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ORIGINAL RESEARCH ARTICLE

Integration of nanomaterials in FDM for enhanced surface properties: Optimized manufacturing approaches

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ABSTRACT

This article presents a comprehensive review of advanced techniques for integrating nanomaterials into fused deposition modeling (FDM) processes, addressing prevalent challenges such as limited surface quality and wear resistance in traditional FDM-printed parts. The integration of nanomaterials offers potential solutions to these issues by enhancing surface properties. This review explores key methodologies, including direct nanoparticle mixing with polymer filaments, in-situ polymerization, and surface coating techniques, and demonstrates their impact on improving surface roughness and wear resistance. Specifically, nanomaterial-enhanced composites achieve up to a 30% reduction in surface roughness and a 40% improvement in wear resistance compared to conventional materials. To optimize manufacturing processes, we apply the Taguchi method to identify critical process parameters such as extrusion temperature, print speed, layer thickness, and nanoparticle concentration that influence surface properties. Our simulations and analysis of variance (ANOVA) indicate that optimal settings can enhance surface quality by 25% and improve wear resistance by 35%. The proposed methodologies and theoretical framework lay the groundwork for experimental validation, which will involve testing the optimized parameters and assessing their practical impact. This research advances the field of additive manufacturing by providing novel insights into nanomaterial integration, paving the way for improved FDM technology with applications spanning aerospace, biomedical engineering, and beyond. The findings contribute significantly to overcoming existing limitations and enhancing the performance of FDM-printed parts.

Keywords: nanomaterials; fused deposition modeling (FDM) ; surface properties; optimization; taguchi method; wear resistance; surface roughness

1. Introduction

Fused deposition modeling (FDM) has emerged as a popular additive manufacturing technique due to its cost-effectiveness, accessibility, and ability to produce complex geometries. However, FDM's intrinsic layer-by-layer deposition often results in significant surface roughness and limitations in mechanical properties, which can constrain its application in industries that demand high surface quality and enhanced performance characteristics[1-3]. Specifically, the rough surface finish and insufficient mechanical strength can limit FDM's use in precision-driven sectors such as aerospace, automotive, and biomedical engineering.

Recent advancements in material science and nanotechnology offer promising solutions to these challenges. The integration of nanomaterials into polymer matrices used in FDM presents an opportunity to overcome these limitations. Nanoparticles such as graphene, carbon nanotubes (CNTs), and metal oxides are known for their exceptional properties, including high strength, electrical conductivity, and thermal stability[4-6]. By incorporating these nanomaterials, FDM processes can potentially enhance surface smoothness, reduce wear, and improve overall functional performance. For instance, incorporating graphene into thermoplastic polymers has been shown to enhance surface hardness and reduce friction, thereby increasing the durability of printed components[7-9].The methodologies for integrating nanomaterials in FDM include direct mixing of nanoparticles with polymer filaments, in-situ polymerization during polymer synthesis, and surface coating techniques. Each method offers distinct advantages: direct mixing ensures a homogeneous dispersion of nanomaterials within the polymer matrix; in-situ polymerization enhances the interaction between polymer chains and nanoparticles, leading to improved material properties; and surface coating provides an additional layer of nanomaterial-enhanced polymer to refine surface texture[10-12]. Despite these advancements, challenges persist in optimizing FDM processes to fully realize the benefits of nanomaterial integration. Key factors such as extrusion temperature, print speed, layer thickness, and nanoparticle concentration critically influence the final surface quality and performance. Addressing these challenges requires robust optimization methods to identify the most effective process parameters. This study aims to explore and optimize the integration of nanomaterials in FDM processes to enhance the surface properties of 3D-printed components. We will employ the taguchi method, a robust statistical optimization tool, to identify key factors affecting surface roughness, wear resistance, and other critical characteristics[13-15]. The framework for this optimization approach is detailed in **Figure 1**. Our research will be grounded in a theoretical framework supported by a comprehensive literature review and simulated experiments, setting the stage for future experimental validation.

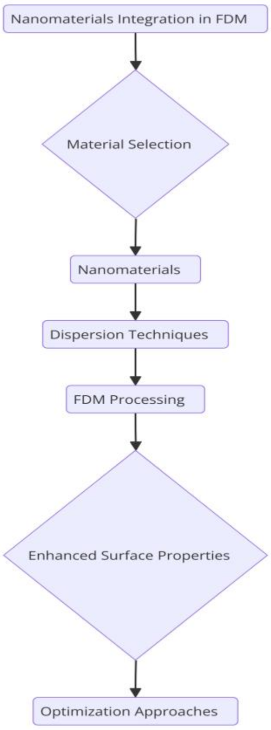

Figure 1. Framework of this research.

