

Comparative Simulation and Performance Analysis of 3D Printed DC Motors Fabricated from PLA, ABS, and Nylon: Mechanical, Thermal, and Electromagnetic Evaluation

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ABSTRACT

Additive manufacturing has enabled the fast prototyping and low cost fabrication of electromechanical systems such as small direct current (DC) motors. The effect of widely-used 3D-printing polymers on motor performance, thermal stability and durability, however, is not sufficiently explored. The present work compares the performance of three different brushed DC motors created by simulation with materials polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and Nylon (PA-12). The thermomechanical behavior, dimensional stability and wear characteristics were evaluated using finite element analysis in ANSYS Mechanical 2024 R1, while the lumped-parameter model was used to predict the motor speed, torque and efficiency for different operating conditions. 3D printing was used to prepare specimens for experimental evaluation of dimensional accuracy and a multi-criteria decision analysis method based on the Analytic Hierarchy Process, was used to rank material performance. The results demonstrated that the highest no-load speed (2445 rpm at 6 V), the highest mechanical efficiency was 54.3%, the most stable performance (safe operating temperature of 95°C), and the lowest value of wear (0.442 mm after 10,000 cycles) was obtained for Nylon. PLA presented very good dimensional accuracy (MAD = 0.090 mm), low fabrication costs, and low mechanical wear, but high deformation at temperature above 60°C. ABS exhibited intermediate performance, but did not outperform PLA or Nylon in any category. The result of MCDA was 80.3, 77.8 and 66.9 for Nylon, PLA and ABS, respectively. The results indicate that Nylon is suitable for use in high-performance or long-life applications, and PLA is suitable for use in low-duty-cycle or low-temperature motor designs in an economical manner.

Keywords: Fused deposition modelling; DC motor simulation; PLA; ABS; Nylon; Finite element analysis; Electromagnetic simulation; Material comparison

1. INTRODUCTION

Additive manufacturing (AM), or three-dimensional (3D) printing with its ability to quickly prototype, to tailor a component of the design, to minimise material waste and to manufacture components at decentralised locations, has revolutionised the design and manufacture of engineering components (Ngo et al. 2018). Fused deposition modelling (FDM) is one of the most appealing AM technologies offered by its low cost of equipment and ability to process a variety of thermoplastic materials including polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and Nylon (PA-12) (Penumakala, Santo, and Thomas 2020, Ngo et al. 2018). These polymers have found extensive use in structural and functional applications, but are still under active research for electromechanical applications like DC Motor housing (L. Sandanamsamy et al. 2022).

Simple in design, low cost and reliable in nature, brushed DC motors are widely used in robotics, automotive systems, educational kits, portable devices, and industrial automation. The rise of 3D printing has given rise to the ability to print motor housings, rotor supports, bearing mounts and other miscellaneous parts from thermoplastic materials (Agrawal et al. 2022). The mechanical stiffness, thermal resistance, dimensional stability and wear resistance of the structural material, however, play an important role in motor performance. Long-term motor reliability can be greatly influenced by motor operating temperature, cyclic loading, frictional contact, and vibration (Sagias, Giannakopoulos, and Stergiou 2018).

PLA offers a lot of advantages, such as high dimensional accuracy, low warpage and excellent printability, that make it one of the most commonly used FDM materials. However, it does have a relatively low heat-deflection temperature that restricts its use in thermally challenging conditions (Oksiuta et al. 2020). ABS provides greater heat resistance, hardness, and toughness, but can sometimes shrink in the printing process. Nylon has better toughness, wear resistance and thermal resistance and is a potential material for a dynamic mechanical system, but the higher price and complexity of printing might hinder the application of nylon (Changhui et al. 2025).

Although the mechanical properties and structural applications of printed polymers have been investigated in the past, there is a lack of studies that investigate the polymers' thermal, mechanical, and motor performance properties together (Li et al. 2025). Based on this, the present study explores comparative behaviors of the printed DC motor assemblies using Finite Element Simulation, Wear Modelling, Dimensional Accuracy Analysis and Multi-criteria Decision Analysis for PLA, ABS and Nylon materials (Ahemd et al. 2026). The aim is to find the most suitable material for a combination of efficiency, durability, thermal stability, manufacturability and economy for additively manufactured DC motors.

