and superior mechanical characteristics (Olhan et al., 2024[1]). According to worldwide forecasts, the market for 3D printing is anticipated to rise from its estimated USD 12.6 billion in 2021 to USD 34.8 billion in 2028 (MarketsandMarkets research, 2020 [2]). AM is a method for fabricating layers of material to create accurate parts. It can also be defined as the process of making a three-dimensional (3D) part from a CAD model. It was created during the end of the 1980s and is now a popular manufacturing technology ([3,4] reported 47 % of 3D printing companies had greater success than in past years and over the next five years, the AM industry is expected to grow by an average of 24 %, or 35 billion US dollars. In 2020, the AM sector has expanded by 7.5 % or roughly 12.8 billion US dollars. Since the process for producing parts is so straightforward, AM methods were widely used in manufacturing sector and home applications, such as for tripods, photo frames, gift accessories, tools, souvenirs and toys. Most common applications are restricted to smaller sizes which will minimize the amount of waste and save energy without the use of larger machines [5]. AM contains several steps that vary according to the type of manufacturing method employed, from design creation to final product [6]. Despite producing a prototype, these basic steps are universal and stay the same. Fig. 2 illustrates the phases that make up the AM process. Currently, AM is used in diverse areas such as ceramic, plastic, biomedical and composite. Current research in bioprinting includes the 3D printing of cardiac valves [7,8].

2.1. History and categories of additive manufacturing

Swainson [9] described a method for fabricating a product directly by using a photosensitive polymer and selective 3D polymerization. Nakagawa et al. (1979)[10] from Tokyo University revealed the application of lamination methods to create genuine tools in 1979. Kodama [11] from Nagoya Municipal Industrial Research Institute created the foundations for additive manufacturing. Kodama invented a prototyping device by using 3D scanning and layering technologies adopted from 3D topographical map-making. Shaikh, S [12]. in his paper reported that the technology's origin is often attributed to Charles W. Hull, who invented stereolithography (SLA) in 1983. The first commercialized 3D printing process capable of fabricating three-dimensional objects directly from digital data. Hull's innovation of the STL file format and the subsequent establishment of 3D Systems in 1986 laid the groundwork for modern AM technologies and standardized digital-to-physical fabrication workflows. Following Hull's invention, other major AM technologies emerged, further expanding the scope of the field. In the late 1980s, Scott Crump developed Fused Deposition Modeling (FDM), a material extrusion-based technique that remains one of the most widely used methods due to its cost-effectiveness and versatility with thermoplastic materials. Around the same time, Carl Deckard pioneered Selective Laser Sintering (SLS) at the University of Texas, introducing a powder-based fusion approach that enabled the fabrication of complex geometries from polymer and metal powders.

The definitions of various AM technology types are shown in Fig. 3, which is based on the International ASTM standard [13]. These include VAT photopolymerization, material extrusion, material jetting, powder bed fusion, binder jetting, and sheet lamination. For instance, a model is constructed layer by layer by utilizing a VAT of liquid photopolymer resin through VAT polymerization. Meanwhile, the sheet lamination process is made up of ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). Some common methods for printing employed the powder bed fusion process, which includes selective laser melting (SLM), selective heat sintering (SHS), electron beam melting (EBM), direct metal laser sintering (DMLS) and selective laser sintering (SLS). Binder jetting employs a powder-based substance and a binder. Furthermore, fused deposition modeling (FDM) is also called fused filament fabrication (FFF), which is a popular process for extruding materials [14].

2.2. Fused deposition modeling (FDM)

FDM is a production method that uses a movable nozzle to eject polymeric material fibers layer by layer to construct a structural design. FDM is the most extensively used because of its simplicity, adaptability, quick processing, minimal waste and ability to deal with various and innovative materials. The FDM technique was developed in 1989 by

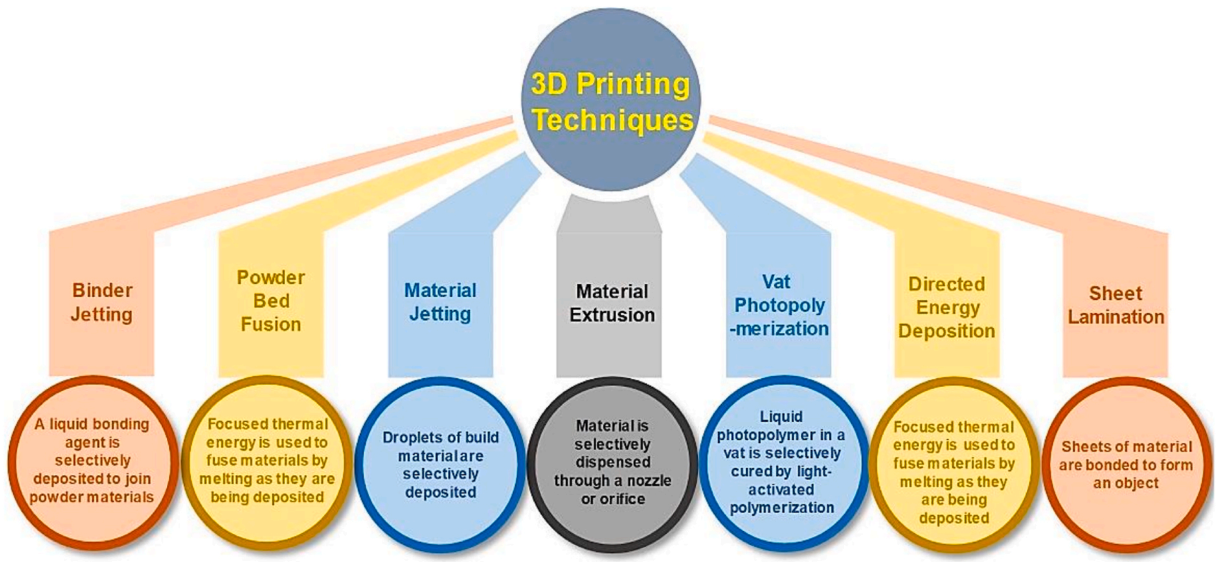

Fig. 3. Types of AM/3D printing technology according to international ASTM standard (Yang et al., 2020).

Stratasys, Ltd., one of the world's top 3D printing businesses. FDM technology constitutes more than 40 % of the worldwide market. FDM is the most widely utilized AM method because of its speed, simplicity, affordability, wide range of material variation and ability to build sophisticated components [14]. Vaidya et al. (2019) reported that the technology was designed for low-volume manufacturing; its advantages were beyond traditional processes such as injection molding or extrusion, including lower energy consumption and lower waste index. Fig. 4 depicts an FDM-3D printer, in which material in the type of filament is fed into the liquefier head via a spool by using the pushing force provided by the grooved bearing and drive gear. Before depositing the layers by using a heated nozzle, the filament is heated up to a glass transition temperature. The liquefier's head moves in the X–Y plane by a tool path provided by programming [15]. Metals, polymer and composites have been developed for application in FDM. However, some of these materials are hazardous to humans and the environment as a whole due to the production of volatile organic compounds [16–18]. The most commonly used raw materials for FDM 3D printers include polylactic acid (PLA), polypropylene (PP), polycarbonate (PC) and acrylonitrile butadiene styrene (ABS) [19,20]. ABS is frequently utilized in the production of toys (such as Lego), home goods, medical tools and pharmaceutical applications. Previous studies, such as those by Soltanmohammadi et al. [21] and Rahmatabadi et al. [22], have explored the use of ABS and PLA in combination with TPU to create new composite filaments. The mechanical test results revealed that increasing the PLA content enhanced strength, while reducing formability, across all loading modes. In contrast, when TPU was added to the ABS mixture, the strength decreased, but both formability and elongation increased.

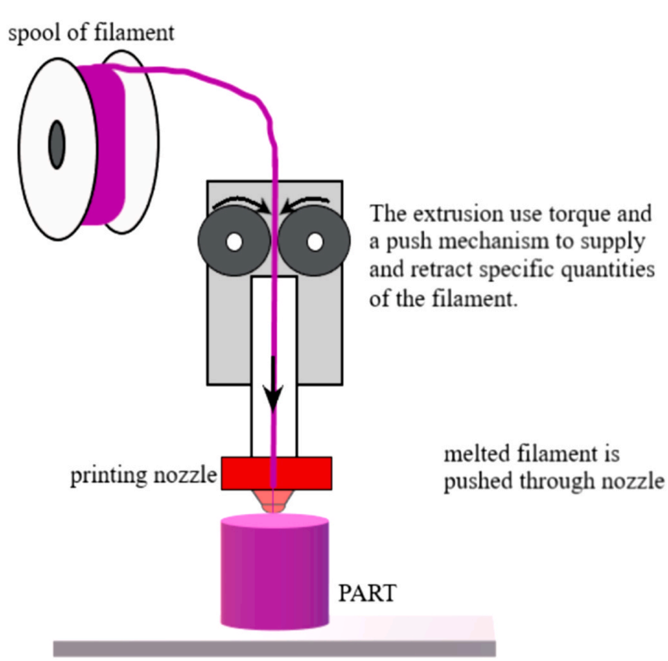

Fig. 4. Schematic diagram of an FDM-3D printer (Mogan et al., 2022).

Rimington et al. [23] discovered that ABS was a reliable thermoplastic polymer that did not leak harmful substances. Specific grades of ABS have recently been deemed FDA food safety compliant, indicating that the materials are suitable with foods. A study by Singh et al. [24] reported that FDM is now widespread in a variety of industries, including automotive, biomedical, consumer products production and smart textile industries. FDM is utilized because it improves the development of products, prototype phase and production process. FDM is also one of the promising technologies among industrial sectors because it reduces product development time and production cost. Research is being conducted to broaden the range of materials that can be used with the technology. Recently, many products relied extensively on polymers, plastics and composites due to their affordable prices and high strength-to-weight ratio. Substantial studies were conducted to address various composites. The majority of research on FDM materials was focused on the material applicability, improving process parameters as well as rheological and mechanical characteristics. Some researchers had proposed different composite materials that may be utilized in FDM and attempted to maximize the material compatibility.