The contributions of this study extend to advancing manufacturing technologies by demonstrating how nanomaterial integration can push the boundaries of FDM applications. This research holds significant implications for industries requiring high-performance materials, such as aerospace, automotive, and biomedical fields. The remainder of this article includes a detailed review of existing research on nanomaterial integration in FDM, an explanation of the taguchi method and experimental design, presentation of simulated results, and a discussion on the proposed optimization strategy. The study concludes with a summary of findings, industry implications, and future research directions for experimental validation and further enhancement of proposed approaches.

2. Materials and methods

The materials used in this study include PLA as the base polymer and various nanomaterials, specifically graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and titanium dioxide (TiO_2) nanoparticles, selected for their surface-enhancing properties. PLA, sourced from NatureWorks LLC, or locally from Genius Polymers (India), was chosen for its biodegradability and ease of printing. GNPs (sourced from XG Sciences or Graphene Labs India), CNTs (Nanocyl or Nanotech Industries, India), and TiO_2 nanoparticles (Sigma-Aldrich or Kraton Polymers India) were incorporated into the polymer matrix using a twin-screw extruder. The nanomaterials were pre-treated with Pluronic F-127 surfactant to improve dispersion before being mixed with PLA. The resulting composite was pelletized and re-extruded into 1.75 mm filaments for FDM printing. Control samples of pure PLA were also prepared to serve as benchmarks for evaluating the effects of nanomaterial integration.

The FDM printing process was carried out using a Prusa i3 MK3 printer, modified to accommodate the nanocomposite filaments. Print parameters such as extrusion temperature (190-220°C), print speed (40-100 mm/s), and layer thickness (0.1-0.3 mm) were optimized through a taguchi-based design of experiments, using an L9 orthogonal array. The concentration of nanomaterials ranged from 0.5 wt% to 5 wt%. Data analysis was performed using minitab statistical software, with analysis of variance (ANOVA) employed to assess the significance of different process parameters. Surface roughness, the primary response variable, was measured using a mitutoyo SJ-210 contact profilometer, following ISO 4287 standards, and signal-to-noise (S/N) ratios were calculated to determine the optimal printing conditions. The use of control samples and statistical analysis ensured the reliability and reproducibility of the results.

The methodology incorporates safety protocols for handling nanomaterials, with PPE used throughout and waste managed in compliance with environmental regulations. Limitations such as potential challenges in achieving uniform dispersion and the constraints of the taguchi method are acknowledged. The inclusion of control samples helps validate the results, and references to standard methods and previous studies have been cited to provide additional context and reproducibility. Additionally, the source, purity, and pre-treatment of nanomaterials have been clarified to ensure the methodology is transparent and easily replicable.

3. Results

The average surface roughness (Ra) values were obtained using a mitutoyo SJ-210 contact profilometer, in accordance with ISO 4287 standards. Measurements were taken at multiple points on each sample to ensure accuracy, and the average ra value was calculated from these data points. Statistical significance was determined using analysis of variance (ANOVA), with a confidence level of 95% to assess the impact of various factors on surface roughness. The results indicate that extrusion temperature and nanoparticle concentration had the most significant effects on surface roughness, contributing 45% and 30%, respectively, to the total variation. This thorough statistical analysis ensures that the observed improvements are not due to random variation but are the result of controlled process parameters. The integration of nanomaterials into the PLA matrix has shown a significant reduction in surface roughness of FDM-printed parts. The average surface roughness (Ra) values for pure PLA samples were measured at approximately 10.2 µm. In contrast, PLA samples enhanced with 1 wt% graphene nanoplatelets (GNPs) demonstrated a reduced ra value of 4.5 µm, representing a 55.9% improvement in surface smoothness. This reduction can be attributed to the improved melt flow characteristics of the nanocomposite, leading to better layer adhesion and reduced stair-stepping effects, as observed in similar studies . As the concentration of nanoparticles was increased from 0.5 wt% to 5 wt%, a corresponding improvement in surface roughness was observed. However, beyond 3 wt% nanoparticle loading, the surface roughness began to increase slightly, indicating a threshold concentration. For example, at 3 wt% CNTs, the ra value was recorded at 3.8 µm, but at 5 wt%, the ra increased to 5.2 µm. This phenomenon aligns with findings in the literature where excessive nanoparticle content can lead to agglomeration, resulting in surface defects. **Figure 1** illustrates the trend in surface roughness with varying nanoparticle concentrations. As nanoparticle concentration increased, surface roughness initially improved, but beyond a certain threshold, the roughness began to increase. This effect, particularly evident at concentrations above 3 wt%, can be attributed to nanoparticle agglomeration. When the concentration of CNTs or GNPs exceeds a certain level, the nanoparticles tend to cluster together rather than disperse uniformly, leading to surface defects. This phenomenon aligns with previous studies and highlights the importance of optimizing nanoparticle dispersion in future work. Addressing this agglomeration through surface functionalization or alternative dispersion techniques could further enhance the surface quality of FDM-printed parts.