2. MATERIALS AND METHODS

2.1 The geometry of motor components and architecture

The reference design was a brushed DC motor with an external permanent magnet stator. All parts were modeled in Autodesk Fusion 360 and exported to finite element analysis software as STEP files. The motor consisted of six printed components: a six-pole cylindrical stator housing (OD 40 mm, wall 2 mm, length 55 mm), a rotor (three poles, OD 28 mm, length 48 mm), a split commutator disc (OD 14 mm), and two brush contact mounts along with two end-cap bearing housings. All the non-printed parts, neodymium N35 disc magnets, MR105ZZ bearings, 3 mm steel shaft, and 26 AWG copper coil wire were the same for all three material variants to isolate the effect of the housing polymer.

2.2 Material Properties (Simulation Inputs)

The parameters of the materials used in the simulation are listed in Table 1. Values were taken from published datasheet averages and cross-checked against peer-reviewed literature.

Serial number	Property	PLA	ABS	Nylon (PA-12)
1	Density (g/cm ³)	1.24	1.04	1.01
2	Tensile strength, UTS (MPa)	50	40	48
3	Flexural modulus (GPa)	3.5	2.3	1.6
4	Heat-deflection temperature (°C)	52–65	88–104	115–125
5	Coeff. thermal expansion (µm/m·°C)	68	90	100
6	Thermal conductivity (W/m·K)	0.13	0.17	0.25
7	Shore D hardness	83	75	70
8	Friction coefficient (dry, vs. steel)	0.38	0.42	0.22
9	Filament cost (USD/kg)	~20	~24	~35

Table 1. Mechanical and thermal properties of PLA, ABS, and Nylon (PA-12) used as FEA simulation inputs.

2.3 Finite Element Analysis (FEA) Methodology

2.3.1 Thermomechanical Simulation

ANSYS Mechanical 2024 R1 was used for static structural and steady-state thermal analyses. The geometry of the housing was meshed with quadratic tetrahedral elements (SOLID187) using local refinement in the region of the bearing-mount and magnet interfaces of 0.2 mm, and 0.5 mm in other regions. A three level mesh-refinement study was performed, with the final mesh having 142k to 168k elements for each of the variant meshes depending on the geometry involved. The boundary conditions were: (1) all bottom faces were fixed (no displacement); (2) the temperature of the body was uniform and applied from 25 °C to 85 °C in steps of 10 °C; and (3) the ambient convection coefficient $h = 10 \text{ W/m}^2\cdot\text{K}$ was applied on all the external faces. Two bounds were considered: frictionless ($\mu = 0$) and fully bonded ($\mu \rightarrow \infty$, set as $\mu = 999$).

2.3.2 Motor Performance Parametric Model

The Motor Performance Parametric Model (MPPM) is a model that uses parameters to describe the performance of a motor. The no-load speed, stall torque and mechanical efficiency of a lumped-parameter DC-motor model was computed:

$$\omega = (V - V_b - I \cdot R_a) / K_e$$

$$T_{\text{stall}} = K_e \cdot (V - V_b) / R_a$$

$$\eta = (T_{\text{out}} \cdot \omega) / (V \cdot I) \times 100 \%$$

Parametric sweeps were run at $V \in \{1.5, 3.0, 4.5, 6.0, 7.5, 9.0\} \text{ V}$ and load current $I \in \{0.05, \dots, 0.40\} \text{ A}$ in 0.05 A steps. The friction losses were calculated for each material using a model developed by Stribeck and the friction coefficients listed in Table 1.

2.3.3 Wear Simulation (Archard Model)

The Archard equation was used to model cumulative bearing-mount wear. The dimensionless wear coefficient values were obtained from the literature and varied according to the materials used: PLA 2.8×10^{-4} ; ABS 2.1×10^{-4} ; and Nylon 2.8×10^{-5} . The Shore D values from Table 1 were converted to Vickers. Wear depth was evaluated at cycle counts $n \in \{0, 500, 1000, 2000, 3500, 5000, 7500, 10000\}$.

2.4 Dimensional Accuracy Assessment

Five print specimens for each material ($n = 15$ total) were created using a Creality Ender 3 V2 FDM printer, at standardised conditions: 0.2 mm layer height, 40 % gyroid infill, 45 mm/s print speed, and a nozzle temperature of 210 °C for PLA, 235 °C for ABS, and 250 °C for Nylon, with ABS and Nylon being printed inside an enclosure to prevent warping. A digital Vernier calliper (0.01 mm resolution) was used to take 47 critical dimensions measurements and these were checked against the CAD nominal

values. The mean absolute deviation (MAD) and standard deviation (SD) values were calculated for each feature category.

