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Study on Fused Filament Fabrication (FFF) 3D Printer Parameter for Polyproplene Biomedical 3D Printing

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Abstract

The increasing demand for high-quality and cost-effective biomedical implants has led to the exploration of advanced manufacturing technologies, including fused filament fabrication (FFF) 3D printing. This study focuses on optimizing FFF parameters for polypropylene (PP), a material valued for its chemical resistance, low density, and flexibility. Challenges such as warping and poor adhesion require precise parameter optimization to ensure high-quality prints. A full factorial design of experiments was conducted using Minitab software, with Infill Density (ID) of 50% and 100% and Layer Height (LH) of 0.1mm and 0.15mm on tensile, charpy impact, and flexural test, strength. Mechanical testing was conducted on samples printed using an Ultimaker 2+ 3D printer, adhering to ASTM standards. Analysis of Variance (ANOVA) was conducted to identify the significant effects of the parameters and their interactions. The results showed that optimized settings of 0.15 mm layer height and 70.7071% infill density yielded superior tensile and impact strength, demonstrating the significance of parameter selection in achieving enhanced mechanical performance. This study contributes valuable insights into the 3D printing parameters for polypropylene in biomedical applications. By addressing key challenges in achieving mechanical integrity, this research lays the groundwork for further advancements in the production of high-quality, patient-specific biomedical implants.

1. Introduction

Around the world, injuries and deaths represent a significant public health issue, particularly in low- and middle-income nations. As per the Ministry of Transport Malaysia, there were approximately 600,000 road accidents in Malaysia in 2023, out of which 12,417 resulted in fatal accidents [1]. The World Health Organization (WHO) reports that among young and middle-aged people, traffic injuries rank as the sixth most common cause of deaths, disabilities, and socioeconomic losses [2]. Traditional manufacturing methods, such as machining, have limitations, notably the high cost and time-consuming process of creating Molds for customized implants [3]. However, with the emergence of additive manufacturing (AM), particularly Fused Filament Fabrication (FFF) 3D printing, has emerged as a promising technology for the fabrication of patient-specific biomedical implants. 3D printing is a process used to build a 3D object in which layers of material is printing above one another by using Computer Aided Design (CAD) to which it reaches the required object (FFF) primarily utilizes thermoplastic filament, subjecting it to localized heat until it reaches its melting point, after which it is extruded layer by layer through a nozzle under specific pressure to achieve the desired product [4]. Fused Filament

Fabrication (FFF) stands out as a widely adopted additive manufacturing technique employing thermoplastic polymers to create 3D geometric items. The choice of filament materials in FFF holds considerable importance, influencing the mechanical, thermal, and electrical conductivity characteristics of the end product [5]. Polypropylene (PP), a thermoplastic polymer, holds significant promise for biomedical applications because of its chemical resistance, low density, and flexibility [6]. However, achieving high-quality PP prints is challenging due to issues like warping (distortion during cooling) and poor layer adhesion [7]. These challenges necessitate careful optimization of printing parameters. Decades of research have focused on improving additive manufacturing processes, including FFF, to address these challenges. Studies have shown that printing parameters like layer height (thickness of each printed layer) and infill density (percentage of material inside the print) greatly influence the mechanical properties of 3D-printed parts.

2. Methodology

The first objective of this methodology is to systematically explore a range of printing parameters which layer height, and infill density, aiming to ensures best print quality and mechanical properties for Polypropylene filaments. Following the best parameter, the performance of the 3D-printed parts will be evaluated through mechanical tests, including tensile testing to measure strength and ductility, charpy impact testing to assess toughness, and flexural testing to evaluate stiffness and resistance to bending. Figure 1 illustrated the overall progress of the project.