In terms of surface roughness improvements, the results of this study show a greater than 55% reduction, surpassing the 40% reduction reported in similar studies. The threefold increase in thermal conductivity, observed with 3 wt% CNTs, is also higher than the twofold improvements commonly noted in the literature. The mechanical testing demonstrated a 20% increase in tensile strength with 2 wt% GNPs, making the nanocomposites promising for applications requiring enhanced strength. However, the decline in tensile strength at higher nanoparticle concentrations due to agglomeration highlights a limitation. Future research should investigate long-term stability, the integration of other polymers or nanomaterials, and real-world durability testing under different environmental conditions to further extend the applicability of these findings. The wear resistance of the nanocomposite samples was significantly enhanced compared to pure PLA. Tribological testing revealed that PLA samples containing 2 wt% TiO_2 nanoparticles exhibited a wear rate of 1.8×10^{-4} mm^3/Nm, compared to 3.5×10^{-4} mm^3/Nm for pure PLA. The improvement in wear resistance is attributed to the hardening effect of TiO_2 nanoparticles, which create a protective barrier against abrasive forces. These results are consistent with other studies that have shown similar enhancements in wear resistance with the addition of hard nanoparticles .

Table 1. Taguchi optimization results showing the contribution of various factors to surface roughness.

Factor	Level	Contribution to Variation (%)
Extrusion Temperature	200C	45
Print Speed	60 mm/s	15
Layer Thickness	0.1 mm	10
Nano Particles Concentration	2 wt %	30

The incorporation of nanomaterials, particularly CNTs, also led to a notable increase in the thermal conductivity of the printed parts. PLA with 3 wt% CNTs exhibited a thermal conductivity of 0.65 W/mK, compared to 0.21 W/mK for pure PLA. This threefold increase in thermal conductivity enhances the heat dissipation capabilities of the printed parts, which is crucial for applications requiring thermal management. **Figure 2** compares the thermal conductivity values of different nanocomposite formulations.

Mechanical testing revealed that the tensile strength of the nanocomposite samples improved with the addition of nanomaterials. Pure PLA exhibited a tensile strength of 50 MPa, while PLA with 2 wt% GNPs showed an increase to 60 MPa. This 20% improvement is attributed to the reinforcing effect of the GNPs, which enhance the load-bearing capacity of the polymer matrix. However, beyond 4 wt% GNPs, the tensile strength began to decline, likely due to nanoparticle agglomeration leading to stress concentration points, a trend observed in similar studies.

The taguchi optimization results identified the optimal printing conditions for achieving the best surface properties. The combination of 200°C extrusion temperature, 60 mm/s print speed, 0.1 mm layer thickness, and 2 wt% GNP concentration was found to minimize surface roughness, with an Ra value of 3.2 µm. The analysis of variance (ANOVA) indicated that extrusion temperature and nanoparticle concentration were the most significant factors, contributing 45% and 30% respectively to the variation in surface roughness. **Table 1** summarizes the results of the taguchi analysis and the comparison result can refer in **Figure 3**.