3. Natural fiber

Aisyah et al. [25] described natural fibers originate from various sources, including biological and geological. Each type of fiber possesses qualities such as resilience, elasticity and heat resistance, which render them valuable for a wide range of textile and industrial applications. For vegetable fiber, it is also referred to as a lignocellulosic substance since fibers it is mostly made up of cellulose, lignin, pectin, hemicelluloses, wax, ash and moisture. Natural fibers are readily accessible and exist in a wide range of variations. Some examples are jute, bamboo, dates, sisal kenaf, oil palm, pineapple, banana, and sisal. Cellulose, which is found in fiber, is a natural polymer with a high degree of stiffness and strength per weight that is utilized to construct lengthy fibrous cells. These cells may be found in plant stems, leaves, and seeds [26]. Wang et al. [27] highlighted that replacing synthetic and carbon fiber with natural fiber presents a promising approach for a better environment and creating new products. Green materials are generally defined as those sourced from renewable resources, requiring lower embodied energy, and producing reduced environmental impacts throughout their life cycle, while eco-friendly refers to products or processes that minimize harm to the environment during production, use, or disposal. Such classifications are often guided by recognized standards and certifications, including LEED (Leadership in Energy and Environmental Design), FSC (Forest Stewardship Council), Cradle-to-Cradle (C2C), and ISO 14001. According to published life cycle assessments (LCAs), natural fiber-reinforced composites and bio-based polymers offer clear advantages over conventional alternatives. Shen et al. (2010) found that bio-based polyethylene emits up to 60 % less CO_2 during production compared to petroleum-based polyethylene. Although a complete LCA specific to this study's material was not conducted due to scope constraints, these established findings indicate that the use of natural fibers and bio-based alternatives can significantly reduce environmental burdens compared to traditional synthetic materials.

3.1. Properties and classification of natural fibers

As indicated in Fig. 5, natural fibers are divided into two categories: natural and produced. The natural-based category includes animal, cellulose and mineral fibers. Oil palm, hemp, jute, flax, and others are cellulose categories, whereas wool, silk, and many others are animal-based. Meanwhile, asbestos is an example of a mineral-based substance. Organic fiber and inorganic fiber are the two types of synthetic or produced fiber. Organic fiber is made of aramid, polyethylene and aromatic polyester. Inorganic fibers include silicon carbide, glass, boron, and carbon [28]. Natural fiber composites have the following attributes: strength, affordable cost, lightweight, high specific strength, non-abrasiveness, sustainability, and biodegradability [29].

Oliveira et al. [31] discovered composites with organic cotton fiber fillers had a lower environmental effect. In general, the environmental

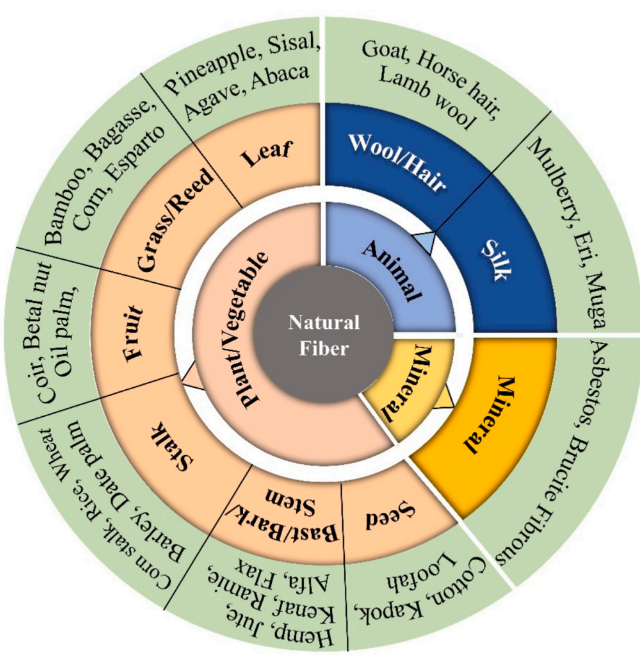

Fig. 5. Group of natural fibers (Kamarian & Song, 2022[30]).

performance of cotton-based composite materials was improved. According to Chen and Luo [32], bamboo fiber possesses hierarchical structures that significantly affect its toughness and mechanical characteristics. These unique structures enable bamboo fiber to exhibit remarkable strength-to-weight ratios, making it an ideal material for various applications in construction and textiles. Therefore, natural fibers are frequently employed in 3D printing filaments [33]. Furthermore, it has become more common in a range of industrial areas, such as construction and automobile manufacturing as well as thermally insulated composites and acoustic materials [34].

The chemical composition of several natural fibers is shown in Table 1. Despite the fact that the fibers are produced from a single plant, the attributes of natural fiber are influenced by a few elements, such as physical features, chemical composition, crystalline cellulose diameters, microfibrillar position, flaws, structure, and separation process. Consequently, the grade and mechanical properties of fiber might vary greatly. Table 2 summarizes the mechanical characteristics of different natural fibers. A variety of variables must be considered to achieve the highest level of performance, including flaws and fiber interactions with the matrix [35], volume fraction [36], moisture absorption [37], orientation [38], and physical properties [39], which are inherent fiber attributes. The use of natural fibers as alternative materials in multiple industries has sparked significant global interest in seeking a cleaner environment and better sustainability.

These fibers have relatively low density, high mechanical attributes, reusable performance and excellent thermal characteristics, making them suitable for reinforcement usage in composites. Natural fiber reinforced polymer composites (NFRPCs) are used in a variety of industries, including manufacturing components, automotive industry, building constructions, household items and packaging. They are also employed in consumer products, including interior panels, household tables, window panels and chairs [55]. The aforementioned materials can also be utilized as a green alternative in automobiles and aircraft interior paneling. From this perspective, it is clear that the potential use of NFRPCs has captured the interest of material researchers and engineers due to their benefits. The integration of natural fibers into polymer matrices for additive manufacturing represents a significant step toward eco-friendly and sustainable production. Natural fibers such as kenaf, jute, and rice husk offer renewability, biodegradability, and lower environmental impact compared to synthetic reinforcements. When combined with biodegradable polymers like PLA, these materials enable the fabrication of green composites with reduced carbon footprint and material waste. In the context of fused deposition modeling (FDM), such composites not only promote circular economy principles but also

Table 1
Chemical compositions (%) of natural fibers.

Natural fiber	Composition (%)				Reference
	Cellulose	Hemicellulose	Lignin	Ash	
Ramie	68.6–91	5–16.7	0.6–0.7	–	Rehman et al. [40]
Hemp	55–77	3.7–13	14–22.4	0.8	Khan et al. [41]
Jute	45–71.5	13.6–21	12–26	0.5–2.0	Selver et al. [42]
Flax	83.3	11.3	2.3	–	Chen et al. [32]
Sugarcane	46	24.5	29.5	2.4	Mulinari et al. [43]
Kenaf	56.8–79.3	9.7–13.6	7.2–18.3	–	Guo et al. [44]
Bamboo	41.8	59.8	29.3	1.5	Yan & Xi [45]
Cotton	82.7–90	5.7	<2	–	Rehman et al. [40]
Coir	36.6	37.0	22.2	1.9	Kochova et al. [46]

Table 2
Mechanical properties of natural fibers.

Natural fiber	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Reference
Ramie	1.4–1.5	400–938	61–128	Sen & Reddy [47]
Hemp	1.1–1.6	285–1735	14.4–44.0	Marrot et al. [48]
Jute	1.3–1.5	393–773	13–26.5	Vijay et al. [49]
Flax	1.3–1.5	340–1600	25–81	Yan et al. [50]
Sugarcane	0.8–1	250–300	17–20	Komuraiah et al. [51]
Kenaf	0.6–1.5	223–1191	11–60	Udoeyo & Adetifa [52]
Bamboo	1.2–1.5	500–575	27.0–40.0	Mwaikambo [53]
Cotton	1.5–1.6	287–800	5.5–12.6	Mwaikambo [53]
Coir	1.2–1.6	170–230	3.0–7.0	Harish et al. [54]

provide a pathway toward lightweight and high-performance components suitable for sustainable engineering applications. Therefore, this study emphasizes the potential of natural fiber–reinforced composites as a promising approach for achieving environmentally responsible additive manufacturing.

3.2. Natural fiber reinforced thermoplastic composites (NFRTC) for FDM

As environmental awareness spreads worldwide, substantial research is being conducted to develop an alternative for synthetic fiber-reinforced polymers (FRPs). Natural fibers were discovered to potentially substitute synthetic fibers like glass or carbon fibers due to advantages, such as sustainable nature, biodegradability, excellent stiffness-to-weight ratio, minimal abrasion and inexpensive cost [56]. Common polymer processing methods, including compression and injection molding, as well as extrusion are used in creating NFRPCs. Natural fibers are abundant in China, and southeastern countries, which have the world's fastest-developing economy [57]. These fibers are mostly utilized for traditional purposes in underdeveloped nations; hence, there is an opportunity for innovative applied technology such as FDM to help their economies grow and perhaps become the hub of production for natural fiber goods. Fig. 6 shows the fabrication process in producing the NFRTC filament for FDM. Table 3 shows applied FDM

Table 3
Past studies on natural fiber reinforced thermoplastic composites for FDM.

