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A critical review of composite filaments for fused deposition modeling: Material properties, applications, and future directions

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Abstract: This review paper provides a comprehensive analysis of recent advancements in the development and application of composite filaments for fused deposition modeling (FDM) 3D printing technology. Focusing on the integration of various materials such as nano-fillers, fibers, and bio-based polymers into polylactic acid (PLA) and other thermoplastics, this study delves into how these composites enhance mechanical, thermal and functional properties of the printed objects. We critically assess studies that investigate the impact of raster orientation, filler content, and material composition on tensile, bending, and impact strength, as well as on the thermal stability and degradation behavior of composite filaments. The review highlights key findings from the literature, including the optimization of filament formulations to achieve superior mechanical performance, improved thermal resistance, and specific functional characteristics suitable for a wide range of applications from biomedical to structural components. Moreover, this paper discusses the challenges associated with composite filament production, including material compatibility, dispersion of nano-fillers, and the need for printer hardware adjustments. Future directions for research in the field are identified, emphasizing the potential for new material combinations, sustainability considerations, and the development of filaments designed for specific industrial applications. An effective way to better meet designers' expectations for qualified materials is composite filaments. This review focuses on how these elements can be applied to improve both product design and functionality. A guide is presented in choosing composite filaments that can meet the features expected from the designed product.

Keywords: 3D printing, composite filaments, fused deposition modeling, material properties, additive manufacturing.

1. Introduction

The advent of three dimensional (3D) printing, or additive manufacturing (AM), has revolutionized the way we conceive, design, and manufacture objects across a myriad of industries, from aerospace and automotive to biomedical and consumer goods. At the heart of this transformation lies fused deposition modeling (FDM), one of the most accessible and widely used 3D printing technologies. FDM's popularity is largely attributed to its simplicity, cost-effectiveness, and the vast array of materials it can process. However, the quest for materials that offer enhanced properties suitable for more demanding applications has led to significant research and development efforts, particularly in the realm of composite filaments. Composite filaments for FDM combine a base material, typically a thermoplastic such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), with reinforcing materials like carbon fibers, glass fibers, metals, or ceramics. These composites

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aim to overcome the limitations of conventional filaments by improving mechanical strength, thermal stability, electrical conductivity and other functional properties. The integration of nano-fillers such as graphene, carbon nanotubes (CNTs), and nano-silica (SiO_2) has also been explored to enhance filament performance further. With improved material properties, FDM 3D printing can transcend its traditional prototyping role, moving towards the production of functional parts that meet the rigorous requirements of industrial applications. The fabrication of personalized objects, previously unachievable with standard filaments, has become possible through the development of composite filaments. This review aims to provide a comprehensive overview of the current state of composite filaments for FDM 3D printing. It will explore the various types of materials used in composite filaments, examining how the incorporation of different fillers affects the physical, mechanical and thermal properties of the printed objects. The impact of printing parameters such as raster orientation and filler density on the performance of composite filaments will also be discussed. The complex relationship between material composition, processing conditions and final properties of 3D printed objects will be highlighted. Furthermore, the review will address the challenges associated with the production and use of composite filaments, including issues related to material compatibility, uniform dispersion of fillers, and the need for specialized printing settings or equipment modifications. Despite these challenges, the potential of composite filaments to push the boundaries of FDM 3D printing is undeniable. In addition to summarizing key findings from recent studies, this review will identify gaps in the current knowledge and suggest directions for future research. With continuing advances in materials science and AM technologies, development of new composite filaments holds great promise to further enhance the capabilities of FDM 3D printing. Thus, it paves the way for greater adoption in high-performance and special applications.

By delving into the intricate world of composite filaments, this review seeks to shed light on the progress made thus far and the potential that lies ahead. It is intended for researchers, engineers, and practitioners in the field of AM who are interested in the latest material innovations and their implications for the future of 3D printing.

1.1. Literatur surway

In the rapidly evolving field of additive manufacturing, particularly within the domain of FDM, the development and application of composite filaments have garnered significant attention. This increase in interest is largely due to the potential of composite materials to significantly improve the mechanical, thermal and functional properties of 3D printed objects. Thus, the use of FDM technology is being extended beyond prototyping to the manufacturing of end-use parts. The literature surrounding composite filaments is extensive and reflects interdisciplinary research aimed at overcoming the limitations of traditional 3D printing materials. This section provides an overview of the existing body of work on composite filaments for FDM, highlighting key themes, findings, and the methodologies employed by researchers to advance the field. The exploration of composite filaments encompasses a wide range of base materials and reinforcements. Base materials commonly include thermoplastics like PLA, ABS, and polyamide (nylon), which are favored for their ease of printing, availability, and relatively low cost. On the other hand, reinforcement materials are very diverse, including carbon fiber, glass fiber, metal, ceramics and various nanoparticles such as graphene, carbon nanotube and nano-silica. Each of these reinforcements brings specific advantages to the composite filament, such as increased tensile strength, improved thermal resistance, enhanced electrical conductivity, or added biocompatibility, catering to the demands of specialized applications. Significant research has focused on the optimization of filament composition, examining how different ratios of matrix to reinforcement materials affect the final properties of printed objects. Studies often utilize a combination of experimental testing and computational modeling to predict the behavior of composite filaments under various loading conditions and printing parameters. Tensile, compressive and flexural tests are routinely conducted alongside more specialized analyses such as dynamic mechanical analysis (DMA), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) to comprehensively evaluate the performance enhancements offered by composite filaments. Another critical area of investigation within the literature is the impact of printing parameters on the properties of objects made from composite filaments. Factors such as nozzle temperature, print speed, layer height, raster angle, and infill density have all been shown to influence the mechanical integrity and surface finish of printed parts. Researchers have systematically varied these parameters to determine optimal printing conditions that maximize the advantages of composite materials. Challenges associated with the use of composite filaments, such as nozzle clogging, uneven material distribution, and the need for printer modifications, are also extensively documented. Solutions to these challenges, including the development of new nozzle designs and the formulation of advanced composite materials with improved flow characteristics, are actively being explored. The literature survey reveals a dynamic and rapidly advancing field, characterized by a constant quest for new material combinations and processing techniques. As this body of work continues to grow, it not only enhances our understanding of composite filament behavior but also pushes the boundaries of what is possible with FDM technology, opening up new horizons for the future of AM. This introduction to the literature survey sets the stage for a detailed examination of specific studies and findings, which collectively illustrate the current state of knowledge in the field of

