International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal Européen des Systèmes Automatisés
Vol. 58, No. 3, March, 2025, pp. 409-419
Journal homepage: http://iieta.org/journals/jesa

Towards a Survey of 3D Printing Technologies of Composite Materials: Design Properties, and Application

Mohamed Ksiouar*, Mouad Garziad, Zakariya El Khoumsi, Radouane Boujmal

Mechanical Engineering Laboratory, Sidi Mohamed Ben Abdellah University, Fez 30000, Morocco

Corresponding Author Email: mohamed.ksiouar@usmba.ac.ma

https://doi.org/10.18280/jesa.580301

Received: 28 January 2025
Revised: 6 March 2025
Accepted: 14 March 2025
Available online: 31 March 2025

Keywords:
3D printing, reinforcing fibers, mechanical properties, thermal properties, optical properties, composite materials

ABSTRACT

This review article summarizes recent advances in 3D printing composite materials, emphasizing the selection of the material, accessible processing technology, and key issues. Particulate fillers and reinforcing fibers dispersed into thermoplastic matrices suitable for additive manufacturing receive special attention. The mechanical, thermal, and optical properties of 3D-printed composite parts are compared and described in relation to their applications. This research demonstrates the application of 3D printing composite materials in biomedical, automotive, and aerospace applications.

1. INTRODUCTION

Additive manufacturing, especially 3D printing, has recently made remarkable advancements, revolutionizing materials engineering and design. In this context, integrating composite materials and 3D printing innovation has raised a captivating range of inquiries about progressing novel conceivable outcomes for optimization and advancement [1].

This common writing survey discusses the multifaceted exchange between composite fabric plans, 3D printing forms, and plan optimization. By targeting the chosen materials, utilized technologies, and various optimization methods, this review provides a balanced view of the current research in this fast and continuously evolving field.

This review contributes to the general body of knowledge by examining reinforcement agents, matrix systems, and new challenges of 3D printing. It provides insights applicable to future research and projects in 3D printing with composite materials.

Marchal et al. [2] conducted an experimental study on the influence of fiber routing strategies—concentric, oriented, and their combination—on the mechanical performance of 3D-printed carbon fiber-reinforced truss structures. The combined routing strategy demonstrated the best strength and stiffness. These findings lay the groundwork for future simulation-driven optimization of fiber paths in composite additive manufacturing. Abderrafai et al. [3] utilized fused filament fabrication (FFF) to print 3D short carbon fiber-reinforced polyamide composites with acceptable strength and heat conductivity profiles. In another paper [4], using FFF to produce composites with continuous glass and carbon fiber-reinforced high-temperature Polyamide 6 (Onyx) revealed dramatic improvement. Specifically, the Onyx + CF composites revealed a remarkable 1243% improvement in Young's modulus and a 1344% improvement in tensile strength concerning neat Onyx samples.

This paper is organized into five parts. In the second part of this paper, we will describe the methodology used in this review; we will outline in the third part the method employed and define each of the primary additive manufacturing processes in turn: Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Selective Laser Melting (SLM). In part four, we will discuss how these processes affect mechanical, thermal, and optical properties and reference several studies to gain comparative insight. This comparative approach aims to reveal research gaps and determine areas of future progress. In section five, we will also discuss the industrial applications of biomedical, automotive, and aerospace technologies to show how the distinctive properties of additively manufactured materials translate into real-world benefits.

By synthesizing proof over the complete writing, our survey points to summarize the common condition of added substance fabricating forms and open windows to more critical advancement in this quickly advancing field.

2. METHODOLOGY

As part of our research, we will focus on the takeover technique. This carefully structured approach offers an attractive and concise format for candid analysis of the current composition. Following this rigorous structure, we guarantee our information's consistent quality and honesty throughout the main stages, which you can find in Figure 1 below:

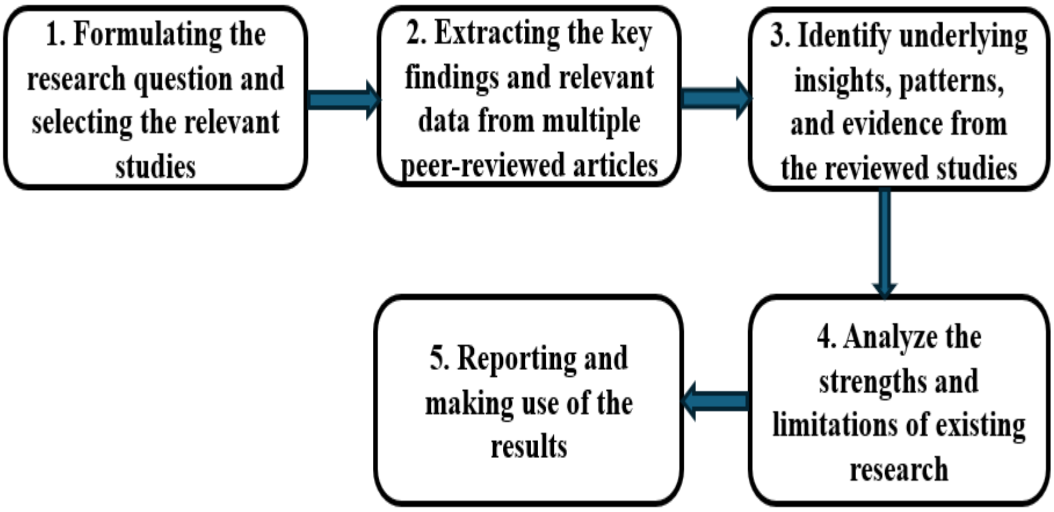

Figure 1. Methodology and approach

3. OVERVIEW OF THE ADDITIVE MANUFACTURING TECHNOLOGIES

3.1 Generalities

Additive manufacturing (AM), or 3D printing, is a layer-by-layer fabrication process that transforms digital CAD models into physical objects. Over the past decade, AM has matured into a cornerstone of Industry 4.0 due to its capacity for mass customization, material efficiency, and reduced waste [5].

The different techniques of AM shown in Figure 2 can be classified according to the materials used in them.

Figure 3 outlines the advancement of added substance fabricating from its initiation within the 1970s to the display.

Figure 2. Additive manufacturing process [6]

3.2 Fused deposition modelling

Fused Deposition Modeling (FDM), a layer-by-layer extrusion-based additive manufacturing (AM) technique, has emerged as a promising alternative to conventional textile production by facilitating direct polymer deposition. This review underscores the transformative potential of FDM in manufacturing adaptable structures while looking at how to prepare parameters that impact mechanical quality and surface characteristics. It also overviews later developments in fiber materials, especially polymer composites and mixes, and points to upgrading the usefulness and printability of FDM-fabricated materials [7].

