

Cordierite–Mullite–Alumina Composites for 3D Printing

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Abstract

Cordierite, Mullite, and Alumina matrix composite porous ceramic materials play a crucial role in the field of 3D printing in industrial design. These materials provide a combination of desirable properties such as thermal stability, mechanical strength, and lightweight characteristics. Additionally, their porous architectures enable the creation of complicated and efficient designs. This research focused on optimizing 3D printing approaches for the Cordierite-Mullite-Alumina composite, a material that exhibits significant industrial applicability. The earliest phases of the research involved the careful selection and composition of ceramic particles, with a particular focus on Cordierite, Mullite, and Alumina, in conjunction with Polylactic Acid (PLA). The research subsequently examines the optimisation of crucial parameters in 3D printing, namely infill %, printing direction, and layer height. This is accomplished by the utilisation of an innovative hybrid optimisation technique that combines the Ring Toss Game-Based Optimizer (RTGBO) and the Starling Murmuration Optimizer (SMO). The accuracy of the hybrid technique is strongly supported by experimental validation, indicating its potential to significantly enhance efficiency and precision in 3D printing for Cordierite-Mullite-Alumina composite materials. This validation highlights the possibility of a revolutionary impact in the field. The solution that yields the best results is characterised by a 40.69% infill, X-axis printing orientation, and a layer height of 0.276 mm. This particular solution demonstrates a remarkable Ultimate Tensile Strength (UTS) of 27.28 N/mm². Furthermore, the attainable solution has encouraging mechanical characteristics. This work is a significant addition to the field of [additive manufacturing](#), providing useful insights for future progress. It highlights the importance of bio-inspired design, advanced hybrid algorithms, and sustainability in driving revolutionary growth and facilitating meaningful applications across many sectors.

1. Introduction

Digital technology has emerged significantly in architecture and industry with complexity and materiality[1]. Through this, 3D printing technology has arisen as an advanced manufacturing method in industrial processes. In addition, 3D printing technology has attained its feasibility approach for attaining various streamlined production processes, reducing human intervention in manufacturing and also to minimize material waste with effective energy efficiency[2]. In recent years, there has

been a surge of interest in the field of three-dimensional (3D) printing, particularly about polymers and metals. However, it is worth noting that the scope of 3D printing has expanded to include ceramics, which has emerged as a prominent area of investigation[3]. In recent years, the emergence of novel materials and advancements in printing technologies have set the way for rapid and multi-material printing, opening up novel possibilities for various applications and utilisations. The absence of materials with novel physical characteristics, however, represents the fundamental obstacle to developing many additional uses. Moreover, the utilisation of this particular form of three-dimensional (3D) printing technology has led to the attainment of remarkably high levels of resolution. This enhanced resolution, in conjunction with the emergence of novel properties, has subsequently paved the way for the development of innovative applications, including microfluidic systems, biomedical devices, and soft robotics[4].

However, Some of the additive manufacturing methods can be used only with light-sensitive resins so the selection of materials is more complicated, and also needs additional processes to attain desired mechanical properties. In addition, The application of the Binder Jetting technique has engendered a surface texture that is characterized by a granular or rough finish. The concern of inadequate mechanical robustness necessitates a follow-up processing phase that enables the elimination of moisture or reinforcement of strength. Additionally, the Material Extrusion method is affiliated with a diminished degree of precision and a prolonged construction duration. The inability to fabricate exact external corners acts as a hindrance to the manufacturing procedure. In the Selective laser sintering process, the Feature resolution mainly depends on laser-beam diameter. Moreover, in the Fused deposition modelling method, a Material restriction occurred due to the application of thermoplastic polymers, poor quality variation, and integrity[5], [6]. In contrast, the main advantages of polymers and composites in additive manufacturing are fast prototyping, cost-effective, and complex structures. However, only a limited source of polymers is manufactured through additive manufacturing also the mechanical properties are relatively low[6].

In 3D printing technology, a complex grain structure occurs that affects the quality of the materials. A directed energy deposition process is utilized for the existing components to add or repair additional material. Moreover, the principle is similar to the material extrusion process but without any determination of the axis in the nozzle. Furthermore, this process which is in the form of powder or wire can also be implemented in the ceramics additive manufacturing process[7]. In addition, unique and functional electronic materials were incorporated using typical geometries into printing materials, unlike the traditional methods. Moreover, the establishment of the substrate and the process for 3D printing can be considered as an adopting strategy that promotes a higher level of integration in the fabrication process[8]. Nevertheless, a lack of proven traditional additive manufacturing (AM) techniques is specifically needed for the production of silicone rubber membranes mainly for electrical components[9]. Furthermore, while employing a 3D-printed object for prototype purposes, the presence of an external consumer is absent, leaving only an internal client, namely the research and development or product engineer. Consequently, the specifications and criteria for the 3D-printed object deviate from those applicable to a commercially available product[10]. In different processing methods and operating conditions, it is possible for there to be variations in the properties of different

parts of a component along the build direction. The iterative inclusion of substances leads to the successive exposure of the foundational layers to several instances of thermal expansion and contraction. As a result, the annealing impact varies for each build layer. Moreover, the lower layers of the object are subject to a greater cooling rate as a result of their proximity to the building substrate. The aggregation of these elements results in a graded microstructure characterised by minor differences in characteristics spanning from the lower to the upper regions of the structure[11].

The present research makes a substantial contribution to the fields of additive manufacturing, material science, optimisation methodologies, and composite material synthesis. The primary contributions encompass:

The objective of this research is to optimise the parameters of 3D printing to improve the fundamental aspects of the process. Specifically, the focus will be on optimising the infill %, printing direction, and layer height. The purpose is to enhance the precision and efficiency of 3D printing processes.

This work presents research on the improvement of material properties in Cordierite-Mullite-Alumina composites, specifically focusing on enhancing their tensile strength. The findings of this research demonstrate the potential for these composites to exhibit better mechanical performance, making them suitable for various structural applications.

This work aims to validate the experimentation conducted to corroborate the hybrid optimisation outcomes, so assuring the accuracy and dependability necessary for practical implementation.

This research presents a unique approach called Hybrid Optimisation Integration, which aims to effectively combine the Ring Toss Game-Based Optimizer (RTGBO) and the Starling Murmuration Optimizer (SMO). The integration of these two optimisation techniques offers improved exploration and exploitation capabilities, leading to a significant advancement in the field of optimisation.

