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Enhancement of Composite Materials Using 3D Printing Technology

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Abstract: With the development of 3D printed composite materials the methods of increasing their mechanical and thermal performance, functionality and properties has become more diverse. Specifically, the focus of this research is on methods of improving the performance of the composite materials through the alteration of the 3D printing parameters including part thickness, fiber direction and density of layers. Continuous fiber reinforcements and hybrid materials have been discussed to overcome issues with anisotropy and the variation of reinforcements density. The findings highlighted here include enhanced tensile strength, thermal stability and the weight-to-strength ratios making the product suitable for aerospace, automotive and health care industries. Challenges such as length scales and dispersion of reinforcements are presented, followed by prospects for further studies in terms of developing multifunctional composites and mass production.
Keywords: 3D Printing Technology, Composite Materials, Fiber Reinforcement, Hybrid Composites, Mechanical Properties, Thermal Stability, Anisotropy, Aerospace Applications, Automotive Industry, Material Optimization

I. INTRODUCTION

A. Purpose and Scope

Composites are hybrid systems formed from two or more dissimilar materials with predetermined characteristics that can work synergistically to obtain an improved performance than the constituents. Its adaptation and high-performance criteria including strength-to-weight ratio and durability have placed them as a necessity in aerospace, automotive, construction, and healthcare sectors. However, manufacturing methods of composites through conventional methods still need to be held back by certain constraints such as high cost, restriction in terms of part geometry complex to form, and inability to achieve consistent physical/mechanical properties throughout the volume.

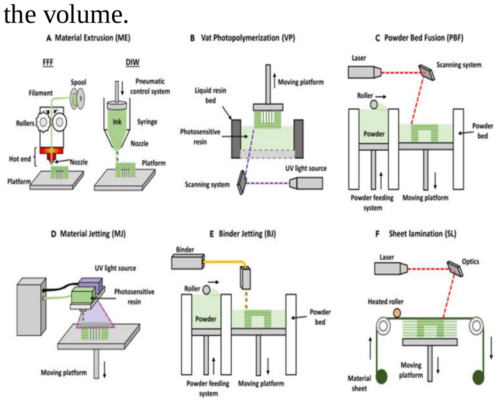

Figure-1: 3D printing of polymer composites: Materials, processes, and applications

3D printing, also referred to as additive manufacturing, is a revolutionary technology in the field of material science to manufacture precise and intricate composite materials. Through the deposition control in material 3D printing overcomes many aforementioned drawbacks of traditional manufacturing while providing improved mechanical, thermal, and electrical characteristics.

The study aim is laid in the context of understanding the potential of the additive manufacturing technique in improving performances, morphology, and versatility of the composite material. The present research seeks to analyze the roles of various 3D printing procedures for creating enhanced composites and to strengthen the foundation for novel solutions that may revolutionize today's manufacturing industries by extending the range of potential applications for advanced-distance composite materials.

B. Background
Traditional composite manufacturing techniques including lay-up, filament winding and the resin transfer molding processes have been employed to produce high-performance materials with excellent mechanical characteristics. The above practices, as good as they may be, require several steps, a lot of material consumption, and a workforce. Furthermore, they also present issues in attaining complex shapes and homestead reinforcement configuration, which somewhat restrict its usefulness in special or complex structures. The new technology of 3D printing, or additive manufacturing, has provided a revolution in the manufacturing processes of composite materials. While conventional approaches involve the fabrication of structures by adding material, layer-by-layer construction in 3D printing is highly precise and flexible. This makes this possible to incorporate bulk reinforcement materials like fibers or nanoparticles systematically into a polymer or a metal matrix. In addition, 3D printing reduces material waste, and manufacturing time, and offers opportunities to design geometries and properties that are difficult to create by conventional manufacturing. In the same way that this revolutionized the field of material science, 3D printing has opened the gates for improved composite materials with better performance characteristics for sustainability and a broader potential application across sectors.

C. Research Problem
However, manufacturing composites conventionally comes with diverse challenges: high wastage of material, time-consuming processes, and; restricted ability to create complex forms. In addition, several composites that compose them have an anisotropic nature, thereby presenting different strength and response directions of forces applied to them unevenly. Opportunities via 3D printing include exactly positioning the bulk of the material and design freedoms; limitations include issues including size, homogenization of reinforcements, and developing efficient bonding between the matrix and reinforcement. Filling these gaps is important to effectively harness 3D printing to improve the performance and deployability of the composite materials.

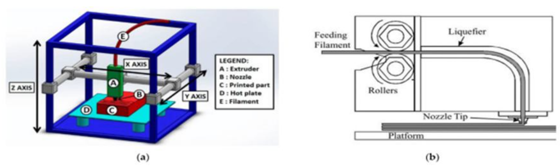

Figure-2: (a) Schematic representation of a typical FDM setup, (b) schematic of the FDM extrusion head and filament deposition process

D. Aims and Objectives
1) *Aim:* To investigate and improve the part properties of 3D printed composite materials based on mechanical, thermal, and functional performance.
2) *Objectives*
- To research in considering the consequent of 3D printing parameters in composites mechanical characteristics.
- To systematically distribute reinforcement.
- To determine the feasibility of using 3D-printed composites for a large-scale application.
- To find out possible uses of composite materials with improved characteristics.

E. Research Questions
1) What role does 3D printing play in improving the mechanical and thermal performance of the composite material?
2) What are the recommended for of print to obtain uniform reinforcement distribution?
3) To what degree are the composite 3D printed for the scale industrial described above?
4) Which industries receive the greatest benefits resulting from the improvement of composites?