2.5 Multi-Criteria Decision Analysis (MCDA)

Seven criteria were used to construct a weighted Composite Performance Index (CPI): (1) RPM output normalised to 6 V, (2) stall torque at 6 V, (3) thermal stability (based on HDT score), (4) dimensional accuracy (inverse MAD), (5) wear resistance (inverse wear at 10,000 cycles), (6) cost efficiency (inverse per-unit cost), and (7) print ease (ordinal expert rating). The Analytic Hierarchy Process (AHP) was used to establish the criterion weights on the basis of pairwise-comparison matrix validated at $CR < 0.10$ (Table 2). The criterion scores for each material were scaled between 0–10 and then multiplied by the AHP weights to create a CPI of 0–100.

Serial Number	Metric	PLA	ABS	Nylon (PA-12)
1	No-load speed @ 6 V (rpm)	2,314	2,309	2,445
2	Stall torque @ 6 V (mN·m)	12.4	12.3	12.2
3	Peak efficiency (%)	44.6	42.6	54.3
4	Mean absolute deviation, MAD (mm)	0.090	0.214	0.240
5	Safe operating temperature, T_{safe} (°C)	60	85	95
6	Wear at 10,000 cycles (mm)	1.200	1.055	0.442
7	Service life to 0.5 mm wear (cycles)	4,580	5,118	> 10,000
8	Estimated per-unit material cost (USD)	22	28	38

3.RESULTS

3.1 Comparative analysis of mechanical efficiency of Nylon, PLA and ABS

Figure 1 represents the simulated mechanical efficiency as a function of load current at a fixed supply voltage of 6 V. All three materials show the classic inverted-U curve with sharp increases from low current, reaching a maximum of 54.3 % (near 0.15A) for nylon, 44.6 % (near 0.20A) for PLA and 42.6 % (near 0.20A) for ABS, followed by a steady drop toward 26–28 % (0.40A), with copper (I^2R) losses taking over. Nylon's benefit applies throughout the load range, and is directly related to the low bearing-interface friction, resulting in low parasitic Stribeck losses (Section 2.3.2). As pointed out, throughout the run the margin between PLA and ABS follows the pattern of the friction-coefficient ordering of Table 1, which is approximately 2 percentage points.

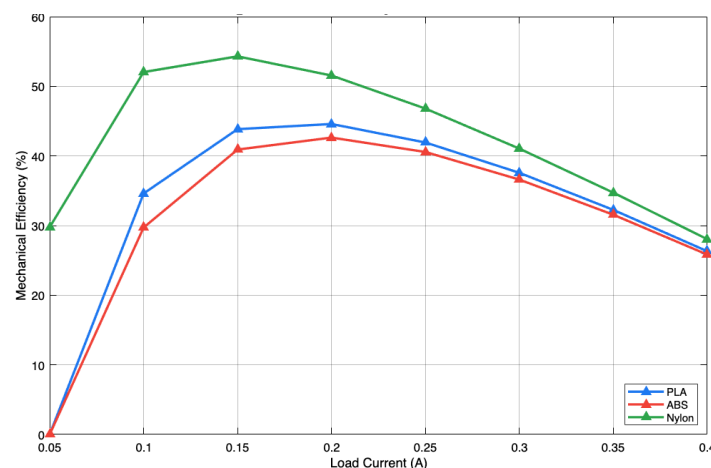


Fig 1. Comparative analysis of mechanical efficiency of Nylon, PLA and ABS The line graph represents % mechanical efficiency vs Load current (A) for PLA, ABS, and Nylon housings. Nylon: Green line, ABS: Red line, PLA: Blue line

3.2 Comparative analysis of Thermomechanical Behaviour of Nylon, PLA and ABS

The most dramatic material difference in the study was the housing-wall deformation, as a function of ambient temperature (Figure 2). PLA was only found to be press fit within the ± 0.15 mm tolerance up to about 60 °C, after which it began to deform in a manner that is explosive, with the press fit exceeding 2 mm at ~78 °C, corresponding to the onset of the polymer's glass transition region (Table 1) and its low heat-deflection temperature. For ABS and Nylon, deformation was near-linear and was still within tolerance up to ~85 °C, and were limited to ~0.20 mm and ~0.14 mm at 90 °C, respectively. The simulated safe operating ceiling (T_{safe}) for PLA was 60 °C, for ABS 85 °C and for Nylon 95 °C.