According to Kristiawan et al. [8], the composition and manufacturing of filaments have an impact on FDM performance in addition to the printing procedure. Filaments are composites or pure polymers with mechanical and thermal qualities enhanced by adding materials like glass fiber and oxidized patterns. Critical process parameters such as extrusion temperature, raster square, and layer thickness are combined and optimized as interactions have a significant impact on partial quality. Despite the versatility of FDM, challenges such as the bond between layer and material uniformity remain important areas for further research and development. Durgun & Ertan [9] examined the impacts of portion introduction and raster point on the mechanical execution and generation fetched of FDM-printed components, concluding that portion introduction has an overwhelming effect on surface harshness and mechanical quality, subsequently highlighting the need for parameter optimization. Dey and Yodo [10] broadly surveyed FDM handle parameter optimization, analyzing their impact on essential portion characteristics such as surface wrap-up, mechanical properties, and dimensional precision. They considered existing optimization procedures and inquired about crevices to advise future headways. In a related test ponder, Nancharaiah et al. [11] inspected the effect of chosen FDM prepare parameters on surface quality and dimensional precision, identifying layer thickness and street width as the foremost influential variables while noticing the negligible impact of raster point. The discussed crevice appeared to fundamentally influence dimensional exactness, fortifying the significance of preparing parameter control, especially layer thickness, in improving the quality of FDM-manufactured parts.

Figure 4 below presents additives AM schematics using FDM.

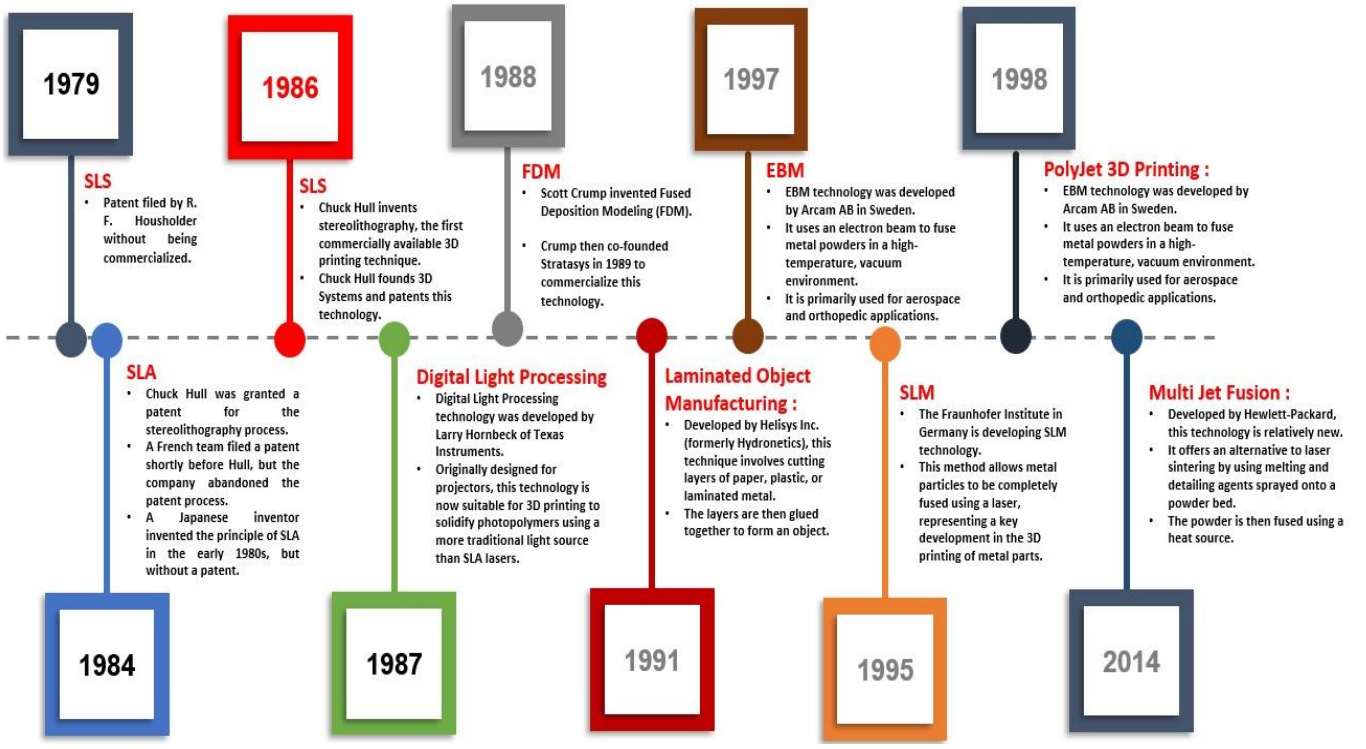

Figure 3. Historical timeline of additive manufacturing

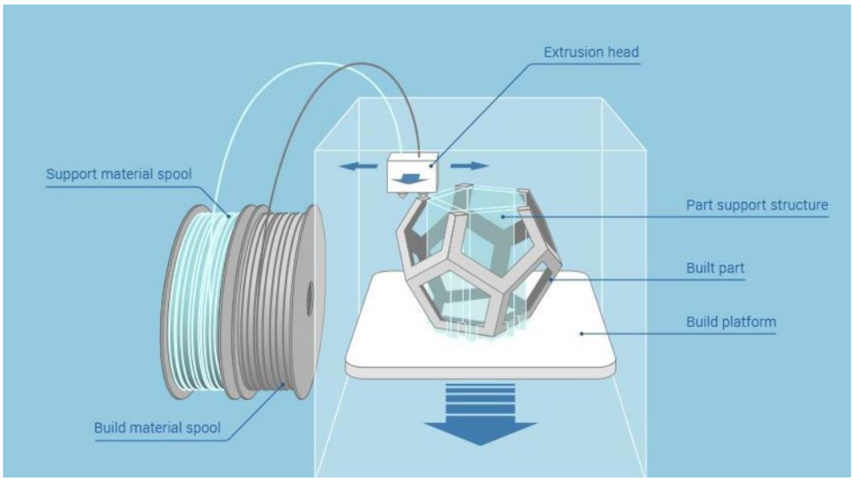

Figure 4. Schematics of AM by FDM [12]

3.3 Stereolithography

Stereolithography (SLA) is a high-resolution additive manufacturing technology that allows UV light to cure liquid resins layer-by-layer. It is progressing to improve partial performance and functionality, especially for the high-speed production of polymer nanocomposites, as soon as it is used in prototypes [13].

Huang et al. [14] offer a precise diagram of the advancement of SLA, categorizing its improvement into four essential eras: checking, projection, nonstop, and volumetric. Each organization presented progressions in determination, printing speed, and fabric flexibility, with current advancements emphasizing multi-material printing and freeform creation to improve essential complexity and usefulness. In a complementary survey, Husna et al. [15] look at later advances in SLA, centering on how basic preparation parameters—including layer thickness, introduction time, print introduction, and laser power—affect mechanical execution and surface quality. They highlight the integration of optimization procedures, such as Genetic Calculations and Fabricated Neural Frameworks, to make strides in immovable quality and manufacturing adequacy. Additionally, their work underscores the extending sending of SLA in fragments like biomedical building, flying, and mechanical manufacturing. However, recognizing a squeezing requires investigating progressed and multi-material frameworks to broaden SLA's capabilities in a feasible generation. In a centered think about, Li et al. [16] investigated the impact of printing introduction on the mechanical properties of SLA-printed photopolymers. Their discoveries uncovered a straight decay in ductile quality with an expanding introduction point, whereas Young's modulus remained consistent, demonstrating isotropic firmness. Break durability displayed a non-linear, cubic reaction with a greatest at 30°, credited to combined malleable and shear disappointment components. Moreover, the EMC-

MTS prescient demonstrates illustrated tall exactness, with break stack expectations veering off by less than 7% from exploratory comes about, recommending solid potential for basic optimization in SLA-fabricated components.

