DE GRUYTER Science and Engineering of Composite Materials 2024; 31: 20220238

Review Article

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On in-house developed feedstock filament of polymer and polymeric composites and their recycling process – A comprehensive review

https://doi.org/10.1515/secm-2022-0238
received September 06, 2023; accepted January 17, 2024

Abstract: In the last few decades, tremendous effort is given to the production of various polymers and polymeric composites components through innovative polymer processing techniques. Fused deposition modeling (FDM) of polymers as a printing technique in additive manufacturing has been explored extensively due to its cost-effectiveness, manufacturing capabilities, flexibility in material selection, and dimensional accuracy. A few reviews of the literature have been done to investigate various applications for polymers, but none have focused on the research on commercial and in-house generated polymers and polymeric composites, particularly those made using the FDM printing technology. Consequently, the study data on the internal development of polymer and polymeric composite filament-based FDM printing is gathered and processed in this work. The work also highlights various types of polymeric composites and recycled polymeric composites with their detailed material characteristics. In addition, various applications of FDM printing of polymeric composites at the industrial scale and domestic level usage are highlighted as the potential to reduce carbon emission through the effective recycling process.

Keywords: polymer, polymeric composites, recycling, mechanical properties, fillers, nano particle reinforcement, FDM printing, additive manufacturing

1 Introduction

The demand for sustainable materials and manufacturing practices has increased over the years with the application of virgin as well as recycled polymers and composites in fused filament fabrication process printing, which emerged as a promising solution. Fused deposition modeling (FDM) printing that has been used extensively for polymer processing and characterization over the last decade. We will examine recent developments in the in-house development of feedstock filaments based on virgin polymer as well as polymeric composites in this literature survey. The research will also include a literature review on the recycling of polymers and composites in 3D printing *via* the FDM route. Due to its promise for faster and more efficient manufacture of parts with complicated geometries, FDM printing, also known as 3D printing for polymers, has gained interest in a variety of industrial areas. Polymers are a key material used in additive manufacturing (AM), and they can be processed using multiple FDM input settings to make functional components. However, the applicability of polymers for 3D printing is quite selective, so polymers must be classified based on their properties. We will address the classification of polymers used in AM based on their chemical structure, thermal characteristics, and mechanical properties, as well as their applicability to various AM processes, in this section of the literature review. Figure 1 shows the classification based on different criteria for commercially available polymers.

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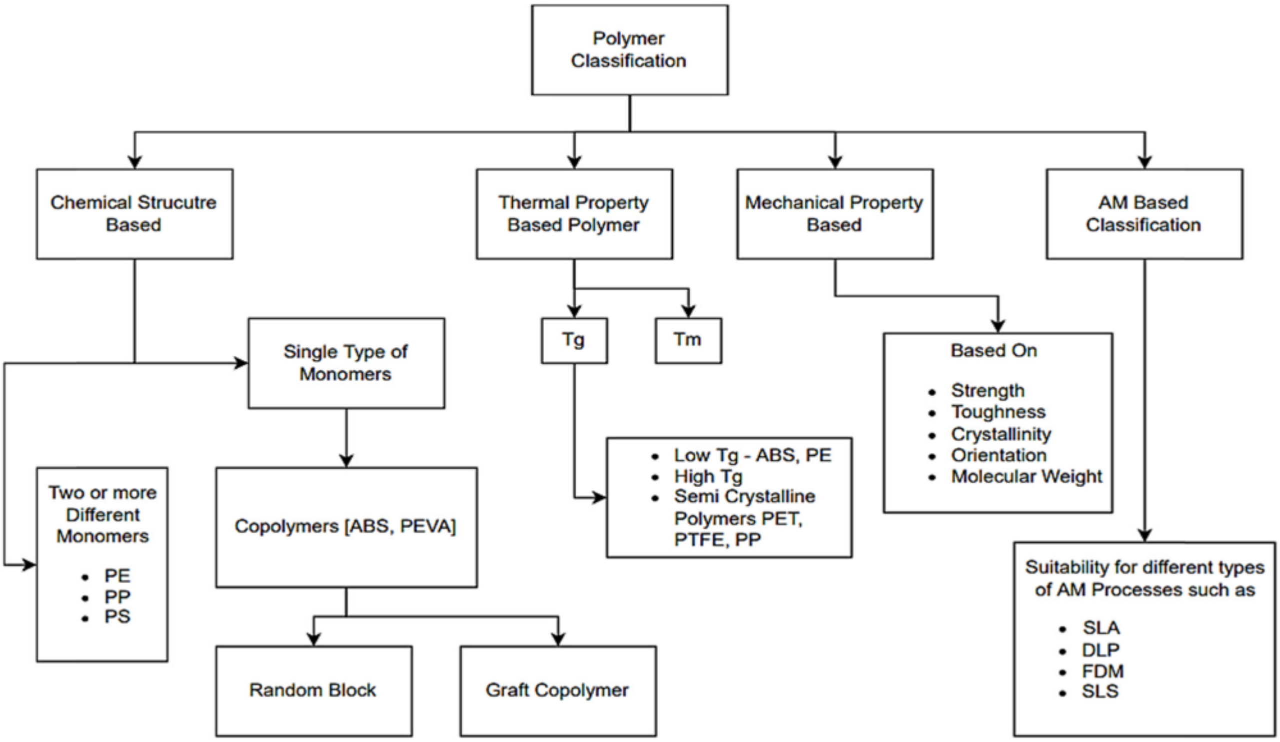

Figure 1: Classification based on different criteria for commercially available polymers.

1.1 Classification based on chemical structure

The chemical structure is primarily determined by the monomers used in their synthesis [1]. For instance, homopolymers consist of a single type of monomers viz polyethylene, polypropylene (PP), and polystyrene (PS). Copolymers, on the other hand, are composed of two or more different monomers, and they can be further classified on the arrangement of monomer units along the polymer chain, for example, random, block, and graft copolymers [2]. Another important class of polymers used in AM is thermoplastic elastomers, which are copolymers with both elastomeric and thermoplastic properties [3,4].

1.2 Thermal property-based classification

The thermal properties of polymers have a direct impact on processing and printing behavior on the FDM platform. Thermal-based classification for the polymers grades polymers into different classes. They have been classified based on their glass transition temperature (T_g) and melting temperature (T_m) [5], which determine their stiffness and flow behavior, respectively. For instance, amorphous polymers such as PS [6] and acrylonitrile-butadiene-styrene (ABS) [7] have low T_g values and exhibit good ductility and toughness, making them suitable for FDM printing. Semi-crystalline polymers, on the other hand, have higher T_g and T_m values and exhibit more rigid and brittle behavior [8], but they can be printed using SLS or SLA techniques. In addition, some polymers exhibit thermal degradation during the printing process, which can lead to the release of toxic gases or cause defects in the printed parts. Therefore, it becomes crucial to consider the thermal stability when selecting them for AM [9].

1.3 Classification based on mechanical properties

As for the thermal properties, the mechanical properties have an important say in deciding the application and the role of the selected polymer [10]. Therefore, the mechanical property-based classification may be one of the important criteria for the selection and the application of the selected polymer. Tensile strength, rheological (time–temperature depending) stress–strain behavior (toughness, elasticity, plasticity, and combinations), and flexural strength are some of the mechanical characteristics that decide the polymer selection – on particle scale as well as on product scale, during fabrication or in the final state. For instance, polyethylene terephthalate glycol (PETG) [11] and polylactic acid (PLA) [12] exhibit good strength and toughness, making them suitable for functional parts due to their high molecular weight. However, the specimen manufactured through the FDM route may have slightly different strength due to processing conditions of FDM setup such as use of raster angle, number of perimeters, nozzle angle, and infill pattern. In addition, some polymers can be reinforced with fillers such as carbon fiber [13,14], glass fiber [15,16], or nanoparticles [17,18] to enhance their mechanical properties. Previous studies have shown that superior mechanical properties can be achieved for the composite polymers if reinforced with fine-grade metallic and nonmetallic powders such as carbon fiber reinforced polymers (CFRPs) and carbon nanotube (CNT)-reinforced polymers in comparison to their unfilled counterparts [19], making them suitable for applications that require high strength and stiffness [20].

1.4 AM technique-based classification

Many studies have classified polymers based on their usage in AM processes. FDM, SLS, and SLA are some of the most commonly used AM techniques, each of which has specific requirements for the polymer properties. For instance, FDM requires polymers with good melt flow characteristics and low viscosity to ensure smooth extrusion and layer adhesion [21]. ABS, PLA, and PETG are some of the commonly used polymers for FDM due to their low viscosity and good adhesion properties [22]. SLS, on the other hand, requires polymers with good powder flowability and thermal stability, such as polyamide and polyetherimide, which can be sintered at high temperatures without degradation [23]. SLA, which uses a photopolymer resin that solidifies upon exposure to UV light, requires polymers with good photopolymerization properties and low shrinkage, such as epoxy and acrylic resins [24]. So, in a more general way, also the mechanism of bonding or connecting single components can be used for differentiation or classification.