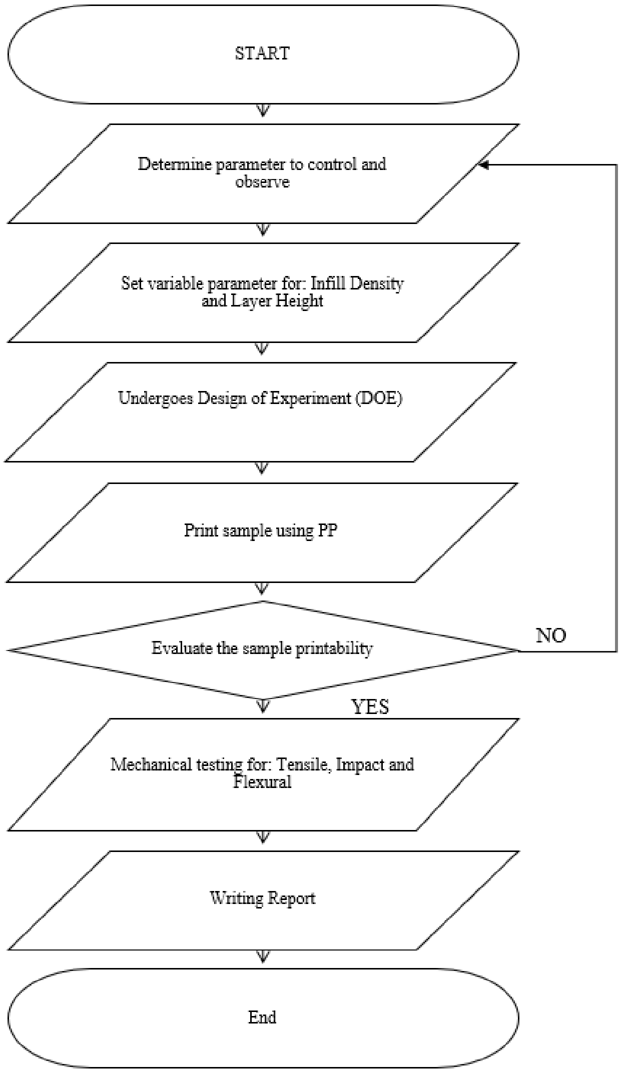


Fig. 1: Flowchart of Methodology

2.1 Material

The Polypropylene (PP) were selected for this research because of their superior properties. The Polypropylene (PP) used in this study is medical-grade standards and comes in granular form from Emory as shown in Table 1.

Table 1: Polypropylene Material Properties [8]

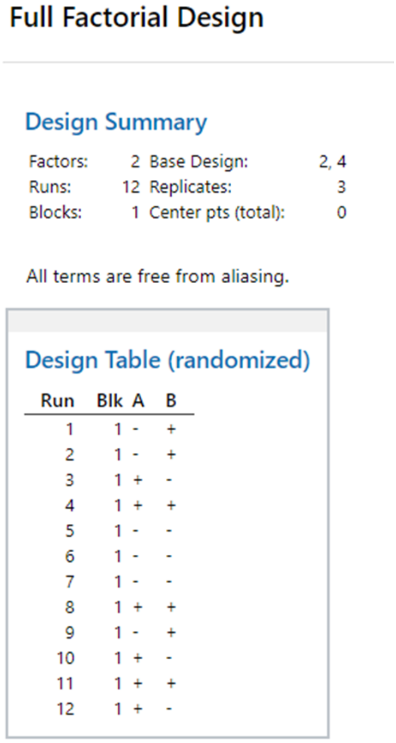
Polypropylene Characteristics	Value
Density	0.9 g/cm^3
Molecular Weight	620,000 g/mol
Yield Tensile Strength	27.5 MPa
Flexural Modulus	1320 MPa
Notched Izod Impact Strength	69 J/m

2.2 Design of Experiment

This study used a design of experiment (DOE) approach with Minitab software to study how infill density and layer height affect the bending and tensile strength of 3D-printed parts. A full factorial design was used with two factors: infill density (50% and 100%) and layer height (0.1 mm and 0.15 mm) according to previous studies used as indicator of testing. Each combination of these factors was tested three times, making a total of 12 experimental runs.

2.2.1 Minitab Software

The experimental design was created in Minitab by selecting a full factorial design with two factors and three replications. The runs were randomized to reduce bias. Specimens were printed based on the combinations of infill density and layer height provided by the design. Figure 2 indicated the design table that generated by the software.



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Full Factorial Design

Design Summary
Factors:     2  Base Design:      2, 4
Runs:       12  Replicates:          3
Blocks:      1  Center pts (total):  0

All terms are free from aliasing.

