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OPTIMIZATION OF 3D PRINTED COMPOSITE MATERIALS FOR LIGHTWEIGHT STRUCTURAL APPLICATIONS

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Abstract

The need to have lighter and high-performance parts in industries like that of aerospace, automotive, and civil engineering has advanced the use of additive manufacturing technologies, especially through composite materials. The study examines the aspect of optimizing the 3D printed composite materials so that they can have improved mechanical behavior and maintain low weights, therefore, taking care of both the issues of structural efficiency and material sustainability. A synergistic blend of design and process parameter optimization was used in which the potential of the computational tools, finite element analysis (FEA) and machine learning algorithms were utilized. Carbon fibers reinforced polymer matrix composites have been chosen because of their good strength-to-weight ratio and compatibility with fused deposition modeling (FDM) methods. Both simulation experiments and experimental works were used to investigate the mechanical effect of critical parameters, including layer height, infill density, print orientation, and fiber placement. Findings show that optimized implementations, such as topology optimization of lattices and parameter optimization, resulted into a 0-25 % reduction in weight, without sacrificing structural integrity. The results highlight the importance of more sophisticated optimization frameworks on enhancing the scalability, and industrial feasibility of 3D printed composites. The research is of special value in the design of lightweight structural solutions as it is possible to use them in more industries where the mixture of performance and weight is paramount. Future research efforts on environmental sustainability and AI-based adaptive control systems in real-time optimization could be focused on process optimization.

Keywords: Additive Manufacturing, 3D Printing, Composite Materials, Lightweight Structures, Optimization, Mechanical Properties, Finite Element Analysis, Carbon Fiber Reinforcement.

1. INTRODUCTION

1.1 Background

Overall, advanced manufacturing (AM) technologies, especially additive manufacturing (3D printing), have transformed the area of production of complex shapes and individual parts in numerous industrial domains with the following benefits: less material waste, design freedom, and fast prototyping (Cheng et al., 2023; Chen et al., 2023). Of them, 3D printed composite materials have attracted much attention given their potential to inherit the low-density characteristic of polymers with the high mechanical performance of fibers or fillers (Ferdousi et al., 2023; Huang et al., 2024). Such integration enables the creation of the new generation of high-performance constructions that will be used to satisfy the increasing demand of lightweight, but strong, parts in aerospace, automotive, and defense industries (Hu et al., 2017; Wang et al., 2022).

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1.2 Importance of Lightweight Structural Applications

Light and sustainable structures are essential in projects where the weight weighs on the actual performance, energy consumption, and sustainability of the natural environment (Chen, Ye, & Dong, 2023). To give an example, in aerospace, minimizing the weight of parts can have a substantial impact on the reduction of fuel, an increasing payload, and greenhouse gas emissions (Moon et al., 2014; Long et al., 2020). By analogy, within the automotive and unmanned aerial vehicles (UAVs) applications, lightweight materials are better than the heavyweight — they enhance speed, stability, and energy efficiency, which will be essential in future transportation strategies (Ichihara & Ueda, 2023; Al Khalil et al., 2022).

1.3 Problem Statement

Nevertheless, manufacturing composite materials in 3D printing, although being very beneficial, still experiences some drawbacks limiting the scope of its use: anisotropic mechanical characteristics, problems of interlayer adhesion, etc. (Subramanian et al., 2024; Abd El-Halim et al., 2025). Some of the findings of the current research emphasize the importance of adopting systematic optimization approaches towards the enhancement of strength-to-weight ratios, at the same time ensuring that the products are manufacturable (Awd Allah et al., 2025; Compton & Lewis, 2014). Besides, the performance of materials is variable with the orientation of the fibers, infill designs, and printing settings demanding overall research involving an experimental and computational methodology (Hu, Gadipudi, & Salem, 2019).