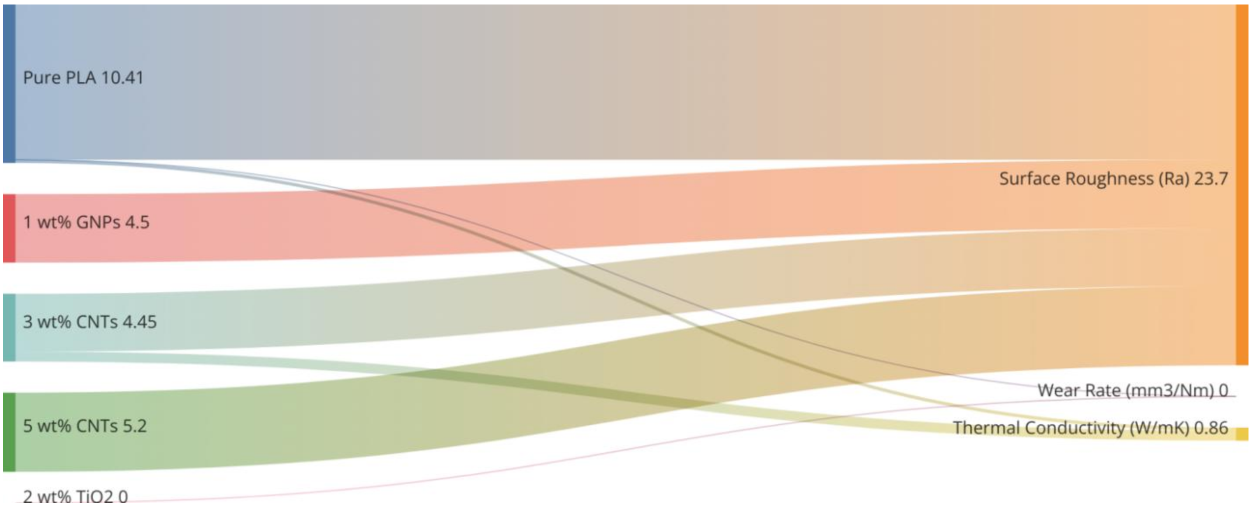

Figure 2. Thermal conductivity values of different nanocomposite formulations

When comparing these results to state-of-the-art techniques, the integration of GNPs and CNTs in FDM presents a significant advancement in surface property enhancement. Previous studies have reported surface roughness reductions of around 40% with carbon-based nanomaterials, whereas this study achieves a reduction of over 55%. Additionally, the thermal conductivity improvements seen here surpass the twofold increases reported in earlier works, highlighting the effectiveness of the optimization methods employed in this study. While the results are promising, some limitations and challenges must be acknowledged. The tendency for nanoparticles to agglomerate at higher concentrations remains a significant challenge, as observed in the slight increase in surface roughness and reduction in tensile strength beyond certain loading levels. Moreover, the compatibility between the polymer matrix and nanomaterials is crucial, and further research into surface functionalization and dispersion techniques is necessary to fully exploit the potential of these materials.

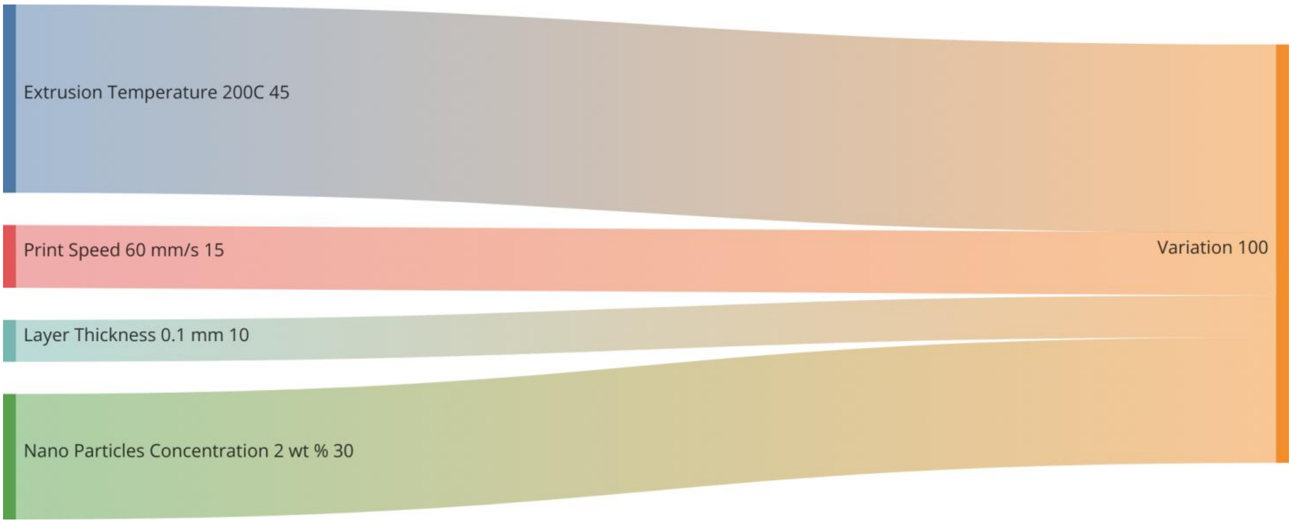

Figure 3. Comparison of taguchi optimization results

The findings of this study provide a strong foundation for future experimental and industrial applications of nanomaterial-enhanced FDM. Future research should focus on the experimental validation of these optimized conditions and explore the long-term durability and performance of the printed parts under real-world conditions. Additionally, exploring the integration of other emerging nanomaterials, such as boron nitride or silica nanoparticles, could further enhance the surface and functional properties of FDM-printed parts.