Schematics of additive manufacturing using the SLA process are shown in Figure 5.

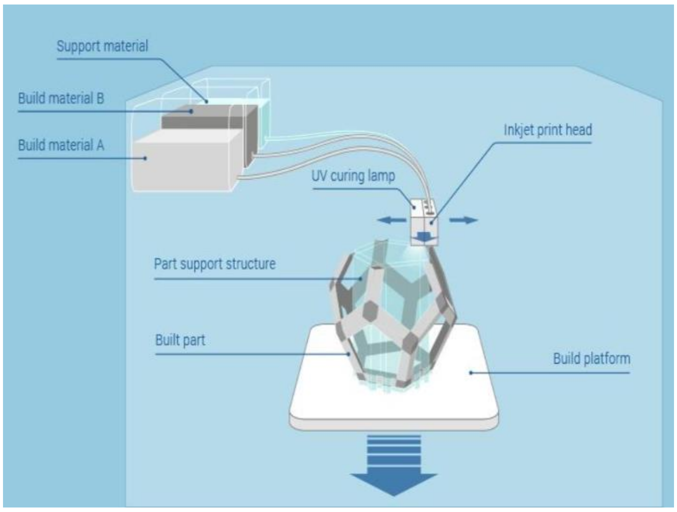

Figure 5. Schematic view of SLA process [12]

3.4 Selective laser sintering

Selective Laser Sintering (SLS) is an advanced powder bed fusion (PBF)-based additive manufacturing (3D printing) technology that constructs three-dimensional objects by partially fusing powdered materials using a laser [17].

Yehia et al. [18] provide a basic survey of the Particular Laser Sintering (SLS) of polymers, highlighting the impact of prepare parameters on portion quality and mechanical properties. Integrating machine learning and incredibly profound learning models is emphasized for upgrading imperfection discovery, preparing control, and real-time checking. The audit diagrams rising patterns in high-performance materials and shrewdly fabricating, situating ML as a key enabler for future progressions in SLS. Jabri et al. [19] give a basic audit of polymer-based Particular Laser Sintering (SLS), emphasizing the impact of key handle parameters—such as laser control, filter speed, and vitality density—on warm behavior, weariness resistance, and surface harshness. The think about highlights that optimizing these factors, at the side powder morphology and construct introduction, is fundamental for making strides in mechanical execution and portion quality in SLS-fabricated components. Azam et al. [20] give an in-depth diagram of later improvements within the particular laser sintering (SLS) of electrically conductive polymer composites (ECPCs), centering mainly on their piezoresistive self-monitoring usefulness. The survey discusses basic manufacture parameters, solidification instruments, and the impact of isolated filler systems in progressing strain location affectability. Moreover, it analyzes progressing challenges and future headings for integrating these materials in progressed applications such as auxiliary well-being checking and wearable sensor advances.

Figure 6 presents visual representations of the SLS technique in additive manufacturing.

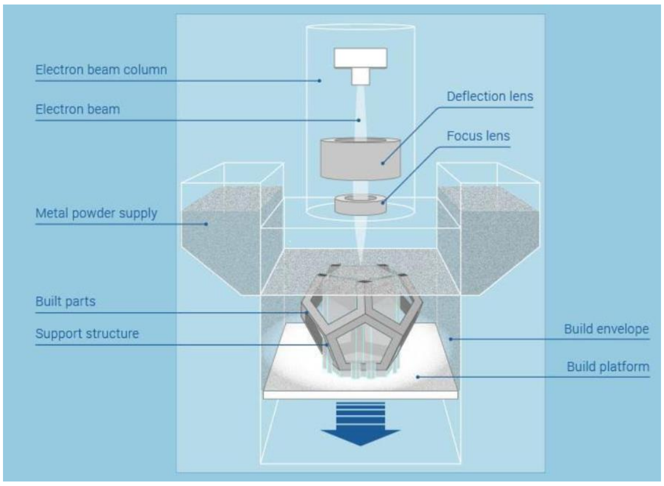

Figure 6. Visual representations of the SLS technique in the field of additive manufacturing are presented [12]

3.5 Selective laser melting

Selective Laser Melting (SLM) is an advanced additive manufacturing technique using high-power lasers to fully melt and fuse metallic powders, producing near-net-shaped, high-density components. Also known as Direct Metal Laser Sintering (DMLS) or LaserCusing, SLM allows the economical fabrication of functional, fully dense parts. Recent advancements in laser and fiber optic technologies have broadened the range of processable materials to include metals such as copper and aluminum, with growing research interest in ceramics and composite materials [21].

Sefene [22] reviews the SLM process, a prominent metal additive manufacturing technique for creating high-strength, lightweight, and geometrically complex components, particularly in the aerospace and biomedical sectors. The study critically examines how material characteristics, process parameters, and simulation tools affect the quality and performance of the fabricated parts. Despite its significant potential, the review highlights ongoing challenges, such as porosity, residual stresses, and limitations in multi-material processing. These issues call for further research to enhance SLM technology's reliability and industrial applicability. In another study, Tian [23] provides a comprehensive overview of SLM technology's development and current status. This paper emphasizes SLM's capability to manufacture high-precision, complex metal parts for various industries, including aerospace, medical, automotive, and mold fabrication. Key advantages of SLM include its high mechanical strength and design flexibility. However, challenges such as spheroidization, porosity, and low efficiency. Soni et al. [24] present a focused review of the capabilities of SLM for processing ferrous and non-ferrous alloys, especially aluminum, titanium, and steel. The article discusses how process parameters influence mechanical, microstructural, and corrosion properties, emphasizing applications in aerospace and biomedical fields. Key issues such as porosity and anisotropy are addressed, with modeling highlighted as a tool for process optimization. The review positions SLM as a driver for next-gen manufacturing, particularly through multi-material and hybrid component innovations.

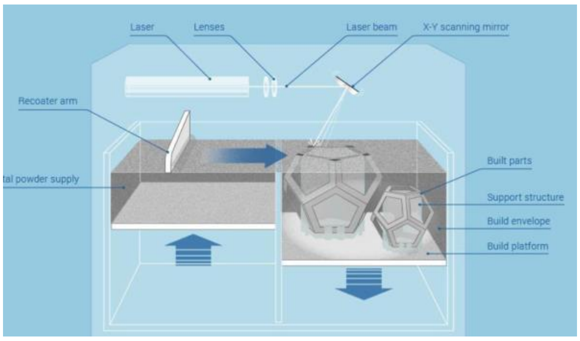

Figure 7. The diagram shows how SLM is used in additive manufacturing [12]

Figure 7 illustrates the use of SLM in additive manufacturing.