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composite filaments for FDM 3D printing. Through this exploration, we aim to capture the breadth of research activities, identify prevailing trends, and underscore the innovative approaches being adopted to address the complex challenges inherent in this area of study.

In this study, the literature review is generally categorized as follows according to the subject areas focused on, although no clear distinctions can be made from each other.

Properties of composite filaments

In a study by Wu et al. (2016), to improve the thermal properties of PLA filament, a composite filament was produced using a PLA and nano-SiO_2 mixture, and the distribution of nano-SiO_2 and the fracture surfaces of the filaments were examined with a scanning electron microscope (SEM). The thermal performances of the composite filament were evaluated using DSC and TGA, showing that as the amount of nano-SiO_2 increased, there was a slight increase in the degree of orientation, friction coefficient, thermal decomposition temperature and glass transition (Tg) temperature. It was mentioned that adding 1% by weight SiO_2 to PLA increased tensile strength, but adding 3% by weight SiO_2 decreased it, demonstrating that nano-SiO_2 dispersed within PLA and could reduce the cohesion between PLA crystals [1].

Daver et al. (2018) showed in the TGA analysis of 3D print samples of mushroom/PLA mixture filaments that pure PLA lost 5% of its mass at 342°C, 10% of its mass at 352°C, 50% of its mass at 378°C, and experienced maximum mass loss at 383°C. They stated that the addition of mushroom to PLA resulted in a 10% mass loss at lower temperatures and a more than 50% mass loss at higher temperatures [2].

Kariz et al. (2018) produced filaments using a 1/9 ratio of wood/PLA, increasing the tensile strength from 55 MPa to 57 MPa, and found that in a 1/1 ratio of wood/PLA mixture, the value dropped to 30 MPa. They determined that adding wood particles up to 10% increased the strength of the filaments, but higher wood ratios decreased it [3].

Haq et al. (2018) observed changes in the mechanical properties of polycaprolactone (PCL/PLA) composite filaments with different molecular weights (400, 6000, and 10,000 g/mol) and mixture ratios (5,10,15 phr) of polyethylene glycol (PEG) in PCL/PLA. They showed that increasing the molecular weight of PEG significantly improved the tensile and impact strength of PCL/PLA and the PCL/PLA/PEG composite increased the tensile strength and elasticity modulus. Increasing the PEG content from 5phr to 15phr decreased the tensile strength and Young's modulus, but increasing molecular weight of PEG from 400 to 10,000 increased the impact resistance of PCL/PLA/PEG composites. They showed that better mechanical properties of PCL/PLA/PEG composites could be achieved by optimizing the PEG content and molecular weight [4].

Kamarudin et al. (2020) found that increasing the ratio of epoxidized jatropha oil (EJO, 1-5%), processed kenaf fiber (TK, 30%), and PLA (65-69%) mixtures decreased the Tg and increased the Tm [5].

Singh et al. (2020) examined the mechanical performance of chitosan-reinforced PLA scaffolds. They determined that the strength of composite samples significantly depends on the chitosan load and density and that the annealing temperature does not affect the mechanical properties. Increasing the chitosan ratio (1%, 1.5%, 2% wt.) in PLA decreased tensile and bending strength but increased compressive strength. Overall, PLA/chitosan composite scaffolds were mechanically effective and suitable for clinical purposes [6].

The study by Jayswal and Adanur (2023) focuses on the production and characterization of composite filaments containing PLA and thermoplastic polyurethane (TPU) for FDM in 3D printing. The article discusses the preparation of PLA/TPU composite filaments via solvent mixing method, examination of their mechanical, thermal and morphological properties, influence of FDM process parameters, and the mechanical behavior of 3D printed samples. According to the findings, the tensile strength and modulus of the filaments decrease as the TPU content increases, while elongation at break increases. Additionally, partial compatibility of polymer components is observed in the composite filament solution [7].