II. LITERATURE REVIEW

A. Overview of Composite Materials
Composites result from the integration of at least two different forms of materials in a manner that offers properties that are superior to those exhibited by each of the individual components [1]. These types of material generally contain a matrix, the fixed phase, and a reinforcement the dispersed phase both of which contribute to the performance. The matrix holds the structure of the composite and supports the applied loads and the reinforcement additions increase the mechanical properties, thermal properties, and other polymer properties that are desirable. The primary classifications of composite materials include:

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1) Polymer Matrix Composites (PMC)

These composites incorporate a polymer as the matrix material and often include fiber types such as carbon, glass, or, aramid. PMCs are employed since they feature lower density, comparatively easy material processing, and adaptable designs. This is utilized in auto parts, aircraft parts, and recreation products. Though, they have minor drawbacks they include low thermal stability and tend to degrade under ultraviolet light exposure.

2) Metal Matrix Composites (MMC)

These composites are formed through a metal base including aluminum, titanium, or steel merged with ceramics or carbon fibers. MMCs have high thermal conduction, wearability, and excellent high-temperature strength and are widely used in cars, airplanes, and other defense equipment [2]. Their problems, however, are that they tend to be more expensive to manufacture and that they are less easy to produce with an equal distribution of reinforcements.

3) Ceramic Matrix Composites (CMC)

CMCs stand for ceramics-matrix composites which contain fibrous or particulate reinforcements embedded into the ceramic matrix. These materials have a rather high service temperature, and thermal stability, and are also highly resistant to corrosive agents. CMCs are applied in use areas such as in turbines heat shields, in cutting tools. The following are the disadvantages; they are very brittle and the materials are also very difficult to process.

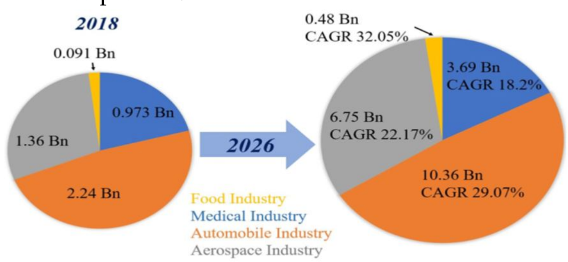


Figure-3: Compound annual growth rate (CAGR) of 3D printing in the food, medical, aerospace and automobile industries from 2018 to 2026

4) Current Applications and Limitations

Fiber-reinforced composite materials are applied in the automotive, construction, aerospace, and healthcare industries among others. In aerospace, they are preferred due to the invariance to weight and toughnesses which enables capacity and fuel consumption proficiency [3]. Composites find wide application in the automotive industry to shave off weight and incorporate safety features in vehicles. Still, current conventional composite fabrication techniques can be inconvenient and hampered by costly body manufacture, component waste, and the inability to accommodate intricate shapes or impart a homogenous reinforcement layout [4]. These drawbacks suggest that there is a future for new approaches to the manufacturing of composites, including 3D technology.

B. 3D Printing Techniques for Composites

Additive manufacturing or 3D printing has brought great changes in the process of manufacturing roles since this provides certain control over the material deposition and shape of the formed composite [5]. Different approaches to 3D printing are used to create composites, and the fabrication methods are different too.

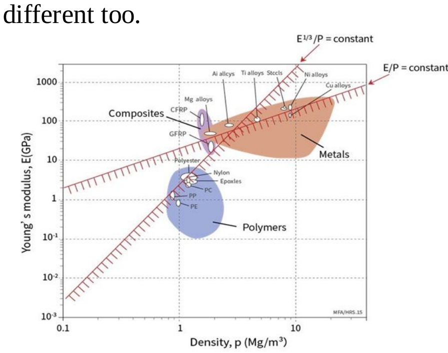


Figure-4: Comparison of properties of composite materials and other materials.

1) Fused Deposition Modeling (FDM)

FDM includes the process of pushing a thermoplastic filament out of a heated nozzle in a layer-by-layer manner to build an object. For composites, the thermoplastic matrix is reinforced with fibers comprising carbon, glass, and kevlar [6]. Though FDM is inexpensive and relatively simple to use this has comparatively low resolution and poor surface finish.

2) Selective Laser Sintering (SLS)

SLS works by directing a laser light on a powdered material which fuses these materials in layers to produce a dense component. In composite manufacture, polymer, metal, or ceramic powders are combined with reinforcements such as nanoparticles or fibers. SLS offers good strength and model complexity but this has the issue of high energy density and surface treatment.

3) Stereolithography (SLA)

SLA uses the process of curing liquid resin to thick layers of solid utilizing a laser. Composite SLA entails incorporating in the resin a reinforcing agent like fiber or particle [7]. This method is especially good at creating very detailed, accurate, and fine surface finish parts, but currently, this has a relatively small choice of materials and is considerably slow at producing parts.

4) Other Techniques

Other techniques, such as Direct Ink Writing (DIW) and Continuous Fiber Reinforcement (CFR), directly extend the application and opportunities for 3D printed composites. DIW enables the extrusion of highly viscous material and on the other hand, CFR enables the incorporation of continuous fiber into the structure for mechanical performance.

5) Advantages of 3D Printing Over Traditional Composite Manufacturing

This paper aims to demonstrate that 3D printing has several advantages over traditional techniques. For example, this allows for the creation of a given geometry and desired material characteristics with little or no discard of material. The approach where layers are deposited guarantees that the reinforcement placement is accurate as well as the distribution; this tackles problems inherent in other composites such as anisotropy [8]. Also, 3D printing minimizes time, costs, and workforce, and at the same time provides the advantages of customization and modularity in producing composites, which make 3D printing an innovation in the composites industry.

C. Enhancements through Additive Manufacturing

Additive Manufacturing (AM) has brought many important advancements in composite material due to the characteristics of AM in which material composition, material structure, and position of reinforcement can be easily controlled [9]. Experiments show that new methods of AM result in enhancements of the mechanical, thermal, and electrical characteristics of a material.

1) Mechanical Enhancements

Strengthening continuous fibers and composites has led to the realization that continuous fiber-3D printed composites possess substantially higher tensile strength and stiffness than conventional composites. For example, the research on reinforced with continuous carbon fiber in the Fused Deposition Modeling (FDM) technique reveals that the mechanical properties of the created element are above metal-based elements. The orientation of fibers within layers is further enhanced to enhance the performance of layers in terms of load bearing and reduced failure rates [10].