4. PHYSICALS CHARACTERISTICS OF COMPOSITE PARTS MANUFACTURED THROUGH 3D PRINTING

4.1 Mechanical properties

Mechanical properties are essential for assessing the performance and longevity of composite parts. The Table 1 below compares key factors like tensile and yield strength across various studies, illustrating how material choice, printing techniques, and post-processing influence the results.

Table 1. Mechanical properties

Study	Research Objectif/Topic	Materials, Machine, Strandars	Variable Parameters	Mechanical Properties
Ambekar et al. [25]	3D-printed carbon nanotube networks, zeolite template, enhanced mechanical properties	Carbon nanotubes, Zeolite, FDM, ASTM D638, ASTM D790	Geometry, layer thickness, printing speed, infill density, CNT/zeolite ratio (qualitative)	Tensile strength, flexural strength, impact resistance, elastic modulus
Camargo et al. [26]	PLA-graphene filament, FDM, mechanical properties	PLA, Graphene, FDM, ASTM D638, ASTM D790	Graphene content, layer height, printing speed, infill pattern	Tensile strength, flexural strength, impact resistance, Young's modulus
Zhang et al. [27]	Graphene oxide, 3D printing, Cu^{2+} adsorption	Graphene oxide, Double-network macro-monolithic adsorbent, 3D printing	Printing speed, layer thickness, GO concentration	Tensile strength, compressive strength
Fortin et al. [28]	Radiopaque filaments, FFF, 3D printing	Radiopaque filaments, FFF, ASTM standards	Filament composition, printing speed, layer thickness, infill density	Tensile strength, elastic modulus
Mazur et al. [29]	Biodegradable PLA composites, FDM, mechanical properties	PLA, by-products, FDM, ASTM D638, D790	By-product content, printing speed, layer thickness, infill pattern	Tensile strength, elastic modulus
Park et al. [30]	Water-soluble 3D micro molds, complex-shaped lipid microparticles, drug delivery	Calcium-based molds, Lipids, Two-Photon Polymerization (TPP), Inkjet Printing (IJP)	Mold geometry, lipid infiltration speed, printing resolution, leaching temperature	Porosity, structural integrity
Bogahawaththa et al. [31]	Energy absorption and mechanical performance of Menger Fractal Cube (MFC) structures	AlSi7Mg aluminum alloy powder, GE additive M2 machine, ASTM E8	Fractal order, printing speed, laser power, layer thickness	Tensile strength, yield strength, fracture strength
Liu et al. [32]	Analyze the mechanical performance and damage mechanisms of 3D printed concrete (3DPC) based on pore structure characteristics	3D printed concrete (3DPC), X-ray Computed Tomography (X-CT), Digital Image Correlation (DIC), GB/T 50081–2002 for mechanical properties of ordinary concrete	Pore structure (size, shape, distribution), Curing time, Loading directions (X, Y, Z), Parallel pore conection model	Compressive strength, splitting tensile strength, flexural strength, mechanical anisotropy, stress concentration
Panda et al. [33]	Evaluate the effect of short glass fiber (GF) reinforcement on the anisotropic mechanical performance of 3D printed geopolymer mortar	Fly ash-based geopolymer, short glass fibers (3 mm, 6 mm, 8 mm), 4-Axis gantry system, Extrusion-based 3D printing	Fiber length (3 mm, 6 mm, 8 mm), fiber percentage (0.25%–1%), Loading direction (T1, T2, T3).	Compressive strength, flexural strength, tensile strength, anisotropic behavior due to layer-wise deposition.
Hanon et al. [34]	Impact of build orientation, raster angle, and layer height on PLA tensile strength and hardness	PLA, FDM, WANHAO Duplicator 6, ISO 527-2 (tensile), ASTM D2240 (hardness)	Orientation (flat, on-edge, upright), raster angle, layer thickness	Young's modulus, UTS, elongation, shore D hardness

4.2 Thermal properties

Thermal properties are essential for assessing the behavior of 3D-printed composites under different temperature conditions. Table 2 compares studies on thermal conductivity, heat transfer, and temperature dependence, highlighting their impact on material performance in various environments.

Table 2. Thermal properties

Study	Research Objectif/Topic	Materials, Machine, Strandars	Variable Parameters	Thermal Properties
Ivanov et al. [35]	PLA composites with GNP/MWCNT for FDM 3D printing	PLA (Ingeo™ Biopolymer PLA-3D850), GNP, MWCNT, Melt extrusion, FDM 3D printer	Filler type (GNP, MWCNT), filler content (0–6wt.%), GNP/MWCNT ratios (e.g., 3% GNP/3% MWCNT)	Thermal conductivity, thermal diffusivity
Kalaš et al. [36]	Dielectric and thermal properties of 24 polymers for FFF in electronics	PC, PETG, ABS-T, ASA, PLA, PVC, TPE, PA12; Prusa MK3S; IEC 60243-1, IEC 62631-3	Polymer type, frequency (0.5 Hz–1 MHz), temperature (ambient to 700°C)	Glass transition (Tg), melting temperature (Tm), oxidation stability (Tox)
Eom et al. [37]	Evaluate thermal insulation of 3D printed spacer materials in cold environments	Thermoplastic Polyurethane (TPU) CUBICON Single Plus, FFF 3D printing ISO 527-2	Pore size (0.6 cm, 0.9 cm) Leg height (0.5 cm, 1.5 cm)	Surface temperature, internal temperature, insulation efficiency
Spinelli et al. [38]	Effect of nanocarbon fillers on PLA for 3D printing	PLA, MWCNTs, GNPs, FDM 3D Printer	Filler type, Filler content (0-12 wt%)	Thermal conductivity, heat dissipation
Lee et al. [39]	Evaluate thermal properties of UV curable acrylate composites using Digital Light Processing (DLP) 3D printing	Butyl acrylate, Diurethane dimethacrylate, Aluminum Nitride (AlN), DLP 3D Printer	Crosslinker-to-monomer ratio, AlN filler content (0-30 wt%)	Thermal conductivity
Stepashkin et al. [40]	PEEK-CF composites: Structure & Thermal	PEEK, Carbon fiber, FDM Z2 3D Printer	Fiber Type, Printing Parameters, Fiber Orientation	Anisotropic thermal conductivity, porosity-induced anisotropy
Tablit et al. [41]	Evaluate the impact of chemical treatments on Arundo donax L. fibre/PLA/PP composite filament for FDM 3D printing.	Arundo donax L. Fibre, PLA, Industrial waste PP, Flash Forge Creator Pro 3D printer.	Fibre treatment type (untreated, alkali, alkali + silane), fibre content, printing parameters.	Glass Transition, temperature, thermal stability
Jiang et al. [42]	Enhance thermal capacity of 3D-printed phase change concrete while maintaining strength	Phase Change Materials (PCM), Paraffin, Concrete, JennyLight 1 + LCD 3D Printe, GB/T50081-2019	PCM Content (0%, 33%, 66%, 99%) Aggregate Type (Basalt vs. Phase Change)	Thermal insulation, latent, heat storage, hydration, temperature, regulation
Wei et al. [43]	Investigate thermal conductivities of metal powders for AM	Inconel 718, 17-4 SS, Inconel 625, Ti-6Al-4V, 316L SS, Transient Hot Wire Method	Gas Composition (Ar, N2, He), Gas Pressure (1.4–101 kPa), Temperature (295–470 K)	Thermal conductivity, gas composition influence, gas pressure influence, temperature dependence, thermal accommodation coefficient
Mantihal et al. [44]	Optimize 3D chocolate printing by correlating thermal and flow properties	Chocolate, Magnesium Stearate (MgST), 3D food printer (Rotary screw extrusion)	Support structures, MgST addition, nozzle temperature	Melting properties, glass transition,

4.3 Optical properties

The optical properties of 3D-printed composites, including light absorption, reflection, and transmission, are crucial for applications like sensors and optical devices. Table 3 below compares various studies, illustrating how different materials and printing methods influence optical performance and potential design improvements.