Thermoplastic	Natural Fiber	Fiber Loading (wt%)	FDM-3D Printer Model	Reference
ABS	Banana fiber	0–5	Accucraft i250	Singh et al. [24]
ABS	Kenaf fiber	0–10	FlashForge Creator Pro	Han et al. [58]
ABS	Macadamia nutshell	0–29	Leapfrog Creatr	Girdis et al. [62]
ABS	Rice straw	0–15	Printrbot Simple Metal	Osman & Atia [59]
PBS	Hemp	0–5	Prusa i3 MK3S	Dönitz et al. [63]
PP	Wood Dust	0–3	–	Nafis et al. [64]
PP	Hemp	0–30	Diamond Age	Milosevic et al. [65]
PLA	Hedysarum coronarium	0–20	Sharebot, Next Generation	Scaffaro et al. [66]
PLA	Agave fiber	0–10	Wanhao Duplicator	Figueroa et al. [67]
PLA	Kenaf fiber	0–7	FlashForge Creator Pro	Shahar et al. [68]
PLA	Kenaf fiber	0–2.5	FlashForge Creator Pro	Jamadi et al. [69]
PLA	Sugarcane fiber	0–15	Architect 3D	Liu et al. [70]
PLA	Astragalus	0–15	Moshu S108	Yu et al. [71]
PLA	Rubber	0–20	Craftbot Plus	Fekete et al. [72]
PLA	Bamboo	0–15	Low-cost 3D printer	Depuydt et al. [73]
PLA	Wood	0–5	Shenzhen 603S	Tao et al. [60]
PLA	Soybean hulls	0–10	MakerBot Replicator Z18	Dey et al. [74]

in previous studies by using natural fibers, such as kenaf, rice straw, banana, sugarcane, wood and hemp as reinforcements in polymer matrices to improve the performance of printed parts. Han et al. [58] used ABS/kenaf fiber composite as material for FDM to print specimens. The filaments produced were varied in terms of volume percentage of kenaf fiber, which were 0 wt%, to 10 wt%. The study had successfully confirmed the ability of kenaf fiber-reinforced ABS composites filament for FDM-3D printer based on mechanical properties (tensile and flexural strength). They used FlashForge model with 1.75 mm diameter of

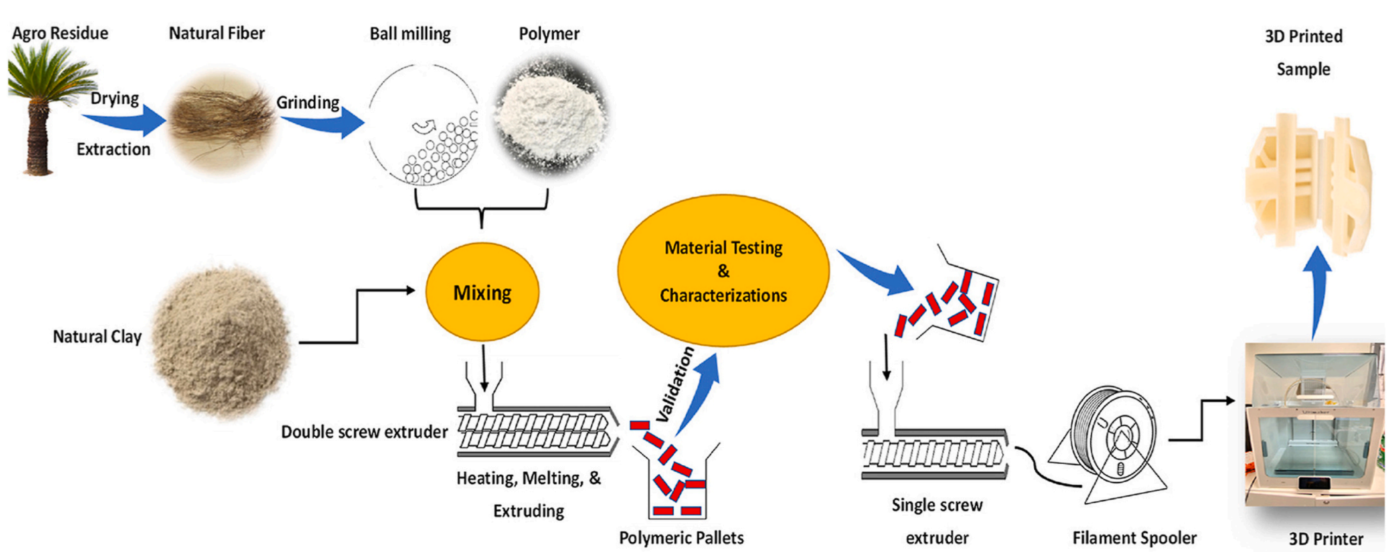

Fig. 6. The fabrication process of NFRTC for FDM (Nazir et al., 2023[61]).

filament. Other researchers who were involved in development of natural fiber for FDM were Osman and Atia [59]. They used ABS mixed rice straw composite to fabricate the filaments which contained 0 wt% to 20 wt% of fiber loading. All fabricated filaments were able to be printed by using a FDM (Printrbot model), with the only the 20 wt% composite filament was unsuccessful to print the samples. This filament was very fragile, hard to handle and typically broke when fed into the FDM extruder. Consequently, it is critical to investigate the flow characteristics (rheology) of new materials before they can be used as FDM filaments. Singh et al. [24] developed and analyzed the thermal, mechanical and morphological properties of ABS/banana fiber filaments (0 wt% and 5 wt%). Filaments with 1.5 mm diameter were used to print the ASTM D638 specimens by using a FDM (Accucraft i250 model). For sustainability of recycled polymers ABS and agriculture waste like banana fiber, the AM route can be gainfully employed for preparation of functional and nonfunctional prototypes with enhanced mechanical performances. Next, Tao et al. [60] fabricated wood floor and PLA composite filaments for the FDM with the application aim to 3D printing. The filaments consisted of wood flour (0 wt% and 5 wt %) in PLA matrix. Both pure PLA and wood/PLA composite filaments were printed as test samples with the FDM (Shenzhen model). The nozzle diameter was 0.4 mm while nozzle temperature was set at 210 °C during printing. The wood/PLA composite filament was able to be printed by the FDM and initial resistance to deformation was improved after adding wood, as compared to pure PLA.

Liu et al. [70] had successfully developed the 0 wt% to 15 wt% of PLA/sugarcane filaments for FDM. To get the cellulose fibers, chemical treatment procedures were utilized to remove them from the sugarcane bagasse crop that had been abandoned. For the purpose of the study technique, PLA composites containing sugarcane were made using FDM 3D-printing technology. Additionally, the morphologies, mechanical characteristics, crystallization properties, and thermal stability of the 3D-printed composites were investigated. The FDM, Architect model was used to print the tensile and flexural specimens, which were ISO527 and ISO178 respectively. In recent year, 5 wt% of hemp reinforced polybutylene succinate (PBS) composite for FDM was developed by Dönitz et al. [63]. In addition to mechanically characterizing hemp-reinforced PBS, this study set out to investigate its additive manufacturing process. The additive manufacturing process was used on all specimens (ASTM D3039) by means of the Prusa i3 MK3S FDM-3D printer. According to the research, adding hemp fibers with overlap might increase the Young's modulus of PBS. Yu et al. [71] studied on the development of PLA/astragalus composite filaments. To develop the filament by using astragalus as much as possible, the mass ratio of astragalus to PLA was first set as 15:85; however, it was found that the nozzle was often blocked, and the printing of the specimens could not be carried out smoothly. Then, the dosage of residue of astragalus (ROA) was gradually reduced and after a series of experiments, the mass ratio of ROA to PLA was finally selected at 11:89. The findings demonstrated that the parameters had a discernible impact on the mechanical characteristics and thermal stability of the printed specimen, however the melting and crystallization properties of the specimens were only marginally influenced by the parameters. In general, by preparing a new material such as natural fiber-based thermoplastic composites for FDM-3D printing, it probably plays a guiding role or blueprint in high-quality utilization of natural fiber and wide application in plastic industries. Besides that, it is of great significance to explore the potential in terms of economic performance of natural fiber for manufacturing composites by FDM technology.

4. Filament fabrication process for FDM

The filament fabrication process was divided into two methods: single-step and two-step processes. Some studies refer to them as an indirect and direct method. Indirect method involves two phases of compounding, either by employing a hot press followed by an extrusion process, or a single screw extruder followed by a twin-screw extruder. Meanwhile, direct method involves a single compounding process using a twin-screw extruder. The key requirement for any thermoplastic material to be used in the FDM-3D printer is compatibility and suitability of the polymer with the existing FDM setup without any major changes to the hardware or software of machine. Nevertheless, many challenges and issues may still be encountered toward the achievement of a high-quality printing, especially when using a newly developed material. The challenge may start with the fabrication of an extruded filament feedstock, whereby a high-quality filament needs to be prioritized prior to it being fed into the FDM. Ideally, a constant filament diameter of 1.75 mm across the entire spool is preferred. However, due to the manufacturing process, there is always a tolerance in which the diameter will be maintained.

4.1. Single-step filament fabrication process

In the past, some researchers produced a filament for FDM by employing a single-step process. For instance, Osman et al. [59] used a single screw extruder to create the ABS/rice straw filaments. The ABS powder and rice straw were sieved, and the particles that were between 12 to 25 mesh and 100–140 mesh respectively. Then, a mixer was used to mix the rice straw and ABS for 50 s. The ABS/rice straw mixture was then fed into the extruder through a hopper, and the temperature was adjusted to 190 °C. Han et al. [58] and Aumnate et al. [75] also used a single-step process to produce ABS/kenaf composite filaments for FDM. A twin-screw extruder operating at 180 °C and 40 rpm was used to compound and extrude a mix of kenaf fiber and ABS granules. The influence of rice straw size on the properties of 3D printed specimens composed of rice straw/PLA composites was investigated by Yu et al. [76]. A twin-screw extruder was utilized in a single-step process to create filaments. The extruder received the blend through a hopper, and the heater was adjusted to maintain a temperature of 170–190 °C from the hopper to the die.