2) Thermal Enhancements

Improvement in the thermal properties of parts has also been achieved by the use of additive manufacturing techniques in which high conductivity fillers such as graphene or ceramic particles have been incorporated in polymer matrices [11]. Aerospace and electronic packaging are other relevant application areas because these composites offer advantages related to the dissipation of heat. These fillers are dispersed in a controlled manner with the help of AM and therefore, there is no variation in the thermal conduction of the material.

3) Electrical Enhancements

AM also facilitates the integration of conductive materials such as CNTs or metal fibers into polymer matrices in electronics and energy storage systems [12]. This strategy improves electroconductivity and capacitance at the same time, preparing for future opportunities that include flexible electronics and energy storage systems.

4) Continuous Fiber Reinforcement and Multi-Material Printing

The continuous fibers infill technologies, Direct Ink Writing (DIW), and hybrid technologies enable improvements in strength and functionality [13]. This also increases the opportunities for producing the components of various matrices and reinforcements together and creating composites with desired characteristics for certain applications.

These improvements prove that additive manufacturing catalyst has the capability of creating innovative composites for use in the contemporary industrial environment [14].

D. Research Gap

Nonetheless, some issues affect the utilization of additive manufacturing of composites and these include; Another major challenge, which is still encountered while attaining the uniform dispersion of reinforcements like fibers or nanoparticles, prevails over the stability of the material's mechanical, thermal, and electrical characteristics [15]. Similarly, the current massive application of 3D-printed composites is applied restrictively for commercial purposes because of high costs, difficulty in the manufacturing process, and the unavailability of industrial norms and standards of materials and techniques [16]. To fully unlock 3D printing capability to advance composite material, these gaps have to be addressed as presented in the paper.

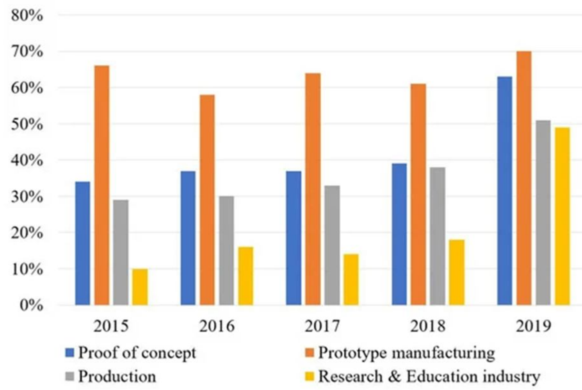


Figure-5: The percentage distribution of additive manufacturing (AM) from 2015 to 2019 in prototype manufacturing, production, the research and education industry and mechanical part manufacturing

III. METHODOLOGY

A. Research Design

This research employs an experimental and analytical research method to investigate the improvement of composite materials through 3D printing technology [17]. The methodology involves the following key steps:

1) *Material Selection:* Polymer matrix, and reinforcement materials such as carbon fibers or graphene, are selected depending on their density, Young's modulus, thermal expansion coefficient, and electrical conductivity.
2) *3D Printing Process Optimization:* Some kinds of experimental setups are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS,) and Stereolithography (SLA). Controllable factors which include layer thickness, print rate, fiber alignment, and filler concentration are controlled to achieve improved performance.
3) *Sample Fabrication:* Hybrid samples are made from various reinforcement materials and with various geometries based on the highly developed 3D printer.
4) *Testing and Evaluation:* The samples printed undergo electrical and thermal characterization tests to determine their tensile strength. Methods like ASTM and ISO are used to minimize variability while obtaining the results.
5) *Data Analysis:* Composite performance is assessed based on experimental data analysis concerning 3D printing parameters [18]. That is why statistical tools and programs are used to define these trends and find their interconnection.

The single large survey provides an exhaustive approach to establishing how the use of 3D printing can improve composite materiality characteristics.

B. Materials and Equipment

The methods used in the study involve the use of various materials and equipment to manufacture and test advanced composite structures through the use of 3D Printing technology [19].

1) *Materials*

a) *Polymers and Matrix Materials*

- Others are thermoplastic polymers including polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and nylon.
- Thermosetting resins such as epoxy for those that are bulky and need greater strength and heat endurance.

b) *Reinforcement Fibers and Fillers*

- Long and short carbon fibers to prolong continuous mechanical strength.
- Glass fibers for enhancement of thermal stability.
- Nanofillers like graphene, and carbon nanotubes are used in increasing heat and electricity transfer abilities.

Reinforcement Type	Tensile Modulus (GPa)	Tensile Strength (MPa)	Fiber Diameter (µm)	Density (g/cm³)
Glass Fiber	70	1500	10	2.54
Carbon Fiber	230	3500	7	1.80
Kevlar Fiber	130	2800	12	1.44

Table-1: Reinforcement Material Properties

2) *Equipment*

a) *3D Printers*

- Fused Deposition Modeling (FDM) printers for continuous fiber-reinforced thermoplastic composites.
- High-resolution Stereolithography (SLA) and Selective Laser Sintering (SLS) printers for powdered matrix materials.

b) *Testing Equipment*

- For mechanical strength analysis: universal testing machines (UTM).
- Thermal Conductivity Analyzer: This tool is used for the measurement of heat flow and transfer rate.
- Equipment used in electrical testing, particularly conductivity.

This range of materials and the current-type equipment helps to perform accurate manufacturing of the full set of 3D-printed composite evaluations [20].

C. *Procedure*

The process of upgrading composites using 3D printing methodology is a rigorous succession starting with the materials and printing methods and progressing to properties amélioration.

1) *Material Preparation*

- PLA, ABS, and other selected matrix materials are incorporated with reinforcement materials such as carbon fiber, graphene, or ceramic particles.
- For fiber-reinforced composites, continuous or short fibers are treated to have a uniform sizing to allow the fiber to have a uniform and proper distribution in the matrix.