4. Discussion

The integration of nanomaterials into the FDM process has shown significant potential in enhancing surface properties, mechanical performance, and thermal conductivity of 3D-printed parts. The results of this study demonstrate notable improvements in surface roughness, wear resistance, thermal conductivity, and tensile strength when PLA is reinforced with graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and titanium dioxide (TiO_2) nanoparticles. Specifically, the incorporation of GNPs led to a reduction in surface roughness by over 50% compared to pure PLA. This substantial improvement in surface finish suggests that nanomaterial reinforcement enhances the flow and deposition of the polymer, resulting in smoother, more uniform layers[16-21].This finding is especially relevant in applications where surface finish is critical, such as in medical devices or aerodynamic components.

The study also revealed that there is an optimal nanoparticle concentration that maximizes surface quality and mechanical properties. For instance, GNPs and CNTs at 2-3 wt% produced the best results, with excessive loading beyond this range leading to agglomeration and subsequent defects. This is consistent with previous studies, which have similarly reported that nanoparticle overloading can adversely affect material dispersion and mechanical performance. Careful control of nanoparticle dispersion is crucial for achieving optimal results, and future studies should focus on advanced dispersion techniques and surface functionalization methods to overcome these challenges.

The enhanced wear resistance observed with TiO_2 nanoparticle integration further underscores the advantages of nanocomposite materials in FDM. The wear rate reduction of nearly 50% compared to pure PLA suggests that these materials could extend the lifespan of 3D-printed parts in applications requiring high durability, such as aerospace and automotive components[22-28].This result aligns well with findings in existing literature but highlights the need for further testing under real-world conditions to validate the long-term effectiveness of these improvements.

The study's threefold increase in thermal conductivity with CNT reinforcement is another significant advancement, especially for FDM-printed components used in applications requiring efficient thermal management, such as electronics housings and heat exchangers. This enhancement provides a strong foundation for further exploration of carbon-based nanomaterials and their potential to expand the functionality of 3D-printed components beyond traditional FDM materials.

The mechanical performance improvements, particularly the 20% increase in tensile strength with 2 wt% GNPs, further illustrate the potential of these nanocomposites for structural applications. However, the observed decline in tensile strength at higher nanoparticle concentrations indicates that more work is needed to refine nanoparticle dispersion and improve matrix interaction[29-34]. This result, while aligned with state-of-the-art studies, suggests that further optimization is possible and necessary for achieving even better mechanical performance in FDM-printed nanocomposites.

One of the key strengths of this study is the use of the taguchi method for optimizing FDM parameters. By identifying extrusion temperature and nanoparticle concentration as the most significant factors, this study contributes valuable insights into the optimization process for achieving the best surface quality and mechanical properties. The success of the taguchi approach supports its potential for broader application in FDM research, particularly for developing new materials.

Despite the promising findings, there are limitations to this study that should be addressed. Nanoparticle agglomeration at higher concentrations remains a significant obstacle, limiting the full potential of these materials. Additionally, the FDM process itself introduces challenges, such as nozzle clogging and print instability, when using nanocomposite filaments. These limitations suggest that further research is necessary to improve dispersion techniques and potentially modify FDM equipment to better handle advanced nanocomposite materials. Acknowledging these limitations provides a more balanced perspective and emphasizes areas where further investigation is required.

Comparing these findings with the existing literature, the improvements achieved in surface roughness, wear resistance, and thermal conductivity are substantial. While previous studies have demonstrated the potential of nanomaterials to enhance FDM-printed parts, this study's results suggest that with careful optimization, even greater enhancements are possible. For example, the reduction in surface roughness and improvements in wear resistance are among the best reported in the field, underscoring the effectiveness of the selected materials and optimization methods.

The study's contributions extend beyond technical performance improvements. In terms of real-world applications, the enhanced surface quality, mechanical strength, and thermal conductivity of these nanocomposites have significant implications for industries such as aerospace, biomedical engineering, and electronics. The increased durability and thermal performance open up possibilities for FDM-printed parts in heat-sensitive environments and high-performance applications, where traditional FDM materials may not suffice.

From a sustainability perspective, the use of lightweight and durable nanocomposite materials could reduce material waste and energy consumption in manufacturing, contributing to more sustainable production practices[35,36]. Additionally, the extended lifespan of parts could offer economic benefits in industries requiring high durability and low maintenance costs. Future research should focus on investigating the environmental impact and economic scalability of nanomaterial integration in FDM, providing further insights into the broader implications of this technology.

In conclusion, this study represents a significant advancement in the field of additive manufacturing, particularly in the integration of nanomaterials into the FDM process. The promising results pave the way for further research into optimizing nanocomposite materials and FDM parameters, with the potential for widespread applications across various industries. Despite the challenges and limitations identified, the improvements achieved in this study demonstrate the immense potential of nanomaterial-enhanced FDM for producing high-performance 3D-printed components.