1.4 Research Objectives

An improved 3D printed composite material whose lightweight features are superior on the one hand and strong on the other hand is the main goal of this study. This involves:

- Determining and tuning important printing factors namely infill density, layer thickness, and fiber orientation.
- Applying computational design methods and lattice type design to these methods where the weight is cut down without compromising the mechanical strength (Vălean, Linul, & Rajak, 2025; Zhang et al., 2022).
- Comparative studies of the performance of artificial intelligence (AI) based tool on multi-objective design process (Chen et al., 2023).

1.5 Scope and Limitations

The work is devoted to the polymer matrix composites reinforced with the carbon fibers, which are produced with the help of fused deposition modeling procedure (FDM), which is a popular and affordable 3D printing technique (Cheng et al., 2023).

Although the proposed optimization approaches in this paper are aimed at enhancing the strength-to-weight ratio, the method used is confined to the laboratory scale study and simulations therefore limiting the research to large-scale manufacturing process scenarios in the industry (Huang et al., 2024; Awd Allah et al., 2025).

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1.6 Structure of the Paper

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2. LITERATURE REVIEW

2.1 Overview of 3D Printed Composite Materials

The ability to add 3D printing along with the excellent mechanical properties of fiber-reinforced polymers allows the creation of composite materials. Such composites can be especially useful in lightweight structural developments due to their high strength to weight ratios, greater stiffness and flexibility in design (Cheng et al., 2023; Chen, Zhang, et al., 2023). Composite materials are at the fore front of the industry as polymer matrix materials composed of carbon or glass fiber reinforcements are compatible to the fused deposition modeling (FDM) and selective laser sintering (SLS) methods (Huang et al., 2024; Ferdousi et al., 2023). Both continuous fiber reinforcement and short fiber-reinforced composite have superior tensile and flexural capability, but tend to be simpler to produce and lower cost due to short fiber reinforcement capability (Subramanian et al., 2024). These properties are however frequently anisotropic due to such practical issues as interlayer adhesion and fiber misalignment, and design and manufacturing parameters thus have to be optimized (Awd Allah et al., 2025).

2.2 Lightweight Structural Requirements

Energy savings and affordable costs in the application of lightweight structures require a key role in the context of aerospace, automotive, and UAV industries (Moon et al., 2014; Long et al., 2020). The primary difficulty consists of the need to balance weight loss efficiency and mechanisms of performance that depends on the composition, inner configuration, and the manufacturing process of materials (Ichihara & Ueda, 2023). More advanced solutions like biomimetic and cellular lattices have been proven to have the potential of saving tremendous amounts of weight without sacrificing strength (Hu et al., 2017; Hu et al., 2019).

2.3 Optimization Approaches

Design Optimization

The most common methods of topology optimization and lattice structure development are extensively implemented, enabling the reduction in weight without affecting the structure (Wang et al., 2022). In addition, the biomimetic design strategies that are guided by naturally occurring structures such as bones and bamboo enhance the stiffness and force properties (Thiyagarajan, 2017; Zhang et al., 2022). Higher end computational

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techniques like finite element analysis (FEA) facilitate in the simulation of stress distributions and in material prediction behavior in different loading conditions (Hu et al., 2019).

Process Parameters optimization

Strength-to-weight ratio of 3D printed composites is directly affected by critical printing parameters, including but not limited to layer height, infill density, fiber orientation and nozzle temperature (Abd El-Halim et al., 2025; Subramanian et al., 2024). These variables have been optimized to improve the crashworthiness and mechanical performance of this type of vehicle through Taguchi design of experiments (Taguchi DOE) and multiple-criteria decision analysis (MCDA) methods of optimization (Awd Allah et al., 2025; Vălean et al., 2025).

Optimization by Computation and AI

AI-driven and machine learning solutions have become valuable in multi-objective optimization with predictive modeling capabilities that allow reducing trial-and-error scenarios in the case of parameter choice (Chen, Zhang, et al., 2023; Ferdousi et al., 2023). Smart optimization schemes make use of genetic algorithms and deep learning to determine the best design and process variables pairs (Cheng et al., 2023).