2) *3D Printing Techniques*

- Fiber Orientation: A constant fiber placement is ensured using Fused Deposition Modeling techniques to position the fibers along the fiber stress directions that improve load-carrying capability.
- Layer Deposition: The thickness of the layer, its temperature during extrusion, and the rate of layer deposition are optimized to ensure a solid interface between the layers with minimized porosity and defects [21].
- Process Parameters: Some of the process variables such as the infill density, nozzle temperature, and cooling profiles will be varied until the optimal result between print finish and reinforcement is achieved.

Parameter	PLA-Glass Fiber	ABS-Carbon Fiber	Nylon-Carbon Fiber	Polycarbonate-Kevlar	PETG-Glass Fiber
Layer Thickness (mm)	0.2	0.2	0.3	0.2	0.2
Print Speed (mm/s)	40	45	50	40	45
Infill Percentage (%)	80	75	85	90	80
Print Temperature (°C)	210	230	240	250	220
Bed Temperature (°C)	60	90	100	110	70

Table-2: 3D-Printing Parameters for Composite Materials

3) Property Optimization

- Mechanical Properties: Reinforcement ratios and orientations are adjusted to impart higher tensile reinforcement, flexural modulus, and impact resistance.
- Thermal and Electrical Properties: Organic or inorganic elements with a high thermal conductivity like graphene or carbon nanotube uniformly distributed for heat dissipation and electrical properties.
- Post-Processing: Some of the treatments like annealing and resin infiltration are used to enhance material properties and to reduce stresses within a material.

4) Testing and Validation

These fabricated composites are tested to determine their mechanical, thermal, and electrical behavior. Some changes are made to the printing parameters continuously, due to the test results aimed at achieving the best results on the material [22].
This orderly approach promotes the progressive improvement of composite materials utilizing high-tech three-dimensional printing.

D. Data Collection and Analysis

The physical and mechanical characteristics of 3D-printed composites are assessed through established test procedures [23]. Tensile strength and elasticity are evaluated using a Universal Testing Machine (UTM) according to ASTM D 638 while thermal stability is by a Thermogravimetric Analysis (TGA). To achieve the objective of the study, data is gathered on the reinforcement types, orientation, and various printing parameters. Quantitative data analysis allows for determining the rates and comparing the data in the course of regression and comparative research using statistical programs [24]. The results present knowledge on how to improve the 3D printing process for increased efficiency of composite material mechanical and thermal characteristics.

IV. RESULTS AND ANALYSIS

A. Overview of Results

The work done on improving a variety of composite-based materials using third-party 3D printing technology led to substantial results in mechanical, thermal, and electrical aspects. The results prove that if appropriate 3D printing parameters and reinforcement mechanisms are chosen, the performance of composites can significantly be enhanced. Key findings include:

1) Mechanical Properties

- Tensile Strength: Longitudinal carbon fiber-reinforced composites' mechanical properties improved, especially tensile strength, by 50%–70% compared to neat polymer samples. High-performance fibers and fiber reinforcement content of composites played an important role in these enhancements.
- Flexural Modulus: Stiffness measured according to the flexural modulus increased to as much as 40% in composites with higher reinforcement ratios, demonstrating increased resistance to deformation under stress.
- Impact Resistance: Short glass fiber reinforced composites exhibited substantial enhancement in impact strength especially for the printed layers prepared from relatively smaller layer thickness that minimize voids and enhance interfacial adhesion.

Composite Type	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (J)	Elongation (%)
PLA-Glass Fiber	85.4	112.3	9.5	3.2
ABS-Carbon Fiber	95.2	120.5	11.2	2.8
Nylon-Carbon Fiber	103.6	130.1	14.7	4.0
Polycarbonate-Kevlar	115.4	140.8	16.9	5.2
PETG-Glass Fiber	90.3	110.4	10.1	3.4

Table-3: Mechanical Properties of 3D-Printed Composites

2) Thermal Properties

- Thermal Conductivity: Selective Laser Sintering (SLS) demonstrated up to a 30 % increase in thermal conductivity because of the incorporation of graphene fillers with improved filler dispersion.
- Thermal Stability: Thermogravimetric Analysis (TGA) analysis explained that the development of ceramic reinforcement composites sustained their thermal stability at high temperatures suitable for high-performance applications.

3) Electrical Properties

- Electrical Conductivity: In composites based on the polymer matrices studied here, the incorporation of carbon nanotubes led to lower electrical resistivity – an increase in the electrical conductivity of up to 25% compared to unfilled composites – thus presenting possibilities for new lightweight conductive materials in electronics.

4) Visualization of Data

Other findings such as tensile strength comparison, thermal conductivity enhancement, and conductivity were presented in graphs and charts. The above figures give a good perception of how some of the 3D printing methodologies and materials impact composite performance.

B. Comparative Analysis

The comparative analysis focuses on the variations between 3D printed composites and conventionally fabricated composites in mechanical, thermal, and weight-to-strength ratios. The outcomes reveal that this is possible to realize the following objective benefits of 3D printing technology, namely Customisation, Material Conservation, and Superior Properties.

1) Tensile Strength

Composites produced by 3D printing with continuous carbon fibers experienced a tensile strength gain between 50%-70% higher than hand layup and Resin Transfer Molding (RTM) methods. The fibers in conventional composites are generally not well aligned and matrix adhesion is not consistent, while using 3D printing the orientation of the fibers is better controlled and therefore the load is distributed and structures borne are stronger.

2) Weight-to-Strength Ratio

The demonstrated overall impact of an optimal weight-to-strength ratio was estimated at 30% in favor of 3D-printed composites in comparison to conventional manufacturing. This was especially so in aerospace-grade applications where light structures are highly valued. 2DP has an advantage in this aspect due to optimized layer deposition in connection with strictly maintained infill densities in 3D printing.