2 Polymeric composites developed on a lab scale

The last decade has seen a tremendous surge in the development of reinforced composites of polymers. Many studies have been performed that highlighted the use of different types of fillers in polymer matrices for the preparation of polymeric composites.

2.1 Natural fiber-reinforced polymers

The utilization of natural fibers in polymer composites, like sisal, jute, flax, hemp, and bamboo [25], has been on the rise because of their favorable mechanical characteristics, affordability, biodegradability, and renewable nature. Natural fibers' mechanical qualities are influenced by their structure, kind, and processing [26]. Prior research has demonstrated the impact of print orientation on natural fiber-reinforced composites. Specifically, in the axial direction, the samples exhibited enhanced mechanical performance. Conversely, the mechanical characteristics are adversely affected by deposition in the transverse direction. This anisotropic behavior is comparable to naturally grown material like timber, in some way longer taking biological additive producing procedure. Researchers have incorporated natural fiber reinforcements by using woven fabrics, mats, chopped fibers, and microfibers in polymeric composites. Numerous factors such as the type of fiber, fiber orientation, fiber content, matrix material, and processing technique influence the mechanical properties of the resulting composite. Several studies have investigated the use of natural fiber-reinforced polymers in FDM printing [27–29]. To create components with better mechanical qualities, these studies have concentrated on optimizing the processing parameters such as extruder temperature, printing speed, and layer thickness.

In a study by Oksman *et al.* [30], flax fibers were added to PP and PLA filament. According to the study, PLA has improved by 50% over virgin PLA. When combined in a 30 to 40 wt% ratio, PLA/flax fiber composites have demonstrated strength comparable to that of PP/flax fiber. In another study by Vaucher *et al.* [31], for FDM printing, PLA filament was mixed with jute fibers. The results of the investigation indicated that the printed samples' increased mechanical strength was improved by the addition of jute fibers. Investigators concluded that increasing the mechanical strength of the samples by 76% can be achieved by adding a 15% wt% of jute fiber to the PLA matrix. In a study by Tokoro *et al.* [32], bamboo fibers were incorporated into PLA filament for FDM printing. The reinforcement of bamboo fibers has led to no significant change in the mechanical performance of the specimens for long lengths of BF. However, for medium length, BF improved the impact resistance.

In a study by Asaithambi *et al.* [33], sisal fibers were incorporated into PLA filament for FDM printing. The study reported the successful reinforcement of 30 wt% of sisal fiber in PLA, which improved the tensile strength along with the Young's modulus of the specimens. In a study by Durante *et al.* [34], broom and hemp fiber were incorporated into ABS filament for FDM printing. The results of the investigation show that the samples' mechanical strength increased by two times when compared to pure ABS. The main problem with incorporating natural fiber into the ABS matrix, according to the authors, is that the fibers do not adhere to the matrix well and are not distributed evenly throughout the composite matrix. In a study by Chow *et al.* [35], sisal fibers were incorporated into the PP filament for FDM printing. The moisture content exposure to the PP/sisal fiber composite has reduced the mechanical strength of the samples but improved the impact strength. In a study by Le Digou *et al.* continuous flax fibers [36] were incorporated into PLA filament for FDM printing. The composite has shown a 4.5 times improvement in tensile strength (maximum tensile stress: 253.7 MPa). The composite has shown excellent strength equivalent to glass fiber/polyimide composites.

In a study by Priselac *et al.*, the PCL/PLA matrix was supplemented with coconut fibers (CF) to prepare feedstock filament for FDM printing. According to the study, the CF/PCL/PLA composites' thermal characteristics have not changed as a result of the FDM printing technique [37]. The authors have observed that CF reinforcement has led to a significant increase in hardness, which became equal to some photopolymers used in printing plate applications.

Chatterjee *et al.* [38] observed that specimens with jute fiber additions ranging from 0 to 10% and varying in plies within the polymeric matrix had superior mechanical strength. The best results have been seen in two-layered polymeric composites of PP and jute fiber; however, additional laminating layers of jute ply in PP weaken the material.

In a study by Shahar *et al.* [39], to apply the suggested composite for ankle-foot orthoses, kenaf fibers were added to PLA filament for FDM printing. Fillers made of kenaf fiber were added to PLA in wt% of 3, 5, and 7. The impact and fatigue strengths of the composite improved dramatically throughout its rising number of life cycles, the researchers discovered, with the increased loading of Kenaf fiber. With an impact strength of 3.19 kJ/m^2, the composite matrix with the 3 wt% addition of kenaf fibers has proven to be the best among the selected matrixes. Pineapple leaf fibers were incorporated into the PLA filament by Suteja *et al.* [40] for FDM printing. The researchers found that the addition of pineapple leaf fibers improved the tensile strength up to 101.3 MPa, which was 63–65 MPa for neat PLA. The study found that the ideal parameters for FDM printing of a particular composite material matrix consisting of PLA/pineapple leaf fibers were an extrusion temperature of 210°C and a feed rate of 15 mm/s.

In a recent study by Paulo *et al.*, flax fibers were incorporated into PLA filament for FDM printing [41]. The PLA's tensile strength has decreased as a result of the flax fiber reinforcement, going from 50 MPa for neat PLA to 43 MPa for PLA/Flax fiber. However, the test results indicated that the composite's bending strength had improved, recording 73 MPa of strength as opposed to 53 MPa for plain PLA bending strength. In a study by Wang *et al.* [42], BF has been incorporated into PLA filament for FDM printing. The BF has shown a positive impact on the tensile strength and modulus of the composite. The researchers also investigated the effect of printing parameters, and it has been observed that higher extruder temperature and lower printing speed resulted in higher mechanical properties.

In a study by Dunne *et al.* [43], composites made of sisal and kenaf fibers were created by employing an ABS/acetone-based binder. The highest tensile strength of the 30% kenaf and 70% sisal fibers is 305.93 kPa, whereas the 100% sisal fiber has a tensile strength of 600 kPa. In addition, it has been noted that the optimal composite ratio – 30 wt% kenaf and 70 wt% sisal fiber – had a higher tensile strength than kenaf fiber alone (279 kPa).

Figure 2(a) shows the NFRP composites used in FDM printing. Figure 2(b) shows the plot for the percentage improvement in mechanical properties for different material composites developed in-house.

From the literature review of natural fiber-reinforced materials, it has been observed that researchers have added natural fibers to polymeric composites in several ways, including woven fabrics, mats, chopped fibers, and microfibers. The mechanical characteristics of the resulting composite relied on several variables, including type, orientation, content, matrix material, and processing method. Numerous studies have examined the application of these composites in FDM printing, with a focus on optimizing parameters such as extruder temperature, printing speed, and layer thickness to enhance mechanical properties. Further, the addition of natural fibers to polymer matrices for FDM printing, such as flax, jute, bamboo, sisal, coconut, and kenaf, has been the subject of numerous investigations. The results are different for every combination of fiber–matrix and loading ratio. These investigations shed light on the individual effects of various fiber materials on the mechanical properties of printed objects and highlight the potential of natural fiber-reinforced composites for FDM printing. Subsequent investigations may concentrate on refining the printing parameters to augment the mechanical properties of these composite materials. Further research on the long-term robustness and environmental sustainability of natural fiber-reinforced composites produced using FDM printing may also prove to be a worthwhile endeavor.