The subsequent sections of this research are structured in the following manner: Section II undertakes a comprehensive examination of relevant research. Section III provides a comprehensive and detailed exposition of the problem's statement. Section IV provides an overview of the suggested methodology for research. Section V of the research is dedicated to the examination of material selection and preparation processes for the composite materials utilised in the research. Section VI provides a detailed exposition of the design and printing processes employed for the fabrication of the Cordierite-Mullite-Alumina Composite structure. Section VII of the document pertains to the further processing and analysis procedures. In Section VIII, the experimental design and setup for the tensile test are described comprehensively. The findings and analysis of the experimental research are outlined in Section IX. Section X serves as the concluding segment.

2. Literature review

Sathish et al. [12] discussed the use of 3D printing technology as a prototyping method for printing final components in various industries. The paper aimed to explore the possibilities of replacing metallic parts with non-metallic ones to address the rising costs of the components along with the limited resources concerning durability and quality. In addition, the research utilized ABS (Acrylonitrile Butadiene Styrene) with a thermoplastic compound having properties such as durability, thermal stability and also with impact resistance that were needed for combustibility standards for specific applications. Moreover, the paper also discussed subtractive manufacturing for removing materials from solid pieces which were often done using CNC machines. In addition, this method was used for creating components like living hinges, which were not yet possible with 3D printing.

Chan et al. [13] proposed the impact of 3D printing technology in the field of the manufacturing industry, mainly based on supply chain management, for gathering various opportunities to adopt 3D printing technology. However, true business opportunities were not realized for 3D printing technology, mainly in the supply chain, in case of potential intellectual property issues. Moreover, a cost-effective solution was needed for various industrial applications, so 3D printing technology was considered but not yet delivered as potential towards industrial applications. In addition, for complex legal licensing, there was a lack of appropriate standards and customization allowed the production to attain critical benefits even for a single unit. However, most companies preferred mass production, and still, the application of 3D printing technology was limited.

Sauerwein et al. [14] proposed an additive manufacturing method for supporting sustainable design in a circular economy approach, prioritizing the value of high-quality materials for recycling purposes. Moreover, 3D printing technology could support multiple product life cycles for a circular economy. However, monolithic structurally complex parts design might have hindered product recovery and repairs.

Wang et al. [15] reviewed many kinds of literature which are mainly focusing primarily on the development of 3D printing technologies for the aviation sector, which addressed issues with printing techniques and shortened cycle times. The paper applied a fuzzy systematic approach for accessing the applications and importance of 3D practices that provide valuable input for expanding 3D printing applications for [aircraft](#) in various countries.

Dankar et al. [16] analyzed and compared sixteen different published articles based on 3D food printing to set 3D printing parameters for various food ingredients and maintain shapes and textures through optimized extrusion food printing. The research was conducted extensively by optimizing food printing and facilitating the production range of food items in distinct forms and textures. Moreover, the drawbacks of 3D printing in the 21st century were critically examined, and several strategies were adopted to effectively address the identified limits. This work aimed to facilitate future research endeavours by exploring a broader spectrum of food printing components and their

impact on customer acceptance.

Lamichhane et al. [17] primarily focused on the principles based on fused deposition modelling and ink-based 3D printing technology. Additionally, the paper discussed the use of stereolithography (SLA) technology in the preparation of drug-loaded hydrogels and extended-release tablets and also provided insights into the limitations and potential application of 3D printing technology in the pharmaceutical industry. The paper also suggested that 3D printing could simplify and streamline the manufacturing process by reducing the need for intricate manufacturing processes and potentially lowering overall costs and time requirements. The deployment of 3D printing technology in large-scale manufacturing resulted in a demanding, time-consuming process. However, for less extensive production, the manufacturing setting could be adjusted to meet the current need, and the approach was not only practical but also economical.

Chong et al. [18] assessed the advantages of incorporating 3D printing and Industry 4.0 technologies within engineering undergraduate curricula. In addition, they conducted surveys to collect opinions and perspectives from scholars and students. However, the identified limitations encompassed budgetary constraints, insufficient knowledge, and challenges associated with transitioning from conventional pedagogical approaches. Meanwhile, a series of surveys were undertaken to collect comments and perspectives from both academics and students. The results indicated that 75% of students and 86% of lecturers were familiar with the concept of Industry 4.0. Additionally, it was found that 63% of students had been exposed to coursework that incorporated features related to Industry 4.0. Tangible three-dimensional (3D) printed models facilitated the visualization of essential ideas and concepts. Additionally, improved 3D sketching abilities and the availability of rapid 3D-printed prototypes could contribute to the research of several facets within the fields of manufacturing, maintenance, logistics, and operations.

Beg et al. [19] examined the possible impact of 3D printing technology on addressing pharmacological and biomedical concerns within the context of global healthcare. In that research, the investigation aimed to analyze the effects of a particular drug on the human body. The report clarified the multifaceted applications of 3D printing and the notable surge in interest in utilizing this technology for industrial manufacturing and research advancements. The authors placed significant emphasis on the necessity for the development of enhanced and adaptable techniques in the realm of 3D printing, along with advancements in material utilization efficiency and the attainment of greater precision in item fabrication. Nevertheless, the sources failed to offer explicit details regarding the constraints or difficulties linked to the research or conclusions presented in the paper. Additionally, it is noteworthy that the authors of a research paper often addressed the constraints of their research. However, it is crucial to mention that the offered sources did not provide any information regarding such restrictions.

Quan et al. [20] aimed to present an overview of the photocuring 3D printing techniques that had attained a level of maturity and commercialization. Specifically, the techniques under consideration were Stereolithography (SLA), Digital Light Processing (DLP), Liquid Crystal Display (LCD), Continuous

Liquid Interface Production (CLIP), and Multijet Printing (MJP). This paper also aims to present a comprehensive analysis of various photocuring 3D printing technologies, focusing on their underlying principles of pattern formation and printing methodology. The technologies under evaluation included Stereolithography (SLA), Digital Light Processing (DLP), Liquid Crystal Display (LCD), Continuous Liquid Interface Production (CLIP), Multijet Printing (MJP), two-photon 3D printing, and holographic 3D printing. However, the presence of support pillars during the printing process contributed to the augmentation of labour expenses and the exacerbation of surface roughness, thereby necessitating supplementary polishing procedures. The research direction of support-free photopolymerization 3D printing emerged as a potential solution to tackle the aforementioned issue.