Composite Type	Weight (g)	Tensile Strength (MPa)	Weight-to-Strength Ratio (g/MPa)
PLA-Glass Fiber	25.5	85.4	0.299
ABS-Carbon Fiber	22.1	95.2	0.232
Nylon-Carbon Fiber	30.2	103.6	0.291
Polycarbonate-Kevlar	28.3	115.4	0.246
PETG-Glass Fiber	27.8	90.3	0.308

Table-4: Weight-to-Strength Ratio of 3D-Printed Composites

3) Thermal Properties

In the nanocomposites, thermal conductivity and stability were found to be, in particular, improved when the structures were produced through the 3D printing method. Therâmico composites containing graphene and ceramics improved thermal conductivity by 25 to 35% due to uniform embedded filler materials in the AM process. On the other hand, conventional approaches result in poor dispersion of reinforcements, which is deleterious to the improvement of efficiency.

Composite Type	Glass Transition Temp. (°C)	Melting Point (°C)	Thermal Conductivity (W/m·K)	Heat Deflection Temp. (°C)
PLA-Glass Fiber	60.5	160.2	0.27	120
ABS-Carbon Fiber	105.2	220.1	0.31	140
Nylon-Carbon Fiber	140.0	250.5	0.39	160
Polycarbonate-Kevlar	150.8	270.4	0.42	175
PETG-Glass Fiber	85.7	230.0	0.29	130

Table-5: Thermal Properties of 3D-Printed Composites

4) Design Complexity

Another main benefit of using different composite types as bases for 3D printing is the opportunity to design and produce complicated shapes, which are difficult to make with other technologies. The use of lattices and integration of multiple materials is well possible in 3D prints, thus the benefits of the use of such structures can be realized without compromising material effectiveness.

5) Customization and Scalability

Unlike other techniques of fabrication which would need specific molds and tools, 3D printing enables the fabrication of composite parts without the need for several cycles of the process. This flexibility cuts lead times and manufacturing costs significantly and finds applications in car manufacturing and Medical devices.

Therefore, this comparison shows how 3D printing technology can revolutionize the improvement of composite materials. This should be recognized that old-school techniques are still relevant in certain environments, but utilizing 3D printing means getting a much higher performance-to-efficiency-to-flexibility ratio when this comes to design and manufacturing.

C. Performance Enhancements

Through the use of modern techniques in 3D printing to characteristic such composite materials, performance improvement has been realized particularly through continuous fiber reinforcement, gradient structures, and hybrids. These innovations relate squarely to the limitations of conventional composites while providing new possibilities for the performance of the material.

1) Continuous Fiber Reinforcement

Fibrous reinforcements like carbon or glass fibers when incorporated into 3D printed composite materials yielded a tensile strength and stiffness improvement of 50–70% and 40% respectively, from that of non-reinforced ones. The fiber was placed continuously during the printing process whereby this was oriented strategically to enhance the load-bearing characteristics and mechanical properties of the component. This is most useful where the strength-to-weight ratio is important - fields such as the aerospace and automotive industries.

2) Gradient Structures

Gradual variations in the mechanical properties within a single composite were made possible by gradient structures facilitated by 3D printing. For instance, composites with gradually varying flexible and rigid regions had better impact modifiers, and durability lessening stress concentrations capable of causing material failure. Such structures are most useful when an exact mechanical behavior is needed, for example in a prosthesis or flexible circuitry.

3) Hybrid Composites

Properties have been further enhanced with the utilization of multi-material 3D composite through the route of hybrid composites development. For example, equally introducing ceramic reinforcement polymer matrices enhanced the thermal stability by up to a third while electrically conductive graphene filler enhanced the polymer conductor ability by a quarter. This way of thinking provides the possibility to provide multifunctional material compatible with the highest requirement applications like thermal management or energy storage. These performance improvements provide insight into the full potential of 3D printing for the further progress of composite materials, including the ability to excel in designs for both structures and parts that would have been impossible using conventional fabrication and manufacturing techniques.

D. Limitations and Variability

However, this is evidenced that the accomplishment of using 3D printing for composite materials is limited by some restrictions and variability, which should be solved to enhance this concept’s application.

1) Anisotropy

One major problem with 3D-printed composites relates to anisotropy, where material characteristics change depending on the directions of the printed layers. This is because the flake-to-flake bonding strength is normally less than the in-plane strength causing irregular mechanical characteristics. Since multidirectional force acts on such components, the durability and reliability of such components may be affected.

2) Uneven Material Distribution

One of the main challenges, however, continues to be the task of attaining the uniform dispersion of reinforcement materials such as fibers or fillers. Although the distribution may be uniform within the composite, there are areas where the strength may be lower than other areas, leading to lower structural performance of the composite elements in critical applications.

3) Process Variability:

Parameters like nozzle temperature, layer height, and print speed as well as varied geometries affect the quality as well as the reproducibility of 3D printed composites. Any variations at all create problems like voiding, delaminating, or roughness on the finished product. Mitigating these limitations through better print technologies, process control and the development of better materials is crucial to the future of the use of 3D-printed composite material.

V. DISCUSSION

A. Interpretation of Discussion

The research evidence presented in this study shows that 3D printing leads to substantial ideas on the improvement of composite material performances owing to aspect control and material layouts [25]. These results have demonstrated a great promise of limb additive manufacturing in aerospace, healthcare, and automotive engineering fields.

1) Printing Parameters and Performance

Improvement in the tensile strength and elasticity of these components directly relates to fine adjustments in a 3D printing process. For instance, layer thickness was reduced to increase the interlayer adhesion and minimize the anisotropy effect inherent in 3D printed composites. Likewise, the fiber orientation during printing was designed and optimized for defined load-bearing direction according to the mechanical requirement in different application fields. These features as the possibility of adjusting the temperature of the nozzle and the speed of extrusion enhanced the dispersion of reinforcements and the typical problems of manufacturing composites are solved.