2.4 Research Gaps

Even though large-scale applications have achieved great progress, there is still a lack of scalability and environmental sustainability (Cheng et al., 2023). Streamlining of optimization procedures, real-time AI interface, and synthesis of environmental-friendly composite material are also important research topics in the future (Chen et al., 2023; Huang et al., 2024).

Summary of Previous Research on Optimization of 3D Printed Composites

Author(s) & Year	Focus Area	Material/System	Optimization Method	Key Findings
Cheng et al. (2023)	Review of lightweight composite design	Continuous fiber-reinforced	Computational optimization	Highlighted role of topology optimization and AI tools
Huang et al. (2024)	Wing spar optimization	Carbon fiber composites	Topology optimization + FEA	Reduced weight by 25% while maintaining stiffness
Ferdousi et al. (2023)	Lightweight hybrid composites	Polymer matrix + fillers	ML-based modeling	Accurate prediction of mechanical performance
Vălean et al. (2025)	Infill pattern optimization	Polymer composites	MCDA	Improved compressive performance through optimized infill
Awd Allah et al. (2025)	Crashworthiness optimization	PETG-CF composites	Multi-criteria decision-making	Identified influence of print parameters on impact energy
Wang et al. (2022)	Topology optimization in load-bearing apps	Bone scaffolds, structural parts	Topology optimization algorithm	Enhanced stiffness and reduced material usage
Hu et al. (2019)	Biomimetic lightweight lattice structures	Cuttlefish-inspired composites	Topology optimization + biomimetics	Improved strength-to-weight ratio
Zhang et al. (2022)	Bio-inspired metamaterials	Bamboo-like structures	Simulation-guided + optimization	High-strength lightweight lattice designs

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3. BACKGROUND AND MOTIVATION

The increased need of light structural components, that are also extensively high-strength has led the rise of advanced manufacturing technologies and material systems in sectors like aerospace, automotive, and defense, etc. (Cheng et al., 2023; Chen, Zhang, et al., 2023). Conventional manufacture is unable to easily form complex geometry without material abundance and weight penalties.

These shortcomings are overcome using the additive manufacturing (AM) and specifically 3D printing, which allow flexibility in design, production on-demand, and minimized material cost (Compton & Lewis, 2014). Out of all AM innovations, 3D printed composite materials have gained high interest because of their capability to integrate lightweight polymer matrices with the reinforcing fibers (e.g., carbon or glass fibers).

They have a better strength-to-weight ratio than the traditional ones and can be specially defined towards particular performance needs (Huang et al., 2024; Ferdousi et al., 2023). Although there are such benefits, most of the processes imply defects leading to reduced industrial applications- these defects are process induced, anisotropic, and in some instances, they are not optimized (Hu, Gadipudi, & Salem, 2019).

Problem Statement

Despite the improvement on mechanical properties when compared to pure polymers, fiber-reinforced composites tend to act very sensitive under different 3D printing parameters or structural design strategies.

There are critical issues:

- Anisotropy and Problems with Layer Adhesion Mechanical strength is greatly dependent on how the parts are built and where any fibers are placed (Abd El-Halim et al., 2025).
- Optimization Complexity - Topology Optimization, the infill patterns, and fiber orientation are only a few pieces of information that need to be weighed to ensure both the light weighting and mechanical rigidity of the design (Awd Allah et al., 2025).
- Computational-Experimental Integration - The experiments, whether on computer or in the laboratory, tend to be either optimized or systematic, and optimization-based workflows are absent (Chen, Zhang, et al., 2023).
- The inability to solve these problems restricts the application of 3D printed composites in major structural contexts where light weight and reliability are a major concern (Wang et al., 2022; Vălean et al., 2025).

The purpose and Objectives of the research

The main objective of the given work is to create the optimization framework of 3D printed composite materials that would strike the optimal lightweight but still push the mechanical strength to the limit.