The article by Kantaros et al. (2023) examines advanced composite materials, particularly filaments containing fillers, used in FDM/FFF 3D printing manufacturing processes. It discusses how various reinforcements such as carbon fibers, glass fibers, and nanoparticles are integrated into the polymer matrix of FDM/FFF filaments. The article explains how the filler material layer enhances mechanical, thermal and electrical properties of 3D printed parts compared to pure polymers, expanding the potential application areas for FDM/FFF 3D printed components. Additionally, the article addresses the challenges encountered in using filler-containing filaments in FDM/FFF 3D printing, including filament extrusion stability, nozzle clogging, and interfacial adhesion between the reinforcement and matrix. Lastly, the article showcases examples demonstrating significant advantages of filler-containing filaments over standard FDM/FFF raw materials in various industries such as aerospace, automotive, medical, electronics and tooling. It also explores the possibility of future advancements and integration of innovative reinforcement materials [8].

Advantages of composite filaments

Liu et al. (2018) produced samples by FDM method using SiC/C/PLA mixtures composite filaments. They determined that as the SiC and C ratio in the filaments increases, the thermal conductivity property increases and the shape recovery time also decreases [9].

Chen et al. (2017) stated that the addition of graphene oxide (GO) to thermoplastic polyurethane (TPU)/PLA/GO nanocomposites increased the compressive modulus by 167% and the tensile modulus by 75.5%. On the other hand, it showed high levels of cell viability in cell culture tests. Thus, they point to the conclusion that a small amount of GO is beneficial for cell proliferation [10].

Çanti et al. (2018) successfully produced composite filaments reinforced with different nano/microparticles (SiO2, ZrB2, Al) in ABS at 175-210°C using a twin-screw extruder. Çanti›s characterization results showed that the new composites could be used as filaments in commercial FDM printers without modification. Adding micro/nanoparticles to ABS increased tensile strength by about 16%, and adding microparticles (ZrB2 and Al alloy) increased the type of stress by at least 18% [11].

Li et al. (2018) showed that using cellulose, glass fiber and PLA to make filaments for FDM 3D printers increased the impact resistance of the cellulose and PLA mixture filament by 34-60% and tensile strength by 43-52% compared to PLA filament. They also found that different ratios of cellulose and PLA mixture filament increased the impact toughness by 13-35% and tensile strength by 54-61% higher than pure PLA [12].

Ertane et al. (2018) produced filaments from a mixture of biochar and PLA, which is 100% recyclable from wood, plants, and soil. They observed that increasing amount of biochar slightly hindered the FDM printing process [13].

Caminero et al. (2019) analyzed the mechanical performance, dimensional accuracy, and texture of 3D printed samples of commercially available PLA, PLA3D850, and PLA-Graphene composite filaments. They stated that PLA 3D850 has less thermal shrinkage and better mechanical properties than conventional PLA. They mentioned that this makes it suitable for high accuracy, high resolution and high performance applications [14].

Charoenying et al. (2020) used an FDM 3D printer to design a capsule for controlling the release and gastric retention of domperidone Tablets. They made the capsule's lid hollow with wall thicknesses of 1.2-1.5mm using polyvinyl alcohol filament, and body with 1-2mm openings using PLA filament for drug release. They investigated how the floating time of the capsule and drug release in the stomach would be affected. It found that a capsule lid thickness of less than 1.3 mm increased stomach floating time and that reducing the size of the holes in the capsule body resulted in longer DOM release. X-ray diffraction (XRD) analyzes showed that the capsules remained in the rabbit stomach for more than 10 hours. Thus, it showed that the capsule was suitable for sustained drug delivery in the stomach with its floating and sustained drug release capabilities [15].

Huerta-Cardoso et al. (2020) mixed agave tequila waste fibers (ATF)/PLA at ratios of 20, 40, and 60 (w/v) and produced them using extrusion molding. They analyzed the tensile, bending, impact and water absorption properties of samples produced using press molding, observing the use of ATF as a filler. The reinforcement material in PLA improved mechanical properties, achieving the best results in a 40% (wt/vol) ATF blend, showing a flexural strength of 98.8 MPa and an impact strength of 6.8 kJ/m^2. These values were close to those of commonly used PLA composite polymers [16].

The article by Zhou et al. (2023) focuses on the development and application of conductive polymer composites (CPCs) for FDM. CPCs combine the electrical conductivity of conductive fillers with the excellent properties of polymers. FDM is a technique that produces products by depositing polymers layer by layer based on a digital model. FDM enables the preparation of complex structures and electronic devices with excellent properties using CPCs. This article introduces FDM technology, material requirements, and the conductivity mechanism of CPCs. Various design ideas for CPCs are summarized, and the current development status of different methods is introduced and compared. Finally, some perspectives on the future development of FDM technology and CPCs for FDM are presented [17].

Materials used in FDM 3D printing

Gkartzou et al. (2017) showed in their study on 3D printing with PLA/lignin mixture filaments that as the lignin content in PLA increased, the values of maximum stress and elongation at break decreased, and DSC analysis showed that increasing the lignin ratio from 5% to 20% did not cause significant changes in Tg, melting temperature (Tm) and melting enthalpy values [18].