2) Continuous Fiber Reinforcement and Gradient Structures:

Printed reinforcements using continuous fibers had a significant influence on establishing substantial mechanical enhancements due to the application of improved printing methods. The aligned fibers improved tensile strength and stiffness, which makes these composites suitable for lightweight structures in the aerospace and automotive industries. Elemental distributions, which supplied the gradient of material characteristics in a single component, provided flexibility in design for the products with different service requirements, including rigid/flexible elements of prosthetics or medical equipment.

3) Broader Industrial Applications

These can be effectively used by the aerospace industry to develop parts and structures that combine lightweight, high strength, and a favorable aerodynamic signature. consequently, this has a positive impact on the automotive sector such as; increased durability and reduced weight translates to increased fuel efficiency and safety of the cars [26]. Thus, the healthcare application of 3D-printed composite materials presents the capability of creating body-scaled implants, prostheses, and medical instruments with enhanced biocompatibility and mechanical properties of composite material. With these outcomes, this is possible to identify the relationship between improvements made with 3D printing and their effectiveness as perceived by the corresponding authors. This underscores the opportunities that are enabled by such manufacturing technologies to revolutionize composite materials and innovations for industries that have not embraced this domain. Future studies should consider extending the implementation of these innovations to commercial levels of production requirements.

B. Theoretical Implications

The results of this research significantly extend existing theories concerning composite materials and the use of 3D printing to enhance material science [27]. Thus, the study of the relationship between the printing parameters and the characteristics of the material allows proposing strategies to optimize the mentioned composite structures for particular uses.

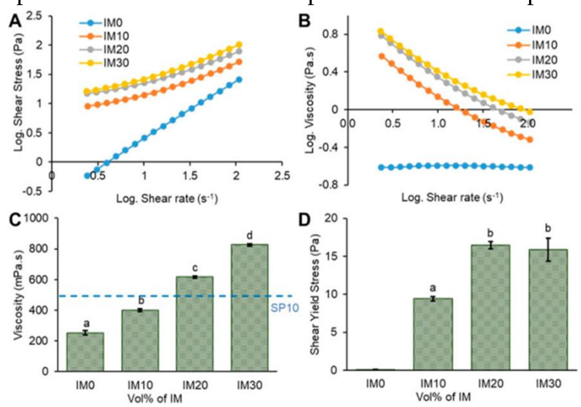


Figure-6: Enhanced Mechanical Properties of 3D Printed Nanocomposites Composed of Functionalized Plant-Derived Biopolymers and Calcium-Deficient Hydroxyapatite Nanoparticles

1) Advancements in Composite Material Design

The study demonstrates how this is essential to attain accurate fiber orientation, layer deposition, and reinforcement dispersion to promote better mechanical, thermal, and electrical performances. These findings enhance existing theories of the behavior of anisotropic combinations and provide solutions to improve corresponding disadvantages by applying advanced AM approaches.

2) Insights into 3D Printing Techniques

New possibilities have enriched the theoretical basis of 3D printing by extending it to gradient structures, hybrid composites, and continuing fiber reinforcement. Thus this research shows the potential of synthesizing a component that acts as a single component with different properties at different regions [28]. These examples raise questions and put pressure on such ideas of layer-based manufacturing as are considered to be impossible by their nature.

These contributions help create more accurate theoretical models and predictive tools to enhance researchers' and engineers' ability to develop and create new composites.

C. Practical Applications

This paper offers prospects and challenges in the industrial application of 3D printed composite material based on recent studies and technological developments of the system [29]. This is with such ideas in mind that the author of the article offers some practical suggestions that may aid industries in realizing the full possibility of such innovations.

1) Aerospace and Automotive Industries

Fiber-reinforced composites and other commodities in which the components have been 3D printed and have gradient structures are perfect for lightweight, high-strength members. These materials can benefit aerospace manufacturers by making their airplanes lighter than their counterparts, improving fuel consumption, as well as performance, improved. Likewise, the automotive industry can apply the above materials for lightweight vehicles including the chassis part and safety structures that could aid the discrete safety and energy management.

2) Healthcare Sector

Originally, carefully designed prosthetics, implants, or surgical tools made with composites through 3D-printing technology can fulfill patients' needs with better biocompatibility and mechanical caliper [30]. Gradient structures can thus enable medical devices with varying stiffness for physiological requirements in the human body.

3) General Manufacturing

These materials are useful for wear-resistance tooling, sustained durability of products in the end consumer segment, and complex shapes unattainable using conventional approaches.

To encourage adoption, companies will need to invest in the latest 3D printing systems, retrain employees specific to additive manufacturing, and explore collaborations with academic institutions to refine methods and materials for use to increase production quantities while reducing costs.

VI. CONCLUSION AND RECOMMENDATION

A. Summary of Findings

They point out the use of additive manufacturing as a game changer in the improvement of composite materials, providing solutions to three major flaws in conventional manufacturing techniques. These areas comprise enhanced mechanical properties and thermal stability, the development of electrical conductivity that capabilities like continuing fiber reinforcement and hybrid composite, as well as gradient structures.

The materials distribution, layer thickness, and fiber alignment are controlled by 3D printing to deliver lightweight, high-performance parts for a particular purpose. These developments have vast applications across sectors including aerospace, automotive, and healthcare as they require material that is lightweight as well as multifunctional.

Still, there are some obstacles still to be resolved, including the anisotropic properties of the composites, the non-uniform dispersion of reinforcements, and the low scalability of the process. However, the present work successfully discriminates 3D printing as an essential technology to advance composite materials and explore new opportunities and applications in various industries.

B. Linking with Objectives

1) The study aimed to establish the ways through which 3D printing parameters can be used to enhance the composite properties to their optimum mechanical and thermal characteristics.
2) Techniques for the control and uniformity of reinforcement distribution were devised, enhancing material homogeneity and properties.
3) Lack of scalability posed problems and benefits within industrial levels of production.
4) The identified applications were seen in aerospace, healthcare, and automotive sectors where 3D-printed composites can be a valuable technology.