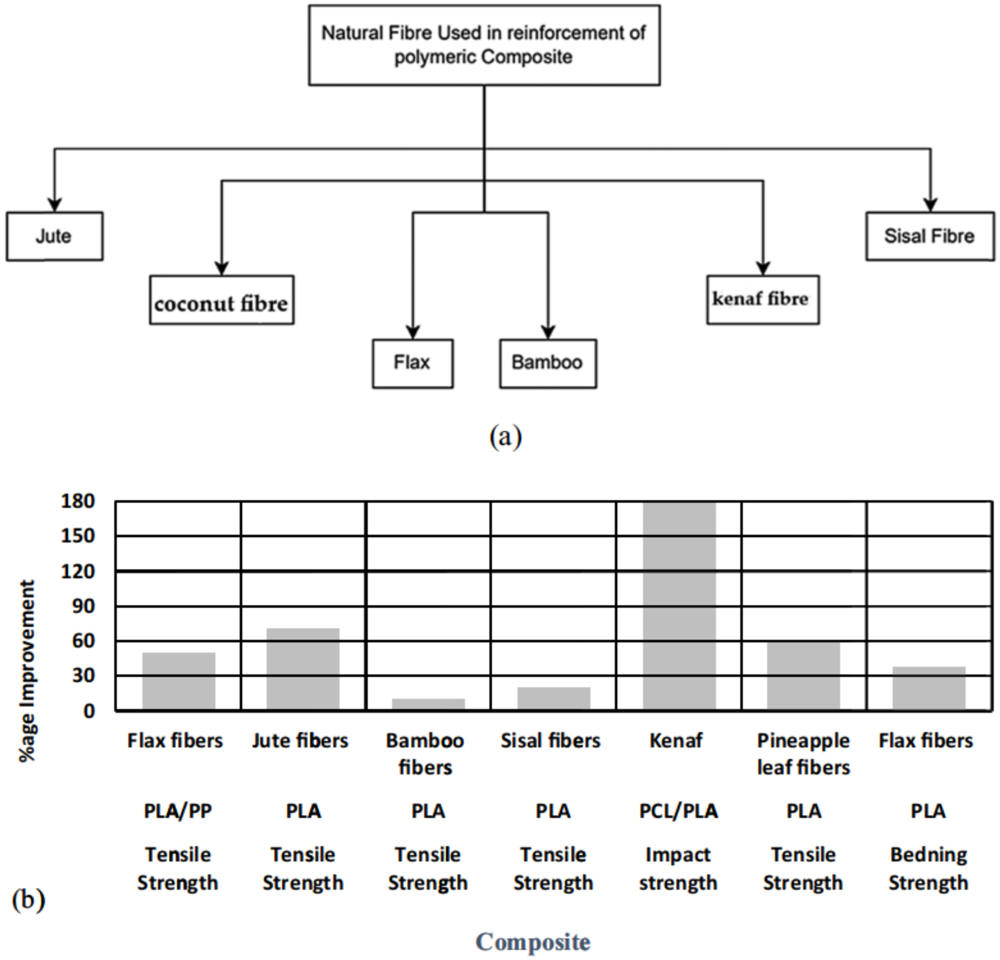

Figure 2: (a) NFRP composites used in FDM printing. (b) Plot for the percentage improvement in mechanical properties for different material composites developed in-house (in comparison to virgin polymer).

2.2 Synthetic fiber-reinforced polymers in FDM printing

FDM printing employs thermoplastic filaments as feedstock, which are heated and extruded layer by layer to form complex 3D geometries. FDM-printed parts are known for their high strength, durability, and accuracy. However, FDM-printed parts may exhibit certain limitations such as poor surface finish, low interlayer adhesion, and limited mechanical properties. Synthetic fiber-reinforced polymers (synthetic-FRPs) have been investigated as a potential solution to overcome these limitations. This literature review aims to explore the current state of the research on synthetic FRP in FDM printing and its impact on the mechanical properties and surface finish of FDM-printed parts.

Synthetic fibers are commonly used in composites to enhance the mechanical properties of polymers. The most commonly used synthetic fibers in composites are glass, carbon, and aramid fibers [44–46]. These fibers have high tensile strength, modulus of elasticity, and so on, which makes them ideal for reinforcing polymers [47,48]. The choice of fiber depends on the desired mechanical properties of the composite, the processing method, and the financial budget. Synthetic fibers can be added to polymers using different methods such as melt blending, solution blending, and *in situ* polymerization. The most commonly used method for synthetic-FRP production is melt blending, which involves mixing the synthetic fibers with the polymer melt before extrusion. The addition of synthetic fibers can improve the mechanical properties of polymers by enhancing tensile strength, modulus of elasticity, and impact resistance.

The synthetic-FRP has been investigated as a potential solution to improve the mechanical properties and surface finish of FDM-printed parts. The strength and rigidity of the printed items can be increased, warpage can be decreased, and interlayer adhesion can be improved by adding synthetic fibers to the polymer matrix. Numerous research studies have looked into how adding various kinds and quantities of synthetic fibers affects the mechanical characteristics of items that are printed using FDM technology. One of the most commonly used synthetic fibers in FDM printing is carbon fiber due to its high strength and stiffness. CFRPs [49] have been shown to significantly improve the mechanical properties of FDM-printed parts. For instance, Chaudhry *et al.* examined the impact of varying carbon fiber addition levels on the mechanical characteristics of FDM printed items. The outcomes demonstrated that the printed parts' tensile strength and modulus of elasticity were enhanced by the addition of carbon fibers [50]. However, the addition of too many carbon fibers resulted in decreased ductility and impact resistance.

Other synthetic fibers that have been investigated in FDM printing include glass fibers and aramid fibers. Glass fiber-reinforced polymers (GFRPs) have been shown to improve interlayer adhesion and reduce warpage [51] in FDM-printed parts. Aramid fiber-reinforced polymers (AFRPs) [52] have also been investigated in FDM printing and have been shown to significantly improve the mechanical properties of FDM-printed parts.

In addition to improving the mechanical properties of FDM-printed parts, synthetic-FRP has also been investigated for their impact on the surface finish of FDM-printed parts. The addition of synthetic fibers can improve the surface finish of FDM-printed parts by reducing the visibility of the layer lines and improving the overall smoothness of the printed part. Several studies have investigated the effect of adding synthetic fibers on the surface finish of FDM-printed parts [53]. A study conducted by Han *et al.* investigated the effect of adding carbon fibers on the surface finish of FDM-printed parts. The results showed that the addition of carbon fibers reduced the visibility of the layer lines and improved the overall smoothness of the printed part [54]. Similar to this, Kumar *et al.*'s study from 2022 looked into how adding glass fibers affected the surface texture of parts that were produced using FDM. The outcomes demonstrated that the inclusion of glass fibers enhanced the printed items' surface quality and decreased surface roughness. When 30 wt% of short glass fiber was put into ABS, the reinforcement of short glass fibers increased the material's tensile strength by 57% and its impact strength by 57% [55].

The use of fiber-reinforced polymer (FRP) in 3D printing has been investigated by several researchers. According to Edwards, FRP can be used to create high-performance printed parts with improved mechanical properties. The authors note that the use of FRP in 3D printing has the potential to revolutionize the manufacturing industry, as it allows for the creation of complex geometries with improved properties [56]. Cordin *et al.* looked into how fiber orientation affected the mechanical characteristics of FRP used in 3D printing. The tensile strength of the printed pieces was discovered to be significantly influenced by the orientation of the fibers by the authors. In addition, the scientists pointed out that, in comparison to conventional printing materials, the use of FRP in 3D printing enabled the development of parts with increased rigidity and decreased weight. The author found that adding 30% wt% of fiber-enhanced water sorption, which in turn influenced the PP polymer's tensile strength. In addition, the study found that the optimal composite preparation was achieved with 0° of fiber orientation, which is parallel to tensile loading; other angles led to a decrease in E Modulus [57].

The type of fiber used in FRP can have a significant impact on the mechanical properties of the printed parts. Mlynek *et al.* [58], Farokhi Nejad *et al.* [59] investigated the mechanical properties of 3D-printed parts made from FRP with different types of fibers, including carbon fiber, glass fiber, and basalt fiber. The performance of fiber-reinforced plastic composites can be enhanced by using high-strength fibers such as carbon, glass, or aramid fibers [60]. Goh *et al.* looked into the mechanical characteristics of FRP pieces that were 3D printed using glass and carbon fiber. It was discovered that using carbon fiber-reinforced FRP produced parts with a greater modulus of elasticity (12.99 GPa) and tensile strength (600 MPa) than glass fiber-reinforced FRP (450 MPa and 7.20 GPa) [61].

The optimization of printing parameters can also have a significant impact on the mechanical properties of printed parts. In a study by Dou *et al.*, the effect of printing factors on the mechanical properties of FRP in 3D printing was examined by the authors. These parameters included printing temperature, nozzle diameter, and layer height. The authors discovered that pieces with greater stiffness and tensile strength were produced by raising the printing temperature. The scientists also observed that parts with better mechanical qualities (tensile strength: 243.53 MPa) were produced with a smaller nozzle diameter and a thinner layer height (0.2 mm), while parts with a larger layer width (0.4 mm) had a lower mechanical strength (164.61 MPa) [62]. Kuncius *et al.* investigated the effect of printing parameters on the interlayer adhesion of FRP in 3D printing. The authors found that increasing the printing temperature and reducing the layer height resulted in improved interlayer adhesion along with improved shear strength of the PLA/CF composite [63]. The authors also noted that the use of a higher infill density resulted in parts with improved mechanical properties.

The use of FRP in 3D printing has many potential applications, particularly in industries where high-performance parts are required. Uhlmann *et al.* looked into how various machining methods might be used to manufacture CFRP with an eye toward the aerospace sector. The productivity of machining CFRP composites may be significantly impacted by the high pressure and feed rate used in abrasive water jet cutting, according to the findings of the authors. Moreover, high-quality items might be produced from CFRP composites using CO_2-based jet cutting [64]. Lin *et al.* investigated the use of FRP in the automotive industry. Given its superior mechanical qualities and lighter weight when compared to conventional materials, the authors concluded that FRP was a good material for 3D printing automotive parts, including body panels and engine components [65]. In a 2013 study, Zaman *et al.* looked into the application of FRP in the building sector. The authors discovered that FRP provided better mechanical qualities and lighter weight than standard materials, making it a promising material for 3D printing structural elements in structures, such as beams and columns. The writers have also emphasized several FRP-related concerns in the building sector, including the impact of moisture, outside temperature, and durability challenges [66]. Figure 3(a) shows the synthetic FRP composites used in FDM printing.