Yu et al. (2017) observed in TGA analyses of FDM 3D printing work with PLA/graphene/CNTs mixtures that PLA lost about 5% of its mass at 310°C, PLA+6% CNT at 287°C, and PLA+2% graphene at 282°C. They stated that the thermal degradation properties of PLA-based composites changed little compared to pure PLA, and the thermal degradation temperature of the composites was approximately 30°C lower. Based on this, it is suggested that the super thermal conductivity feature of the graphene/CNT phase in PLA accelerates heat diffusion [19].

Ausejo et al. (2018) stated that mixtures of thermoplastic PLA and polyhydroxyalkanoate (PHA) could be used in biocompatible 3D printing applications. The 3D printed material using a PLA / PHA mixture showed suitable mechanical properties, thermal stabilities, and cell viability for tissue engineering applications. Biological tests on 3D print samples showed no toxicity against cell growth and demonstrated good biocompatibility with HEK293 cells [20].

Mansour et al. (2018) found that adding carbon fiber to polyethylene terephthalate glycol (PETG) material at a 1/4 ratio decreased the damping capacity of the resulting product [21].

Corcione et al. (2019) used pure PLA and spray-dried hydroxyapatite (sdHA)/PLA filaments for FDM 3D printing. They found that the presence of sdHA did not affect the decomposition temperature of PLA, with thermograms showing almost no change after 270°C [22].

Kumar et al. (2020) conducted a study on biapplications using PLA, biocompatible polyamide (PA6), and TiO_2 mixtures alongside pure PLA filaments in the same 3D print samples. SEM and energy-dispersive X-ray spectroscopy (EDS) analyses showed that internal solidification gaps formed at the joining parts of the PLA layer with PA6/TiO_2, negatively affecting the samples' bending strength [23].

Nevado et al. (2020) produced a polymer/ceramic mixture of PLA and biphasic calcium phosphates (BCPs) at a diameter of 1.7 mm using single screw extrusion, finding the filaments slightly brittle but suitable for FDM printers. BCPs were obtained by combustion synthesis, and the filaments were made considering a mixture of 15% BCP and 85% PLA by weight. Biological tests showed that the ceramic and polymer mixture filaments were not toxic to Detroit cells, Saos-2, and U937 macrophages, did not affect their proliferation, and allowed for cell anchorage in adhesion analyses. They observed sufficient compatibility between the material and osteoblasts in terms of viability, proliferation, and adhesion. However, they noted that other types of testing should also be considered to recommend such filaments for bone tissue engineering applications in 3D printing [24].

The study by Del Pilar Fabra Rivera et al. (2023) focuses on the production of PLA composites using FDM and examines their mechanical, thermal and morphological properties. The article describes how PLA composites with different layer thicknesses, infill densities, and infill patterns are printed using FDM. The printed samples undergo tensile, bending, impact, and hardness tests, while their thermal stability is evaluated through TGA. Additionally, the fracture surfaces of the samples are observed using SEM. The results indicate that the mechanical and thermal properties of PLA composites vary depending on FDM process parameters. Furthermore, the fracture mechanisms of PLA composites are correlated with the morphology of the fracture surfaces [25].

The study by Palaniappan et al. (2023) focuses on the development and application of CPCs for FDM. CPCs combine the electrical conductivity of conductive fillers with the excellent properties of polymers. FDM is a technique that produces products by depositing polymers layer by layer based on a digital model. FDM enables the preparation of complex structures and electronic devices with excellent properties using CPCs. This article first introduces FDM technology, material requirements, and the conductivity mechanism of CPCs. It then summarizes various design ideas for CPCs and introduces the current development status of different methods, comparing them. Finally, it presents some opinions on the future development of FDM technology and CPCs for FDM [26].

Effect of printing parameters

Letcher and Waytashek (2014) evaluated studies on the production of composite filaments for use in 3D printers. They tested the orientation effects on part strength by performing tensile tests at 0, 45 and 90° raster orientation angles on 3D printed samples made with PLA filament. They found the highest tensile strength at 45° raster orientation condition with 64 MPa, the highest bending strength at 102 MPa with 0° raster orientation, and the worst fatigue test values at 90° raster orientation [27].

Naveed (2020) examined the defects in 3D printed samples produced with PLA at raster orientation angles of 0°, 30°, 45°, 60° and 90° using SEM analysis of microstructure images. They noted that samples printed at 0, 30°, and 60° showed solidification gaps between two rasters on the outer surfaces. Ultimately, this indicates that the rasters were not connected properly during printing, causing gaps on the inner layer surfaces. Samples printed at 60° had longer average gap lengths (1.2 mm), while those at 45° had shorter gaps [28].

Vinay et al. (2024) investigates the impact of processing parameters on the adhesion strength of metal-polymer composites produced through FDM. Employing a design of experiments approach, the authors optimize parameters including nozzle temperature, bed temperature, layer height, and extrusion speed. Adhesion strength is assessed through peel and lap shear tests, while microstructure and interfacial bonding are analyzed via SEM and energy dispersive spectroscopy. Results indicate that adhesion strength increases with higher nozzle and bed temperatures, but decreases with increased layer height and extrusion speed. Optimal parameters are identified as 230°C nozzle temperature, 70°C bed temperature, 0.2 mm layer height and 30 mm/s extrusion speed. Authors conclude that processing variables significantly affect adhesion strength, suggesting FDM as a viable method for enhancing adhesion properties in metal-polymer composites [29].