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These are three fundamental goals:

Objective 1: Process-based: Design strategies, such as topology optimization and lattice integration, should be optimized to derive the effect of optimization to keep the weight of the structure but increase stiffness and it carrying capability (Huang et al., 2024; Hu et al., 2017).

Objective 2: With the help of such Systematic methods as Design of Experiments (DOE) and multi-criteria decision analysis (MCDA), determine and optimize the key parameters of the printing process, including infill density, layer thickness, and fiber orientation, etc. (VĂlean et al., 2025; Awd Allah et al., 2025).

Objective 3: Use computational intelligence, such as machine learning and finite element analysis (FEA) to predict the performance and minimize the trial and error in optimisation (Ferdousi et al., 2023; Chen, Zhang, et al., 2023).

Research Approach

The proposed study uses a mixed approach in which computational simulations and experimental verification are used. To start workflow, the selection of materials is made where carbon-fiber-reinforced polymer composites are chosen since these materials were already applied in high-performance operations (Subramanian et al., 2024). The purpose of the development of lightweight geometries using topology optimization techniques and biomimetic lattice design is to create a lightweight structure (Hu et al., 2019; Zhang et al., 2022). The statistical method or Taguchi DOE and superior decision-making models or MCDA are then used to get the critical process parameters optimized (Vălean et al., 2025). To perform predictive modeling, machine and genetic learning algorithms combined with FEA modeling provide the opportunity to optimize multiple objectives simultaneously through FEA-based multi-objective optimization in terms of weight and mechanical capability (Chen, Zhang, et al., 2023; Ferdousi et al., 2023). Optimized samples have their faces tested experimentally (like in tensile strength, compressive load and energy absorption) to verify computational answers (Awd Allah et al., 2025; Abd El-Halim et al., 2025).

Expected Contributions

There are three dimensions in which this research contributes.

- Technical innovation Development of a computationally integrated optimization framework of lightweight composite structures.
- Industrial Applicability- Development of verified design rules of aerospace and automobile industry, with the productivity of better fuel, cost reductions, and protection.
- Scientific Advancement 3D printed composite knowledge on the connection between design strategies, process parameters, as well as mechanical performance (Cheng et al., 2023; Chen, Zhang, et al., 2023).

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Moreover, in this study, sustainability refers to the minimization of material wastes and Energy which falls in line with the global initiatives of green manufacturing (Compton & Lewis, 2014).

4. METHODOLOGY

4.1 Research Design

This research is hybrid research as it includes both the computational simulations and the experimental validation in AI-based optimization. This is to maximize 3D printed composite materials to lightweight structures. Gardener et al. note that the research process involves selection of materials, optimization of design, optimization of the processes as well as process parameters, simulation analysis and actual fabrication of the materials followed by mechanical testing.

4.2 Research workflow

The methodology is well-planned in the following order as presented in Figure 1:

See figure 1: Optimization of 3D printed composite materials

Step in the Workflow

2 **Literature Review & Gap Analysis:** The purpose of reviewing literature and gap analysis will be to identify the issues and gaps in the available studies (Cheng et al., 2023; Chen et al., 2023).

3 **Material:** University Choice Polymer Matrix and Fiber Reinforcement (Carbon fiber composites are preferred basis of structural strength).

4 **Design Optimization:** Topology optimization and biomimetic lattice design should be implemented in order to reduce the weight.

5 **Computational Simulation:(**Finite Element Analysis) (FEA) is used to model stress, deformation and failure behavior based on Finite Element Analysis (FEA).

6 **Optimization of Process Parameters:** Taguchi DOE, MCDA and Genetic Algorithms can be utilized to obtain the best printing settings.

7 **Optimization Samples:** Fabrication of Manufacture designs by means of 3D printing that relies on FDM.

8 **Mechanical Testing:** Conduct tensile, compression and crash worthiness tests on validation.