Table 3. Optical properties

Study	Research Objectif/Topic	Materials, Machine, Strandars	Variable Parameters	Optical Proprieties
Inamura et al. [45]	Development of G3DP2 technology for transparent glass 3D printing	Transparent glass, G3DP2 platform	Temperature control, motion control, printing speed	Transparency, Optical clarity, Light transmission, Refractive index
Gonzalez-Hernandez et al. [46]	Validation of laser 3D printing combined with high-	SZ2080™ hybrid material, Transforms to glass-ceramic via calcination, Ultrafast Laser Direct-Write (LDW)	Laser intensity scanning speed, calcination	Transparency in the visible range, high resolving power,

	temperature calcination to create free-form, inorganic micro-optics.	Nanolithography, High-Temperature Calcination (1100°C).	temperature, pre-compensation angle for shrinkage control.	refractive index
Kotz et al. [47]	Miniaturization of chemical synthesis through high-performance 3D printing.	Silicate glasses, Ceramics, Fluorinated polymers, Stereolithography, FDM, Two-Photon Polymerization	Viscosity, printing resolution, thermal post-processing conditions, chemical resistance.	High optical transparency
Martín-Sómer et al. [48]	Develop low-cost solar collectors for water treatment	PLA (3D printing), Recycled Reflective Materials (Aluminium Foil, Cans), ZMorph VX 3D Printer, Open-source Arduino Control System	Reflective material type, Solar tracking angle, UV LED intensity	Reflectivity,
Huang et al. [49]	Control microstructure in SLM using Optical Engine	Alloys, SLM Machine, Solidification Principles	Laser shape, cooling rate	Adaptive irradiation, thermal control
Aguirre-Cortés et al. [50]	3D Printing in Photocatalysis	Photoactive materials: TiO2, Cu-doped TiO2, g-C3N4, MoS2, Support materials: Silica, Polyamide, Ceramic, 3D printing filaments: PLA, ABS, PVA, PP, PET, PETG, Light sources: LED (visible/UV), 3D printers: SLA, FDM, DLP	Reactor design (size, tortuosity, surface area), catalyst loading and distribution, ink formulation	Absorption, light scattering, and transmittance

5. APPLICATIONS

5.1 Biomedical applications

3D composite printing has been a topic of interest in biomedical applications, specifically focusing on developing tailored prosthetics, biodegradable bone implants, and custom-made medical devices. Onică et al. [51] conducted a 6-year follow-up study on 3D-printed subperiosteal titanium implants in 36 edentulous patients with severe jaw atrophy. Only 25% of cases were successful, with a survival rate dropping from 62.3% at 3 years to 54.1% at 6 years—complications affected over two-thirds of implants, including infections, structural exposure, and mobility. Disappointments were connected to destitute delicate tissue integration and plan restrictions. The consideration highlights the guarantee and clinical dangers of PSIs, calling for progressed embed conventions and long-term approval. Similarly, Alam et al. [52] demonstrated that metal-loaded PLA nanocomposite scaffolds have more excellent antibacterial activity, improved mechanical strength, and high bioactivity and are great candidates for bone tissue engineering. Burns et al. [53] also validated the new era of 3D extrusion bioprinting with microbial inks by demonstrating their ability to self-renew, provide biosynthesis support, and provide bio sequestration support. These innovative bio-inks, developed by genetic modification of microbes, are of unimaginable promise in biomedical applications ranging from drug targeting and tissue engineering to biosensor development over challenges and promise in health science and technology. Rumon et al. [54] also discussed extensively new strategies for increasing hydrogels' mechanical strength by prioritizing stress and cross-linking advances for biomedical applications. Their work highlights the challenging trade-off among mechanical properties, biocompatibility, and degradability and provides important design directions for future tissue substitutes. The paper also lays the ground for the promise of stimuli-responsive and self-healing hydrogels to achieve optimal clinical success for regenerative medicine and wound healing. Clinic validation, however, must be investigated further.

Lu et al. [55] Developed and evaluated a patient-specific 3D-printed prosthetic composite to reconstruct massive bone defects. This innovative composite integrates a custom-designed 3D-printed prosthesis, beta-tricalcium phosphate (β-TCP) bioceramic granules, and vascularized fibula grafts. Combining these components aims to enhance osseointegration and restore limb function in patients undergoing limb-salvage surgeries following malignant surgery. Similarly, Zhang et al. [56] optimized personalized tibial implants using Selective Laser Melting (SLM) and topological design. The implants were lightweight, with improved stress distribution and mechanical performance. Their porous structure mimics natural bone for better biocompatibility. SLM-produced implants showed high surface quality and structural integrity, supporting clinical potential. From a different perspective, Huang et al. [57] review the use of AM in oral implantology, highlighting its role in producing customized dental components. AM technologies like SLA, FDM, SLM, and EBM enable precise, material-efficient fabrication from CAD models. These methods enhance surgical and restorative outcomes compared to traditional techniques. However, long-term clinical effectiveness requires further study, particularly of implants and bone regeneration tools.

5.2 Automotive

3D printing has revolutionized the car industry by quickening prototyping, empowering customized portion generation, and optimizing fabricating forms. Szalai et al. [58] investigated utilizing FDM-based 3D printing for fabricating cutting devices in car and gadgets sheet metal applications. Their discoveries appeared that 3D-printed PLA apparatuses with optimized plans met wear resistance measures, cutting generation costs by up to 90%. This consideration highlights the potential of FDM innovation for quick prototyping and small-scale generation within the car segment, advertising clear headings for future investigation and development. Yang et al. [59] give a nitty gritty survey of AM applications within the car industry, emphasizing its preferences for creating lightweight, complex, and customized components. Their investigation underscores AM's significant role in cultivating development and moving forward effectiveness, especially in quick prototyping and end-use portion generation. The creators examine key challenges, such as fabric impediments, item quality, and the requirement for standardized forms, to assist in fortifying AM's potential to reshape the industry.