Singh et al. (2024) investigated increasing the mechanical properties of composites prepared by adding multiwalled carbon nanotubes (MWCNT) at different rates (1%, 2%, and 3% by weight) to the ABS matrix. In the study, it was observed that MWCNTs were homogeneously distributed in the ABS matrix and their effects on mechanical properties were examined. The addition of MWCNT resulted in significant improvements in tensile strength and thermal properties compared to pure ABS. In particular, composites containing 3%

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MWCNT showed an increase in tensile strength of up to 60% compared to pure ABS. Research results have revealed that MWCNTs are evenly distributed within the ABS matrix and these composites have superior mechanical properties, especially for use in the automotive and aerospace industries [30].

The study by Kargar and Ghasemi-Ghalebahman (2023) investigates the production of carbon fiber-reinforced PLA composites using FDM and examines their fatigue life and tensile strength. The article presents experimental studies where the infill density (50% and 75%) and raster angle (0, 45, and 90°) were varied to determine the optimal process parameters for enhancing the mechanical properties of FDM-produced parts. Experimental results indicate that increasing the infill density and decreasing the raster angle enhance the tensile strength, but the fatigue behavior is more complex and dependent on the infill density. Additionally, the effects of 100% infill density, raster width and nozzle diameter on mechanical properties are also investigated [31].

Table 1. Synthesizing some research efforts on PLA and its composites

References	Material Composition	Key Findings	Implications
Letcher and Waytashek (2014)	PLA	Highest tensile strength at 45° raster orientation (64 MPa), highest bending strength at 0° (102 MPa), worst fatigue at 90°.	Orientation affects part strength significantly, providing guidelines for optimizing print settings for specific mechanical properties.
Wu G. et al. (2016)	PLA and nano-SiO_2 mixture	Addition of 1% SiO_2 increased tensile strength; 3% SiO_2 decreased it. Improved thermal properties with nano-SiO_2.	Nano-fillers can enhance or degrade mechanical properties, highlighting the need for balance in composite filament formulations.
Liu W. et al. (2018)	SiC/C/PLA mixtures	Increased thermal conductivity and reduced shape recovery time with increased SiC and C ratios.	Demonstrates the potential for FDM materials with improved thermal management capabilities.
Gkartzou et al. (2017)	PLA/lignin mixture	Increasing lignin content decreased maximum stress and elongation at break; little change in Tg, Tm, and melting enthalpy.	Suggests a trade-off between biodegradability and mechanical performance with lignin as a filler.
Yu et al. (2017)	PLA/graphene/CNT mixtures	Slight decrease in thermal degradation temperature with additives, indicating accelerated heat diffusion.	Highlights the potential for advanced thermal management in PLA composites with graphene/CNT.
Chen et al. (2017)	TPU/PLA/GO nanocomposites	Increased compression and tensile modulus, excellent cell viability, indicating GO's benefit for cell proliferation.	GO's addition to composites can enhance mechanical properties and biocompatibility for medical applications.
Daver et al. (2018)	Mushroom/PLA mixture	Addition of mushroom affected thermal degradation, with a significant mass loss at higher temperatures.	Indicates potential for biodegradable composites with altered thermal properties.
Çanti et al. (2018)	ABS with nano/microparticles (MWCNTs, SiO2, ZrB2, Al)	Increased tensile strength with micro/nanoparticle addition, showing promise for enhanced FDM filament properties.	Suggests that adding micro/nanoparticles can significantly improve the mechanical strength of ABS composites.
Kariz et al. (2018)	Wood/PLA mixtures	Wood particles up to 10% increased strength; higher ratios decreased it.	Highlights the potential for wood particle reinforcement in PLA but notes the limitations of filler content.
Li et al. (2018)	Cellulose, glass fiber, and PLA	Increased impact resistance and tensile strength with cellulose and PLA mixture compared to pure PLA.	Demonstrates the effectiveness of cellulose and glass fibers in enhancing mechanical properties of PLA filaments.
Ausejo et al. (2018)	PLA/PHA mixtures	Suitable mechanical properties, thermal stabilities, and cell viability for tissue engineering applications.	Indicates potential for PLA/PHA mixtures in biocompatible 3D printing applications.
Vinay et al. (2024)	Metal-polymer composites	Optimized nozzle and bed temperatures improve adhesion strength; processing variables significantly affect metal-polymer composite properties.	Points to the importance of processing parameters in achieving strong adhesion in metal-polymer composites.
Zhou, X., et al. (2023)	Conductive polymer composites (CPCs)	Introduction to CPCs for FDM, focusing on electrical conductivity and complex structure capabilities.	Suggests a growing field of FDM applications in electronics and complex structures with conductive properties.
Palaniappan et al. (2023)	Conductive polymer composites (CPCs)	Discusses FDM technology, CPC design ideas, and future development perspectives.	Reinforces the potential and challenges of developing CPCs for advanced FDM applications.
Jayswal and Adanur (2023)	PLA/TPU composites	Tensile strength and modulus decrease with increased TPU content; increased elongation at break.	Highlights the trade-offs in mechanical properties with TPU content, indicating customization potential for specific applications.

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The conclusion here is that the mechanical, physical, and chemical properties of the filaments planned to be produced significantly depend on the raw material and mixture ratios. Additionally, 3D printing parameters have a significant impact on the mechanical properties of parts produced with FDM 3D printers.