9 **Data Analysis:** Learn to carry out the analysis of simulation results and compare them with experimental works to justify optimization models.

4.4 Material Selection

It was decided to use carbon fiber-reinforced polymer composites because of strength-to-weight ratio, their temperature stability, and the suitability to FDM-based 3D printing (Huang et al., 2024; Subramanian et al., 2024). Continuous composite reinforced

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applications are implied to make fibers longer and shorter to increase the stiffness and the rigidity of the structures.

4.5 Design Optimization

They were also produced by means of topology optimization and involved adapting biomimetic lattice patterns (such as honeycomb and bamboo geometries) that were incorporated into the design to minimize the costs at the weight level without sacrificing strength (Hu et al., 2017; Zhang et al., 2022).

The optimization objectives entail:

- Optimal strength-to-weight ratio
- Reduce materials utilized
- Limits are allowable displacement and stress limits which are limited to material properties.

4.6 Process Parameter Optimization

It has been revealed that process parameters have extensive ramifications on mechanical properties of printed composites.

The parameters that were being optimized were the following:

- Infill Density
- Layer Thickness
- Print Orientation
- Nozzle Temperature
- Fiber Orientation

Critical Process Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Infill Density (%)	20	50	80
Layer Thickness (mm)	0.1	0.2	0.3
Print Orientation (°)	0°	45°	90°
Nozzle Temp (°C)	200	220	240

The Taguchi DOE, MCDA, and Genetic Algorithms of optimization will be used to determine the parameter combinations that will give minimum weight and maximum strength (Awd Allah et al., 2025; Vălean et al., 2025).

Computational Analysis

Analysis of structural performance was used under tensile and compressive loads; FEA was used to make these predictions. Predictive optimization using machine learning models was done using the desired machine learning models that had been trained with experimental data (Ferdousi et al., 2023; Chen et al., 2023). Multi-objective optimization took the form of a genetic algorithm.

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Experimental Validation

Ideal designs were produced through 3D printers based on FDM.

The following mechanical tests were made:

- Tensile Test: tensile strength ultimate, and extension.
- Compression test: supporting power, bending, deformation.
- Crashworthiness Assessment: The absorption of the energy in the impact (Awd Allah et al., 2025).

ANOVA was used to analyze the data according to the significance of parameters to check the results of the computation.

Performance Metrics

Performance consideration was centralized on:

- Strength-to-weight ratio
- The rigidity and strength of structure
- Per cent weight reduction to baseline designs

5. RESULTS

These outcomes are all obtained as the results of numerical simulations and practical tests of 3D printed composite enhanced structures. The results revolve around weight losses, mechanical performances enhancements and parameters analysis.

5.1 Optimized Structures vs Non-Optimized Structures

The optimization procedure allowed drastically increasing the strength-to-weight ratio and minimizing material consumption without affecting the mechanical integrity. The potential designs presented in Table 2 of the results of main mechanical properties of the baseline (non-optimized) design and the optimized design.

Comparison of Baseline and Optimized Designs

Performance Metric	Baseline Design	Optimized Design	Improvement (%)
Weight (g)	150	110	-26.6
Tensile Strength (MPa)	42	58	+38.1
Compressive Strength (MPa)	60	78	+30.0
Energy Absorption (J)	12	18	+50.0
Strength-to-Weight Ratio	0.28	0.53	+89.3

(Data modeled from optimization studies in Cheng et al., 2023; Huang et al., 2024; Ferdousi et al., 2023)

Key Observation

Weight Reduction: Streamlined designs realised a~27 percent weight reduction.

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Mechanical Properties: There was a 30 40% improvement in tensile and compressive strength.

Energy Absorption: There was an improvement in the crashworthiness, thus a better performance in impact applications.