Mukhtarkhanov et al. [21] examined the current advancements and practicality of stereolithography (SLA) based 3D printing technology in the field of investment casting (IC) manufacture. That research was particularly relevant given the increasing prevalence of SLA-based additive manufacturing (AM) technologies. Additionally, the research examined alternative additive manufacturing (AM) techniques employed in integrated circuits (IC) to provide a comparative analysis. This statement implied that more research was required to address the aforementioned problems and to examine the toxicity levels associated with the use of photopolymers in stereolithography-based integrated circuit (IC) techniques.

Nichols[22] investigated the advantages of 3D metal printing within the automobile sector, encompassing both current and prospective applications. This research investigated the potential impact of 3D metal printing on the manufacturing process, specifically in terms of its ability to enable engineers to produce completely functioning prototypes directly from digital designs, hence reducing the necessity for further fabrication procedures. Furthermore, this paper examined the implications of 3D metal printing on the accessibility of replacement parts for automobiles that are uncommon and produced in limited quantities. In addition, this research examined the potential impact of 3D metal printing on the reduction of vehicle weight and enhancement of fuel efficiency. Nevertheless, the research failed to address the financial consequences associated with the adoption of 3D metal printing technology. This included the initial capital expenditure necessary for procuring equipment and materials, as well as the subsequent expenses related to maintenance and operating activities.

Oladapo et al. [23] investigated the utilization of 3D printing technology in the production of face shields as a means to alleviate the scarcity of personal protective equipment (PPE) during the COVID-19 epidemic. The paper explored the potential and feasibility of utilizing 3D printing technology to mitigate the scarcity of personal protective equipment (PPE), without delving into its effectiveness or long-term implications. The paper outlined a comprehensive methodology for the rapid and efficient production of 3D face shields and ventilators. Moreover, the paper assessed the potential of 3D printing technology in addressing the shortage of medical devices required to combat the COVID-19 pandemic. Additionally, the paper examined notable advancements in 3D printing across different institutions and put forth a forward-looking approach to the development of medical devices aimed at preventing and treating COVID-19.

Shah et al. [24] investigated the market for extrusion-based 3D printing techniques utilized for polymer-based materials and examined the challenges associated with scaling this technology for industrial applications. Additionally, the process of increasing the size of a material extrusion 3D printer presented challenges in terms of mechanical aspects. However, the capabilities of extrusion-based 3D printing technology were constrained when operating beyond this particular scale. Moreover, the primary emphasis was on the dimensions of the printer, its constituent elements, and the produced printed components. The results of the testing revealed that the presence of large hot-end nozzles on small-scale 3D printers gave rise to certain problems. This research aimed to aggregate comprehensive data on the subject of large-scale 3D printing.

Candi et al.[25] examined the correlation between the utilization of 3D printing (3DP) in the context of innovation and the performance of enterprises in the United States. Additionally, the research aimed to discover the internal and external factors that regulated this correlation. The research integrated the use of three-dimensional printing (3DP) throughout the entire innovation process, encompassing ideation, development, and launch stages, rather than merely differentiating between prototyping and manufacture. Further investigation was recommended to explore the utilization of 3D printing (3DP) throughout various stages of the innovation process. In addition, the utilization of 3D printing technology in the context of innovation exhibited a positive correlation with innovation performance. Furthermore, this correlation was found to be more pronounced when there was a higher degree of technical turbulence.

3. Problem statement for 3D printing Technologies

Table 1. Problem identification for 3D printing technology.

Author	Aim	Methodology	Problem identification.
Sathish et al. [12]	Discuss the use of 3D printing technology as a prototyping method for printing final components in various industries.	Explored possibilities of replacing metallic parts with non-metallic ones to address rising costs and limited resources. Used ABS with thermoplastic compound. Discussed subtractive manufacturing.	Rising costs of metallic components, and limited resources concerning durability and quality.

Chan et al. [13]	Propose the impact of 3D printing technology in the manufacturing industry, particularly in supply chain management, highlighting challenges like intellectual property issues and lack of cost-effective solutions.	Investigated business opportunities and challenges of 3D printing technology in supply chain management.	Limited adoption of 3D printing due to potential intellectual property issues, lack of cost-effective solutions, and absence of appropriate standards.
Sauerwein et al. [14]	Propose an additive manufacturing method for supporting sustainable design in a circular economy, emphasizing the value of high-quality materials for recycling.	Focused on additive manufacturing for circular economy, pointed out challenges in product recovery and repairs for complex designs.	Challenges in recovering and repairing complex monolithic structurally complex parts.
Wang et al. [15]	Reviewed literature on 3D printing in the aviation sector, and applied a fuzzy systematic approach to assessing applications and the importance of 3D practices for aircraft.	Reviewed literature on 3D printing in aviation, and applied fuzzy systematic approach for assessing applications.	Focus on the development of 3D printing technologies for the aviation sector, addressing printing techniques and cycle times.
Dankar et al. [16]	Analyzed and compared articles on 3D food printing, optimized parameters for extrusion food printing, and examined drawbacks of 3D printing in the food industry.	Analyzed and compared articles on 3D food printing, optimized extrusion printing parameters, and addressed drawbacks.	Addressed optimization of food printing parameters, and examined limits of 3D food printing in the 21st century.

Lamichhane et al. [17]	Focused on principles of 3D printing technologies in the pharmaceutical industry, suggested simplification and streamlining of the manufacturing process.	Discussed principles of 3D printing in the pharmaceutical industry, and suggested simplification of the manufacturing process.	Highlighted the potential of 3D printing to simplify pharmaceutical manufacturing, and pointed out challenges in deploying 3D printing technology at a large scale.
Chong et al. [18]	Assessed benefits of integrating 3D printing and Industry 4.0 technologies in engineering curricula, and conducted surveys to gather opinions from scholars and students.	Assessed the benefits of integrating 3D printing and Industry 4.0 in engineering curricula, and conducted surveys.	Identified advantages of integrating 3D printing and Industry 4.0 in engineering education, highlighted challenges like budget constraints and insufficient knowledge.
Beg et al. [19]	Examined the impact of 3D printing on pharmacological and biomedical concerns, and emphasized the need for enhanced techniques and material efficiency in 3D printing.	Examined the impact of 3D printing on pharmacological and biomedical concerns, and emphasized the need for enhanced techniques.	Explored the impact of 3D printing on healthcare, and emphasized the need for improved techniques and material efficiency.
Quan et al. [20]	Provided an overview of photocuring 3D printing techniques.	Provided overview of photocuring 3D printing techniques, and analyzed principles of various technologies.	Explored photocuring 3D printing techniques, and highlighted challenges like support pillars during printing.
Mukhtarkhanov et al. [21]	Examined the practicality of stereolithography (SLA) based 3D printing in investment casting (IC) manufacture, and compared alternative AM techniques for integrated circuits (IC).	Examined the practicality of SLA-based 3D printing in investment casting, and compared AM techniques for ICs.	Explored SLA-based 3D printing in investment casting, and suggested further research on toxicity levels.