The pie chart (▶**Figure 1**) shows the distribution of material types utilized in the composite filament studies for FDM 3D printing. It highlights the diversity in material use, with PLA-based composites forming a significant portion of the studies, followed closely by other composite materials, biocompatible composites, pure PLA and ABS. This visualization underscores the research community's interest in exploring a wide range of materials to enhance the properties and applications of 3D printed objects.

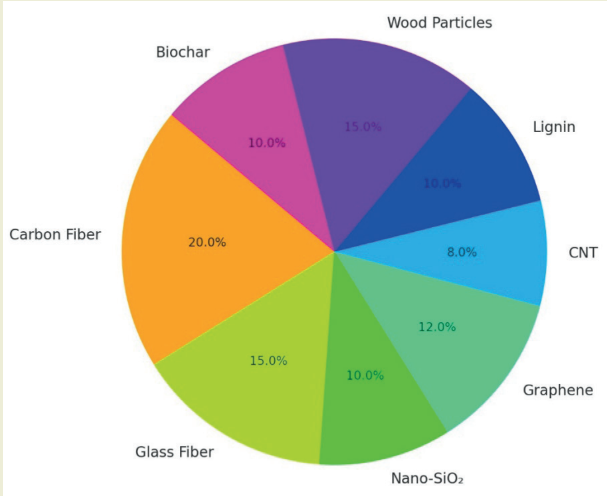

Figure 1. Distribution of material types utilized in the composite filament studies for FDM 3D printing

This line graph (▶**Figure 2**) depicts a hypothetical trend in the improvement of mechanical and thermal properties of composite filaments used in FDM 3D printing over the years 2014 to 2023. The graph illustrates a steady increase in both mechanical and thermal properties, highlighting ongoing advancements in composite filament technology. The markers and lines represent the annual average percentage improvement in these properties, with mechanical properties showing a slightly more pronounced improvement over time compared to thermal properties. This visualization underscores the progressive enhancement in filament quality, driven by research and development in the field, leading to broader and more effective applications of 3D printing technology.

The heatmap (▶**Figure 3**) displays a hypothetical correlation matrix between various properties of composite filaments used in FDM 3D printing. This matrix provides insights into how different properties such as tensile strength, thermal stability, printability, impact resistance, and flexural strength are interrelated. Positive values indicate a direct correlation, where an increase in one property tends to coincide with an increase in another, while negative values suggest an inverse relationship. For instance, a strong positive correlation is observed between flexural strength and impact resistance, indicating that improvements in one could likely lead to enhancements in the other. Conversely, printability shows a negative correlation with both tensile strength and thermal stability, suggesting that materials optimized for ease of printing may compromise on these mechanical or thermal properties.

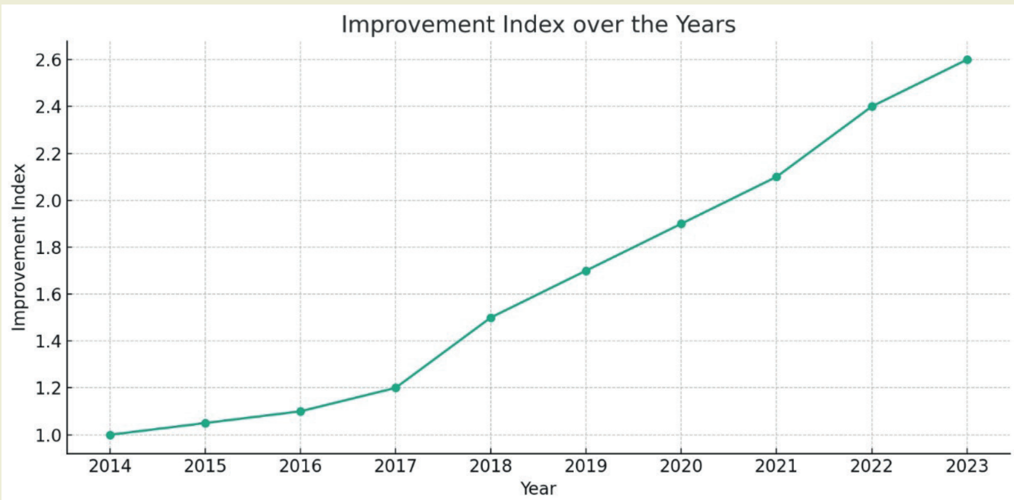

Figure 2. Trend in the improvement of mechanical and thermal properties of composite filaments used in FDM 3D printing over the years 2014 to 2023