4.2. Two-step filament fabrication process

Sekar et al. [77] used the two-step fabrication process depicted in Fig. 7 to produce PLA/OPF (oil palm fiber) composite filament. The first step in the process was material preparation, which included cleaning, soaking, and drying the fibers. The fibers that had dried were crushed and sieved. The fibers' lengths varied from 20 mm to 40 mm, while their diameters ranged from 0.2 mm to 0.5 mm. After that, PLA granules were heated up for a whole day at 60 °C. Fibers and PLA were manually mixed and then stored in an oven. The blends were repeatedly mixed and heated until they were completely mixed to form a composite lump. Next, the blends were pre-heated in a hot press machine for 5 min at 180 °C. They were then hot-pressed for 15 min at a pressure of 2 tons and then cold-pressed for an additional 5 min. Subsequently, the composite was crushed to create granules. When fiber is fed directly into an extruder with PLA granules this pre-processing (mixing and hot-press) minimizes the fiber's sedimentation. According to the TGA results, the thermal degradation temperature can be lowered by adding fiber up to 10 wt%. It shows that fiber composites have higher thermal stability at 210 °C and guarantees that the composites will not deteriorate during printing if the nozzle is set to that temperature.

Nurul et al. [78] developed pineapple leaf fiber (PALF) reinforced PLA filament for FDM using two-step fabrication process. Grinding, sieving, and altering the surface of the fiber were the first steps in the process. Next came hot pressing, crushing, and filament extrusion. According to the findings, the PALF/PLA composites were effectively extruded into filaments. Fouladi et al. [79] are researchers who have also worked on the production of filaments employing a two-step fabrication method. To create the FDM filaments, they combined PLA with coconut fiber. The coconut shells were fragmented into smaller particles with a hammer and subsequently subjected to ball milling to

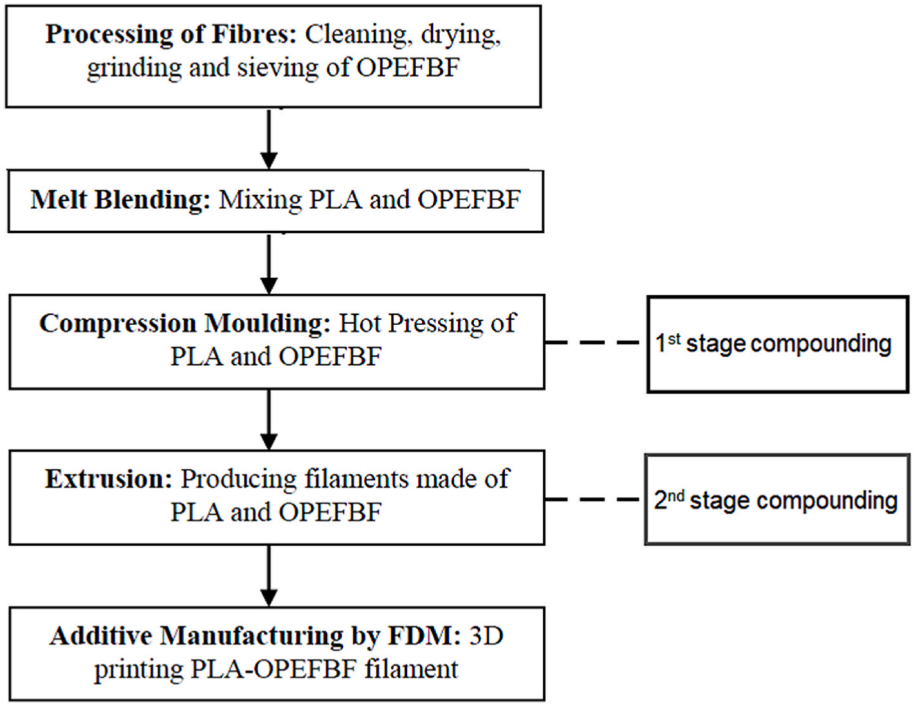

Fig. 7. Filament fabrication method using two-step of compounding (Sekar et al., 2021).

produce coconut shell powder (CSP), which was then sieved to a particle size of less than 500 μm. To reduce the moisture level, the coconut fibers were cleansed with distilled water, sun-dried for a day, and then oven-dried for 2 h at 60 °C. After that, the fibers were treated with an alkaline solution to decrease the amount of lignin and hemicellulose on their surface. The mixing of PLA and coconut fibers was the initial step in the production of the composite. After that, the composite was hot-pressed into a plate with a thickness of 1 mm. The composite plate was subsequently chopped up into smaller pieces and dried at 90 °C for an hour to eliminate any remaining moisture. PLA/coconut fiber filament was created using a twin-screw extruder set to a die temperature of 190 °C.

According to Le Guen et al. [80], there were two consecutive processes involved in producing the rice husk/PLA filaments: (a) compounding the polymer and rice husk at a weight percentage of 10 % to create pellets, and (b) extruding the filament for FDM. The twin screw extruder, equipped with a vacuum chamber and a 40 L/D ratio, was used for both processes. To guarantee more homogeneity, the filament was created in two steps [81]. The wood was combined with PLA in the first phase to create pellets, which were then extruded into filaments in the second step. Wood flour and PLA granules were dried for 24 h at 103 °C and 12 h at 60 °C, respectively, before compounding. A twin-screw extruder was used to compound the mixtures once they had dried. A Brabender KDSE extruder was utilized to create the wood/PLA filaments, and the extrusion temperatures were adjusted from the hopper to the die to be 220-210-175 °C, respectively. Ayrilmis et al. [82] investigated how the wood flour content affected the surface characteristics of 3D-printed parts composed of PLA filament and wood flour. There were two processes involved in the filament production process. Employing a twin-screw extruder, the various ratios of PLA and wood were first turned into granules. A single-screw extruder was then used to create the filaments from the dried granules. Yu et al. [71] used a two-step production process to make astragalus/PLA filaments for FDM. After astragalus and PLA were manually mixed, a twin-screw extruder (SHJ-20) was used to pelletize the mixture. Then, using a twin-screw extruder (KS-HXY) at a temperature of 170 °C–190 °C from hopper to die, the astragalus/PLA composite filaments were produced. Two compounding steps were used by Shahar et al. [68] to produce the kenaf/PLA filament. The initial phase involved compounding the kenaf/PLA mixtures using a twin-screw extruder and then crushing them into pallets. Subsequently, those pallets were fed into the single screw extruder's hopper to produce a 1.75 mm diameter FDM filament.

4.3. Advantages of two-step filament fabrication

Table 4 lists the mechanical properties of natural fiber-reinforced thermoplastic composites for FDM. The PLA/kenaf filament manufactured by Shahar et al. [68] in a two-step process had the maximum tensile strength (54.8 MPa) when compared to Aumnate et al. [75] at 28 MPa and Jamadi et al. [69] at 40 MPa, who created the PLA/kenaf filaments in one step. Furthermore, when an additional percentage of fiber was added to the ABS matrix, the ABS/kenaf filament made by Han et al. [58] using a single-step fabrication process showed a declining trend. The size of kenaf fiber was averaged at 120 μm. The SEM observation conducted by Shahar et al. [68] on the 3D printed sample containing 3 wt% of kenaf/PLA composite revealed that the kenaf particles were evenly distributed throughout the matrix, with no discernible phase segregation on the surface of the granules. As shown in Table 4, Krapez et al. [81], Tao et al. [60], and Narlıoğlu et al. [83] produced the PLA/wood filaments. The PLA/wood filaments that were produced in two steps by Krapez et al. [81] demonstrated the highest values of the printed part's tensile and flexural strength. This indicates that two-step processes have greater benefits than one-step process when it comes to the production of natural fiber composite filaments, according to previous studies. Furthermore, the comparisons demonstrated that a satisfactory mechanical property was produced by the two-step of the filament fabrication process. When fiber and thermoplastic granules are directly inserted into an extruder, a two-step process can thereby guarantee greater homogeneity and minimize fiber sedimentation.

4.4. Single-screw extruder

The process of making a natural fiber composite filament using single and twin-screw extruder is shown in Fig. 8. It shows process which starts

Table 4
Mechanical properties of natural fiber reinforced thermoplastic composites for FDM using single and two steps of filament fabrication process.

Thermo-plastic	Natural fiber	Process (Single/Two steps)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Impact Strength (KJ/m^2))	Reference
PLA	Kenaf	Two steps	54.8	–	–	3.2	Shahar et al. [68]
PLA	Kenaf	Single step	28.0	–	–	–	Aumnate et al. [75]
PLA	Kenaf	Single step	40.0	0.9	59.3	–	Jamadi et al. [69]
ABS	Kenaf	Single step	21.5	–	26.5	–	Han et al. [58]
PLA	Wood	Two steps	28.6	–	23.8	–	Krapez et al. [81]
PLA	Wood	Single step	20.0	–	–	–	Tao et al. [60]
PLA	Wood	Single step	8.0	–	9.4	–	Narlıoğlu et al. [83]