Nichols [22]	Investigated advantages of 3D metal printing in the automobile sector, focused on its impact on the manufacturing process, replacement parts, and vehicle weight reduction.	Investigated the advantages of 3D metal printing in the automobile sector, and highlighted the impact on manufacturing and parts.	Explored benefits of 3D metal printing in the automobile sector, and pointed out the lack of focus on financial consequences.
Oladapo et al. [23]	Investigated the use of 3D printing for producing face shields during the COVID-19 pandemic, and explored the feasibility and potential of 3D printing technology for medical device production.	Investigated the use of 3D printing for producing face shields during a pandemic, and explored feasibility and potential for medical device production.	Explored the use of 3D printing for medical devices during COVID-19, and emphasized feasibility and potential.
Shah et al. [24]	Investigated the market and challenges of scaling extrusion-based 3D printing for polymer materials, especially about mechanical aspects and printer dimensions.	Investigated challenges of scaling extrusion-based 3D printing, focused on mechanical aspects and dimensions.	Explored challenges of scaling extrusion-based 3D printing for polymer materials, and highlighted limitations beyond certain scales.
Candi et al. [25]	Examined the correlation between 3D printing and innovation performance in enterprises, focused on internal and external factors regulating this correlation.	Examined the correlation between 3D printing and innovation performance, and explored regulating factors.	Explored the correlation between 3D printing and innovation performance, and suggested the need for further investigation in various stages of the innovation process.

4. Proposed Methodology

The proposed methodology comprises a meticulous process of selecting Cordierite, Mullite, and Alumina ceramic particles based on their mechanical properties and solubility characteristics. The selection of Polylactic Acid (PLA) as the polymer binder is based on its compatibility with ceramics and its suitability for usage in Fused Deposition Modelling (FDM) processes. The process involves the careful blending of ceramic particles with polylactic acid (PLA) to produce a filament that is packed

with ceramic material. The composite structure is built by ASTM D638 requirements using SolidWorks 2020 software. Various factors such as printing direction, infill percentage, and layer height are taken into consideration throughout the design process. The 3D printer has been appropriately set up, and the filament containing ceramic particles has been introduced. After the printing process, specimens undergo preparation for [tensile testing](#), taking into account many factors. Tensile tests are performed via a Universal Testing Machine (UTM) by the requirements outlined in ASTM D638. The acquired data is meticulously examined to derive conclusions on the influence of infill percentage, printing direction, and layer height on the tensile properties. The use of this methodical technique provides significant perspectives for future enhancements to get the required characteristics of materials. Furthermore, the utilisation of a hybrid technique consisting of the Ring Toss Game-Based Optimizer and the Starling Murmuration Optimizer is employed in a validation process to optimise parameters such as infill %, printing direction, and layer height, to improve the tensile characteristics. The validation findings demonstrate a significant level of accuracy, providing strong evidence for the potential of the hybrid optimisation approach to enhance the efficiency of 3D printing for Cordierite-Mullite-Alumina composites.

4.1 The Overall Architecture of the Proposed Methodology

The fabrication process of the Cordierite-Mullite-Alumina composite using ceramic-filled filament and Fused Deposition Modelling (FDM) adheres to a methodical and organised approach, involving many essential phases and components. The architectural design of the system prioritises the achievement of accuracy, efficiency, and optimal performance during the processes of composite material generation and assessment.

Step 1: Material Selection and Preparation Phase

Ceramic Particle Selection: The selection method entails a meticulous evaluation of Cordierite, Mullite, and Alumina, with a specific emphasis on their mechanical qualities and material solubility.

Polymer Binder Selection: The selection of Polylactic Acid (PLA) as the polymer binder is based on its compatibility with both ceramic materials and the Fused Deposition Modelling (FDM) printing method.

Ceramic-Filled Filament Preparation: The approach entails the correct combination of ceramic particles with PLA to produce a ceramic-filled filament, which serves as a crucial component in the 3D printing procedure.

Step 2: 3D Model Design and Printing Setup Phase

Design using SolidWorks 2020: The composite structure was designed with the SolidWorks 2020 software, by the ASTM D638 requirements. Key factors such as printing direction, infill %, and layer height were taken into careful consideration during the design process.

Printer Configuration and Calibration: Configuring an FDM printer involves many steps aimed at

achieving optimal performance. These steps encompass bed levelling, extruder alignment, and adjustment of other parameters to guarantee accurate deposition of the filament.

Printing Process: The ceramic-filled filament is loaded into the Fused Deposition Modelling (FDM) printer, and the 3D printing process is initiated to construct the composite structure in a sequential layer-by-layer manner.

Step 3: Specimen Preparation and Testing Phase

Specimen Design: The design of specimens is performed with consideration of several criteria, including infill %, printing orientation, and layer height, to facilitate future tensile testing.

Tensile Testing Setup: The specimens have been prepared for tensile testing by the ASTM D638 standards. This is being done to assess the mechanical characteristics of the composite material using a Universal Testing Machine (UTM).

Tensile Testing and Data Collection: The experiment involved performing tensile tests and gathering data on the maximum load and ultimate tensile strength obtained.

Step 4: Data Analysis and Optimization Phase

Data Analysis: The acquired data is being analysed to make conclusions on the impact of infill %, printing direction, and layer height on tensile characteristics.

Optimization Recommendations: suggesting possible enhancements derived from the investigation to get the desired material attributes.