Moreover, Böckin and Tillman [60] conducted a Life Cycle Appraisal (LCA) comparing conventional and added substance fabricating within the car segment, with a center on Powder Bed Combination (PBF) for metal motor components. Their investigation uncovered that whereas current AM innovation gives direct natural benefits, future advancements—particularly when combined with clean vitality utilization and lightweight design—could altogether decrease the generally natural effect of vehicles all through their lifecycle; such consideration highlights the significance of surface choices in optimizing the inherent slopes of AM in-car products, confirming the common determination of the industry to take functional choices.

5.3 Aeronautical

AM supports the aerospace industry, creating lightweight structures and complex geometries and advancing with upkeep, repair, and update (MRO) forms. Montanari et al. [61] fundamentally look at utilizing aluminum (Al) amalgams in AM for aeronautical components, examining the focal points and challenges of absconds, microstructure, mechanical properties, and post-processing procedures. Their ponder highlights that the requirement for modern amalgam details moved forward quality confirmation conventions and progressed post-processing strategies to completely open AM's transformative potential in aviation applications.

Building on this viewpoint, Uhlmann et al. [62] investigate the utilization of Particular Laser Softening (SLM) innovation for fabricating titanium combination (TiAl6V4) components within the aviation division. Their investigation illustrates the key benefits of topological optimization and lightweight plan in the assembly of ACARE 2020 and Flightpath 2050 maintainability targets, which center on diminishing fuel utilization and emanations. Moreover, thinking about it underscores the pivotal part of hot isostatic squeezing (HIP) in moving forward microstructural consistency, minimizing porosity, and improving aviation components' mechanical quality and security.

6. CONCLUSIONS

This review has summarized the recent advancements in 3D-printed composite materials, emphasizing their mechanical, thermal, and optical properties. It also covers the key technologies, the performance characteristics of printed parts, and their applications in biomedical, automotive, and aerospace engineering. This paper emphasizes the interplay between material selection, process parameters, and geometric design in enhancing the mechanical performance of 3D-printed composites. Biocompatible and multifunctional printing advances support their use in biomedical and structural applications. Thermal properties, improved through nanofillers and anisotropic designs, enable controlled heat transfer for implants and diagnostics. Optical properties, including transparency and refractive index, are optimized via material choice and post-processing, supporting applications in optics, photocatalysis, and solar devices. From a perspective, 4D printing, which combines composite materials with smart behaviors (such as shape memory), paves the way for advanced applications in fields like soft robotics and active medical devices. Thus, 3D printing of composites is a rapidly growing field, offering solutions tailored to a wide range of needs, from technical performance to environmental sustainability. Another alternative uses 3D printing to create molds that shape composites through conventional lamination or resin infusion. Additionally, some hybrid approaches involve printing porous structures and then impregnating them with resin during post-processing, which helps optimize weight and stiffness.

REFERENCES

[1] Wang, X., Jiang, M., Zhou, Z., Gou, J., Hui, D. (2017). 3D printing of polymer matrix composites: A review and prospective. Composites Part B: Engineering, 110: 442-458. https://doi.org/10.1016/j.compositesb.2016.11.034

[2] Marchal, V., Zhang, Y., Labed, N., Peyraut, F. (2022). Experimental investigation of the impacts of fibre routing strategy on the properties of composite printing. Procedia CIRP, 109: 311-315. https://doi.org/10.1016/j.procir.2022.05.255

[3] Abderrafai, Y., Mahdavi, M.H., Sosa-Rey, F., Hérard, C., Navas, I.O., Piccirelli, N., Lévesque, M., Therriault, D. (2022). Additive manufacturing of short carbon fiber-reinforced polyamide composites by fused filament fabrication: Formulation, manufacturing and characterization. Materials & Design, 214: 110358. https://doi.org/10.1016/j.matdes.2021.110358

[4] Vedrtnam, A., Ghabezi, P., Gunwant, D., Jiang, Y., Sam-Daliri, O., Harrison, N., Goggins, J., Finnegan, W. (2023). Mechanical performance of 3D-printed continuous fibre Onyx composites for drone applications: An experimental and numerical analysis. Composites Part C: Open Access, 12: 100418. https://doi.org/10.1016/j.jcomc.2023.100418

[5] Dipu, M.N.H. (2024). An overview on additive manufacturing technology: Last decade’s literature, components, generic process, printing categories, associated materials, advantages, disadvantages, and research gaps.

[6] Kambale, B. (2021). Which additive manufacturing process is right for you? The Manufacturing Report. https://manufacturing.report/articles/which-additive-manufacturing-process-is-right-for-you.

[7] Sapkota, A., Ghimire, S.K., Adanur, S. (2024). A review on fused deposition modeling (FDM)-based additive manufacturing (AM) methods, materials and applications for flexible fabric structures. Journal of Industrial Textiles, 54: 15280837241282110. https://doi.org/10.1177/15280837241282110

[8] Kristiawan, R.B., Imaduddin, F., Ariawan, D., Ubaidillah, Arifin, Z. (2021). A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. Open Engineering, 11(1): 639-649. https://doi.org/10.1515/eng-2021-0063

[9] Durgun, I., Ertan, R. (2014). Experimental investigation of FDM process for improvement of mechanical