Research on synthetic fiber-reinforced polymers (synthetic-FRP) is underway to improve the surface quality and

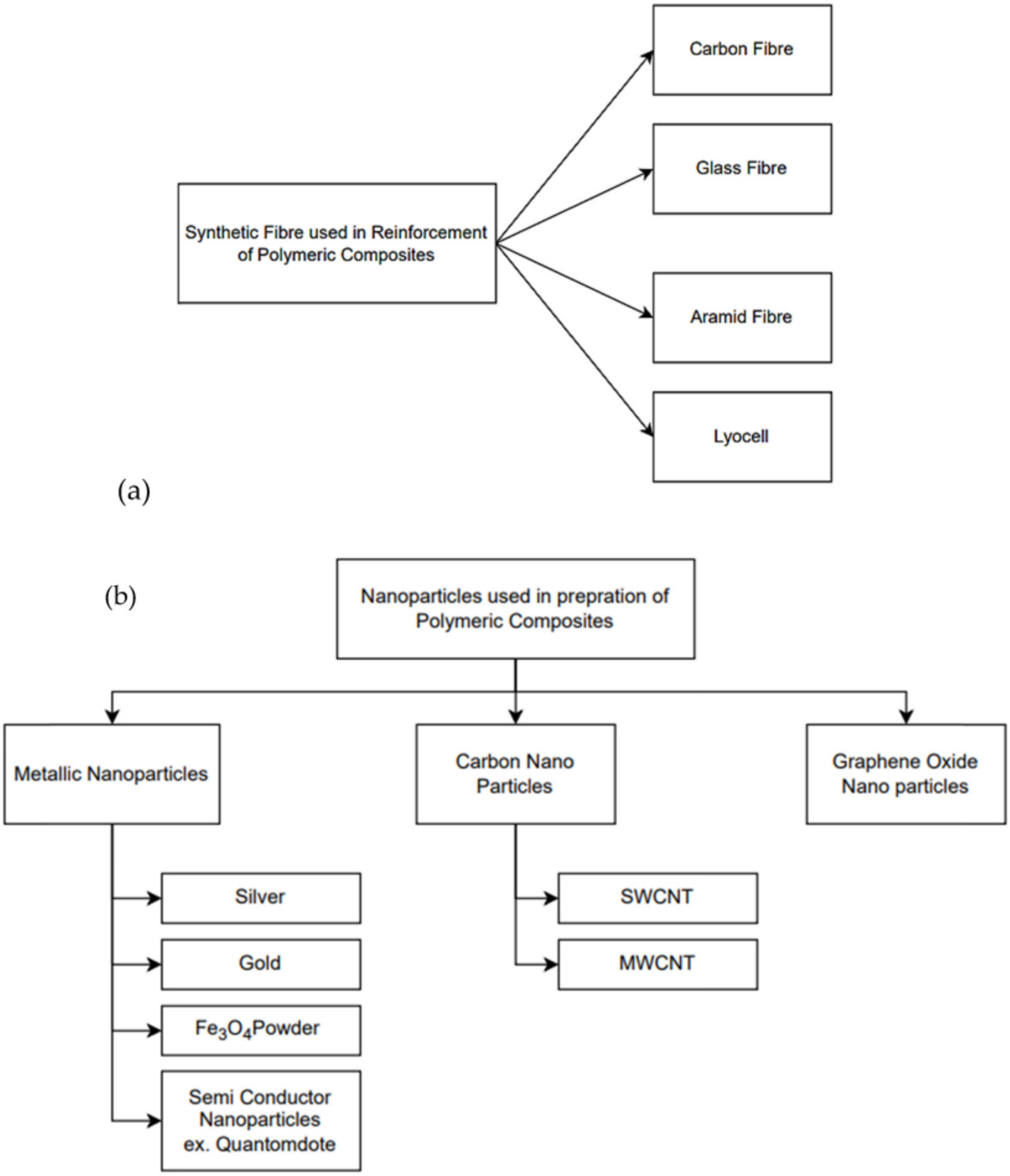

Figure 3: (a) Synthetic-FRP composites used in FDM printing. (b) Nanoparticle-reinforced polymeric composites used in FDM printing.

mechanical characteristics of 3D-printed objects using FDM. If overused, CFRPs can decrease ductility and impact resistance while significantly increasing tensile strength and elasticity. AFRPs greatly improve mechanical qualities, while GFRPs improve interlayer adhesion and lessen warping. Synthetic fibers enhance the surface polish by eliminating obvious layer lines, in addition to their mechanical benefits. Performance can be further enhanced by fine-tuning printing parameters including temperature, nozzle diameter, layer height, and infill density. Synthetic-FRP in 3D printing appears to have a bright future with applications in the construction, automotive, and aerospace industries. For wider usage, issues with moisture sensitivity, durability, and environmental concerns must be resolved. In conclusion, if materials and processes are properly managed, synthetic FRP has a lot of potential for advanced manufacturing.

2.3 Nanoparticle-reinforced polymeric composites

Polymer-nanoparticle composite materials have attracted significant attention in the past few decades due to their unique properties and potential applications in various fields, including electronics, biomedical engineering, and energy storage. The incorporation of nanoparticles into polymer matrices can result in enhanced mechanical, electrical, and thermal properties, as well as improved stability and biocompatibility. In this literature review, we provide an overview of recent research in the field of polymer–nanoparticle composites. Figure 3(b) shows the nanoparticle-reinforced polymeric composites used in FDM printing.

2.3.1 Metallic nanoparticle-reinforced polymeric composites

Various types of nanoparticles, such as metallic, magnetic, and semiconductor, have been investigated for their potential use in polymer composites. Metallic nanoparticles, such as silver and gold, have attracted significant attention due to their unique antimicrobial properties. According to a study by Podstawczyk *et al.*, the PLA matrix enhanced with silver nanoparticles has demonstrated both antimicrobial and 3D printable qualities. Additional research has revealed that the addition of silver nanoparticles to PLA material resulted in only slight modifications to its bulk properties [67]. Furthermore, the optical characteristics of the composite are impacted by the gold or silver nanoparticles. Due to the impact of metallic nanoparticles on optical characteristics, which have been demonstrated to strongly rely on their size, shape, and composition (Barmina *et al.*), metallic nanoparticles are a desirable option for use in plasmonic devices [68]. The potential applications of magnetic nanoparticles, including iron oxide (Fe_3O_4), in nonstructural engineering applications have also been the subject of much research. When iron oxide (Fe_3O_4) and other reinforcements are loaded into PLA matrix at weights ranging from 5 to 20 wt%, magnetic properties are observed; mechanical properties remain similar to those of conventional PLA matrix [69,70]. Several studies these days have worked and explored the 4D behavior of polymeric matrixes. 4D property deals with the fourth dimension 3D-printed specimen, that is, "time," which means the specimen can alter its shape or other properties based on external and internal stimuli. The magnetic properties of these nanoparticles make them attractive for 4D printing especially 3D printing of tiles for arctic regions to replace wood-based products [71–73]. In addition, the incorporation of magnetic nanoparticles into polymer matrices can result in composite materials with unique properties, such as the ability to respond to magnetic fields [74]. Semiconductor nanoparticles, such as quantum dots, have also been investigated for their potential use in polymer composites [75]. These nanoparticles exhibit unique optical properties, such as size-dependent emission spectra, making them attractive for use in optoelectronic devices [76].

The process of *in situ* polymerization is one way to create polymer–nanoparticle composites. With this method, during the polymerization process, nanoparticles are created inside a polymer matrix. When compared to conventional combinations of polymers and nanoparticles, the resultant composite material appears homogenous and can display better qualities [77]. In addition, the use of *in situ* polymerization can also provide control over the size and distribution of nanoparticles within the polymer matrix. For instance, *in situ* polymerization was utilized by Han *et al.* to add carbon nanotube (CNT) to a polyvinyl alcohol (PVA) matrix for supercapacitor application. The resultant composite material showed good electrical (electroconductivity of around 0.44 S/m) and mechanical (tensile strength: 54.8 MPa) characteristics, together with a specific capacitance of 164.6 F/g, indicating that it could be a viable option for use in high-performance energy storage devices. It was discovered through additional life cycle evaluation research that the produced composite can hold 91% of its electrical capacitance for 2,000 cycles [78].

Another approach to producing polymer–nanoparticle composites is through the use of functionalized nanoparticles. Functionalized nanoparticles [79] are coated with a layer of organic molecules, such as surfactants or polymers, which improve their compatibility with the polymer matrix. By using functionalized nanoparticles, the mechanical and electrical properties of the polymer matrix may be improved through better dispersion. For instance, *in situ* polymerization was used by the researchers to create a composite material in a study conducted by Bajpai *et al.* [80] of silver nanoparticles within a polyacrylamide matrix for antimicrobial applications. The resulting composite material showed excellent antibacterial activity against *Escherichia coli*.

Recent research has also focused on the development of biocompatible polymer–nanoparticle composites for use in biomedical applications. McKeon-Fischer *et al.*, for instance, created a composite scaffold consisting of polymers and nanoparticles that can be utilized in tissue engineering. To make a scaffold, the researchers combined poly (L-lactic acid) (PLLA) polymer with gold nanoparticles. The resultant composite scaffold was a strong contender for application in regenerative medicine since it demonstrated outstanding biocompatibility and had the capacity to stimulate cell development. A low reinforcement level (7 wt%) of Au in PLLA may be regarded as the ideal amount of reinforcement because further high loading of Au in the PLLA matrix has no discernible effect [81].