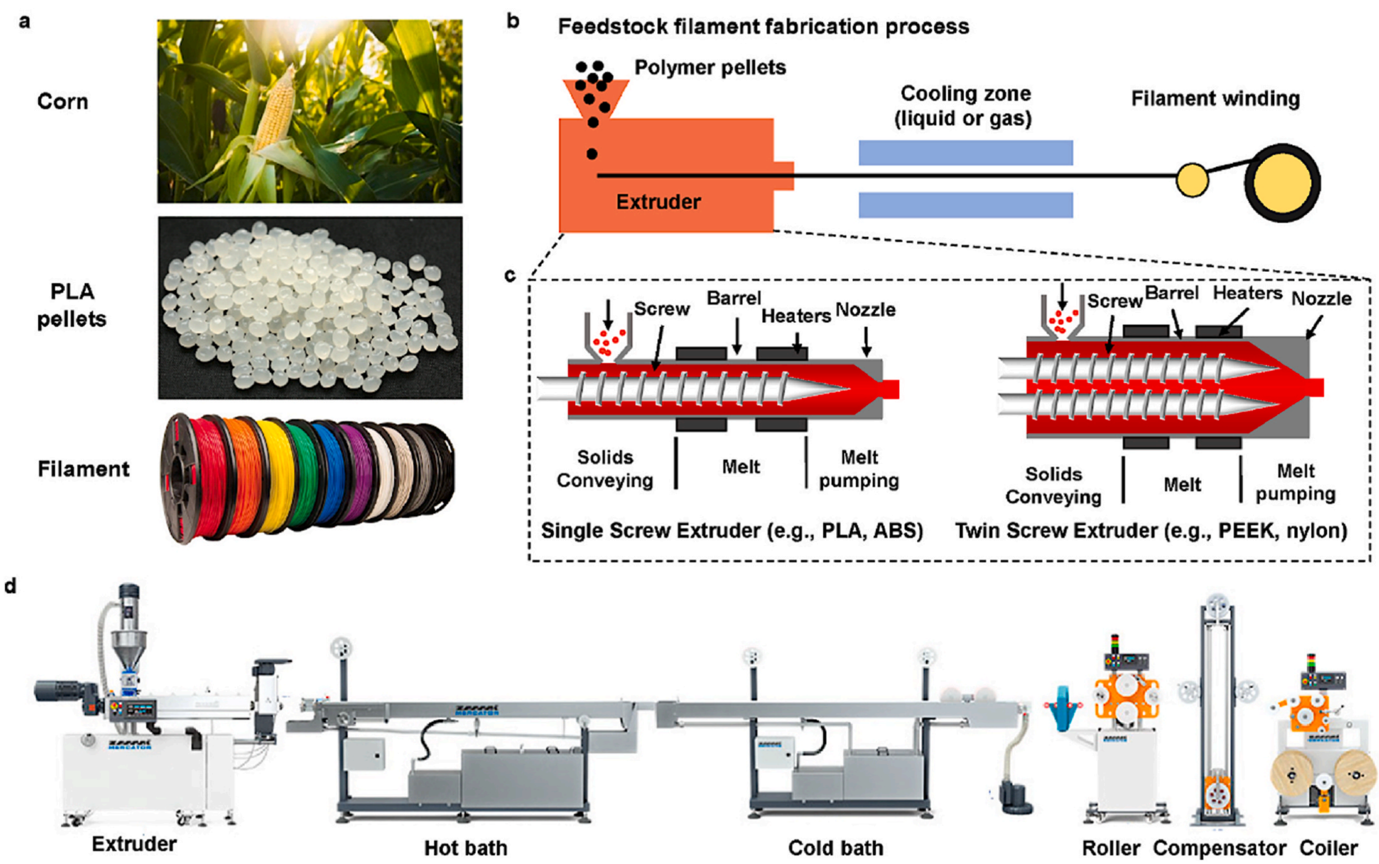

Fig. 8. The process for fabricating a filament (a) material preparation (b) an overall process in the fabrication of a filament (c) single-screw and twin-screw extruder (d) filament production line for FDM in industry (Park & Fu, 2021[94]).

with material preparation and the PLA is pelletized and extruded into filaments by a single or twin-screw extruder. Typically, the process of thermoplastics filaments is usually fabricated by using single-screw or twin-screw extruders [84]. Extruders were invented in the 1870s to produce sausage. Single-screw extruder had evolved since the 1930s and was utilized to blend semolina flour with water to a pasta [85]. The characteristics and acceptability of the produced filaments were directly impacted by procedures like drying, mixing and sieving the fibers. It required surface treatment and drying to ensure a strong bond between the fiber and polymer matrices. A single rotating screw inside a static tubular barrel with three zones included compression, feed, and metering that made-up up the single-screw extruder design [86]. Hypersensitive-to-heat materials should not be processed by using single-screw extruders due to the increasing resistance and heat generated as the screw speed increased. Due to its ability to operate at high pressure and perfect for high-viscosity polymeric materials, a single-screw extruder is particularly well-suited to the production of extrusion-based parts [87]. Furthermore, during the extrusion process, a substantial amount of pressure was applied, compressing the materials to create filaments. Due to a lack of shear deformation, it could potentially result in agglomeration and insufficient mixing [88]. Mishra et al. [89] studied the effect of processing conditions of unreinforced and reinforced thermoplastic elastomer filaments by using single-screw extruder. The results showed that the extruded reinforced filaments were generally of lower diameter than the unreinforced filaments. In addition, lower extruder pressure and higher torque were observed in extruding reinforced filaments as compared to unreinforced filaments. Tao et al. [60] created the wood flour/PLA filament for FDM by utilizing a Wellzoom single-screw extruder with parameter settings of 175 °C for the barrel temperature and 2 m/min^{-1} speed. The composite granules were first heated to 103 °C for a duration of 4 h to eliminate moisture. Then, by using a single-screw extruder (3Devo) with a screw speed of 4 rpm and barrel temperatures of 175 °C, 180 °C, 190 °C, and 180 °C for four zones, Pereira et al. [90] created the rice husk composite filaments.

The PLA granules were oven dried at 80 °C for 4 h and then combined with rice husk to create compositions of 5–20 wt%. The extrusion process plays a crucial role in maintaining the fiber integrity and quality of the composite filament. The choice between single-screw and twin-screw extruders significantly affects fiber length retention and the resulting mechanical performance of printed parts. In general, twin-screw extruders promote more uniform fiber dispersion and better mixing due to enhanced shear and intermeshing action; however, this also increases the likelihood of fiber length breakage and reduction in aspect ratio [91]. In contrast, single-screw extruders impose lower shear stresses, thus preserving longer fiber lengths, but may result in uneven fiber distribution within the polymer matrix [92]. The screw speed also influences fiber degradation behavior. Higher rotational speeds generate greater shear and thermal energy, leading to more severe fiber fragmentation and a corresponding decrease in mechanical strength. Conversely, operating at moderate screw speeds helps to maintain fiber length and interfacial adhesion, which translates to improved tensile and flexural properties of the final printed composites [93]. Therefore, an optimal combination of extruder configuration and screw speed is essential to balance fiber dispersion with length preservation, ensuring the desired mechanical performance in FDM-based natural fiber–reinforced composites.

4.5. Twin-screw extruder

To create identical combinations of two or more distinct materials, a twin-screw extruder was utilized. Bouvier and Campanella [95] discovered that by using a twin-screw extruder to produce a natural fiber-reinforced thermoplastic filament allowed light dispersion and distributive blending. A twin-screw co-rotator was utilized to combine the fibers and the polymer, which allowed for the possibility of combining the polymer matrix with natural filler. To ensure the materials were properly mixed, the extruder was used to increase the shear tension that existed between the barrel and the rotating screws. By utilizing a twin-screw extruder (Haake), Liu et al. [70] were able to manufacture a composite filament for FDM that was composed of sugarcane and PLA. The fiber and PLA granules were dried at a temperature of 60 °C for 10 h before to the extrusion process. From the hopper to the die, the temperature for the extrusion process was chosen to be between 170 °C and 195 °C. 1.75 ± 0.05 mm was the diameter of the extrudate filament, and the screw speed was set at 50 revolutions per minute (rpm). In the interim, Han et al. [58] developed a kenaf/ABS composite filament by employing a twin-screw extruder (HTGD 20) with a die diameter of 1.75 mm. The use of a twin-screw extruder was also utilized by Nafis et al. [64] to manufacture a PP/wood composite filament that is recyclable. 1.5–1.79 mm was the diameter of the filament that was extruded. During the extrusion process, the temperature of the barrel was adjusted to a range of 160–200 °C, and the screw speed was set at 42 revolutions per minute. The barrel temperature was a crucial factor in the production of high-quality composite filament materials. The physical qualities of the filament that is extruded would be affected if the barrel temperature was considered incorrectly. The feed zone, the transition zone, and the melting zone were the three distinct heating zones that were separated within the barrel. To create a PLA/soybean filament, Dey et al. [74] utilized a twin-screw extruder in their manufacturing process. The various zones of the twin-screw extruder barrel were heated to temperatures that ranged from 138 °C to 171 °C to achieve the desired temperature regulation of the barrel. When the molten composite had reached its full melting point, it was removed from the melting zone by means of a strand die. The continuous composite string was then submerged in a water bath that was heated to 90 °F. There were four different types of filaments that were successfully made, each with a diameter of 1.75 ± 0.1 mm.

5. Characterization of natural fiber composites for FDM

It has been proven that by using natural fibers it can strengthen and enhance the mechanical characteristics of filaments and printed products [74]. The cellulose content of fibers and spiral angle at which the microfibrils build the fiber axis within their inner structure were intrinsic factors that affected the mechanical properties. Currently, the majority of FDM research was concentrated on creating new composite materials. Therefore, to enhance the performance of the printed parts, it is important to examine the properties of a newly developed material for FDM. It was important to characterize the mechanical, thermal, and physical properties of the newly fabricated composites for FDM to fully understand the printing parameters and enhance the quality of the printed parts [96]. The comparative analysis in Table 5 demonstrates the influence of FDM parameters on the mechanical and physical properties of natural fiber–reinforced composites. Lower layer heights and higher infill densities significantly enhance tensile strength and stiffness due to improved interlayer bonding and reduced void formation. Conversely, increasing printing speed tends to elevate porosity and decrease strength, likely due to insufficient fusion between deposited layers. These findings are consistent with previous studies on fiber–polymer composites fabricated via FDM.

5.1. Mechanical properties

In the development of a new composite materials for FDM 3D printers, it is crucial to comprehend how fillers and fibers impact the mechanical properties of the polymer matrix. The superior quality of natural fiber is one of the primary components in making natural fiber reinforced composite (NFRC) with enhanced mechanical characteristics such as tensile strength, flexural strength, impact strength, toughness and durability. Fig. 9 (a) depicts the UTS of printed parts by FDM that were obtained from various studies on composite materials with the percentage of fiber content. The result demonstrated that employing PLA mixed with 10 wt% macadamia nutshell produced the highest

Table 5
Effect of FDM printing parameters on mechanical and physical properties of natural fiber–reinforced composites [97].