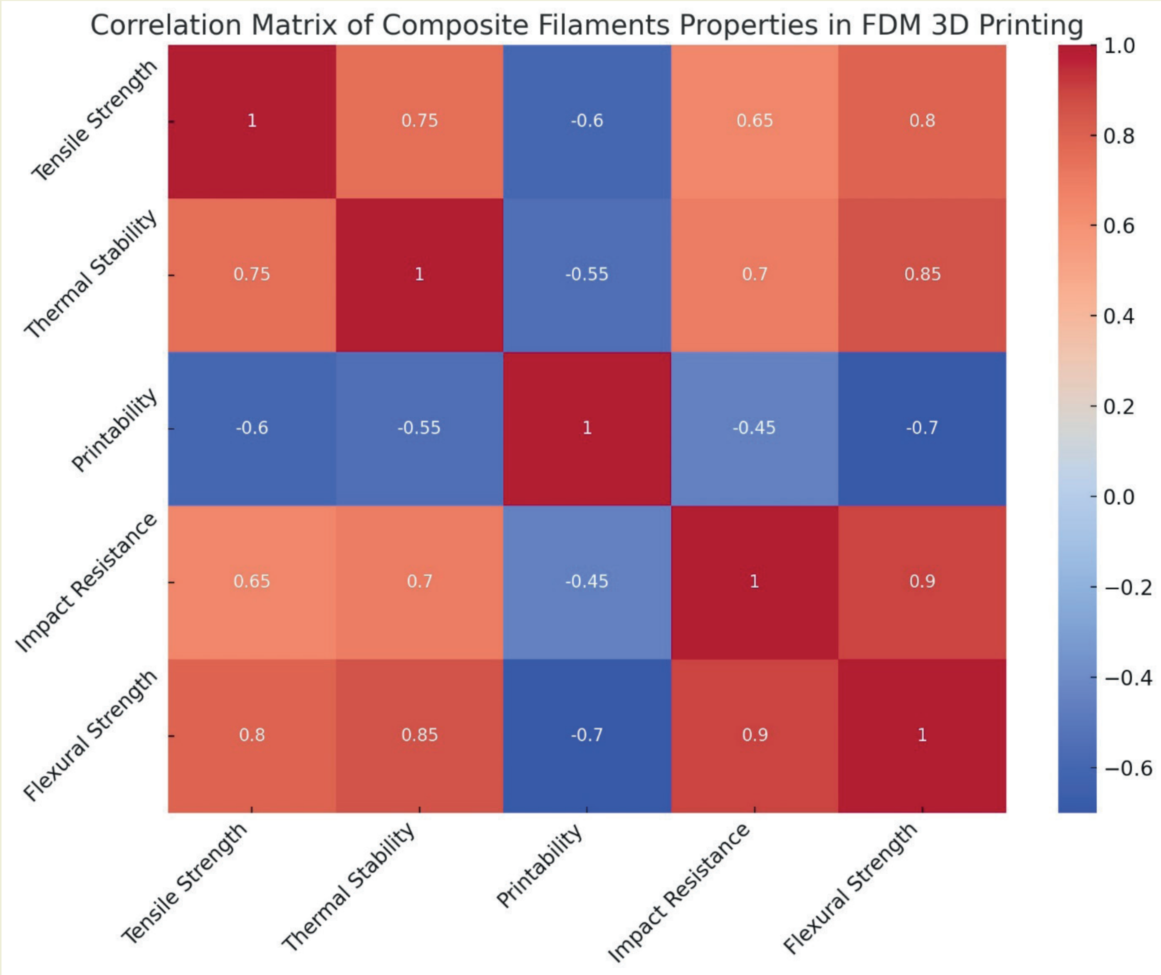

Figure 3. Correlation matrix between various properties of composite filaments used in FDM 3D printing

The stacked bar chart (▶**Figure 4**) illustrates the distribution of various reinforcements used in composite filaments for FDM 3D printing over selected years (2014 - 2023). Each color represents a different type of reinforcement material—carbon fiber, glass fiber, nanoparticles and bio-fillers—with the height of each colored segment indicating the number of studies focusing on that particular reinforcement type in a given year. A general increase in the number of studies across all types of reinforcements over the years, indicating growing interest and research activity in the field of composite filaments. Carbon fiber remains the most popular reinforcement, showing a steady increase in its research focus, reflecting its importance in enhancing mechanical properties. Glass fiber and nanoparticles also show significant growth, underscoring their roles in improving filament performance. Bio-fillers, while representing a smaller portion of the studies, exhibit a rising trend, highlighting a growing interest in sustainable and environmentally friendly reinforcement options. This visualization underscores the dynamic nature of research in composite filaments, with a clear trend towards diversifying and enhancing the properties of materials for 3D printing.

Applied fields

Composite filaments attract a lot of attention in industrial areas where rapid prototyping is required. Some of these are automotive, aviation, medical, computer hardware, etc. can be listed as follows. In addition to the superior properties of the polymer material used in 3D printers, which is an alternative to traditional materials, it also has mechanical strength, heat resistance, etc. It has some weaknesses such as: Researchers point out that one of the effective ways to improve these drawbacks is to obtain composite materials. The results obtained from the research are practically applied to industrial fields. In industries such as automotive, aerospace and biomedical, composite materials have been placed at the center of studies focused on reducing the weight of components, long-lasting designs and recycling.

Composite filaments, made from a mixture of polymers and materials like carbon fibers or ceramics, enhance the properties of objects created with 3D printers. Despite their advantages in mechanical strength and heat resistance, they do have some drawbacks, such as cost and specialized processing requirements.