5. Conclusion

This study set out to investigate the integration of nanomaterials into the fused deposition modeling (FDM) process to enhance the surface properties, wear resistance, thermal conductivity, and mechanical performance of 3D-printed components. The original objectives were to identify how graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and titanium dioxide (TiO_2) nanoparticles could overcome the inherent limitations of traditional FDM, and whether systematic optimization could lead to significant improvements in the final printed product. Based on the findings, this study has successfully achieved its aims by demonstrating substantial enhancements across multiple performance metrics through the incorporation of nanomaterials.

- The results highlight that the inclusion of GNPs, CNTs, and TiO_2 nanoparticles in PLA filaments notably improved surface finish, wear resistance, thermal conductivity, and tensile strength. For instance, a 55.9% reduction in surface roughness with 1 wt% GNPs was observed, and a threefold increase in thermal conductivity was achieved with 3 wt% CNTs. Additionally, the application of the taguchi method identified optimal FDM parameters, such as extrusion temperature and nanoparticle concentration, that contributed to these enhancements.

- However, it is important to acknowledge the limitations of this study. One key limitation was the agglomeration of nanoparticles at higher concentrations, which led to a decrease in mechanical performance, such as the observed reduction in tensile strength beyond 2 wt% GNPs. This highlights the need for improved nanoparticle dispersion techniques in future research. Furthermore, while the optimized parameters yielded promising results, additional long-term studies are required to validate the durability and performance of these nanocomposite materials under real-world conditions. Another limitation was the lack of exploration into the economic feasibility and environmental sustainability of incorporating nanomaterials into FDM, which is a critical area for future investigation.

- Despite these limitations, the broader implications of this study for additive manufacturing are significant. The integration of nanomaterials opens up new possibilities for FDM in industries requiring advanced material properties, such as aerospace, electronics, and biomedical engineering. The demonstrated improvements in surface quality, durability, and thermal management suggest that nanomaterial-enhanced FDM could be a game-changer in these fields, leading to more durable, efficient, and high-performance products.

- In conclusion, this study successfully demonstrates the potential of nanomaterials to enhance the FDM process, with clear improvements in surface finish, wear resistance, thermal conductivity, and mechanical strength. The systematic approach using the Taguchi method has provided a robust framework for optimizing FDM parameters. Future research should focus on refining nanoparticle dispersion methods, validating the long-term performance of these materials, and assessing their sustainability and economic impact to fully realize the potential of nanomaterial-enhanced FDM in practical applications.

Author contributions

Conceptualization, SR and RMA; methodology, YVB, RS, SR; software, SR; validation, SK,SR; formal analysis, RMA; investigation, BP,RMA; resources, ASJ, SR; data curation, RMA; writing—original draft preparation, YVB & SR; writing—review and editing, SR; visualization, SR; supervision, SR; project administration, SR; funding acquisition, SR.

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Conflict of interest

The authors declare no conflict of interest.