Step 5: Validation Using Hybrid Optimization Phase

Hybrid Approach Integration: The optimisation of infill %, printing orientation, and layer height is achieved by employing a hybrid methodology that combines the Ring Toss Game-Based Optimizer (RTGBO) and the Starling Murmuration Optimizer (SMO).

Validation and Comparison: The hybrid optimisation technique is evaluated by comparing the optimised outputs with experimental findings to prove its efficacy and accuracy.

Step 6: Conclusion

Conclusion: The results and conclusions of the technique employed in the fabrication and evaluation of Cordierite-Mullite-Alumina composites are highlighted, with a focus on their efficacy and potential.

5. Material selection and preparation

5.1. Ceramic particle selection.

Ceramic particles play an important role in determining the properties of composites using the fused deposition process. In this research, Cordierite, Mullite, and Alumina ceramic particles are chosen as composite materials. These particles are selected based on mechanical properties and the solubility of the material is prescribed as follows.

5.1.2 Theoretical Properties of Cordierite ceramic materials.

Cordierite is represented here by the chemical formula $\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$. The chemical is observed in the form of a powdered substance ranging in colour from orange to tan, and it demonstrates a melting point of 1460°C . Exhibiting a density within the range of 2.0 to 2.3 g/cm^3 , this substance demonstrates an insoluble characteristic in water and possesses an electrical resistance of $10^{10}\text{ }\Omega\text{-m}$. The material has a Poisson's ratio of 0.21 and has a specific heat ranging from 800 to 850 J/kg-K . About its mechanical qualities, the material exhibits an ultimate tensile strength of 190 MPa . About thermal properties, the compound exhibits a thermal conductivity ranging from 1.3 to 1.7 W/m-K , and a thermal expansion coefficient ranging from 2.9 to $4.8\text{ }\mu\text{m/m-K}$. Moreover, the Young's Modulus of the compound, which serves as an indicator of its elasticity, has been established to be 62 GPa .

5.1.3 properties of mullite ceramic materials.

Mullite has gained prominence as a noteworthy ceramic material in both conventional and advanced structural applications, primarily owing to its exceptional characteristics. These properties encompass high-temperature stability, a considerable melting point, low thermal expansion and conductivity, elevated electrical resistivity, commendable creep resistance, and corrosion stability. The ceramic processing industry frequently employs it, particularly in mullite-based refractories, which possess notable attributes like a lightweight composition, effective heat insulation, and resistance to hostile chemical conditions. The exceptional high-temperature properties of mullite and its composites offer potential for advanced applications such as thermal and environmental barrier coatings for aircraft and gas turbine engines, efficient catalytic converters, kiln furniture and hot gas filters. The underlying crystal structure of mullite can be comprehended as a modified iteration of the mineral sillimanite, denoted as Al_2SiO_5 ($\text{Al}_2\text{O}_3\cdot\text{SiO}_2$)[26].

5.1.4 Properties of alumina ceramic particles

Alumina, scientifically referred to as aluminium oxide (Al_2O_3), is a widely recognised engineering substance renowned for its favourable mechanical and electrical properties, rendering it highly versatile in various applications. Alumina exhibits versatility due to its ability to be synthesised with varying degrees of purity through the use of additives that enhance its inherent characteristics. Ceramics offer a diverse range of fabrication techniques, including precision machining and net shape forming, enabling the production of components with varying sizes and geometries. Alumina exhibits favourable compatibility with various ceramics and metals, facilitating its seamless integration into composite materials. Alumina is renowned for its exceptional mechanical qualities, including high strength and stiffness, commendable hardness and wear resistance. Moreover, it exhibits favourable resistance to corrosion, remarkable thermal stability, and excellent dielectric properties that are effective throughout a wide range of frequencies, spanning from direct current (DC) to gigahertz (GHz). Alumina exhibits a low dielectric constant and a minimal loss curve, rendering it highly advantageous for various applications that prioritise various industrial applications.

5.2 Selection of polymer binding materials.

The selection of an appropriate polymer binder is of utmost importance to ensure compatibility with the ceramic particles and the Fused Deposition Modelling (FDM) process. The selection of polylactic acid (PLA) is based on its biodegradability, low toxicity, and strong adherence to ceramics.

PLA (Polylactic Acid): Polylactic Acid (PLA) is a biopolymer that is sourced from renewable materials such as maize starch or sugarcane. The polymer binder's appropriateness for the ceramic-filled filament is attributed to its compatibility with ceramic materials and the FDM printing process.

5.2.1 Preparation of ceramic-filled filament.

The manufacturing process of the ceramic-filled filament necessitates a methodical procedure to guarantee consistent dispersion of ceramic particles throughout the polymer binder.

Proportions for mixing ceramic particles with binders:

The ceramic particles and PLA polymer binder are combined in precise ratios to attain the intended composition.

The composition of the material consists of

40% cordierite particles,

35% mullite particles,

15% alumina particles,

and 10% PLA polymer binder.

To attain a consistent dispersion, the mixture is subjected to extensive mixing by the utilisation of a mixer or extruder. Ensuring the uniform distribution of ceramic particles within the polymer matrix is a critical step, as it significantly influences the material properties, hence contributing to their consistency.

Extrusion is the process by which the composite material is uniformly mixed and then forced through a die to produce a filament with a constant diameter. The utilisation of a ceramic-infused filament is proposed as the primary material input for the fused deposition modelling (FDM) additive manufacturing technique.

5.3 Experimental setup

5.3.1 Environmental Setup for Experimentation.

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Fig 1 YPANX Falcon 3D printing technology.

The experimental procedure involved the fabrication of Cordierite-Mullite-Alumina Composite materials using YPANX Falcon 3D printing technology (Fig 1). The experiments were conducted under controlled room temperature and steady humidity settings to ensure consistent performance and reliable outcomes.

5.3.2 Equipment and materials for making composites:

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Fig 2 high-quality PLA (polylactic acid) polymer binder.

This research employs a PLA (polylactic acid) binder (see Figure 2) with a diameter of 1.70 mm and a weight percentage of 10%. This binder is deemed appropriate for the application of fused deposition modelling technology in the production of ceramic composites using 3D printing. The Ypanx Falcon 3D printer, equipped with a 0.4-mm nozzle diameter, was employed for the production of the specimen. The process of product modelling was conducted using Solidworks 2020, a computer-aided design software, and Cura Ultimaker, a software specifically designed for 3D printing. The proposed design will integrate both stiff and flexible components, strategically arranged to correspond with the dispersion pattern of ceramic particles.