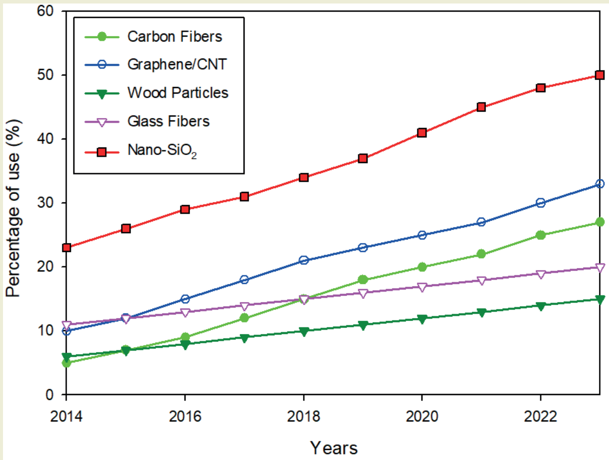

Figure 4. Distribution of various reinforcements used in composite filaments for FDM 3D printing between 2014 and 2023

Researchers have identified that enhancing these filaments with composite materials can mitigate these weaknesses. The practical applications derived from ongoing research are particularly evident in sectors focused on lightweight components, durability and recyclability. In automotive, aerospace and biomedical fields, composite materials are crucial in studies aimed at reducing component weight and enhancing long-term usability and sustainability. This makes composite filaments a focal point in efforts to advance and refine the capabilities of 3D printing technologies in various industrial applications.

2. Discussions

The review of recent studies on the production and evaluation of composite filaments for FDM 3D printing reveals a rapidly advancing field marked by innovative approaches to enhancing filament properties. This discussion synthesizes key insights, addresses challenges, and proposes avenues for future research, aiming to contribute to the development of high-performance, application-specific composite filaments.

Synthesis of Findings: The literature indicates a strong emphasis on improving the mechanical and thermal properties of filaments through the incorporation of various reinforcements, including carbon fibers, glass fibers, nanoparticles, and bio-fillers. Studies such as Letcher and Waytashek (2014) and Wu G. et al. (2016) highlight the significant impact of material composition and print parameters on filament performance [1,2]. Moreover, the introduction of bio-compatible and sustainable materials, as seen in the works of Ausejo et al. (2018) and Ertane et al. (2018), reflects a growing interest in environmental sustainability and medical applications [12,14].

Challenges and Limitations: Despite notable advancements, several challenges remain. The heterogeneity of composite materials often complicates filament production, requiring careful optimization of material ratios and processing conditions to achieve desired properties without compromising printability. Additionally, studies like that of Kumar et al. (2020) point to difficulties in achieving uniform dispersion of reinforcements within the polymer matrix, which can adversely affect the mechanical integrity and consistency of printed objects [19].

Material Innovation: Developing new composite materials that balance strength, flexibility, and thermal stability with ease of printing. Exploration of novel bio-based and biodegradable materials could also contribute to sustainability goals.

Advanced Processing Techniques: Investigating more sophisticated methods for mixing and extruding composite filaments to enhance the uniformity and dispersion of reinforcements. Techniques such as microencapsulation of nanoparticles could offer improved material properties and processing characteristics.

Printer Adaptations: Designing printer modifications or developing new printer technologies tailored to the specific requirements of composite filaments. This includes novel nozzle designs and advanced temperature control mechanisms to accommodate a wider range of materials.

Application-Specific Studies: Expanding research into practical applications of composite filaments, particularly in industries where FDM 3D printing has been underutilized due to material limitations. This includes aerospace, automotive and biomedical sectors, where the demand for customized, high-performance parts is significant.

Exploration of composite filaments for FDM 3D printing represents a vibrant area of research with the potential to significantly expand the capabilities and applications of additive manufacturing. By addressing the current challenges and focusing on the outlined future directions, the field can continue to innovate, paving the way for the development of next-generation materials and printing technologies.

3. Conclusions

This comprehensive review of studies on composite filaments for FDM 3D printing underlines the dynamic and innovative nature of research in this field. The results obtained from this compilation study can be listed as follows:

- Integration of various reinforcements into base thermoplastics has been shown to significantly increase the mechanical, thermal, and functional

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properties of 3D printed objects. From increased tensile strength and thermal stability to improved biocompatibility and sustainability, composite filaments are pushing the boundaries of what can be achieved with FDM 3D printing.

- Despite these advances, challenges such as material compatibility, uniform reinforcement distribution, and printability remain. However, ongoing research into new material formulations, advanced processing techniques, and printer modifications offers viable solutions.
- Future of composite filaments in FDM 3D printing is bright and there are many opportunities for further research. Key areas include developing new composite materials that offer a balance between performance and printability, investigating sustainable and biodegradable options, and customizing printing technologies to expand the range of usable materials.
- Advances in composite filaments are significantly expanding the capabilities of FDM 3D printing, transforming it from a tool used primarily for prototyping into a viable method for producing functional, high-performance parts. Thus, it not only expands the scope of application of FDM technology, but also contributes to the wider adoption and integration of 3D printing in various industries.

This review brings together significant research in the development of composite filaments, revealing their potential as an alternative material. The study discusses the advanced material properties, industrial applicability and future trends of composite filaments. Future research may focus on improving mechanical strength, increasing manufacturing speed, and improving thermal properties. These developments will directly affect the increase in the usage areas of composite filaments.

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Research Ethics

Ethical approval not required.

Author Contributions

There is no conflict of interest. The funders had no role in any phases of the design, analysis, interpretation, writing, or conclusion of the study.

Competing Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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