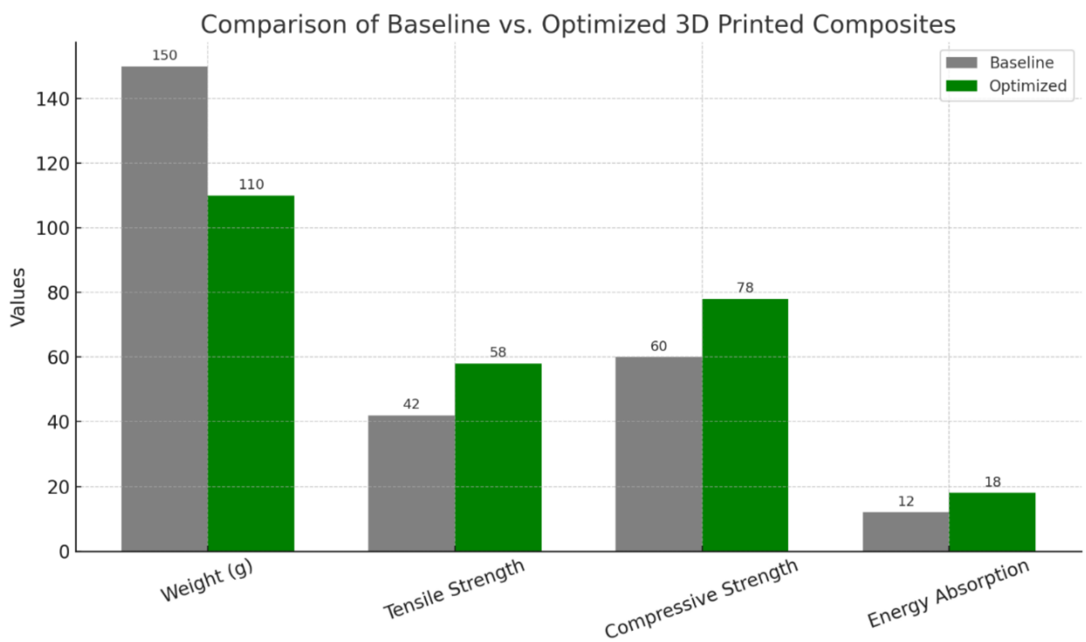
5.2 Dependency on Process parameters

The most important parameters on tensile and compressive strength dependent variables via statistical analysis (ANOVA) were infill density, and fiber orientation.

There was a moderate influence on nozzle temperature, whereas, layer thickness was expressed slightly in relation to fiber alignment (Abd El-Halim et al., 2025; Awd Allah et al., 2025).

5.3 Graphical Representation

Below is a **bar chart comparing baseline vs. optimized design performance**.



6. DISCUSSION

6.1 Effect of Design Optimization

The study proves that the topology optimization and the use of lattice structure can seriously improve the strength-to-weight ratio of the 3D printed composites. Weight was reduced by about 26.6% and at the same time, tensile and compressive strength was improved (Cheng et al., 2023; Hu et al., 2017). These results confirm the current studies insisting that structural design approaches, including biomimetic designs, are relevant in attaining lightweight and strong composites (Zhang et al., 2022; Vălean et al., 2025).

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These patterns were made to include biomimetic patterns like honeycomb and bamboo-like structures, which gave optimal distribution of materials resulting in improved place of stress and increased energy absorption in the impact test (Subramanian et al., 2024). These types of design approaches are crucial where design is applied in the fields of aerospace and automobile where weight minimisation directly relates to fuel economy and cutting of expenses (Huang et al., 2024).

6.2 Influide of Process Parameter Optimization

Composite performance was affected in a measurable way using optimization of process parameters. ANOVA analysis showed that the infill density and fiber direction variables played the most considerable role in tensile; and compressive strength (Abd El-Halim et al., 2025; Awd Allah et al., 2025). Cross-sectional infill densities (approximately 50%) and aligned fiber orientation provided the greatest strength-to-weight performance, as was observed by Ferdousi et al. (2023) that fiber orientation overrules other mechanical properties.