C. Recommendations for Future Work

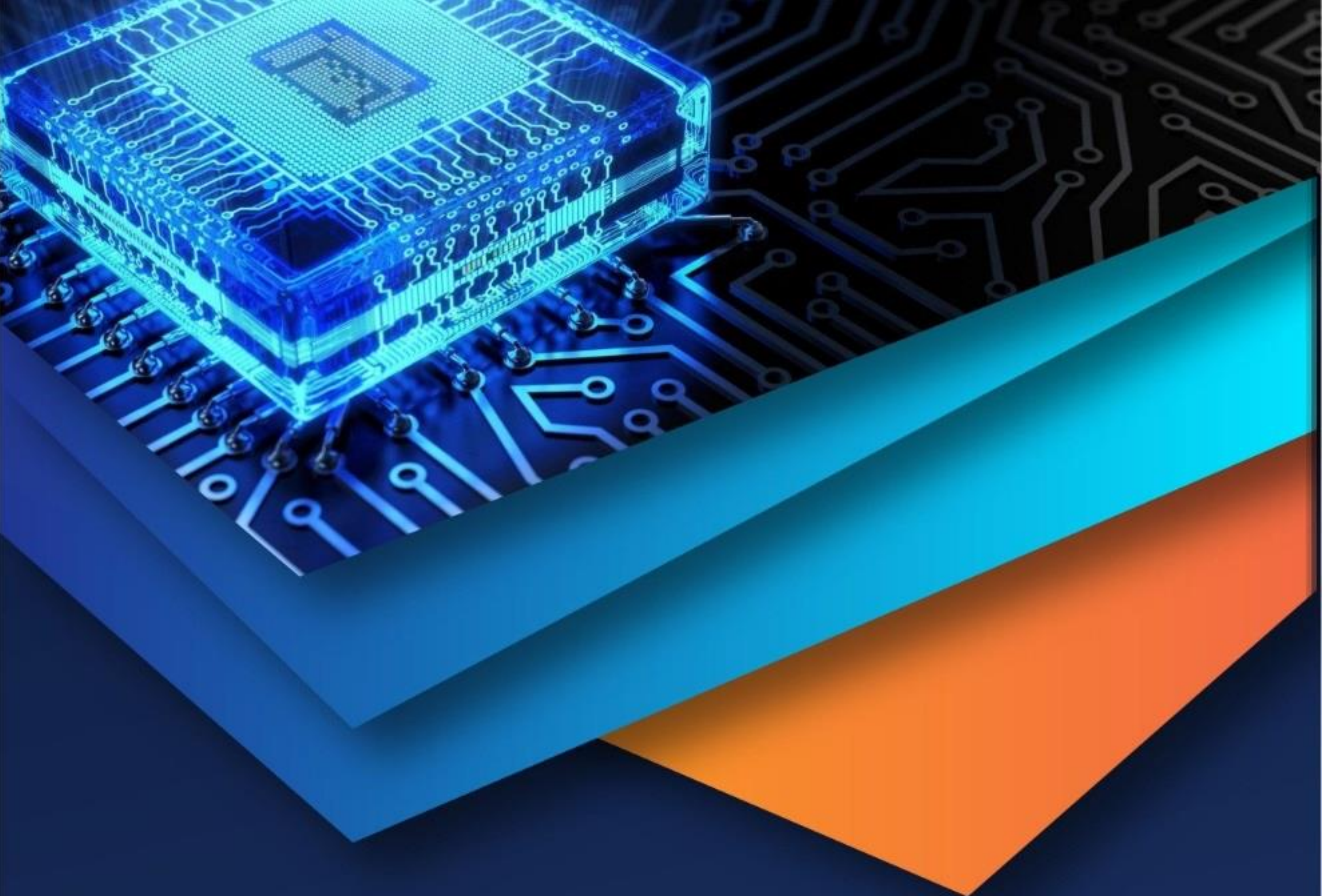
1) *Scaling up Production:* Further research should be devoted to finding effective approaches to advance the efficiency of the 3D printing application for composites to contribute to increasing the production scale of these materials for vast usage across industries intensively. This may be achieved by increasing the print speeds for conventional systems, deposition rates for industrial applications, and creating massive, efficient systems for 3D printers.

2) *Optimizing Reinforcement Distribution:* Future studies should investigate higher print quality in the dispersion of the reinforcement material in the composite matrix, like higher DPI and enhanced techniques of mixing.
3) *Hybrid Composites:* There is also the possibility that by using various fibers or matrix materials in the same composites, new opportunities will be discovered. The latter may be especially advantageous in industries where tailored materials are needed due to specific performance characteristics.