In addition to tissue engineering, polymer–nanoparticle composites have also been investigated for drug delivery applications. Iron oxide nanoparticles in a polyester polymeric matrix were used to create a polymeric composite material for targeted medication delivery in a work by Hamidian *et al.* The composite material is a good option for targeted drug delivery applications because it can release the drug under regulated conditions when exposed to a magnetic field [82].

The literature review on nanoparticles in polymer composites suggested that the nanoparticle composites have unveiled their potential in diverse areas, including antimicrobial properties, optics, magnetism, and optoelectronics. Of particular note are metallic nanoparticles like silver and gold, which possess potent antimicrobial properties. The incorporation of silver nanoparticles into PLA matrices enhances antimicrobial qualities without significantly altering bulk properties. These metallic nanoparticles also impact optical characteristics, offering potential in plasmonic devices. Magnetic nanoparticles, such as iron oxide, introduce magnetism to PLA matrices, making them appealing for 4D printing and specialized applications. Furthermore, semiconductor nanoparticles, like quantum dots, display unique optical features, suitable for optoelectronic devices. The technique of *in situ* polymerization creates homogenous composites, promising enhanced control over nanoparticle distribution. This research hints at exciting prospects, including advanced 3D printing, high-performance energy storage, drug delivery, tissue engineering, and controlled magnetic drug release across diverse sectors.

2.3.2 CNT-reinforced polymeric composites

Carbon nanoparticle composite materials have received significant attention from researchers due to their unique and remarkable properties such as high surface area, excellent electrical conductivity, high mechanical strength, and thermal stability. This literature review aims to provide an overview of the current state of research on carbon nanoparticle composite materials, including their preparation methods, properties, and applications, based on relevant studies published by various authors.

As Soni *et al.* highlight, carbon nanoparticle composite materials have been produced using a variety of preparation techniques. Carbon nanoparticles are added to a polymer solution and agitated to evenly spread the nanoparticles in a process known as solution blending. Melt blending is the process of combining CNT with a molten polymer and then solidifying it [83]. When monomers are polymerized in the presence of carbon nanoparticles, a polymer matrix with nanoparticles scattered throughout is formed. This process is known as *in situ* polymerization. By using an electric field to spin a polymer solution containing carbon nanoparticles, nanofibers are produced [84].

Carbon nanoparticle composite materials possess several unique properties that make them suitable for various applications. Their high surface area-to-volume ratio enables them to be used as effective adsorbents for gases and pollutants [85]. In addition, their excellent electrical conductivity makes them useful in the field of electronics and energy storage. Their high mechanical strength and thermal stability also make them ideal for use in structural and thermal management applications [86].

Mallakpour and Khadem have described the diverse range of applications that carbon nanoparticle composite materials have discovered in many fields. They have been employed as efficient adsorbents for volatile organic molecules, organic contaminants, and heavy metal ions in the environmental field [87,88]. In the energy sector, they have been employed in energy storage devices, including supercapacitors and batteries. In the biomedical field, they have been utilized for drug delivery, bioimaging, and tissue engineering [89]. In addition, they have been employed in various structural and thermal management applications in the aerospace, automotive, and construction industries [90,91].

According to a study by Shin *et al.*, the electrical characteristics of TPU composite are affected differently by the loading of short and long CNT particles in TPU. On the other hand, the longer CNT particle has provided greater electromagnetic shielding (EMI: 42.5 dB) [92]. For numerous bending cycles, the produced composite containing 10% CNT in the TPU matrix has provided EMI shielding values with just slight losses. In certain studies, iron oxide sandwich structures have been coated on carbon fiber and combined with boron nitride/silicone rubber (BN/SR) to improve the structure's electromechanical characteristics [93]. According to a study by Arash *et al.*, a key factor in determining the mechanical properties of PMMA/CNT composites is the aspect ratio of CNT. In addition, it has been noted that the PMMA/CNT composite's elastic modulus increased from 3.9 to 6.85 GPa when the aspect ratio (L/D ratio) of CNT increased from 7.23 to 22.05 [94].

Various studies have highlighted the use of CNT particle reinforcement in various polymers for different range of applications. Carbon nanoparticles are incorporated through techniques like solution blending, melt blending, *in situ* polymerization, and electrospinning. These methods enable the creation of composite materials with diverse structures and properties. The remarkable attributes of these materials open the door to various applications. Their high surface area makes them effective adsorbents for gases and pollutants. Exceptional electrical conductivity is advantageous in electronics and energy storage, while mechanical strength and thermal stability find use in structural and thermal management applications.

In the future, research in this field is likely to focus on enhancing the performance of carbon nanoparticle composite materials for specific applications. Further work may explore novel preparation methods, such as 3D printing, to customize material structures. In addition, optimizing composite properties through the precise control of nanoparticle dispersion and aspect ratios will be a key area of interest. As these materials find applications in diverse sectors, the potential for advancements in environmental, energy, biomedical, and industrial fields is substantial. Moreover, the development of multifunctional composites, such as those with improved electromagnetic shielding and mechanical properties, will continue to be a significant research avenue.

2.3.3 Graphene oxide (GO)-based nanoparticle-reinforced polymeric composites

GO has emerged as a promising material for reinforcing polymer composites due to its unique properties such as high surface area, excellent mechanical and electrical properties, and high chemical stability. The incorporation of GO into polymer matrices leads to enhanced mechanical properties, thermal stability, and barrier properties. In this literature review, we summarize recent developments in the field of GO-reinforced polymer composites, including their preparation methods, characterization techniques, and mechanical, thermal, and barrier properties.

The mechanical characteristics of the resultant composites are greatly enhanced by the addition of GO to polymer matrix. Ryu and Shanmugharaj, for instance, created GO/PP composites by melt blending and reported adding 0.1–5 wt% of GO. The investigation showed that the mechanical properties of PP were significantly influenced by the chain length of the GO particles. When the GO chain length was raised to 18, the tensile strength and modulus improved by 29.4 and 47%, respectively. Similarly, increased loading of GO resulted in the highest mechanical performance of PP-based samples being reported [95].

Liang *et al.* reported that the addition of 0.5 wt% GO and 9 wt% of CF to poly (lactic acid) (PLA) increased the tensile strength and modulus by 73.33 and 231.71%, respectively, compared to pure PLA. However, only CF/PLA has shown improvement in tensile strength by 43% and in tensile modulus by only 128.51% [96]. The thermal stability of polymer composites is further enhanced by the inclusion of GO. According to Wang *et al.* adding 2 wt% graphene nanoparticles (GNP) to PLA raised the degradation temperature by 60°C when compared to pure PLA and also resulted in a heavier residue after thermal degradation (7% increase in remaining residual weight). The study also demonstrated the beneficial effects of GNP reinforcement in the PLA matrix, showing increases in tensile strength of 43.5% and flexural strength of 29% [97].

Similarly, Liu *et al.* used 3-aminopropyltriethoxysilane (APTS) *in situ* polymerization to create GO/polyimide (PI) composite sheets. According to the study, adding 1.5 wt% of GO-APTS reinforcement to the PI matrix greatly increased the PI material's tensile strength (45%) and young modulus (15%). The study also found that adding 1.5 wt% GO-APTS to PI strengthened it and increased its thermal stability [98].

The addition of GO to polymer matrices also improves their barrier properties, such as their water barrier properties. Ma *et al.* prepared poly(vinyl alcohol)/GO composites using *in situ* polymerization. The study has reported that the addition 0.01–0.08 wt% GO reduced the moisture permeability by 78% compared to pure PVA. However, the slight addition of 0.04 wt% of GO particles in PVA has improved the tensile strength to 50.8 MPa from 42.3 MPa of the PVA material matrix [99]. Similarly, Upadhyay *et al.* synthesized GO/high-density polyethylene (HDPE) composites by melt blending. Their findings indicated that the incorporation of 3 wt% GO enhanced the mechanical strength (20 MPa for tensile strength and 600 MPa for elastic modulus) and elongation capacity of the HDPE by 70%. The study's *in vitro* examination revealed that the HDPE/GO (3 wt%) composite's stated metabolic activity makes it suitable for usage as a substrate for cell growth [100].

Wang *et al.* (2021) have prepared 9.6 wt% GO reinforced/polyethylene glycol (PEG) as phase change material composites using solution blending. The study has reported increased thermal conductivity by up to 111% and resistance peak decreased by 33.4% [101]. Similarly, Abdullah and Ansari in 2015 observed infusing 1.5–6% GO by volume to epoxy resin. The study concluded that when the composite's brittleness significantly increased, epoxy's impact strength reduced. Maximum Young's modulus of 206 MPa has been noticed for 6 vol% of GO composite with maximum percentage elongation of 65%, while maximum tensile strength of 13 MPa was noticed for reinforcement level 1.5 vol% of GO in epoxy resin [102].