properties and production cost. Rapid Prototyping Journal, 20(3): 228-235. https://doi.org/10.1108/RPJ-10-2012-0091
[10] Dey, A., Yodo, N. (2019). A systematic survey of FDM process parameter optimization and their influence on part characteristics. Journal of Manufacturing and Materials Processing, 3(3): 64. https://doi.org/10.3390/jmmp3030064
[11] Nancharaiah, T.R.D.R.V., Raju, D.R., Raju, V.R. (2010). An experimental investigation on surface quality and dimensional accuracy of FDM components. International Journal on Emerging Technologies, 1(2): 106-111.
[12] Tanrikulu, A.A. (2017). Microstructure and mechanical properties of additive manufacturing titanium alloys after thermal processing. Master's thesis, Portland State University.
[13] Manapat, J.Z., Chen, Q., Ye, P., Advincula, R.C. (2017). 3D printing of polymer nanocomposites via stereolithography. Macromolecular Materials and Engineering, 302(9): 1600553. https://doi.org/10.1002/mame.201600553
[14] Huang, J., Qin, Q., Wang, J. (2020). A review of stereolithography: Processes and systems. Processes, 8(9): 1138. https://doi.org/10.3390/pr8091138
[15] Husna, A., Ashrafi, S., Tomal, A.A., Tuli, N.T., Rashid, A.B. (2024). Recent advancements in stereolithography (SLA) and their optimization of process parameters for sustainable manufacturing. Hybrid Advances, 7: 100307. https://doi.org/10.1016/j.hybadv.2024.100307
[16] Li, Y., Teng, Z. (2024). Effect of printing orientation on mechanical properties of SLA 3D-printed photopolymer. Fatigue & Fracture of Engineering Materials & Structures, 47(5): 1531-1545. https://doi.org/10.1111/ffe.14265
[17] Gueche, Y.A., Sanchez-Ballester, N.M., Cailleaux, S., Bataille, B., Soulairol, I. (2021). Selective laser sintering (SLS), a new chapter in the production of solid oral forms (SOFs) by 3D printing. Pharmaceutics, 13(8): 1212. https://doi.org/10.3390/pharmaceutics13081212
[18] Yehia, H.M., Hamada, A., Sebaey, T.A., Abd-Elaziem, W. (2024). Selective laser sintering of polymers: process parameters, machine learning approaches, and future directions. Journal of Manufacturing and Materials Processing, 8(5): 197. https://doi.org/10.3390/jmmp8050197
[19] Jabri, F.E., Ouballouch, A., Lasri, L., Alaiji, R.E. (2023). A comprehensive review of polymer materials and selective laser sintering technology for 3D printing. Journal of Achievements in Materials and Manufacturing Engineering, 118(1): 5-17. http://dx.doi.org/10.5604/01.3001.0053.7286
[20] Azam, M.U., Belyamani, I., Schiffer, A., Kumar, S., Askar, K. (2024). Progress in selective laser sintering of multifunctional polymer composites for strain-and self-sensing applications. Journal of Materials Research and Technology, 30: 9625-9646. https://doi.org/10.1016/j.jmrt.2024.06.024
[21] Yap, C.Y., Chua, C.K., Dong, Z.L., Liu, Z.H., Zhang, D.Q., Loh, L.E., Sing, S.L. (2015). Review of selective laser melting: Materials and applications. Applied Physics Reviews, 2(4): 041101. https://doi.org/10.1063/1.4935926
[22] Sefene, E.M. (2022). State-of-the-art of selective laser melting process: A comprehensive review. Journal of Manufacturing Systems, 63: 250-274. https://doi.org/10.1016/j.jmsy.2022.04.002
[23] Tian, Q. (2021). The development status of selective laser melting technology (SLM). Journal of Physics: Conference Series, 1798(1): 012045. https://doi.org/10.1088/1742-6596/1798/1/012045
[24] Soni, N., Renna, G., Leo, P. (2024). Advancements in metal processing additive technologies: Selective laser melting (SLM). Metals, 14(9): 1081. https://doi.org/10.3390/met14091081
[25] Ambekar, R.S., Oliveira, E.F., Kushwaha, B., Machado, L.D., Sajadi, M., Baughman, R.H., et al. (2020). Zeolite-inspired 3D printed structures with enhanced mechanical properties. arXiv preprint arXiv:2002.00468. https://doi.org/10.1016/j.addma.2020.101628
[26] Camargo, J.C., Machado, Á.R., Almeida, E.C., Silva, E.F.M.S. (2019). Mechanical properties of PLA-graphene filament for FDM 3D printing. The International Journal of Advanced Manufacturing Technology, 103: 2423-2443. https://doi.org/10.1007/s00170-019-03532-5
[27] Zhang, H., Shi, Z., Liu, X., Wang, B., Niu, W., Cai, W., Wu, Z., Zhu, Y., Guo, Q., Wang, H. (2025). Insights into graphene oxide double-network macro-monothlic adsorbent through 3D printing: Mechanical properties and Cu^{2+} adsorption mechanism. Separation and Purification Technology, 363: 132140. https://doi.org/10.1016/j.seppur.2025.132140
[28] Fortin, M.A., Zekraoui, S., Lescot, T., Akbari Taemeh, M. (2025). Radiopaque Filaments for Fused Filament Fabrication (Fff) 3d Printing. Available at SSRN 5142165.
[29] Mazur, J., Sobczak, P., Panasiewicz, M., Łusiak, P., Krajewska, M., Findura, P., Obidziński, S., Żukiewicz-Sobczak, W. (2025). Mechanical properties and biodegradability of samples obtained by 3D printing using FDM technology from PLA filament with by-products. Scientific Reports, 15(1): 5847. https://doi.org/10.1038/s41598-025-89984-0
[30] Park, J., Brugger, J., Bertsch, A. (2025). Additive manufacturing of water-soluble 3D micro molds for complex-shaped lipid microparticles. Nature Communications, 16(1): 1734. https://doi.org/10.1038/s41467-025-56984-7
[31] Bogahawaththa, M., Mohotti, D., Hazell, P.J., Wang, H., Wijesooriya, K., Lee, C.K. (2024). Energy absorption and mechanical performance of 3D printed Menger fractal structures. Engineering Structures, 305: 117774. https://doi.org/10.1016/j.engstruct.2024.117774
[32] Liu, C., Zhang, R., Liu, H., He, C., Wang, Y., Wu, Y., Liu, S., Song, L. (2021). Analysis of the mechanical performance and damage mechanism for 3D printed concrete based on pore structure. Construction and Building Materials, 299: 125572. https://doi.org/10.1016/j.conbuildmat.2021.125572
[33] Panda, B., Paul, S.C., Tan, M.J. (2017). Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. Materials Letters, 209: 148-152. https://doi.org/10.1016/j.matlet.2017.07.123
[34] Hanon, M.M., Dobos, J., Zsidai, L. (2021). The influence of 3D printing process parameters on the mechanical performance of PLA polymer and its correlation with hardness. Procedia Manufacturing, 54: 124-131.