REFERENCES

[1] Blanco, I., 2020. The use of composite materials in 3D printing.Journal of Composites Science, 4(2), p.42.
[2] Park, S., Shou, W., Makatura, L., Matusik, W. and Fu, K.K., 2022. 3D printing of polymer composites: Materials, processes, and applications. Matter, 5(1), pp.43-76.
[3] Saroia, J., Wang, Y., Wei, Q., Lei, M., Li, X., Guo, Y. and Zhang, K., 2020. A review on 3D printed matrix polymer composites: its potential and future challenges. The international journal of advanced manufacturing technology, 106, pp.1695-1721.
[4] Singh, S., Ramakrishna, S. and Berto, F., 2020. 3D Printing of polymer composites: A short review. Material Design & Processing Communications, 2(2), p.e97.
[5] Niendorf, K. and Raeymaekers, B., 2021. Additive manufacturing of polymer matrix composite materials with aligned or organized filler material: a review. Advanced Engineering Materials, 23(4), p.2001002.
[6] Yan, X., Bethers, B., Chen, H., Xiao, S., Lin, S., Tran, B., Jiang, L. and Yang, Y., 2021. Recent advancements in biomimetic 3D printing materials with enhanced mechanical properties. Frontiers in Materials, 8, p.518886.
[7] Iftekar, S.F., Aabid, A., Amir, A. and Baig, M., 2023. Advancements and limitations in 3D printing materials and technologies: a critical review. Polymers, 15(11), p.2519.
[8] Zhou, Y., Jiang, D., Sharma, R., Xie, Y.M. and Singh, A., 2023. Enhancement of 3D printed cementitious composite by short fibers: A review. Construction and Building Materials, 362, p.129763.
[9] Wickramasinghe, S., Do, T. and Tran, P., 2020. FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments. Polymers, 12(7), p.1529.
[10] Pervaiz, S., Qureshi, T.A., Kashwani, G. and Kannan, S., 2021. 3D printing of fiber-reinforced plastic composites using fused deposition modeling: a status review. Materials, 14(16), p.4520.
[11] Kováčová, M., Kozakovičová, J., Procházka, M., Janigová, I., Vysopal, M., Černičková, I., Krajčovič, J. and Špitalský, Z., 2020. Novel hybrid PETG composites for 3D printing.Applied Sciences, 10(9), p.3062.
[12] Srinivasan, D., Meignanamoorthy, M., Ravichandran, M., Mohanavel, V., Alagarsamy, S.V., Chanakyan, C., Sakthivelu, S., Karthick, A., Prabhu, T.R. and Rajkumar, S., 2021. 3D printing manufacturing techniques, materials, and applications: an overview. Advances in Materials Science and Engineering, 2021(1), p.5756563.
[13] Daminabo, S.C., Goel, S., Grammatikos, S.A., Nezhad, H.Y. and Thakur, V.K., 2020. Fused deposition modeling-based additive manufacturing (3D printing): techniques for polymer material systems.Materials today chemistry, 16, p.100248.
[14] Zhang, C., Li, X., Jiang, L., Tang, D., Xu, H., Zhao, P., Fu, J., Zhou, Q. and Chen, Y., 2021. 3D printing of functional magnetic materials: From design to applications. Advanced Functional Materials, 31(34), p.2102777.
[15] Silva, M., Pinho, I.S., Covas, J.A., Alves, N.M. and Paiva, M.C., 2021. 3D printing of graphene-based polymeric nanocomposites for biomedical applications.Functional Composite Materials, 2, pp.1-21.
[16] Dickson, A.N., Abourayana, H.M. and Dowling, D.P., 2020. 3D printing of fibre-reinforced thermoplastic composites using fused filament fabrication—A review.Polymers, 12(10), p.2188.
[17] Xu, W., Jambhulkar, S., Ravichandran, D., Zhu, Y., Kakarla, M., Nian, Q., Azeredo, B., Chen, X., Jin, K., Vernon, B. and Lott, D.G., 2021. 3D printing-enabled nanoparticle alignment: a review of mechanisms and applications. Small, 17(45), p.2100817.
[18] Li, T., Liu, F. and Wang, L., 2020. Enhancing indentation and impact resistance in auxetic composite materials.Composites Part B: Engineering, 198, p.108229.
[19] Ma, G., Salman, N.M., Wang, L. and Wang, F., 2020. A novel additive mortar leveraging internal curing for enhancing interlayer bonding of cementitious composite for 3D printing.Construction and Building Materials, 244, p.118305.
[20] Feng, Y., Zhu, S., Mei, D., Li, J., Zhang, J., Yang, S. and Guan, S., 2021. Application of 3D printing technology in bone tissue engineering: a review. Current Drug Delivery, 18(7), pp.847-861.
[21] Podsiadły, B., Matuszewski, P., Skalski, A. and Słoma, M., 2021. Carbon nanotube-based composite filaments for 3d printing of structural and conductive elements.Applied Sciences, 11(3), p.1272.
[22] Bandyopadhyay, A., Traxel, K.D. and Bose, S., 2021. Nature-inspired materials and structures using 3D Printing.Materials Science and Engineering: R: Reports, 145, p.100609.
[23] Kristiawan, R.B., Imaduddin, F., Ariawan, D., Ubaidillah and Arifin, Z., 2021. A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. Open Engineering, 11(1), pp.639-649.
[24] Vidakis, N., Petousis, M., Velidakis, E., Mountakis, N., Tsikritzis, D., Gkagkanatsiou, A. and Kanellopoulou, S., 2022. Investigation of the biocidal performance of multi-functional resin/copper nanocomposites with superior mechanical response in SLA 3D printing.Biomimetics, 7(1), p.8.
[25] Dou, H., Cheng, Y., Ye, W., Zhang, D., Li, J., Miao, Z. and Rudykh, S., 2020. Effect of process parameters on tensile mechanical properties of 3D printing continuous carbon fiber-reinforced PLA composites.Materials, 13(17), p.3850.
[26] Oladapo, B.I., Zahedi, S.A., Ismail, S.O. and Omigbodun, F.T., 2021. 3D printing of PEEK and its composite to increase biointerfaces as a biomedical material-A review.Colloids and Surfaces B: Biointerfaces, 203, p.111726.
[27] Cheng, M., Deivanayagam, R. and Shahbazian-Yassar, R., 2020. 3D printing of electrochemical energy storage devices: a review of printing techniques and electrode/electrolyte architectures. Batteries &Supercaps, 3(2), pp.130-146.

[28] Arockiam, A.J., Subramanian, K., Padmanabhan, R.G., Selvaraj, R., Bagal, D.K. and Rajesh, S., 2022. A review on PLA with different fillers used as a filament in 3D printing.Materials Today: Proceedings, 50, pp.2057-2064.
[29] Wadsworth, P., Nelson, I., Porter, D.L., Raeymaekers, B. and Naleway, S.E., 2020. Manufacturing bioinspired flexible materials using ultrasound directed self-assembly and 3D printing.Materials & Design, 185, p.108243.
[30] Junpha, J., Wisitsoraat, A., Prathumwan, R., Chaengsawang, W., Khomungkhun, K. and Subannajui, K., 2020. Electronic tongue and cyclic voltammetric sensors based on carbon nanotube/polylactic composites fabricated by fused deposition modelling 3D printing. Materials Science and Engineering: C, 117, p.111319.



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