It has been observed that the addition of GO increases the toughness of polymeric composites, which is an important feature of polymeric materials. For instance, Zhang *et al.* used the freeze-thaw approach to generate GO/poly (vinyl alcohol) (PVA) composite-based hydrogel for biomedical applications. According to the study, adding 0.8 wt% of GO to the PVA matrix enhanced the compressive strength by 36% and the tensile strength by 132%. However, the toxicity value of PVA has not changed despite the addition of just 0.8 wt% GO [103].

Due to its exceptional qualities, such as its high surface area, mechanical strength, electrical conductivity, and chemical stability, GO is becoming more and more recognized for its role in strengthening polymer composite components. The review's summary of recent studies shows how GO can greatly improve the mechanical properties of these composites, leading to impressive increases in modulus and tensile strength. Furthermore, by increasing the temperature at which polymer composites degrade and improving mechanical strength, GO helps to improve thermal stability in these materials. GO also strengthens the tensile strength and decreases moisture permeability, improving the barrier qualities of polymers, particularly with regard to water resistance. Moreover, the addition of GO strengthens polymer matrices, rendering them appropriate for a range of uses, such as serving as growth substrates for cells. This study topic has a bright future ahead of it, with possible applications in a wide range of industries, including biomedical, automotive, and aerospace. The next phase is likely to concentrate on improving synthesis techniques and boosting manufacturing to make them more useful. With improved performance in heat regulation, barrier qualities, and structural integrity, graphene-based composites seem ready to transform materials science. Continued research and useful application are expected in the next years.

3 Reuse of polymers in FDM printing

In recent years, 3D printing using fused deposition modeling (FDM) has become increasingly popular for rapid prototyping and manufacturing. However, the widespread adoption of FDM printing has also led to a rise in plastic waste generated from failed prints, support structures, and other byproducts of the printing process. To address this issue, many individuals and organizations have turned to reusing polymeric materials for further use in FDM printing. This not only reduces the amount of plastic waste that ends up in landfills or oceans but also promotes a more sustainable and environmentally friendly approach to 3D printing [104–106]. In this context, the recycling of polymeric material for FDM printing is an important topic that deserves attention and exploration. Figure 4 shows the recycling of the polymeric matrixes with various routes.

Polyethylene terephthalate (PET) with HDPE polymer is one of the most often utilized recycled polymers in FDM. The viability of reusing HDPE and PET as composites in FDM was examined by Ávila and Duarte, who also proved the thermo-mechanical approach for the reuse of polymeric waste. According to the study, the waste composite's compressive qualities fluctuate between 60 and 80 wt% depending on how much HDPE is loaded into the PET waste matrix. The maximum E-modulus of 1.46 GPa was reported for the 80/20 wt% ratio of PET/HDPE, while a maximum tensile stress of 27.90 MPa was observed for the 70/30 wt% ratio, according to the authors [107].

Similarly, polycarbonate (PC) was investigated by Reich *et al.* as a sustainable 3D printing material. According to the study, the mechanical characteristics of the recycled PC filaments (tensile strength: 64 MPa) were comparable to those of the virgin PC filaments that are sold commercially (tensile strength: 62–65 MPa). The study has also shown that recycled PC components could find useful uses in the category of heat-resistant products [108]. However, the reused PC filaments had a higher melting temperature, which required a higher extrusion temperature to melt the filament. The study concluded that reused PC could be a viable alternative to virgin PC for 3D printing applications.

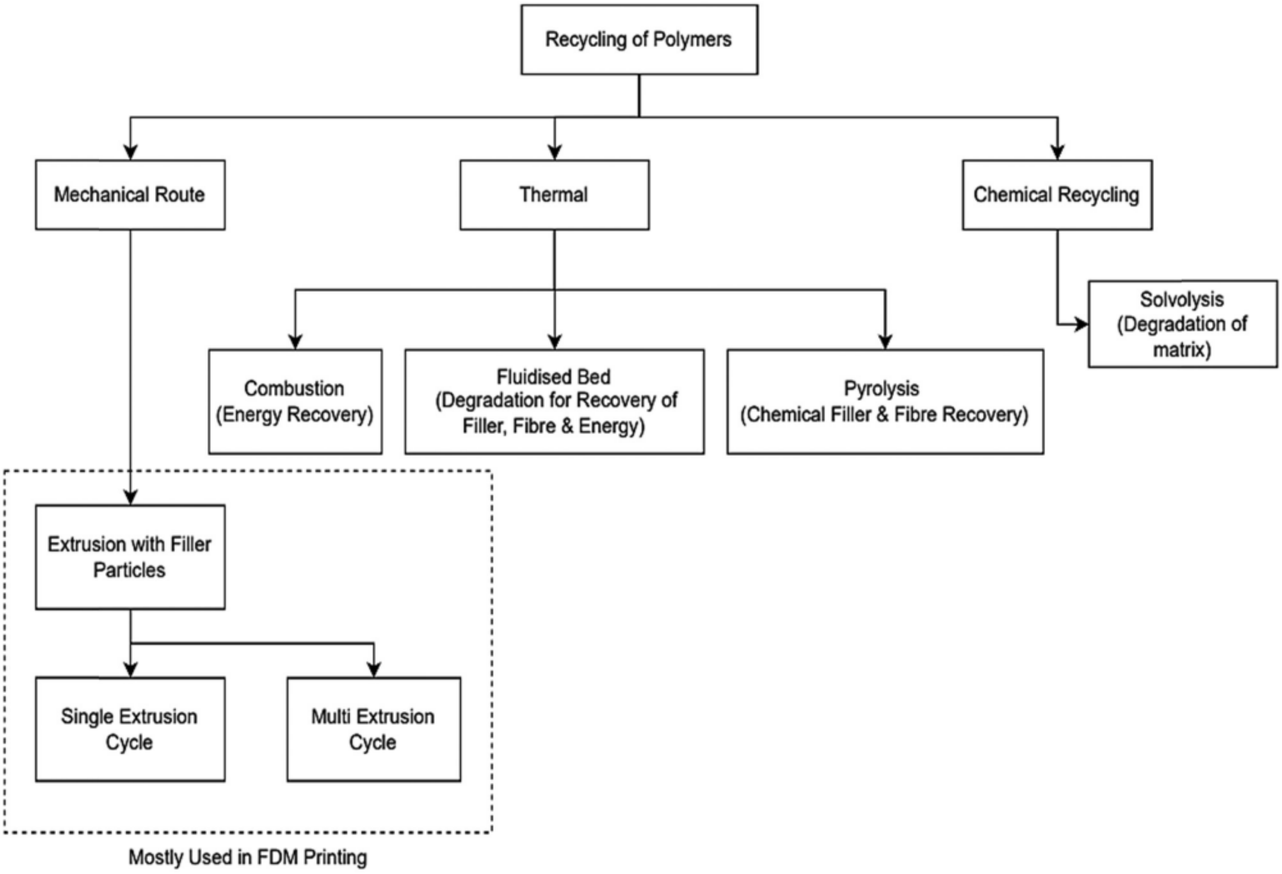

Figure 4: Recycling of the polymeric matrixes with various routes.

Another polymer that's frequently employed again in FDM is polyethylene terephthalate, or PET. Zander *et al.* looked at the solvent extraction method of reusing PET bottles in combination with PP and PS to create a blend material for 3D printing filament. The study discovered that although the recycled PET filament displayed superior elongation at break, its mechanical properties were inferior to those of the virgin PET filament. The 75/25 wt% ratio of the PP/PS blend was discovered to have the highest crystallinity, and it was seen to decrease with the level of reinforcement [109].

Reused composites are another promising material for sustainable 3D printing. Idrees *et al.* attempted to prepare feedstock filament of reused PET bottles by reinforcing biochar material in a polymeric matrix. The study has suggested a 32% increase in the tensile strength of PET when reinforced with 0.5 wt% of biochar. Similarly, the 5 wt% reinforcement level of biochar has significantly improved the tensile modulus of the PET by 60% [110]. The study conducted by Chong *et al.* has shown that the HDPE matrix can be effectively reused as a material matrix that has shown water rejection, thermal stability, and comparable extrusion rates [121]. Krieger *et al.* investigated the life cycle assessment for HDPE and LDPE materials. The study has suggested that HDPE polymeric material when studied for centralized recycling involved less embodied energy in comparison to the LDPE matrix which involved 80% embodied energy for transportation and collection. Further, the growth of 3D printers at domestic levels may have a high impact on the reduction of HDPE and LDPE waste [111].

According to one such study, PET waste polymeric material and LDPE virgin polymer are the best materials for 3D printing applications. To determine which of the several polymeric materials would be best for 3D printing, the author employed a multi-criteria decision-making approach [112]. In a similar vein, the mechanical and thermal characteristics of the PET waste matrix have been considerably impacted by HDPE reinforcement. Compared to pristine PET, the composite material matrix is now more robust due to the addition of 5 wt% of HDPE to the PET matrix [31].

In one such investigation, the impact of a tiny quantity of PLA in the PET matrix was noted by La Mantia *et al.* The study found that while there have been notable changes in the rheological characteristics of PET, minute amounts of PLA had no effect on the mechanical performance or thermal stability of PET [113]. Kumar *et al.* have reported on the recycling of PLA material for different stages of recycling and have observed that the addition of Fe_3O_4 powder in the PLA matrix has a positive impact on increasing the recycling life of PLA with the improved mechanical performance of the composite [114].