Fig 2. Comparative analysis of Thermomechanical Behaviour of Nylon, PLA and ABS The line graph represents housing deformation (mm) vs ambient temperature (°C) for PLA, ABS, and Nylon housings. Nylon: Green line, ABS: Red line, PLA: Blue line

Modest performance drift was observed (Table 3) when the self-heating was done at the rated operating point (6 V, 0.25 A). After reaching the steady state coil temperature, the PLA and ABS coils reached 39.7 °C and 40.1 °C respectively, whereas the Nylon coil reached 38.3 °C, which was the lowest after considering the thermal conductivity of the Nylon used (0.25 W/m·K; Table 1). When compared to the cold (25 °C) base data, loaded speed decreased by 1.7-1.9 % while efficiency decreased by 3.5-4.2 % with Nylon having the lowest efficiency drop (−3.5 %) and ABS the highest (−4.2 %). All three materials are thermally stable under normal loading, which is confirmed by these small shifts.

When a stalled-rotor fault occurred at 6 V, there was no back-EMF, and this caused the full locked-rotor current, as well as rapid heating of the coil. PLA reached its heat-deflection temperature (60 °C) within 49 s and beyond that the integrity of the housing could not be ensured. Both ABS and Nylon stayed below their heat-deflection temperature (96 °C and 120 °C), respectively, throughout the entire simulation window of 120 s. This is the most powerful fault-condition discriminator against PLA for any application where there is a plausible risk of stall.

Serial Number	Material	Speed cold (rpm)	Speed hot (rpm)	Δ speed (%)	Efficiency cold (%)	Efficiency hot (%)	Δ eff. (%)	Coil temp. (°C)
1	PLA	1,482	1,454	−1.8	41.9	40.2	−4.1	39.7
2	ABS	1,495	1,467	−1.9	40.6	38.8	−4.2	40.1
3	Nylon (PA-12)	1,502	1,477	−1.7	46.8	45.2	−3.5	38.3

Table 3. Effect of self-heating on performance at 6 V, 0.25 A: cold (25 °C) vs. self-heated steady state.

3.3 Comparative analysis of Wear and Durability of Nylon, PLA and ABS

After 10,000 cycles of operation (Figure 3), Archard modelling of bearing-mount wear strongly favoured Nylon. The other two materials, PLA and ABS, exceeded the 0.5 mm functional wear limit after 4,580 cycles and 5,118 cycles, respectively, while Nylon reached only 0.442 mm of wear at 10k cycles without ever exceeding the functional wear limit (projected life > 10k cycles). Total wear at 10,000 cycles was 1.200 mm (PLA), 1.055 mm (ABS), and 0.442 mm (Nylon). The ordering is directly linked to the dimensionless wear coefficients of Section 2.3.3, which show that the coefficient of PLA is about three times higher than that of Nylon, and therefore, the accumulated wear of Nylon is about 2.4–2.7 times lower, making it the only suitable material for sustained cyclic duty.