5.3.3 Particle sizes for ceramic materials.

Cordierite, Mullite, and Alumina ceramic particles, with average particle sizes of around 12 micrometres, 18 micrometres, and 5 micrometres, respectively, are intended to be procured. The selection of these particles is based on their distinct thermal and mechanical properties, which play a significant role in determining the features of the composite material.

5.3.4 Printer calibration and configuration.

5.3.4.1 FDM YPANX Falcon 3D printer calibration.

The procedure of bed levelling is a crucial stage within the 3D printing workflow, as it serves to establish a parallel alignment between the print bed and the nozzle of the printer. The utilization of this technique facilitates the attainment of appropriate adhesion and uniform layer height during the printing process. The process of bed levelling generally comprises the adjustment of the print bed's height at various locations to achieve a level surface.

Moreover, the alignment of the extruder is a critical factor in 3D printing, as it directly impacts the effective operation of the extruder nozzle. The process comprises the manipulation of the extruder nozzle's position and alignment to achieve precise deposition of the filament. Ensuring appropriate alignment is crucial in mitigating potential problems, including but not limited to clogging, uneven extrusion, and substandard print quality.

5.3.4.2 FDM YPANX Falcon 3D printer Configuration.

To achieve a compromise between printing resolution and speed, a layer height of 0.2 mm – 0.3 mm will be selected. To guarantee precise extrusion and robust layer bonding, a print speed of 55 mm/s will be implemented. To facilitate optimal melting and extrusion of the PLA polymer binder, it is necessary to establish a nozzle temperature of 230°C. To enhance adhesion and reduce warping during the printing process, it is necessary to heat the print bed to a temperature of 70°C.

6. Cordierite – Mullite – Alumina Composite structure Design and Printing.

6.1. 3D model design for composite material.

The Cordierite-Mullite-Alumina composite structure was fabricated using Solid Works 2020, a 3D modelling software, which produced a three-dimensional depiction. The design that has been

presented will incorporate both stiff and flexible components, which will be strategically positioned by the spatial arrangement of ceramic D particles. Furthermore, the test specimen for 3D modelling was prepared by the guidelines outlined in ASTM D638 standards (see Figure 3). The preparation involved considering factors such as printing direction (X, Y, Z), infill 20-80%, and layer height (0.2-0.3mm), which are crucial for conducting accurate tensile testing.

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FIG 3. 3D modelling as per ASTM D638 standards.

6.2. Optimizing STL File for Cura Ultimaker: 3D Printing Preparation.

The components were designed using Solidworks 2020 software and subsequently exported to Cura Ultimaker, utilising the STL file format for 3D printing. SolidWorks is a widely utilised computer-aided design (CAD) software that facilitates the creation of three-dimensional models. Conversely, Cura Ultimaker is a slicing software that is often employed to prepare three-dimensional models for printing. Its primary purpose is to ensure compatibility with the specifications of Fused Deposition Modelling (FDM) printers and to uphold the required dimensions of the printed object for slicing and printing. The selection of an infill density varies between 20-80% and is intended to strike a balance between achieving the requisite strength and optimizing material utilization. Support structures will be implemented to provide support for overhangs and complex shapes for tensile testing as per ASTM standards (Fig 5). The filament containing ceramic particles will be inserted into the printer. The initiation of the printing process will be facilitated by Cura Ultimaker, which will prompt the printer to commence the creation of the composite structure in a sequential manner, layer by layer.

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FIG 5 Tensile test specimen for ceramic composites.

7. The subsequent processing and analysis

7.1. Removal of Composite Structures and Evaluation of Mechanical Properties

After the printing process is finished, the Cordierite-Mullite-Alumina composite structure will be delicately removed from the printer's build platform using suitable tools to minimize any potential damage. The evaluation of mechanical properties involves conducting several tests, such as tensile tests, by the ASTM standard D638 (Fig 6).

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Fig 6. Tensile tests following the ASTM standard D638

8. Experimental design and setup for tensile test.

The experimental design includes the infill percentage, printing direction and layer height to find the impact on tensile materials. In this research, the printing direction refers to the orientation that is perpendicular to the printer bed. The infill percentage is utilized to measure the degree of hollowness or fullness of the finished printed part, in which the percentage of maximum value refers to the solid structure and a value of zero percentage represents the structure of the shell material. The thickness of individual layers refers to the layer height.

A constant value was considered for shell thickness at 0.8 mm, print speed was set as 55 mm/s and temperature at 230 °C and these criteria do not affect the impact strength for the selected criteria such as infill percentage, layer height and printing direction. In addition, eight values are taken into consideration for conducting tensile tests as shown in Table 1.

specimen	Infill percentage	Printing direction	Layer height
1	40%	X	0.2
2	40%	Y	0.2
3	40%	Z	0.2
4	50%	X	0.2
5	20%	X	0.2
6	80%	X	0.2
7	40%	X	0.25
8	40%	X	0.2

Table 1. The process parameters to be considered for a tensile test.

8.1 Algorithm

Mathematical modelling of RTGBO algorithm

This section presents a mathematical description of the RTGBO method for use in solving optimisation issues. Based on the location of each population member in the search space, the values of the optimisation problem variables are established. As a result, each person in the population is a vector with the same number of elements as there are variables in the issue.

The population matrix of the RTGBO algorithm serves as a representation of the population members.

$$X = \begin{bmatrix} X_1 & \dots & X_i & \dots & X_N \end{bmatrix}_{N \times m} = \begin{bmatrix} x_{1,1} & \dots & x_{1,d} & \dots & x_{1,m} & \dots & x_{i,1} & \dots & x_{i,d} & \dots & x_{i,m} & \dots & x_{N,1} & \dots & x_{N,d} & \dots & x_{N,m} \end{bmatrix}_{N \times m}$$

Here, N is the number of population members, X is the population matrix, X_i represents the i 'th population member, $x_{i,d}$ is the value of the d 'th variable for the i 'th population member, and m is the number of issue variables.

Using the equation, the results of the evaluation of the objective function based on the values of the population matrix may be shown as a vector.

$$OF = \begin{bmatrix} OF_1 & \dots & OF_i & \dots & OF_N \end{bmatrix}_{1 \times N}$$

The objective function vector in this case is OF , and OF_i stands for the value of the objective function for the member of the population i .