Similarly, the multi-extrusion cycle for HDPE with multi-wall CNT (MWCNT) reinforcement has improved the density of the composite. The multi-extrusion cycle has also improved the tensile strength and thermal properties of the HDPE waste polymeric matrix. The tensile strength improved from 63 to 68 MPa for the third time extruded filament of HDPE/MWCNT. Further, the modulus was increased to 97% for the third recycling time [115].

Dalloul *et al.* investigated the mechanical and thermal properties of the waste composite by incorporating cellulose nanofibrils (CNF) into an HDPE waste polymeric matrix. The material's tensile modulus has improved by 23% thanks to the 10 wt% CNF reinforced matrix. In comparison to pure HDPE, the composite has also produced reduced warping and a good print quality effect [116]. Several other studies have reported the use of many reinforcements, which can be used as filler in the waste polymeric material matrix such as SiC and Al_2O_3 [117], and MWCNT [118]. Atakok *et al.* evaluated the reused PLA matrix in FDM printing and compared it to the virgin PLA matrix. The study has observed that a layer thickness of 0.25 mm and infill percentage of 70% resulted in the maximum mechanical strength of reused PLA (tensile strength: 60 MPa), which was near to the virgin PLA material properties [119].

In flexible digital manufacturing, recycled PET mixed with HDPE polymer is a common material (FDM). Research has demonstrated that the amount of HDPE incorporated into the PET waste matrix can affect the compressive properties of waste composites. Since PC possesses mechanical properties similar to those of virgin PC filaments, it has also been researched as a sustainable material for 3D printing. Higher extrusion temperatures are required due to the higher melting temperatures of the repurposed PC filaments. Another material that shows promise for sustainable 3D printing is recycled composites. PET's tensile strength may be increased by 32–60% by reinforcing biochar material in a polymeric matrix, according to studies. With comparable extrusion speeds, thermal stability, and water rejection, the HDPE matrix can be effectively repurposed as a material matrix. The decrease in HDPE and LDPE waste could be significantly impacted by the rise in home 3D printers. The ideal materials for 3D printing applications are thought to be LDPE virgin polymer and PET waste polymeric material. HDPE reinforcement has had a major impact on the mechanical and thermal properties of the PET waste matrix. The tensile modulus and thermal characteristics of an HDPE waste polymeric matrix have also been enhanced by the use of CNF. Fillers in the waste polymeric material matrix can be other reinforcements like SiC, Al_2O_3, and MWCNT.

4 Summary

An attempt has been made to portray the polymer and polymeric composites created for FDM printing platforms during the past ten years in this review study. The various polymeric composites and recycled polymeric composites with their specific material properties are also highlighted in the paper. A wide range of polymeric composites, including natural reinforced polymeric composites (NFRP), self-reinforced polymers (synthetic-FRP), metallic and non-metallic nanocomposites, CNT/polymeric composites, silver and gold nanoparticle-based composites, and GO have been developed over the past ten years.

Because of the versatility of AM, which enables composite feedstock filament to operate on many platforms like SLS, SLA, DLP, FDM, *etc.*, an extensive array of reinforcements is already available. By adding reinforcement to the foreign element, the created composites have altered the mechanical, rheological, and thermal characteristics of the polymer as necessary. It is possible to conclude the literature review by saying that FDM printing, one of the AM methods for polymers, has been thoroughly investigated because of its affordability, manufacturing potential, material selection flexibility, and dimensional precision. According to the study, FDM printing of polymeric composites has a plethora of uses in both industry and household settings, and it has demonstrated the ability to lower the planet's carbon footprint through recycling.

The review has also revealed that most research works do not focus on long-term behavior or the effects of aging, but for practical application, this might be a crucial feature, particularly when considering the life cycle of automobiles or even built structures (for facades, 20, 30 years, and main structure, 80 years). The authors believe there is a lot of room for more study in this area. Furthermore, aside from mixed blending of reinforcement in polymeric base, very few approaches dealing with surface property alteration of polymeric 3D-printed specimens have been established in the recent 10 years. The author therefore sees possibilities in the creation of an FDM printing process

Table 1: Summary table for FDM feedstock filaments and its recycling

Study	Reinforcement	Matrix material	Result
Natural fiber-reinforced matrix			
Oksman *et al.* [30]	Flax	PLA	Improved tensile strength and modulus
Ma and Joo [120]	Jute	PLA	Incorporating jute fibers into PLA filament for FDM printing improved mechanical strength by 76% with 15 wt% jute fiber addition
Tokoro *et al.* [32]	Bamboo	PLA	Bamboo fibers in PLA filament for FDM printing had no impact on mechanical performance for long fibers but improved impact resistance with medium-length bamboo fibers
Asaithambi *et al.* [33]	Sisal	PLA	Adding 30 wt% sisal fibers to PLA filament in FDM printing enhanced tensile strength and E modulus, successful reinforcement
Durante *et al.* [34]	Flax	ABS	Adding broom and hemp fibers to ABS filament doubled mechanical strength, but challenges arose regarding compatibility, adhesion to the matrix, and uniform distribution in the composite matrix
Chow *et al.* [35]	Sisal	PP	Moisture content exposure to the PP/sisal fiber composite has reduced the mechanical strength of the samples, whereas impact strength got improved
Le Digou *et al.* [36]	Flax	PLA	Continuous flax fibers in PLA filament for FDM printing achieved 4.5 times increase in tensile strength (253.7 MPa), comparable to glass fiber/polyimide composites
Priselac *et al.* [37]	Coconut	PLA	CF in PCL/PLA matrix for FDM printing retained thermal properties. CF reinforcement substantially increased hardness; matching photopolymers used in printing plates
Chatterjee *et al.* [38]	Jute	ABS	Adding 0–10% jute fibers enhanced mechanical strength, with the best results in 2-ply PP/Jute composites. Additional plies of jute in PP reduced strength
Shahar *et al.* [39]	Kenaf	PLA	Introducing Kenaf fiber fillers in PLA at various ratios showed improved impact and fatigue strength. The best matrix was with 3 wt% Kenaf fibers, achieving an impact strength of 3.19 kJ/m^2
Suteja *et al.* [40]	Pineapple leaf fibers	PLA	Pineapple leaf fibers enhanced tensile strength to 101.3 MPa, from 63 to 65 MPa in neat PLA. Optimal FDM printing conditions included an extrusion temperature of 210°C and a feed rate of 15 mm/s
Paulo *et al.* [41]	flax fibers	PLA	Incorporating flax fibers reduced PLA's tensile strength from 50 to 43 MPa but improved bending strength from 53 to 73 MPa in the composite
Wang *et al.* [42]	Bamboo fibers	PLA	Higher extruder temperature and lower printing speed resulted in higher mechanical properties
Dunne *et al.* [43]	Sisal and kenaf fibers composites	ABS solution as binder	A composite of 30 wt% kenaf and 70 wt% sisal fibers exhibited a maximum tensile strength of 305.93 kPa, surpassing 100% kenaf fiber's strength of 279 kPa but lower than 100% sisal fiber's 600 kPa
Synthetic fiber-reinforced composites (synthetic-FRP)			
Koloor *et al.* [44], Khan *et al.* [45] and Mohammadyan-Yasouj *et al.* [46]	Glass, carbon, aramid	Polymers	Enhance tensile strength, modulus of elasticity, and impact resistance in composites
Chaudhry *et al.* study [50]	Carbon	Polymer matrix	Increased tensile strength and modulus of elasticity in FDM-printed parts by adding carbon fibers. Excessive carbon fiber addition reduced ductility and impact resistance

(Continued)