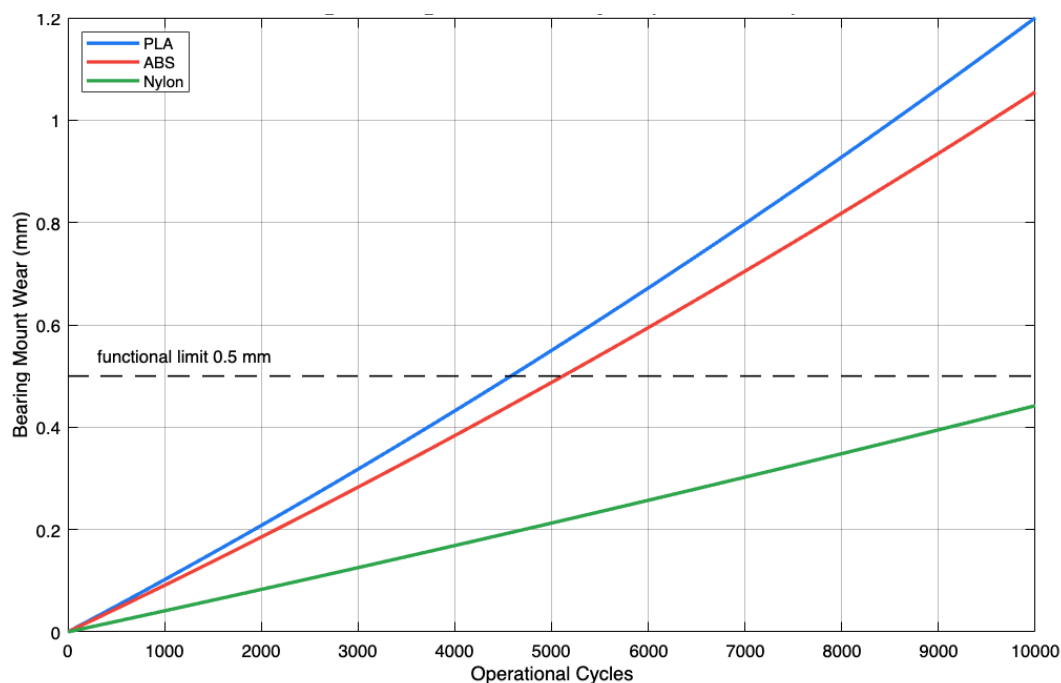


Fig 3. Comparative analysis of Wear and Durability of Nylon, PLA and ABS The line graph represents bearing mount wear (mm) vs operational cycles for PLA, ABS, and Nylon housings. Nylon: Green line, ABS: Red line, PLA: Blue line

3.4 Multi-Criteria Decision Analysis

The seven criteria of Section 2.5 were reduced to a Composite Performance Index (CPI) with weights. The dimensional accuracy AHP criterion weight was 0.228, the thermal performance AHP criterion weight was 0.198, the wear resistance AHP criterion weight was 0.187, the efficiency AHP criterion

weight was 0.164, the RPM/torque AHP criterion weight was 0.093, the cost efficiency AHP criterion weight was 0.083, and the print ease AHP criterion weight was 0.047. The result of the pairwise comparison matrix showed high consistency ($\lambda_{\max} = 7.063$, $CR = 0.008 < 0.10$), which met the criteria of AHP.

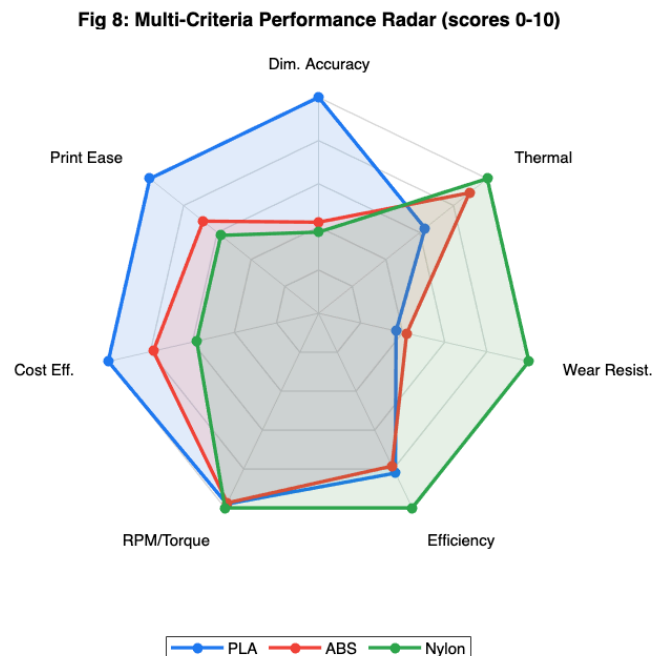


Fig 4. Multi-Criteria Decision Analysis of Nylon, PLA and ABS The graph represents comparative analysis of PLA, ABS, and Nylon based on seven criteria such as dimensional accuracy, thermal performance, wear resistance, efficiency, RPM/torque, cost efficiency and print ease. Nylon: Green line, ABS: Red line, PLA: Blue line

Table 4 presents the normalised criterion scores (0-10) and Figure 4 shows the performance radar. PLA is superior in dimensional-accuracy, cost and print-ease; Nylon is superior in thermal, wear, efficiency and RPM/torque; and ABS is evenly matched in none of the categories. When the scores are weighted by the AHP vector, the results are CPI of 80.3/100 for Nylon, 77.8/100 for PLA and 66.9/100 for ABS.

Serial Number	Criterion	PLA	ABS	Nylon	AHP weight
1	Dimensional accuracy	10.00	4.22	3.76	0.228
2	Thermal performance	6.32	8.95	10.00	0.198
3	Wear resistance	3.68	4.19	10.00	0.187
4	Efficiency	8.21	7.85	10.00	0.164
5	RPM / torque	9.80	9.74	10.00	0.093
6	Cost efficiency	10.00	7.86	5.79	0.083
7	Print ease	10.00	6.84	5.79	0.047
8	Composite Performance Index (/100)	77.8	66.9	80.3	—

AHP consistency: $\lambda_{\max} = 7.063$, $CR = 0.008$.