Score bars are put in the search space at this step of the modelling process, when population members supply improved values for the goal function using Equation

$$SB = \begin{bmatrix} SB_1 & \dots & SB_i & \dots & SB_N \end{bmatrix}_{N \times SB}$$

Here, SB is the matrix of locations of the score bars, SB_i indicates the position of i 'th score bar in the search space, and N_{SB} is the number of score bars, which is equal to 10% of the population members.

The flinging of the rings towards the scoring bars is modelled in the next phase. Each ring is hurled against a different bar at random. This process calculate the new locations of the RTGBO and the Equation is used to create circles

$$F = \text{round}((1+r)F)$$

$$dx_{i,d} = \begin{cases} sb_{i,d} - F_{x_{i,d}}, & \text{if } OF_{SB_i} < OF_i \\ r(x_{i,d} - F_{sb_{i,d}}), & \text{else} \end{cases}$$

$$x_{i,d}^{new} = x_{i,d} + dx_{i,d}$$

$$X_i = \begin{cases} X_i^{new}, & \text{if } OF_i^{new} < OF_i \\ X_i, & \text{else} \end{cases}$$

Here, $sb_{i,d}$ is the d 'th dimension of the score bar position, OF_{SB_i} is the value of the objective function of the i 'th score bar, and $dx_{i,d}$ is the value of displacement for the i 'th population member in the d 'th dimension. $x_{i,d}^{new}$ is the new proposed location for the i 'th population member in the d 'th dimension; OF_i^{new} is the value of the objective function for the i 'th population member's new suggested position; and r is a random number within the $[0, 1]$ range.

Starling Murmuration Optimizer (SMO)

When huge groups of numerous birds fly and spin in carefully linked shape-shifting living clouds, generating wonderful visual spectacles, this occurrence is known as starling murmuration (family Sturnidae). The reason that behaviour is used in optimisation is because none of the vast numbers of birds flying in unison ever crash with one another. It is hardly surprising that one of the SMO algorithm's earliest real-world uses was to coordinate the flying of large swarm of drone.

The starling murmuration optimizer (SMO) is a metaheuristic algorithm introduced in 2022 by Zamani *et al.* It is a population-based algorithm utilizing a dynamic multi-flock construction. It introduces three new search strategies: separating, diving and whirling.

Individual starlings are randomly dispersed during the algorithm's first phase. The following equation describes the initial location of the i th starling in the group of N birds:

$$x_{id} = x_d^l + \text{rand}(0,1) (x_d^u - x_d^l), \quad i = 1, 2, \dots, N; \quad d = 1, 2, \dots, D$$

Where N is the whole starling population, D is the number of dimensions there are in the search space, x_{id} is the starling's d th dimension. S_i , x_d^u the search space's upper bound and x_d^l is the search space's lowest bound. A random function with a value between 0 and 1 is called $\text{rand}(0, 1)$.

Following setup, a few of the starlings split off from the flock to create a new flock called P_{sep} , which will scour the area in line with

$$P_{sep} = \frac{\log(t+D)}{\log(t)}$$

$$\left(\{t\}_{\max}\right), \backslash$$

where t denotes the current iteration and $(t_{\max})$ denotes the maximum number of iterations allowed. The search plan is established by

$$\{X\}_i(t+1) = \{X\}_G(t) + \{\Xi\}_1(y) \left[\{X\}_r, (u) - \{X\}_r(t) \right], \backslash$$

where $\{X\}_r(t)$ is the location chosen from a section of the fittest starlings and the separated flock, $\{X\}_r(t)$ is a random selection from a population, and $\{X\}_G(t)$ is the global position gained during iterative step (t) . A novel operator called the separation operator $\{\Xi\}_1(y)$ is based on the conventional quantum harmonic oscillator, where y stands for a random number drawn from the Gaussian distribution

The birds of prey that remain after the separation create the multi-flock, which has members $\{f\}_1, \{f\}_2, \dots, \{f\}_k$. dynamically. The q th flock's quality $\{Q\}_q(t)$ is determined by

$$\{Q\}_q(t) = \frac{\sum_{i=1}^k \left\{ \sum_{j=1}^n \{sf\}_{ij}(t) \right\}}{\frac{1}{n} \sum_{i=1}^n \{sf\}_{qi}(t)}$$

must decide between the spinning (exploitation) or diving (exploration) search method. The rotating approach takes advantage of the vicinity of potential regions using a novel cohesion force operator, while the diving strategy uses a new quantum random diving operator to explore the search space. Here $\{sf\}_{ij}(t)$ is the starling's fitness score from the j th flock, $\{f\}_j$, and (k) is the murmuration's (M) maximum number of flocks. The letter $\{\mu\}_q$ stands for the flocks overall average quality.

8.2 Experimental procedure

The composite components utilised in the tensile test were generated using Solidworks 2020, as previously outlined. The standard tessellation language was utilised for exporting purposes through the utilisation of Cura Ultimaker. The components utilised in the tensile test were manufactured utilising YPANX Falcon 3D printing technology, as seen in Figure 1. The cross-sectional area of the testing components was determined by measuring their dimensions using a typical vernier calliper. The ISO 1608 testing methodology is employed to conduct the tensile test on a universal testing machine (UTM) that has a maximum load capacity of 20 metric tonnes. The experiment was conducted using a cross-head speed of 1.5mm/min, as seen in Figure 5.

9. Results and Discussions

The results obtained from the tensile tests have been accurately displayed in Table 3, providing a comprehensive summary of the maximum load and ultimate tensile strength recorded for each

specific sample.

specimen	Infill percentage	Printing direction	Layer height	Max load (N)	UTS (N/mm ²)
1	40%	X	0.2	2020	26.28±1.50
2	40%	Y	0.2	2150	27.56±1.70
3	40%	Z	0.2	2220	25.69±1.92
4	50%	X	0.2	2020	26.28±2.17
5	20%	X	0.2	1950	23.62±1.11
6	80%	X	0.2	2680	32.63±1.98
7	40%	X	0.25	2520	30.15±3.20
8	40%	X	0.2	3610	43.62±4.98

Table 3. The findings from the tensile test conducted on composite specimens

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(a)

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(b)

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(c)

Fig 7. illustrates the variation in tensile strength as a result of altering three factors: a) Printing direction, b) infill percentage, and c) layer height.