Printing Parameter	Level	Tensile Strength (MPa)	Tensile Modulus (MPa)	Porosity (%)	Key Observation
Layer Height (mm)	0.1	42.8	1650	2.1	Finer layers improve bonding, lower porosity
	0.2	38.5	1590	3.0	Moderate interlayer adhesion
	0.3	34.2	1500	4.1	Higher layer height increases voids
Infill Density (%)	40	32.7	1485	5.2	Low density reduces strength due to voids
	60	38.0	1555	3.8	Balanced infill enhances load distribution
	80	43.6	1670	2.5	High density minimizes porosity
Printing Speed (mm/s)	40	43.1	1640	2.8	Slow speed ensures better layer fusion
	60	39.4	1580	3.5	Adequate bonding maintained
	80	35.8	1520	4.3	Higher speed reduces bonding quality

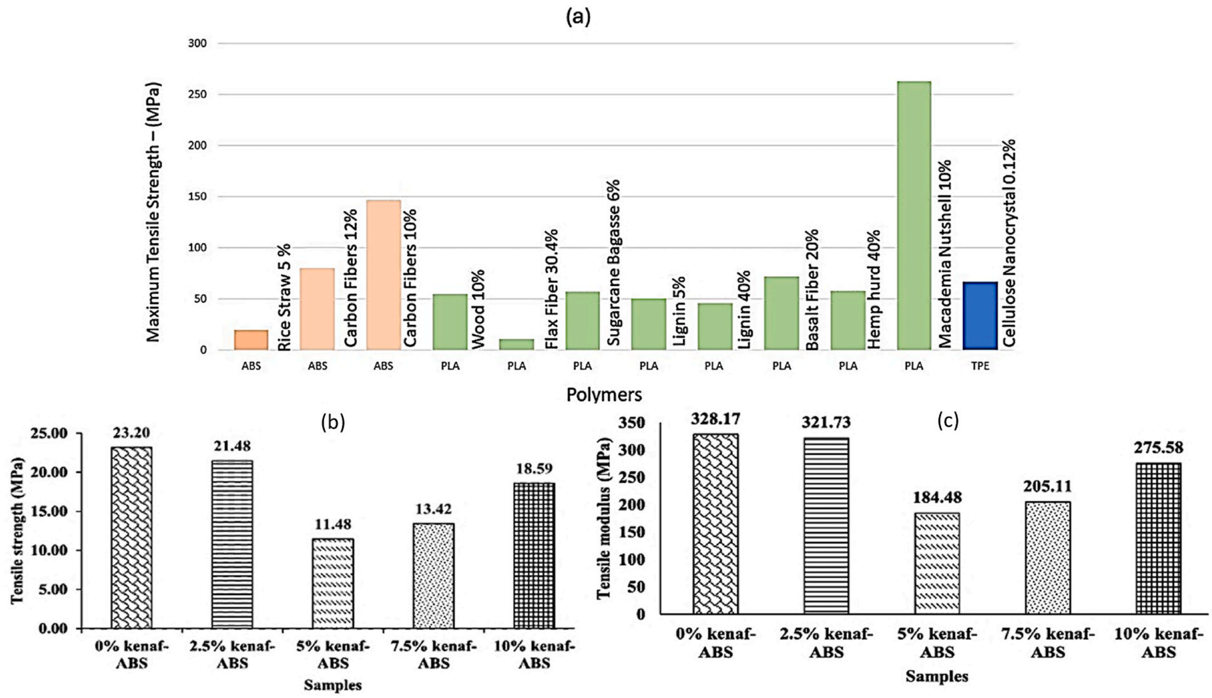

Fig. 9. (a) The maximum tensile strength of composite materials with fiber loading, wt% (Ahmed et al., 2020[101]), (b) Tensile strength and (c) tensile modulus for kenaf/ABS composites with varying fiber percentage (Han et al., 2022).

ultimate tensile strength (UTS) of the printed part [98]. Conversely, a flax fiber (30.4 wt%) reinforced PLA had the lowest UTS [99]. While Liu et al. [70] combined PLA with sugarcane bagasse and found that the flexural modulus steadily dropped as the fiber content increased and that the tensile strength of printed parts was maximum at 6 wt% of fiber. Kariz et al. (2020) investigated into the wood content which affected the FDM-printed parts. When 10 % wood was added, the tensile strength of filaments rose to 57 MPa when compared to plain PLA (53 MPa); however, as wood content grew, it fell to 30 MPa for filaments containing 50 % wood. The 0–40 wt% hemp-reinforced thermoplastic composite materials for FDM were developed by Xiao et al. [100]. The tensile and flexural strength of printed specimens dropped as hemp fiber content increased. The reduction in mechanical characteristics was associated with inadequate interfacial bonding, which was the cause of voids and interlayer gaps created at the hemp-polymer interface as well as between layers during the FDM process.

Furthermore, Torrado et al. [102] blended jute fiber with ABS and found that this mixture reduced UTS by 9 % but improved plasticity and boosted fracture strength by 28 %. The jute composite printed samples had the highest level of roughness among the four materials (ABS/titanium dioxide, ABS/zinc oxide, ABS/alumina and ABS/strontium titanate composites). Additionally, it was found that by adding jute to ABS, warping was reduced and increased dimensional stability. Stoof et al. [103] investigated the mechanical characteristics of printed samples with 10–30 wt% of harakeke (*phormium tenax*) mixed thermoplastic PLA. Tensile strength tends to decrease as fiber content rises. The 20 wt % harakeke was the outlier, with an average rise of 5.4 % over PLA although average value of PLA was within range. Poor interfacial bonding and the amounts of void in the filament and the samples were likely the causes of low strengths. Han et al. [58] conducted the mechanical test on the kenaf/ABS composite samples. Fig. 9 (b) and 9 (c) show the tensile strength and tensile modulus of 0 wt% to 10 wt% kenaf/ABS composites. The result demonstrated that the tensile strength was slightly lower than pure ABS. Nonetheless, as the fiber content rose, the pattern of graph showed a positive increase. The results of the morphological study indicated that the kenaf fiber and ABS matrix had poor interfacial bonding due to the existence of porosity and fiber pullout. According to mechanical properties, this study had effectively validated the suitability of ABS polymer composite filament reinforced with kenaf fiber for FDM-3D printers. Šafka et al. [104] revealed the systematic method of producing coir/ABS fiber composites. Based on this experiment, natural fiber should be dried at 100 °C for 3–4 h to remove moisture. The 15 % coir fiber/ABS composite sample was printed by using a hatch style of 0.39 mm, a layer thickness of 2 mm, 100 % infill density, 245 °C working temperature, and 1.26 m/min printing speed. It was remarkable to note that the maximum tensile strength of the pure ABS material printed via FDM printing was 39 MPa, 34 % higher than the value of the pure ABS material produced by injection molding. By comparing the printed composite to the injection-molded composite, the coir fiber addition decreased the tensile strength and modulus by 15 % and 25 %, respectively. Since fiber-to-fiber interaction could rise rather than fiber-to-matrix interaction, which decreased the strength of FDM composites with a maximum fiber percentage of 10 wt%, it was envisaged that change in fiber content in a smaller amount during FDM printing could enhance strength.

The reduction in mechanical properties of natural fiber composites is primarily attributed to inadequate interfacial bonding between the hydrophilic fibers and hydrophobic polymer matrices. The hydroxyl groups on the fiber surface attract moisture, leading to poor matrix wetting and weak interfacial adhesion. As a result, stress is not efficiently transferred across the interface, causing fiber pull-out and interfacial debonding under load. Additionally, surface impurities such as waxes, lignin, and pectin act as barriers to bonding. These interfacial weaknesses are the main causes of reduced tensile and flexural strength in untreated composites. To overcome this limitation, surface modification techniques such as alkali, silane, and acetylation treatments have been shown to improve fiber–matrix compatibility and enhance mechanical performance [105].

5.2. Thermal properties

As reported by Balla et al. (2019), as most natural fibers deteriorated at higher processing temperatures, thermal stability was an essential factor for the efficient processing of NFRCs. Heating between 100 °C and

300 °C caused chemical and physical changes in fiber that led to deterioration. According to Ornaghi et al. [106], hemicellulose decomposition was an initial step in the early thermal degradation of natural fibers and was correlated with moisture content. Because of their greater capacity to absorb moisture, natural fibers with high hemicellulose concentrations could potentially deteriorated at lower temperatures than those with low hemicellulose concentrations. The selection of appropriate materials and proper configuration of FDM parameters during printing were the two main components that determined how efficiently the FDM process works. FDM was typically produced with an amorphous polymer material. An amorphous polymer had indiscriminately oriented molecules and without a crystalline structure in both the molten and solid phases. An amorphous melt readily solidified in a relatively short time upon cooling because it could not crystallize. When adding tiny layers one after the other, this behavior was particularly important to get a well-printed sample [107].

Although the successful prints require specific characteristics, for example, a low glass transition temperature (T_g), melting point (T_m), and minimal tendency for shrinkage upon solidification, the number of polymers compatible with FDM-3D printers is currently quite limited. The capability for extrusion of material, capacity of parts to shrink during cooling (which could cause warping, but is not the only factor), and thermostability of end product were going to be affected by the T_g. However, the T_m provided some indications regarding the extrusion temperature (T_e), the final T_e will be significantly affected by how the feeding mechanism is set up in the FDM-3D printer. As shown in Fig. 10 (a) and (b), Pereira et al. [90] investigated the rice husk (RS)/PLA thermal behavior of composite for FDM. The alkali-treated RH exhibited a slight decrease in weight in the TGA range that exceeded 100 °C, which could be a consequence of moisture in these samples evaporating, confirming the results from FTIR spectroscopy. Additionally, the treated RH lost a small amount of weight between 180 °C and 250 °C. However, all examined samples like a rice RH, pure PLA and composite filaments showed an abrupt reduction in weight between 250 °C and 400 °C, which was evidence of significant thermal degradation. In the meantime, all samples at this temperature range exhibited strong peaks of DTG. Nonetheless, the rice husk exhibited a small peak in the DTG and the TGA thermograms demonstrated the rice husk retained 30 % of its residual weight at 400 °C. These findings demonstrated that rice husk existed in the PLA matrix of the composites and that it remained after the PLA matrix was thermally degraded, providing the composites with greater thermal resistance at above 400 °C.