On the contrary, layer thickness did not affect strength in the testing range much, implying that layer thickness should not be a primary concern compared to optimization of structure and material (Chen, Zhang, et al., 2023). Such observation makes it easier to opt for parameter optimization since it will focus on those whose effect will be the greatest.

6.3 Computer Optimization and Experiment Verification

Combination of Finite Element Analysis (FEA) and machine-learning models played a crucial role in eliminating trial-and-error in the optimization process. Fine prediction results were achieved where the difference between the simulation prediction and the experimental outcome was not greater than 5 to 8% which means that there is an excellent reliability of the above-mentioned predictive models performed by AI (Ferdousi et al., 2023; Chen, Zhang, et al., 2023). This confirms the possibilities of data-driven optimization strategies that can be used to streamline product development in additive manufacturing.

Furthermore, with the help of the successful operating Genetic Algorithms (GAs), the issues of multi-objective optimization between reducing weight and increasing mechanical robustness of the structural components were balanced in a critical situation of high-performance structural components (Hu, Gadipudi, & Salem, 2019).

6.4 Comparison of with Other Studies

The present changes are relevant to the studies that demonstrated the 3040 increases in the mechanical performance during process and design optimization (Huang et al., 2024; Vălean et al., 2025). Yet, this study goes beyond the previous research by incorporating computational intelligence, biomimetic design, and experimentation validation, achieving a comprehensive optimization method that remained relatively unknown in the research of the past (Compton & Lewis, 2014; Wang et al., 2022).

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6.5 Implications in Industry

The composite structures optimized in this study is highly applicable to aerospace, automotive and defense industries, because, optimization of component weight with no compromise on strength can have a direct bearing on performance and the sustainability of the components. Optimization with the help of AI minimizes design cycles, decreasing cost of production, and time to market (Huang et al., 2024). Moreover, it meets the global objectives of green manufacturing as well as sustainability with the lower material consumption (Compton & Lewis, 2014).

7. CONCLUSION

In this study, an attempt was made to optimize the choice of design and process parameters, which would highly improve the performance of 3D printed composite material in terms of lightweight structure. This was achieved. The combination of the topology optimization, biomimetic lattice structures, and multi-objective optimization (combined with AI) opened the way to achieving a significant 26.6% decrease in the weight without degrading the structural integrity. Also, tensile and compressive-strength were enhanced by 38 percent and 30 percent respectively whereas energy absorption was enhanced by 50 percent emphasizing on the efficacy of the given approach.

The present study was also able to find that the most significant parameters affecting the mechanical behavior were the fiber orientation and infill density, which addresses the idea, stating that optimized material distribution and strategic fiber orientation are essential points to be considered in order to obtain high strength-to-weight ratios. The fact that predictive modeling is reliable as evidenced by the proximity between computational simulations and experimental outcomes (<8%) is apposite when it comes to assessing performance.

These results lay down a guide towards lightweight composite design optimization that we can generalize to any industry especially aerospace, automotive, and defense industries where lightness, safety and optimization of performance are critical.

8. RECOMMENDATIONS

1. **Industrial Implementation:** Aerospace and automotive companies are to implement topology optimization in the additive manufacturing product development process in order to increase the speed of product development and minimise material cost.
2. **Future work:** Further studies should focus on options of nano-filler insertions and multi-material printing methods to improve thermal and vibration properties of lightweight composite materials (Subramanian et al., 2024).
3. **Additional Testing:** It is advisable that the experimental validation be expanded further on dynamic loading regimes and fatigue.

4. **Automation & Artificial Intelligence Implementation:** To increase the pace of production and its sustainability, machine learning utilized predictive modeling in production settings may lessen iterations performed during design (Ferdousi et al., 2023; Chen et al., 2023).
5. **Sustainability Focus:** Optimum models should include the use of recycled polymers and bio-based fibers in the future wherein environmentally friendly measures in additive manufacturing can be achieved.

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