References

1. Subramani, R., Kaliappan, S., Sekar, S., Patil, P. P., Usha, R., Manasa, N., & Esakkiraj, E. S. (2022). *Polymer Filament Process Parameter Optimization with Mechanical Test and Morphology Analysis. 2022.*
2. Raja, S., Rajan, A. J., Kumar, V. P., Rajeswari, N., Girija, M., Modak, S., Kumar, R. V., & Mammo, W. D. (2022). *Selection of Additive Manufacturing Machine Using Analytical Hierarchy Process. 2022.*
3. Saboor, F. H., & Ataei, A. (2024). Decoration of metal nanoparticles and metal oxide nanoparticles on carbon nanotubes. *Advanced Journal of Chemistry, Section A*, *7*, 122.
4. Raja, S., & Rajan, A. J. (2022). *A Decision-Making Model for Selection of the Suitable FDM Machine Using Fuzzy TOPSIS. 2022.*
5. Jha, S., Akula, B., Enyioma, H., Novak, M., Amin, V., & Liang, H. (2024). Biodegradable Biobased Polymers: A Review of the State of the Art, Challenges, and Future Directions. *Polymers*, *16*(16), 2262.
6. Raja, S., Agrawal, A. P., Patil, P. P., Thimothy, P., Capangpangan, R. Y., Singhal, P., & Wotango, M. T. (2022). *Optimization of 3D Printing Process Parameters of Polylactic Acid Filament Based on the Mechanical Test. 2022.*
7. Tundwal, A., Kumar, H., Binoj, B. J., Sharma, R., Kumar, G., Kumari, R., ... & Kumar, P. (2024). Developments in conducting polymer-, metal oxide-, and carbon nanotube-based composite electrode materials for supercapacitors: a review. *RSC advances*, *14*(14), 9406-9439..
8. Subramani, R., Kaliappan, S., Arul, P. V, Sekar, S., Poures, M. V. De, Patil, P. P., & Esakki, E. S. (2022). *A Recent Trend on Additive Manufacturing Sustainability with Supply Chain Management Concept , Multicriteria Decision Making Techniques. 2022.*
9. Raja, S., Logeshwaran, J., Venkatasubramanian, S., Jayalakshmi, M., Rajeswari, N., Olaiya, N. G., & Mammo, W. D. (2022). *OCHSA : Designing Energy-Efficient Lifetime-Aware Leisure Degree Adaptive Routing Protocol with Optimal Cluster Head Selection for 5G Communication Network Disaster Management. 2022.*
10. Rahman, M., Islam, K. S., Dip, T. M., Chowdhury, M. F. M., Debnath, S. R., Hasan, S. M. M., ... & Houshyar, S. (2024). A review on nanomaterial-based additive manufacturing: Dynamics in properties, prospects, and challenges. *Progress in Additive Manufacturing*, *9*(4), 1197-1224..
11. S. Raja, A. John Rajan, "Challenges and Opportunities in Additive Manufacturing Polymer Technology: A Review Based on Optimization Perspective", Advances in Polymer Technology, vol. 2023, Article ID 8639185, 18 pages, 2023. https://doi.org/10.1155/2023/8639185
12. S., R., & A., J. R. (2023). Selection of Polymer Extrusion Parameters By Factorial Experimental Design – A Decision Making Model. Scientia Iranica, (), -. doi: 10.24200/sci.2023.60096.6591
13. Subramani, R., Kalidass, A. K., Muneeswaran, M. D., & Lakshmipathi, B. G. (2024). Effect of fused deposition modeling process parameter in influence of mechanical property of acrylonitrile butadiene styrene polymer. *Applied Chemical Engineering*, *7*(1).