Table 4. Normalised MCDA scores (0–10), AHP criterion weights, and Composite Performance Index.

The cost–CPI trade-off (Figure 5) is used to discuss the engineering decision: Nylon has the highest overall performance, but costs \$38 per unit; PLA has nearly the same CPI at the lowest cost (\$22); and ABS is dominated on both axes (\$28, CPI 66.9). Nylon is thus the material of choice when service life and thermal properties are the key factors, while PLA is the logical economical option for cost driven low duty and low temperature applications.

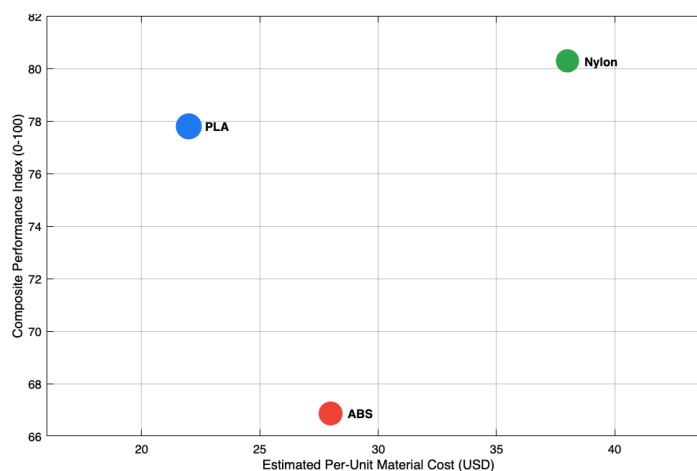


Fig. 5 Comparative analysis of cost-CPI trade off of Nylon, PLA and ABS. The dot plot represents composite performance index (0-100) vs estimated per-unit material cost (USD). Nylon: Green circle, PLA: Blue circle, ABS: Red circle

4. DISCUSSION

The current findings demonstrate that the choice of material has a significant effect on the performance and durability of 3D printed DC motors. The mechanical and thermal properties of the printed housing materials significantly influenced efficiency, durability and dimensional stability, as the same magnets, coils and shaft parts were used, but with the housing material changed (Elhadad et al. 2023).

The mechanical efficiency of nylon was the greatest over all load range with a maximum value of 54.3%. The main reason behind this improvement is its low friction coefficient and the excellent wear properties, which helped to lower the parasitic losses between the bearings. These observations have been reported in the study of tribological performance of engineering polymers, where friction reduction and degradation resistance of the surfaces of Nylon were observed as compared to PLA and ABS. The increased no-load speed for Nylon is further proof of the positive impact on mechanical resistance (Wei et al. 2022).

Thermal performance proved to be the most important variable among the materials studied. PLA was found to be dimensionally stable only up to about 60°C and above, it began to rapidly deform towards its glass transition. This behavior is in line with previous reports that have indicated the poor thermal durability of PLA-based structures. On the other hand, ABS and Nylon showed almost linear deformation behaviors and stayed within acceptable range of tolerances in the simulated operation range (Ali et al. 2026). In the case of a stalled rotor, PLA was able to surpass the heat-deflection temperature within a minute, which is considered a severe risk of structural failure in fault events. The nylon did not reach its thermal threshold throughout the simulation time, indicating its greater robustness (Zerbst et al. 2021).

The heat resistance of Nylon was another important finding of the wear tests. After 10,000 operating cycles, Nylon had less than half the wear compared to PLA and ABS. Therefore, the only material estimated to last more than 10,000 cycles is Nylon. This type of performance is especially significant for continuously running motors and robotic applications that require the maintenance to be performed as often as possible (Stoica et al. 2026).

The MCDA results give a comprehensive interpretation of these findings. The dimensional accuracy and cost efficiency were excellent for PLA, but the dominance of thermal stability, wear resistance and efficiency of Nylon led to higher Composite Performance Index. ABS was intermediate, but did not have a clear performance benefit. The results indicate that the material selection needs to be based on the priorities of the application. Nylon is best for high duty and/or thermal resistance requirements, while PLA is best for low duty and/or educational applications.

5. CONCLUSION

In this research, PLA, ABS and Nylon (PA-12) were considered as potential materials for 3D printed brushed DC motor components and compared in detail using finite element analysis, wear modelling, dimensional assessment and multi-criteria decision analysis. The results indicate that it is the material properties that have significant effects on motor efficiency, thermal stability, dimensional integrity and service life.