Table 1: *Continued*

Study	Reinforcement	Matrix material	Result
Butt *et al.* [51]	Glass	Polymer matrix	GFRPs improved interlayer adhesion and reduced warpage in FDM-printed parts
Qiao *et al.* [52]	Aramid	Polymer matrix	AFRPs significantly improved the mechanical properties of FDM-printed parts
Han *et al.* [54]	Carbon	Polymer matrix	Addition of carbon fibers improved the surface finish of FDM-printed parts by reducing visibility of layer lines and enhancing overall smoothness
Kumar *et al.* [55]	Glass	Polymer matrix	Adding glass fibers improved surface quality and reduced roughness in FDM printed parts. With 30 wt% short glass fiber inclusion, ABS showed a 57% increase in tensile and impact strength
Edwards [56]	—	FRP	FRPs in 3D printing enhance mechanical properties, offering potential for revolutionary manufacturing with complex, improved geometries
Cordin *et al.* [57]	—	FRP	Fiber orientation impact on tensile strength was observed in 3D printing with FRP. FRP enabled more rigid, lighter parts than conventional materials. Optimal preparation involved 0° fiber orientation, parallel to loading, improving E Modulus
Pervaiz *et al.* [60]	Carbon, glass, basalt	FRP	Performance enhancement in fiber-reinforced plastic composites using high-strength fibers such as carbon, glass, or aramid fibers
Goh *et al.* [61]	Carbon, glass	3D printed FRP	Using carbon fiber-reinforced FRP produced parts with greater modulus of elasticity (12.99 GPa) and tensile strength (600 MPa) than glass fiber-reinforced FRP (450 MPa and 7.20 GPa) in 3D printing
Dou *et al.* [62]	—	3D-printed FRP	Higher printing temperature produced pieces with greater stiffness and tensile strength. Smaller nozzle diameter and thinner layer height (0.2 mm) resulted in better mechanical qualities (tensile strength: 243.53 MPa), while larger layer width (0.4 mm) had lower mechanical strength (164.61 MPa)
Kuncius *et al.* [63]	—	3D-printed FRP	Increased printing temperature and reduced layer height improved interlayer adhesion and shear strength of the PLA/CF composite in 3D printing with FRP. Higher infill density resulted in parts with improved mechanical properties
Uhlmann *et al.* [64]	Carbon fiber	FRP	High pressure and feed rate in abrasive water jet cutting had a significant impact on machining CFRP composites. CO_2-based jet cutting allowed high-quality items to be produced from CFRP composites
Zaman *et al.* [66]	—	FRP	FRP offered better mechanical qualities and lighter weight than standard materials. Explored the impact of moisture, outside temperature, and durability challenges
Nano particle-reinforced composites			
Podstawczyk *et al.* [67]	Silver nanoparticles	PLA	Enhanced antimicrobial and 3D printable qualities. Minor bulk property modifications
Barmina *et al.* [68]	Gold or silver nanoparticles	Polymer composites	Impact on optical characteristics based on size, shape, and composition. Suitable for plasmonic devices
Kumar *et al.* [69,70]	Iron oxide (Fe_3O_4) and other reinforcements	Polymer composites	Magnetic properties observed at 5–20% weight, while mechanical properties remained similar to conventional PLA
Kumar *et al.* [71–73]	Magnetic nanoparticles (*e.g.*, iron oxide)	Polymer composites	Attractive for 4D printing, such as arctic region tiles. Ability to respond to magnetic fields

(Continued)

Table 1: *Continued*

Study	Reinforcement	Matrix material	Result
Kausar [75]	Semiconductor nanoparticles (*e.g.*, quantum dots)	Polymer composites	Unique optical properties, size-dependent emission spectra. Suitable for optoelectronic devices
Haneman and Szabó [77]	*In situ* polymerization	Polymer matrix	Homogeneous composite material, better properties. Control over nanoparticle size and distribution
Han and Szabó [78]	Carbon nanotube (CNT)	PVA	Good electrical and mechanical characteristics. Specific capacitance of 164.6 F/g for high-performance energy storage devices
Glogowski *et al.* [79], Bajpai *et al.* [80]	Functionalized nanoparticles	Polymer matrix	Improved mechanical and electrical properties through better dispersion. Antibacterial activity against *Escherichia coli*
McKeon-Fischer *et al.* [81]	Gold nanoparticles	PLLA	Composite scaffold for tissue engineering. Strong biocompatibility and cell growth stimulation
Hamidian *et al.* [82]	Iron oxide nanoparticles	Polyester polymeric matrix	Polymeric composite for targeted drug delivery Controlled drug release under magnetic field exposure
Soni *et al.* [83]	Carbon nanoparticles	Polymer solution	Preparation techniques include solution blending, melt blending, *in situ* polymerization, and electric field spinning
Agboola *et al.* [85]	Carbon nanoparticles	N/A	High surface area-to-volume ratio for effective gas and pollutant adsorption. Excellent electrical conductivity
Zhang *et al.* [86]	Carbon nanoparticles	N/A	High mechanical strength and thermal stability for structural and thermal management applications
Mallakpour and Khadem [87]	Carbon nanoparticles	N/A	Applications in environmental, energy, biomedical, and various industries
Shin *et al.* [92]	Short and long CNT	TPU	Different effects on electrical characteristics. Longer CNT provides greater electromagnetic shielding
Guo *et al.* [93]	Iron oxide-coated carbon fiber	BN/SR	Improved electromechanical characteristics in composite structures
Arash *et al.* [94]	PMMA/CNT composites	PMMA	Aspect ratio of CNT affects mechanical properties. Elastic modulus increased with higher aspect ratio
Ryu and Shanmugharaj [95]	GO	PP	GO addition (0.1 to 5%) influenced PP mechanical properties; higher GO chain length improved tensile strength and modulus (29.4 and 47%, respectively)
Liang *et al.* [96]	GO	PLA	GO (0.5 wt%) and CF (9 wt%) increased tensile strength and modulus significantly in PLA
Wang *et al.* [97]	GO	PLA	Adding 2 wt% GNP to PLA improved thermal stability, increased tensile strength (43.5%), and flexural strength (29%)
Liu *et al.* [98]	GO-APTS	Polyimide (PI)	GO-APTS (1.5 wt%) reinforcement increased PI's tensile strength (45%) and Young's modulus (15%) and improved thermal stability
Ma *et al.* [99]	GO	Poly(vinyl alcohol) (PVA)	Adding 0.01–0.08 wt% GO reduced moisture permeability by 78% and improved tensile strength (50.8 MPa)
Upadhyay *et al.* [100]	GO	HDPE	3 wt% GO increased mechanical strength and elongation capacity of HDPE. Suitable for use as a substrate for cell growth
Wang *et al.* [101]	GO	PEG	9.6 wt% GO/PEG composites showed increased thermal conductivity (up to 111%) and reduced resistance peak by 33.4%
Abdullah and Ansari [102]	GO	Epoxy resin	GO addition (1.5–6% by volume) increased Young's modulus, reduced impact strength, and improved tensile strength
Zhang *et al.* [103]	GO	PVA	0.8 wt% GO enhanced compressive strength (36%) and tensile strength (132%) without affecting PVA toxicity

(Continued)

Table 1: *Continued*

Study	Reinforcement	Matrix material	Result
Summary for the recycling of polymeric matrices			
Ávila and Duarte [107]	PET waste	HDPE and	HDPE loaded into PET waste matrix produced compressive qualities ranging from 60 to 80%, with maximum E-modulus of 1.46 GPa for 80/20 wt% PET/HDPE
Reich *et al.* [108]	—	PC	Recycled PC filaments showed mechanical characteristics (tensile strength: 64 MPa) similar to commercially sold virgin PC filaments
Zander *et al.* [109]	PP and PS blend	PET	Recycled PET filament with PP and PS showed superior elongation at break but inferior mechanical qualities compared to virgin PET
Idrees *et al.* [110]	Biochar reinforcement	Reused PET bottles with	0.5 wt% biochar reinforcement in PET increased tensile strength by 32% and 5 wt% biochar improved tensile modulus by 60%
Krieger *et al.* [111]	LDPE	HDPE	HDPE had lower embodied energy in centralized recycling compared to LDPE, which involved 80% embodied energy for transportation and collection
Exconde *et al.* [112]	PET waste	LDPE virgin polymer	Employed multicriteria decision-making approach to determine best materials for 3D printing
La Mantia *et al.* [113]	PLA	PET	Minor PLA addition in PET had no effect on mechanical performance or thermal stability of PET
Kumar *et al.* [114]	Fe_3O_4 powder	PLA with	Addition of Fe_3O_4 powder in PLA matrix improved recycling life of PLA with enhanced mechanical performance
Kumar *et al.* [115]	MWCNT	HDPE	Multi-extrusion cycle improved density, tensile strength, and thermal properties of HDPE waste polymeric matrix
Dalloul *et al.* [116]	CNF reinforcement	HDPE waste polymeric matrix	10 wt% CNF reinforced matrix improved tensile modulus by 23%, reduced warping, and improved print quality
Atakok *et al.* [119]	virgin PLA	Reused PLA	A layer thickness of 0.25 mm and 70% infill resulted in maximum mechanical strength for reused PLA (Tensile strength: 60 MPa)
Chong *et al.* [121]	—	HDPE	Reused HDPE matrix showed water rejection, thermal stability, and comparable extrusion rates

that can offer modified surface qualities at a specific area or layer.

Table 1 shows the summary of all the literature studied for the present review work.

Acknowledgement: The authors are grateful to D Y Patil International University, for their moral support throughout. Also, the authors acknowledge financial support from Universität der Bundeswehr München to cover the APC of the journal for the publication process.

Funding information: The Open Access fee for publication of the manuscript is supported by the Universität der Bundeswehr München.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results and approved the final version of the manuscript. SK: conceptualization, data collection, writing – original draft preparation, review and editing, validation, visualization, supervision, project administration, resource, and funding; IS: literature review, data analysis, writing, critical evaluation, and validation; AA: literature review, data analysis, writing, critical evaluation, and validation; SB: data collection, writing – original draft preparation, review and editing, and validation; SSRK: data collection, writing – original draft preparation, review and editing, critical evaluation, validation, supervision, project administration, resource, and funding; GS: literature review, data analysis, writing, critical evaluation, validation, resource, and funding.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: All data generated or analysed during this study are included in this published article and its supplementary information files.

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