Yu et al. [76] studied the thermal characteristics of rice straw/PLA bio-composites for FDM-3D printer. As seen in Fig. 10(c) and (d), the addition of rice straw particle (RSP) to the PLA matrix sped up deterioration of PLA, leading to weakened PLA thermal properties. Pure rice straw began to decompose significantly faster than PLA. The temperature at which the RSP/PLA composite decomposed was typically slightly lower than that of pure PLA. Therefore, a slightly faster rate of decomposition was caused by a higher fiber amount. Yang & Yeh [108] analyzed wood/PLA composites by using differential scanning calorimetry (DSC). The results reveal that, for each sample, the T_g of PLA was around 60 °C during the second heating phase. By adding wood fibers to PLA, a second heating subsequently produced a cold crystallization exothermic within 90–110 °C. In the meantime, two melting peaks were identified at 140 °C and 147 °C based on the wood/PLA filament DSC curve. The initial peak related to the melting of crystals of varied sizes created by the conformational purity of PLA matrix and chain

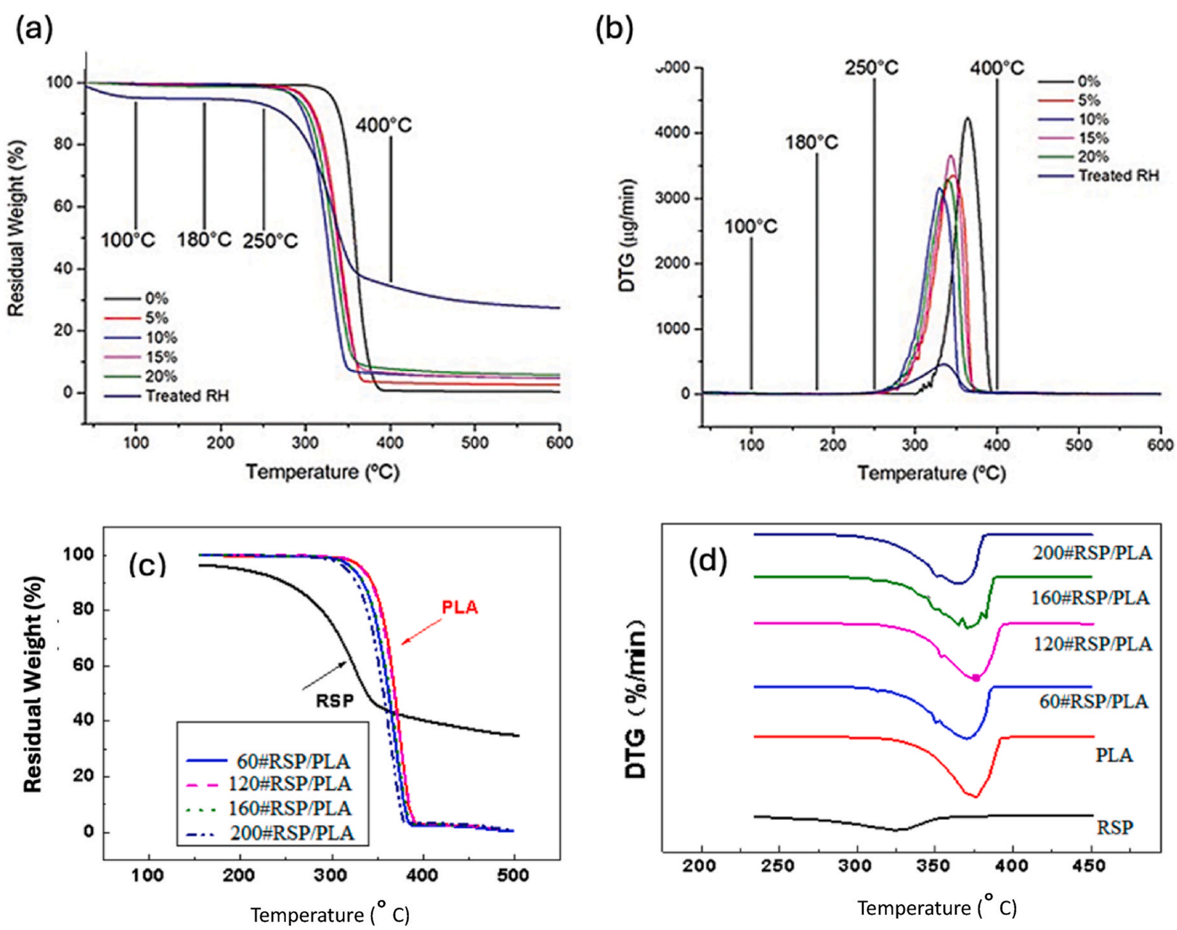

Fig. 10. (a) TGA (b) DTG of rice husk/PLA composite (Pareira et al., 2023) (c) TGA curves and (d) DTG curves for samples at 20 K/min in a nitrogen atmosphere (Yu et al., 2021).

alignment. Furthermore, not all samples showed evidence of the exothermic crystallization of the PLA matrix after cooling at a rate of 10 °C/min. Therefore, in this research the PLA matrix did not crystallize in the wood/PLA parts because its crystallization rate was too slow to achieve crystal region.

5.3. Physical properties

Natural fibers usually absorb a lot of moisture during processing, which can cause the fiber to swell and lose its dimensional stability. According to Pereira et al. [90], adding rice husk fibers to PLA had a negative impact on the printed parts' density and absorption of water. The findings indicated that 5 wt% rice husk samples absorbed more water than 10 wt% rice husk samples. This difference in water absorption percentage was associated with uneven fiber dispersion along the filament. Furthermore, printing flaws within the part could have caused voids that served as extra water storage areas. Although the data showed that the composites absorbed more water than pure PLA, printing flaws could be the cause of variations in absorption between 5 wt% and 10 wt % rice husks. According to the study by Yu et al. [76], as shown in Fig. 11, the water absorption (%) of rice straw/PLA composites increased as the immersion time increased. The water absorption evaluation on the composite specimens revealed that each of the 3D-printed specimens with different pretreatments of rice husk considerably differed from each other such as alkaline solution and ultrasonic wave. A reduction in porosity and voids between filaments in the 3D-printed samples could potentially be demonstrated by the pretreatment of rice husk. A prolonged submersion in water can fill these gaps with water, increasing the amount of water that entered the specimens.

Mohammed et al. [109] found that, as Fig. 12 illustrates, a variety of internal factors influence the water absorption capabilities of natural fiber composites. Natural composite properties, fiber loading and alignment, fiber-matrix interaction, matrix type, surface area of the composites, void presence, humidity, lumen size, and temperature of the immersing media are some of these factors. Furthermore, the composites' surface has an impact on how well they absorb water. Fickian diffusion is a process that encapsulates the overall water absorption characteristics of composites, as reported by Azka et al. [110]. According to Fick's law, the absorption of the natural fiber composites can potentially be ascertained using Eq. (1) [111].

$$\frac{M_t}{M_\infty} = kt^n \tag{1}$$

Where k and n are the diffusion kinetic parameters, k also is the slope of

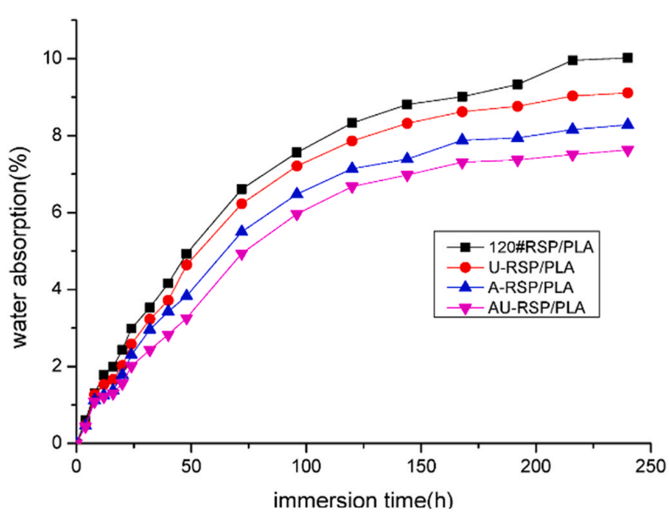

Fig. 11. Water absorption curves for unmodified and modified rice straw/PLA composites (Yu et al., 2021).

the $Mt/t^{1/2}$, M_t is the water absorption at time (t), and $M\infty$ is the sample's equilibrium moisture content. Diffusion governed the water absorption in the early stages. The Fickian law of diffusion governs the water absorption if n is 0.5. The highest possible water absorption and the diffusion coefficient (D) related to the mass gain., M_t can be calculated by two equations, if $\frac{M_t}{M_\infty} < 0.6$ using Eq. (2). If $\frac{M_t}{M_\infty} > 0.6$, the absorption curve is determined by Eq. (3) [111]. Where h is the thickness of the composite and D is the diffusion coefficient. Eq. (4) could be used to determine the D.

$$\frac{M_t}{M_\infty} = \frac{4}{h}\left(\frac{D}{\pi}\right)^{1/2} t^{1/2} \tag{2}$$

$$\frac{M_t}{M_\infty} = 1 - exp\left(-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right) \tag{3}$$

$$D = \pi\left(\frac{kh}{4M_\infty}\right)^2 \tag{4}$$

Ayrilmis et al. [82] observed that after 28 days of immersion in water, the water absorption of specimens (wood/PLA composite) rose significantly when the layer thickness was increased from 0.05 mm to 0.3 mm. The porosity of the samples increased as the printing layer thickness rose, leading to higher water absorption. When the thickness of the printing layer rose, the gaps between the filaments in the printed samples also increased. A further explanation was that as the thickness of the printing layer increased, a greater surface area containing wood flour was in contact with water. The wood/PLA filament contained a natural hydrophilic material with a high amount of hydroxyl groups in its molecular chains. The free hydroxyl groups in cellulose and hemicellulose create hydrogen bonds that attached to water molecules. This led to greater water absorption for samples with a larger surface area.