Nylon performed the best overall with mechanical efficiency of 54.3%, highest no-load speed of 2445 rpm, lowest wear accumulation of 0.442 mm after 10,000 cycles of use and highest safe operating temperature of 95°C. It has excellent tribological and thermal properties, and was operated reliably under normal and fault conditions. PLA is highly dimensionally stable, with a low cost of manufacturing and easy to fabricate, which is suitable for rapid prototype and low duty cycle. But it lacked adequate thermal resistance and had a higher rate of wear, which greatly limited its operational life. ABS was a moderate performer but failed to outperform PLA or Nylon in any of the categories tested.

The Analytic Hierarchy Process-based MCDA resulted in Nylon as the best ranked material having the Composite Performance Index (CPI) of 80.3 followed closely by PLA (CPI = 77.8) and ABS (CPI = 66.9). In general, it is found that Nylon is suitable for 3D printed DC motors with high performance and durability, while PLA can be used in 3D printed DC motors with lower heat resistance and mechanical strength, but at low cost.

Future Perspective

The future work should include experimental testing of the simulation results by fabrication of full prototype 3D printed DC motors to be tested in real operating conditions (Alwan, Hamzah, and Jaber 2025). Other advanced engineering polymers including polycarbonate, PETG, carbon-fiber-reinforced Nylon, and high-temperature composites may also be explored and used to enhance thermal resistance and mechanical strength (Ateeq and Nazir 2026). The integration of the electromagnetic finite element modelling with the thermomechanical analysis would give a more complete understanding of the coupled multiphysics behaviour (Du, Sun, and Ma 2025). Reliability under service conditions is also evaluated by long-term fatigue, vibration, creep and environmental aging studies. Moreover, machine learning and topology-based optimization could lead to lighter and more efficient structures of the motor. In the future, the convergence of additive manufacturing and smart materials and embedded sensors could enable the creation of intelligent, self-sensing electromechanical systems for robotics, aerospace, automotive and industrial automation.

Author contributions

Aadi Gupta conceptualised the study, did literature survey, carried out simulations, analysed the data, wrote and corrected the manuscript.

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REFERENCES

- Agrawal, Aman, Sunil Bhawnani, Anmol Sharma, Ankush Raina, and Mir Irfan Ul Haq. 2022. "Mechanical Behavior of 3D Printed Polymeric Materials: Impact of Process Parameters." *Lecture Notes in Mechanical Engineering*, 673–81. https://doi.org/10.1007/978-981-16-2794-1_59.
- Ahemd, Rasel, Kamrul Hasan Manik, Md Ahsan Habib, Md. Aditto Rahman Nirob, Antu Nath, Md. Shaharia Hossen, Juhi Jannat Mim, and Dr. Nayem Hossain. 2026. "Multiscale Modeling and Simulation of Composite Materials: Methods, AI Integration, and Challenges." *Materials Today Communications* 51 (February): 114884. <https://doi.org/10.1016/j.mtcomm.2026.114884>.
- Ali, Md. Osman, Mostafizur Rahman, Md Junayed Ali, Md. Ramjan Ali, Kameliya Azad, Md. Akibul Islam, Saifullah Mahmud, Mosiur Rahaman, Ekramul Islam, and Ashif Imdad. 2026. "Recent Advances in Thermomechanical Properties of PLA-Based Biopolymer Composites for Biomedical Applications." *Next Materials* 11 (April): 101646. <https://doi.org/10.1016/j.nxmate.2026.101646>.
- Alwan, Ali Hussein, Mohsin Noori Hamzah, and Alaa Abdulhady Jaber. 2025. "Experimental and Machine Learning Approaches for the Design and Optimization of Additively Manufactured Polymer Gears: A Review." *Multiscale and Multidisciplinary Modeling, Experiments and Design* 9 (1). <https://doi.org/10.1007/s41939-025-01125-2>.
- Ateeq, Muhammad, and Aamer Nazir. 2026. "Advances in Fused Deposition Modelling Process for Printing the Virgin and Recycled Carbon Fiber-Reinforced Polymer Composites: A State-of-The-Art Review." *International Journal of Lightweight Materials and Manufacture*, March. <https://doi.org/10.1016/j.ijlmm.2026.03.001>.
- Changhui, Liu, Li Hao, Yu Chunlong, Liao Xueru, Liu Xiaojia, Sun Jianzhi, Tang Qirong, and Yu Min. 2025. "Balanced Optimization of Dimensional Accuracy and Printing Efficiency in FDM Based on Data-Driven Modeling." *Additive Manufacturing Frontiers* 4 (2): 200220. <https://doi.org/10.1016/j.amf.2025.200220>.