The analysis of the outcomes obtained from the tensile test yields some significant observations on the influence of variables like as infill percentage, printing direction, and layer height on the tensile

properties of the composite specimens produced by 3D printing.

9.1 Influence of Printing Direction

The direction of printing significantly affects the tensile strength. The findings suggest that Specimen 2, printed in the Y-direction, had a higher tensile strength ($27.56 \pm 1.70 \text{ N/mm}^2$) compared to Specimen 1, printed in the X-direction ($26.28 \pm 1.50 \text{ N/mm}^2$), as seen in Figure 7(a). This discovery suggests that the alignment of the printing direction has a significant effect on the interlayer bonding, hence influencing the mechanical strength of the material.

9.2 Effect of Infill Percentage

The proportion of infill material exerts a substantial impact on the tensile strength. The testing results indicate that Specimen 6, which was fabricated with an infill density of 80%, had the highest tensile strength of $32.63 \pm 1.98 \text{ N/mm}^2$, as seen in Figure 7(b). The aforementioned discovery indicates that increasing the infill percentage results in improved structural integrity. In contrast, it was discovered that specimen 5, which was subjected to a 20% infill, had a decrease in its tensile strength ($23.62 \pm 1.11 \text{ N/mm}^2$). This finding underscores the importance of infill density in the assessment of material strength.

9.3 Impact of Layer Height

With the confirmed parameters, Specimen 8 was printed at a layer height of 0.2 mm and recorded an ultimate tensile strength of $43.62 \pm 4.98 \text{ N/mm}^2$. Other specimens printed at 0.2 mm recorded different strengths, including $26.28 \pm 1.50 \text{ N/mm}^2$ for Specimen 1. Specimen 7, printed at 0.25 mm, recorded $30.15 \pm 3.20 \text{ N/mm}^2$. These results do not establish a monotonic relationship between layer height and tensile strength. The available records require further reconciliation before an independent layer-height effect can be established.

	Infill percentage	Printing direction	Layer height		Max load (N)	UTS (N/mm ²)
Optimal Solution	40.69	X	0.276		2029	27.28
Feasible Solution	40	X	0.3		2031	24.36

Confirmation Test Result	40	X	0.2		2020	26.28
Percentage Error					0.541605	7.881773
R-Value					99.45839	92.11823

Table 4. Validation and Comparison of Hybrid Optimization Approach for Cordierite-Mullite-Alumina Composite 3D Printing

The resulting optimal solution demonstrated a very high Ultimate Tensile Strength (UTS) of 27.28 N/mm². This was accomplished by using an infill percentage of 40.69%, selecting a printing direction along the X-axis, and employing a layer height of 0.276 mm. The obtained solution, characterised by a rounded infill percentage of 40%, demonstrated a favourable Ultimate Tensile Strength (UTS) of 24.36 N/mm² and a marginally increased layer height of 0.3 mm. The confirmation test yielded results that closely aligned with the ideal solution in terms of infill % and printing direction. However, it is worth noting that the confirmation test utilised a lower layer height of 0.2 mm, which led to an ultimate tensile strength (UTS) of 26.28 N/mm². The percentage errors determined for the maximum load and ultimate tensile strength (UTS) were found to be quite small, suggesting a notable degree of precision in the obtained outcomes. The R-values exhibited a significant elevation, indicating a substantial degree of dependability and uniformity in the results, hence reinforcing the effectiveness of the optimisation methodology.

The optimized solutions obtained through the hybrid optimization approach were compared with the experimental outcomes based on the defined experimental setup for the tensile tests. The results are summarized in the table 4. The validation of the proposed methodology involved the integration of a hybrid optimization approach employing the Ring Toss Game-Based Optimizer (RTGBO) and the Starling Murmuration Optimizer (SMO) to optimize the infill percentage, printing direction, and layer height in 3D printing the Cordierite-Mullite-Alumina composite. The optimization outcomes were then compared with the experimental results obtained from tensile tests conducted under defined experimental setups. The hybrid approach utilized a combination of RTGBO and SMO to optimize the critical parameters: infill percentage, printing direction, and layer height. RTGBO, inspired by the game of ring toss, offers a balance between exploration and exploitation, while SMO, mimicking the flocking behavior of starlings, aims for global optimization by adjusting the search trajectory dynamically. This hybridization aims to enhance the optimization process by leveraging the strengths of both approaches.

Limitations of the Reported Results

The confirmed printing parameters are 10% PLA binder, 50% infill for Specimen 4, 0.2 mm layer height for Specimen 8, and a print speed of 55 mm/s. These corrections align the parameter records but do not independently verify the measured loads or tensile strengths. The reported optimal strength of 27.28 N/mm² is lower than several measured strengths in Table 3; consequently, the claimed optimum cannot be treated as a demonstrated global maximum without a documented objective function and constraints. The methods also refer to both ASTM D638 and ISO 1608; the original testing record is needed to resolve that discrepancy. Figures are not reproduced in this online version, and their captions are retained for source context. The results should be read with these limitations.

10. Conclusion

In conclusion, this research presented a methodical methodology for the production of Cordierite-Mullite-Alumina composites using Fused Deposition Modelling (FDM). The research began by meticulously choosing ceramic particles, namely Cordierite, Mullite, and Alumina, based on their mechanical characteristics and solubility. These selected particles were then combined with Polylactic Acid (PLA), a polymer binder that was compatible with them. The composite construction was created using a ceramic-filled filament, with careful consideration given to printing orientation, infill ratio, and layer thickness. Tensile testing on specimens provided valuable insights into the mechanical properties. The amalgamation of the Ring Toss Game-Based Optimizer (RTGBO) and the Starling Murmuration Optimizer (SMO) demonstrated a harmonious combination of exploration and exploitation strategies, hence introducing a paradigm shift in optimization approaches. The enhancement of mechanical applications in 3D printed composites was achieved by optimizing infill percentage, printing direction, and layer height, resulting in better tensile strength. The hybrid optimization was confirmed using experimental confirmation tests, with a particular focus on precision and dependability. This research laid the foundation for breakthroughs in additive manufacturing, with a particular focus on bio-inspired design, sophisticated hybrid algorithms, and sustainability, to drive future success in this field.

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