Several studies have proposed different strategies to mitigate the water absorption tendency of natural fiber composites. Chemical treatments such as alkali, silane, and acetylation effectively reduce the hydroxyl groups on fiber surfaces, improving interfacial adhesion and lowering moisture uptake. The use of coupling agents and compatibilizers enhances the fiber–matrix compatibility, while surface coatings and hybridization with synthetic or less hydrophilic fibers further improve dimensional stability. These approaches collectively contribute to enhancing the long-term performance of natural fiber composites by minimizing moisture-induced degradation [105,112].

6. Challenges and prospects

Although natural fiber–reinforced composites (NFRCs) have shown great potential in additive manufacturing (AM) due to their biodegradability, low cost, and favorable mechanical-to-weight ratio, several critical challenges still hinder their widespread adoption and industrial scalability. Firstly, for fiber dispersion and agglomeration achieving uniform fiber dispersion remains one of the primary challenges in composite filament and feedstock preparation. Natural fibers tend to agglomerate due to hydrogen bonding and van der Waals forces, leading to uneven distribution within the polymer matrix. This poor dispersion results in localized stress concentration and diminished mechanical performance. High fiber loading, irregular fiber geometry, and insufficient compounding efficiency exacerbate this issue. Twin-screw extrusion and optimized screw designs have been reported to improve fiber dispersion, but they also risk fiber length degradation, which affects reinforcement efficiency. Secondly, the challenges fot water absorption and dimensional stability of natural fiber composites are the presence of hydroxyl groups in cellulose, leads to excessive moisture absorption. This moisture uptake compromises fiber–matrix adhesion, promotes swelling, and reduces long-term mechanical stability. Surface modification methods such as silane, alkali, acetylation, and maleic anhydride coupling are effective but may increase production costs and processing

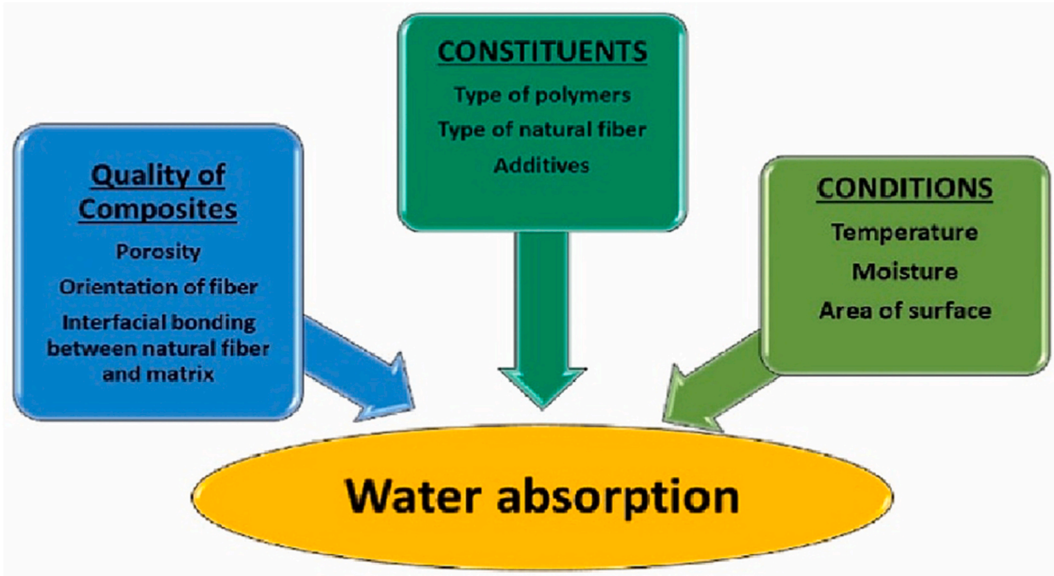

Fig. 12. Influence of water absorption on the efficiency of natural fiber composites (Mohammed et al., 2023).

complexity. Future approaches may integrate nanocoatings or plasma treatments to achieve long-lasting hydrophobicity without compromising biodegradability. Thirdly, maintaining consistent flow is difficult when incorporating fibers. Print head clogging occurs frequently due to fiber entanglement, irregular fiber aspect ratios, and poor melt homogeneity. Inadequate rheological control during printing also leads to nozzle pressure fluctuations and print defects. To overcome these challenges, recent studies emphasize optimizing fiber length (<0.5 mm), using coupling agents to enhance flow compatibility, and employing temperature-controlled nozzles or screw-assisted print heads for stable extrusion performance. Despite these challenges, NFRCs hold strong promise for sustainable manufacturing. Advancements in fiber surface engineering, hybrid composite formulations, and machine learning–based process optimization are expected to significantly improve printability and mechanical performance. The integration of digital process monitoring and closed-loop extrusion control systems can further enhance consistency. Moreover, combining natural fibers with nanofillers (e.g., nanocellulose, graphene, or clay) can improve barrier, thermal, and mechanical properties while maintaining biodegradability. In the long term, developing fully bio-based and recyclable composite systems aligned with circular economy principles will be the key driver for commercialization and adoption in industrial AM applications.

7. Conclusion

According to reviews conducted on mechanical, thermal and physical properties of natural fiber reinforced thermoplastic composite, it can be concluded that.

i. A low density, good mechanical properties, recyclable quality, and high strength are all characteristics of these natural fibers that make them ideal for use as reinforcement in composites. Therefore, the natural fiber with thermoplastic materials could potentially contribute to good impacts on the environment and enhance the mechanical properties of materials. Natural fibers are abundantly available in the tropical regions of developing countries, such as South America, Africa and Asia. Mostly, these fibers are used for conventional purposes. Because of this, it is necessary to discover cutting-edge application technology such as fused deposition modeling (FDM) to further develop their economies and achieve the potential to become the production center for natural fiber goods.

ii. Increasing of the fiber content in NFRCs is required to achieve maximized mechanical performance. On the other hand, it was found that an excessive quantity of fiber led the deposition heads to become blocked and an increase in the brittleness of the feedstock. Consequently, it is of the utmost importance to have a comprehensive grasp of the impact that natural fibers and the characteristics that they possess have on the rheological properties of polymer matrices.

iii. The properties of the fabricated filament will influence the feedability and must have a low ductility and enough stiffness, so that it avoids being crushed and avoid buckling by feeding rolls. The filaments must be of suitable diameter to keep a consistent supply of material at the printer nozzle while feeding filaments during printing. Meaning that, a comprehensive study on a fabricated filament is needed to confirm its performance in terms of the printability, strength, dimensional stability, and porosity. Different process parameters, e.g., printing temperature, speed, build orientation, raster orientation, layer thickness, and infill density will affect the performance of the final parts or products.

iv. It is critical to understand how fibers and fillers affect the mechanical characteristics of the polymer matrix when the composite materials are created as feedstock for FDM-3D printers. The thermal degradation behavior of natural fibers must be assessed, based on their composition and structural characteristics, and must be improved before they can be used to manufacture NFRCs with desired mechanical performance. In addition, natural fibers often have a high capacity to absorb moisture, which can cause the fibers to expand and lose their dimensional stability when they are stored or after they have been processed.

v. Natural Fiber Reinforced Thermoplastic Composites (NFRTC) hold great promise for advancing sustainable Fused Deposition Modeling (FDM) applications. However, significant research gaps and challenges must be addressed, including achieving consistent fiber dispersion, enhancing fiber-matrix bonding, and overcoming variability in natural fiber properties. Optimizing single and dual stage compounding processes is also essential to improve material performance and printability. By addressing these limitations, NFRTC can contribute to producing eco-friendly, high-performance 3D printed parts. Future research should focus on developing standardized processing techniques and evaluating long-term recyclability to fully unlock the potential of NFRTC for industrial-scale FDM.

vi. Although natural fiber composites show strong potential for industrial applications in automotive, construction, and consumer products, several challenges still hinder full-scale industrialization. These include the variability of fiber properties due to natural origin, moisture sensitivity, poor interfacial bonding, and the lack of standardized manufacturing protocols. Furthermore, issues such as limited fiber supply chains, higher preprocessing costs, and concerns about long-term environmental durability and recyclability remain critical. Addressing these challenges through process optimization, fiber modification, and sustainable design approaches is essential to enhance the industrial feasibility of natural fiber composites

Overall, the results confirm that appropriate control of printing parameters is crucial for optimizing the performance of fiber–reinforced composites fabricated through FDM. However, several research gaps remain that warrant further investigation. Future studies should focus on the influence of different fiber surface treatments and compatibilizers on the interfacial adhesion between natural fibers and thermoplastic matrices. Additionally, the optimization of multi-fiber or hybrid reinforcement systems could provide improved mechanical stability and reduced anisotropy in printed parts. Further exploration into predictive modeling, including machine learning approaches, may also help establish correlations between printing parameters, porosity, and mechanical properties. Finally, expanding the study to include dynamic mechanical, thermal, and long-term durability analyses will provide a more comprehensive understanding of the structural behavior of FDM-printed green composites.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Author contribution

Conceptualization, Mohd Nazri Ahmad; methodology, Mohd Nazri Ahmad; software, Mohd Nazri Ahmad; validation, Mohd Nazri Ahmad; formal analysis, Mohd Nazri Ahmad; investigation, Mohd Nazri Ahmad; resources, Mohd Nazri Ahmad; data curation, Mohd Nazri Ahmad; writing—original draft preparation, Mohd Nazri Ahmad; writing—review and editing, Mohd Nazri Ahmad and Mohamad Ridzwan Ishak; visualization, Mohd Nazri Ahmad; supervision, Mohamad Ridzwan Ishak; project administration, Mohd Nazri Ahmad; funding acquisition, Ahmad Shah Hizam Md Yasir.

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Declaration of competing interest

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