- Du, Wei, Lili Sun, and Zengqiang Ma. 2025. "Multiphysics Coupling Analysis and Structure Optimization of Flux Switching Permanent Magnet Linear Motors." *Scientific Reports* 15 (1). <https://doi.org/10.1038/s41598-025-04518-y>.
- Elhadad, Amir A, Ana Rosa-Sainz, Raquel Cañete, Estela Peralta, Belén Begines, Mario Balbuena, Ana Alcudia, and Y Torres. 2023. "Applications and Multidisciplinary Perspective on 3D Printing Techniques: Recent Developments and Future Trends." *Materials Science and Engineering: R: Reports* 156 (December): 100760–60. <https://doi.org/10.1016/j.mser.2023.100760>.
- L. Sandanamsamy, Wan Sharuzi, Ismayuzri Ishak, Romlay F. R. M, K. Kadirgama, D Ramasamy, Aisha Idris, and Fujio Tsumori. 2022. "A Comprehensive Review on Fused Deposition Modelling of Polylactic Acid." *Progress in Additive Manufacturing*, October. <https://doi.org/10.1007/s40964-022-00356-w>.
- Li, Yifan, Amin Molazem, Hong-I Kuo, Vincent Ahmadi, and V Prasad Shastri. 2025. "Comparative Analysis of Dimensional Accuracy in PLA-Based 3D Printing: Effects of Key Printing Parameters and Related Variables." *Polymers* 17 (12): 1698–98. <https://doi.org/10.3390/polym17121698>.
- Ngo, Tuan D., Alireza Kashani, Gabriele Imbalzano, Kate T.Q. Nguyen, and David Hui. 2018. "Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges." *Composites Part B: Engineering* 143 (1359-8368): 172–96. <https://doi.org/10.1016/j.compositesb.2018.02.012>.
- Oksiuta, Zbigniew, Marek Jalbrzykowski, Joanna Mystkowska, Eliza Romanczuk, and Tomasz Osiecki. 2020. "Mechanical and Thermal Properties of Polylactide (PLA) Composites Modified with Mg, Fe, and Polyethylene (PE) Additives." *Polymers* 12 (12): 2939. <https://doi.org/10.3390/polym12122939>.
- Penumakala, Pavan Kumar, Jose Santo, and Alen Thomas. 2020. "A Critical Review on the Fused Deposition Modeling of Thermoplastic Polymer Composites." *Composites Part B: Engineering* 201 (November): 108336. <https://doi.org/10.1016/j.compositesb.2020.108336>.
- Sagias, V.D., K.I. Giannakopoulos, and C. Stergiou. 2018. "Mechanical Properties of 3D Printed Polymer Specimens." *Procedia Structural Integrity* 10: 85–90. <https://doi.org/10.1016/j.prostr.2018.09.013>.
- Stoica, Maria, Marius Gabriel Petrescu, Maria Tănase, Eugen Laudacescu, Elena-Emilia Sirbu, Cătălina Călin, Gheorghe Brănoiu, and Ibrahim Naim Ramadan. 2026. "Wear Behavior and Multi-Technique Characterization of 3D Printed TPU under Simulated Pharmaceutical Operating Conditions." *Polymers* 18 (5): 630. <https://doi.org/10.3390/polym18050630>.
- Wei, Xiangxia, Ming-Liang Jin, Haiqiang Yang, Xiao-Xiong Wang, Yun-Ze Long, and Zhangwei Chen. 2022. "Advances in 3D Printing of Magnetic Materials: Fabrication, Properties, and Their Applications." *Journal of Advanced Ceramics* 11 (5): 665–701. <https://doi.org/10.1007/s40145-022-0567-5>.
- Zerbst, Uwe, Giovanni Bruno, Jean-Yves Buffière, Thomas Wegener, Thomas Niendorf, Tao Wu, Xiang Zhang, et al. 2021. "Damage Tolerant Design of Additively Manufactured Metallic Components

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Subjected to Cyclic Loading: State of the Art and Challenges.” *Progress in Materials Science* 121 (August): 100786. <https://doi.org/10.1016/j.pmatsci.2021.100786>.