https://doi.org/10.1016/j.promfg.2021.07.038
[35] Ivanov, E., Kotsilkova, R., Xia, H., Chen, Y., Donato, R.K., Donato, K., Godoy, A.P., Di Maio, R., Silvestre, C., Cimmino, S., Angelov, V. (2019). PLA/graphene/MWCNT composites with improved electrical and thermal properties suitable for FDM 3D printing applications. Applied Sciences, 9(6): 1209. https://doi.org/10.3390/app9061209
[36] Kalaš, D., Šíma, K., Kadlec, P., Polanský, R., Soukup, R., Řeboun, J., Hamáček, A. (2021). FFF 3D printing in electronic applications: Dielectric and thermal properties of selected polymers. Polymers, 13(21): 3702. https://doi.org/10.3390/polym13213702
[37] Eom, R., Lee, H., Lee, Y. (2019). Evaluation of thermal properties of 3D spacer technical materials in cold environments using 3D printing technology. Polymers, 11(9): 1438. https://doi.org/10.3390/polym11091438
[38] Spinelli, G., Lamberti, P., Tucci, V., Kotsilkova, R., Ivanov, E., Menseidov, D., Naddeo, C., Romano, V., Guadagno, L., Adami, R., Meisak, D., Bychanok, D., Kuzhir, P. (2019). Nanocarbon/poly(lactic) acid for 3D printing: Effect of fillers content on electromagnetic and thermal properties. Materials, 12(15): 2369. https://doi.org/10.3390/ma12152369
[39] Lee, S., Kim, Y., Park, D., Kim, J. (2021). The thermal properties of a UV curable acrylate composite prepared by digital light processing 3D printing. Composites Communications, 26: 100796. https://doi.org/10.1016/j.coco.2021.100796
[40] Stepashkin, A.A., Chukov, D.I., Senatov, F.S., Salimon, A.I., Korsunsky, A.M., Kaloshkin, S.D. (2018). 3D-printed PEEK-carbon fiber (CF) composites: Structure and thermal properties. Composites Science and Technology, 164: 319-326. https://doi.org/10.1016/j.compscitech.2018.05.032
[41] Tablit, S., Krache, R., Amroune, S., Jawaid, M., Hachaichi, A., Ismail, A.S., Meraj, A. (2024). Effect of chemical treatments of Arundo donax L. fibre on mechanical and thermal properties of the PLA/PP blend composite filament for FDM 3D printing. Journal of the Mechanical Behavior of Biomedical Materials, 152: 106438. https://doi.org/10.1016/j.jmbbm.2024.106438
[42] Jiang, J., Zheng, C., Wang, F., Xu, W., Wang, L., Chen, Z., Su, W. (2022). Novel 3D printing phase change aggregate concrete: Mechanical and thermal properties analysis. Materials, 15(23): 8393. https://doi.org/10.3390/ma15238393
[43] Wei, L.C., Ehrlich, L.E., Powell-Palm, M.J., Montgomery, C., Beuth, J., Malen, J.A. (2018). Thermal conductivity of metal powders for powder bed additive manufacturing. Additive Manufacturing, 21: 201-208. https://doi.org/10.1016/j.addma.2018.02.002
[44] Mantihal, S., Prakash, S., Godoi, F.C., Bhandari, B. (2017). Optimization of chocolate 3D printing by correlating thermal and flow properties with 3D structure modeling. Innovative Food Science & Emerging Technologies, 44: 21-29. https://doi.org/10.1016/j.ifset.2017.09.012
[45] Inamura, C., Stern, M., Lizardo, D., Houk, P., Oxman, N. (2018). Additive manufacturing of transparent glass structures. 3D Printing and Additive Manufacturing, 5(4). https://doi.org/10.1089/3dp.2018.0157
[46] Gonzalez-Hernandez, D., Varapnickas, S., Merkininkaitė, G., Čiburys, A., Gailevičius, D., Šakirzanovas, S., Juodkazis, S., Malinauskas, M. (2021). Laser 3D printing of inorganic free-form micro-optics. Photonics, 8(12): 577. https://doi.org/10.3390/photonics8120577
[47] Kotz, F., Risch, P., Helmer, D., Rapp, B.E. (2019). High-performance materials for 3D printing in chemical synthesis applications. Advanced Materials, 31(13): 1805982. https://doi.org/10.1002/adma.201805982
[48] Martín-Sómer, M., Moreno-SanSegundo, J., Álvarez-Fernández, C., van Grieken, R., Marugán, J. (2021). High-performance low-cost solar collectors for water treatment fabricated with recycled materials, open-source hardware and 3D-printing technologies. Science of The Total Environment, 784: 147119. https://doi.org/10.1016/j.scitotenv.2021.147119
[49] Huang, W.C., Chang, K.P., Wu, P.H., Wu, C.H., Lin, C.C., Chuang, C.S., Lin, D.Y., Liu, S.H., Horng, J.B., Tsau, F.H. (2016). 3D Printing Optical Engine for Controlling Material Microstructure. Physics Procedia, 83: 847-853. https://doi.org/10.1016/j.phpro.2016.08.088.
[50] Aguirre-Cortés, J.M., Moral-Rodríguez, A.I., Bailón-García, E., Davó-Quiñonero, A., Pérez-Cadenas, A.F., Carrasco-Marín, F. (2023). 3D printing in photocatalysis: Methods and capabilities for the improved performance. Applied Materials Today, 32: 101831. https://doi.org/10.1016/j.apmt.2023.101831
[51] Onică, N., Budală, D.G., Baciu, E.R., Onică, C.A., Gelețu, G.L., Murariu, A., Balan, M., Pertea, M., Stelea, C. (2024). Long-term clinical outcomes of 3D-printed subperiosteal titanium implants: A 6-year follow-up. Journal of Personalized Medicine, 14(5): 541. https://doi.org/10.3390/jpm14050541
[52] Alam, F., Shukla, V.R., Varadarajan, K.M., Kumar, S. (2020). Microarchitected 3D printed polylactic acid (PLA) nanocomposite scaffolds for biomedical applications. Journal of the Mechanical Behavior of Biomedical Materials, 103: 103576. https://doi.org/10.1016/j.jmbbm.2019.103576
[53] Burns, N., Rajesh, A., Manjula-Basavanna, A., Duraj-Thatte, A. (2025). 3D extrusion bioprinting of microbial inks for biomedical applications. Advanced Drug Delivery Reviews, 217: 115505. https://doi.org/10.1016/j.addr.2024.115505
[54] Rumon, M.M.H., Rahman, M.S., Akib, A.A., Sohag, M.S., Rakib, M.R.A., Khan, M.A.R., Yesmin, F., Shakil, M.S., Khan, M.M.R. (2025). Progress in hydrogel toughening: Addressing structural and crosslinking challenges for biomedical applications. Discover Materials, 5: 5. https://doi.org/10.1007/s43939-025-00178-x
[55] Lu, Y., Chen, G., Long, Z., Li, M., Ji, C., Wang, F., Li, H., Wang, Z., Li, J. (2019). Novel 3D-printed prosthetic composite for reconstruction of massive bone defects in lower extremities after malignant tumor resection. Journal of Bone Oncology, 16: 100220. https://doi.org/10.1016/j.jbo.2019.100220
[56] Zhang, G., Li, J., Zhang, C., Xie, J., Zhou, X., Wang, A. (2021). Design optimization and manufacturing of bio-fixed tibial implants using 3D printing technology. Journal of the Mechanical Behavior of Biomedical Materials, 117: 104415. https://doi.org/10.1016/j.jmbbm.2021.104415
[57] Huang, S., Wei, H., Li, D. (2023). Additive

manufacturing technologies in the oral implant clinic: A review of current applications and progress. Frontiers in Bioengineering and Biotechnology, 11: 1100155. https://doi.org/10.3389/fbioe.2023.1100155
[58] Szalai, S., Szívós, B.F., Nemes, V., Szabó, G., Kurhan, D., Sysyn, M., Fischer, S. (2025). Investigation of FDM-based 3D printing for optimized tooling in automotive and electronics sheet metal cutting. Applied Sciences, 15(1): 442. https://doi.org/10.3390/app15010442.
[59] Yang, J., Li, B., Liu, J., Tu, Z., Wu, X. (2024). Application of additive manufacturing in the automobile industry: A mini review. Processes, 12(6): 1101. https://doi.org/10.3390/pr12061101.
[60] Böckin, D., Tillman, A.M. (2019). Environmental assessment of additive manufacturing in the automotive industry. Journal of Cleaner Production, 226: 977-987. https://doi.org/10.1016/j.jclepro.2019.04.086
[61] Montanari, R., Palombi, A., Richetta, M., Varone, A. (2023). Additive manufacturing of aluminum alloys for aeronautic applications: Advantages and problems. Metals, 13(4): 716. https://doi.org/10.3390/met13040716
[62] Uhlmann, E., Kersting, R., Klein, T.B., Cruz, M.F., Borille, A.V. (2015). Additive manufacturing of titanium alloy for aircraft components. Procedia CIRP, 35: 55-60. https://doi.org/10.1016/j.procir.2015.08.061