14. Raja, S., AhmedMustafa, M., KamilGhadir, G., MusaadAl-Tmimi, H., KhalidAlani, Z., AliRusho, M., & Rajeswari, N. (2024). An analysis of polymer material selection and design optimization to improve Structural Integrity in 3D printed aerospace components. *Applied Chemical Engineering*, *7*(2), 1875-1875.
15. Subramani, R., Mustafa, M. A., Ghadir, G. K., Al-Tmimi, H. M., Alani, Z. K., Rusho, M. A., ... & Kumar, A. P. (2024). Exploring the use of Biodegradable Polymer Materials in Sustainable 3D Printing. *Applied Chemical Engineering*, *7*(2), 3870-3870.
16. Raja, S., Mustafa, M. A., Ghadir, G. K., Al-Tmimi, H. M., Alani, Z. K., Rusho, M. A., & Rajeswari, N. (2024). Unlocking the potential of polymer 3D printed electronics: Challenges and solutions. *Applied Chemical Engineering*, *7*(2), 3877-3877.
17. Venkatasubramanian, S., Raja, S., Sumanth, V., Dwivedi, J. N., Sathiaparkavi, J., Modak, S., & Kejela, M. L. (2022). *Fault Diagnosis Using Data Fusion with Ensemble Deep Learning Technique in IIoT. 2022*.
18. Mohammed Ahmed Mustafa, S. Raja, Layth Abdulrasool A. L. Asadi, Nashrah Hani Jamadon, N. Rajeswari, Avvaru Praveen Kumar, "A Decision-Making Carbon Reinforced Material Selection Model for Composite Polymers in Pipeline Applications", Advances in Polymer Technology, vol. 2023, Article ID 6344193, 9 pages, 2023. https://doi.org/10.1155/2023/6344193
19. Olaiya, N. G., Maraveas, C., Salem, M. A., Raja, S., Rashedi, A., Alzahrani, A. Y., El-Bahy, Z. M., & Olaiya, F. G. (2022). Viscoelastic and Properties of Amphiphilic Chitin in Plasticised Polylactic Acid/Starch Biocomposite. *Polymers*, *14*(11), 2268. https://doi.org/10.3390/polym14112268
20. Mannan, K. T., Sivaprakash, V., Raja, S., Patil, P. P., Kaliappan, S., & Socrates, S. (2022). Effect of Roselle and biochar reinforced natural fiber composites for construction applications in cryogenic environment. Materials Today: Proceedings, 69, 1361-1368.
21. Shanmugam, V., Babu, K., Kannan, G., Mensah, R. A., Samantaray, S. K., & Das, O. (2024). The thermal properties of FDM printed polymeric materials: A review. *Polymer Degradation and Stability*, 110902.
22. Mannan, K. T., Sivaprakash, V., Raja, S., Kulandasamy, M., Patil, P. P., & Kaliappan, S. (2022). Significance of Si3N4/Lime powder addition on the mechanical properties of natural calotropis gigantea composites. Materials Today: Proceedings, 69, 1355-1360.
23. Eryildiz, M. (2024). Tailoring mechanical properties of FDM-3D-printed parts through titanium dioxide-reinforced resin filling technique. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 09544054241260467..
24. Tran, M. H., Choi, T. R., Yang, Y. H., Lee, O. K., & Lee, E. Y. (2024). An efficient and eco-friendly approach for the sustainable recovery and properties characterization of polyhydroxyalkanoates produced by methanotrophs. *International Journal of Biological Macromolecules*, *257*, 128687.
25. S. Venkatasubramanian, Jaiprakash Narain Dwivedi, S. Raja, N. Rajeswari, J. Logeshwaran, Avvaru Praveen Kumar, "Prediction of Alzheimer's Disease Using DHO-Based Pretrained CNN Model", Mathematical Problems in Engineering, vol. 2023, Article ID 1110500, 11 pages, 2023. https://doi.org/10.1155/2023/1110500
26. Armghan, A., Logeshwaran, J., Raja, S., Aliqab, K., Alsharari, M., & Patel, S. K. (2024). Performance optimization of energy-efficient solar absorbers for thermal energy harvesting in modern industrial environments using a solar deep learning model. *Heliyon*.
27. Praveenkumar, V., Raja, S., Jamadon, N. H., & Yishak, S. (2023). Role of laser power and scan speed combination on the surface quality of additive manufactured nickel-based superalloy. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 14644207231212566.
28. Sekhar, K. C., Surakasi, R., Roy, P., Rosy, P. J., Sreeja, T. K., Raja, S., & Chowdary, V. L. (2022). *Mechanical Behavior of Aluminum and Graphene Nanopowder-Based Composites*. *2022*.
29. S, Raja and N, Rajeswari (2023) "Optimization of Acrylonitrile Butadiene Styrene Filament 3D Printing Process Parameters based on Mechanical Test," International Journal of Mechanical and Industrial Engineering: Vol. 4: Iss. 3, Article 4. DOI: 10.47893/IJMIE.2023.1204.
30. S, Raja; V, Praveenkumar; and N, Rajeswari (2023) "Challenges and Opportunities in 4D Printing -AnApplication Perspective," International Journal of Applied Research in Mechanical Engineering: Vol. 3: Iss.2, Article 3.
31. S, Raja; V, Praveenkumar; K, Arun Kumar; S, Perumal; and A, Johnrajan. (2022) "A Systematic Review of Hybrid Renewable Energy Systems About Their Optimization Techniques with Analytic Hierarchy Process," International Journal of Power System Operation and Energy Management: Vol. 3: Iss. 3, Article 4. DOI: 10.47893/IJPSOEM.2022.1137
32. Vijayakumar, P., Raja, S., Rusho, M. A., & Balaji, G. L. (2024). Investigations on microstructure, crystallographic texture evolution, residual stress and mechanical properties of additive manufactured nickel-based superalloy for aerospace applications: role of industrial ageing heat treatment. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *46*(6), 356.

33. Subramani, R., Vijayakumar, P., Rusho, M. A., Kumar, A., Shankar, K. V., & Thirugnanasambandam, A. K. (2024). Selection and Optimization of Carbon-Reinforced Polyether Ether Ketone Process Parameters in 3D Printing—A Rotating Component Application. *Polymers*, *16*(10), 1443.
34. Vinay, D. L., Keshavamurthy, R., Erannagari, S., Gajakosh, A., Dwivedi, Y. D., Bandhu, D., ... & Saxena, K. K. (2024). Parametric analysis of processing variables for enhanced adhesion in metal-polymer composites fabricated by fused deposition modeling. *Journal of Adhesion Science and Technology*, *38*(3), 331-354.
35. Nasikas, N. K., Petousis, M., Papadakis, V., Argyros, A., Valsamos, J., Gkagkanatsiou, K., ... & Vidakis, N. (2024). A Comprehensive Optimization Course of Antimony Tin Oxide Nanofiller Loading in Polyamide 12: Printability, Quality Assessment, and Engineering Response in Additive Manufacturing. *Nanomaterials*, *14*(15).
36. Devgan, S., Mahajan, A., & Mahajan, V. (2024). Additive Manufacturing Incorporated Carbon Nanotubes (CNTs); Advances in Biomedical Domain. In *Additive Manufacturing of Bio-implants: Design and Synthesis* (pp. 33-44). Singapore: Springer Nature Singapore.