Design Table (randomized)
Run  Blk  A  B
  1    1  -  +
  2    1  -  +
  3    1  +  -
  4    1  +  +
  5    1  -  -
  6    1  -  -
  7    1  -  -
  8    1  +  +
  9    1  -  +
 10    1  +  -
 11    1  +  +
 12    1  +  -
```

Fig. 2: A full factorial design conducted using Minitab software

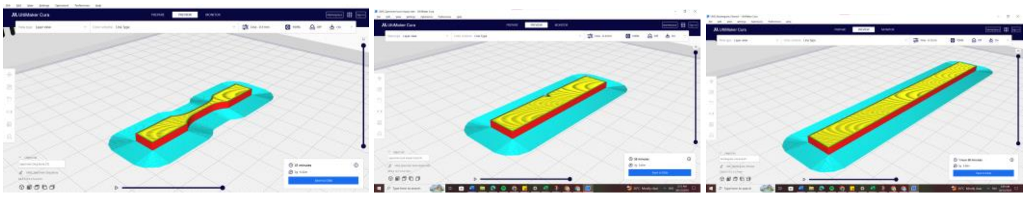
The data were analysed in Minitab using factorial analysis. ANOVA was used to check how infill density, layer height, and their interaction affected bending and tensile strength. Main effects and interaction plots were created to show the results more clearly.

2.3 3D Printing

The Ultimaker 2+ was chosen for this study due to its exceptional compatibility with polypropylene (PP) and its advanced features that meet the specific requirements of the research.

2.3.1 Ultimaker Cura

Ultimaker Cura software as in Figure 3 were used in this study as the slicing software to prepare 3D models for printing on the Ultimaker 2+ 3D printer. The software plays a crucial role in converting the 3D model into machine-readable G-code, which contains the instructions for the printer.



(a) (b) (c)

Fig. 3: Slicing of (a) dog bone (b) rectangular with notch (c) rectangular

2.4 Sample Preparation

3D models for Polypropylene (PP) were designed using SOLIDWORK software. These designs were prepared based on standard testing geometries: tensile, charpy, and flexural specimens. A total of 36 samples were printed using the Ultimaker 2+ 3D printer, divided equally among three types of mechanical testing.

2.4.1 Sample Specifications

The design dimension followed the standard ASTM to ensure compliance with the relevant testing standards, enabling accurate evaluation of the mechanical properties of the printed polypropylene (PP) specimens. Figure 4 shows ASTM D638 Type V standard dimension for dog bone, Figure 5 shows ASTM D6110 standard dimension for rectangular with notch and Figure 6 ASTM D790 standard dimension for rectangular.

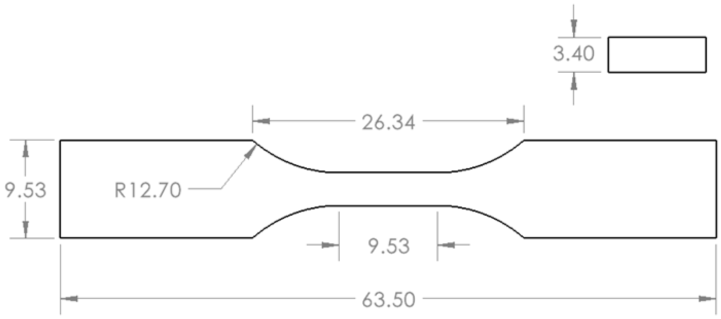


Fig. 4: ASTM D638 Type V standard dimension

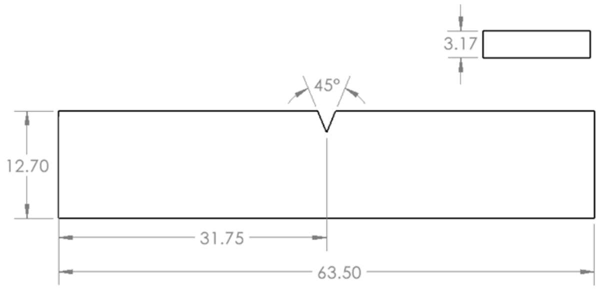


Fig. 5: ASTM D6110 standard dimension for rectangular with notch

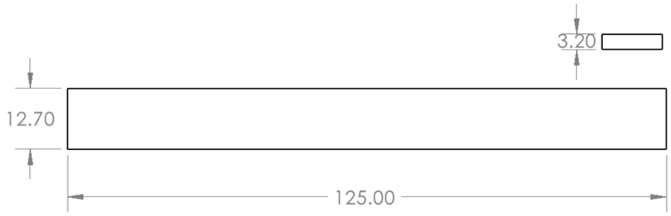
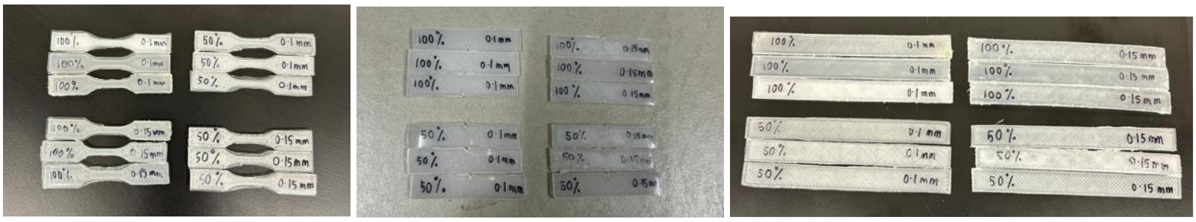


Fig. 6: ASTM D790 standard dimension for rectangular

2.4.2 Sample Printing

Three types of samples were printed: dog bone, rectangular and rectangular with notch. Using the Ultimaker 2+ 3D printer, 12 samples of each type were successfully printed as shown in Figure 7.



(a) (b) (c)

Fig. 7: (a) dog bone sample for tensile testing (b) rectangular with notch sample for charpy impact testing (c) rectangular sample for flexural testing

2.5 Mechanical Test

In this study, mechanical testing was conducted to evaluate the properties of 3D-printed polypropylene (PP) specimens. Several standard tests were done to measure the tensile, impact and flexural strength of the sample.

2.5.1 Tensile Test

The tensile test was conducted using Universal Mechanical Testing Machine (Model: LLOYD instruments LR30K) as in Figure 8. The test was setup using parameter set in Table 2, The machine was control using computer software named NEXYGEN. Dog-bone-shaped specimens were printed according to ASTM D638 standards for this tensile testing.

Table 2: Setting for tensile test in NEXYGEN software

Speed	50.00 mm/min
Gauge length	10 mm
Area	12.8 mm^2

Fig. 8: Tensile sample being clamped

2.5.2 Charpy Impact Test

Charpy impact test was carried out using Instron CEAST 9050 Series Pendulums. During testing, a pendulum impactor strikes the specimen at a consistent energy level, causing it to fracture as shown in Figure 9.

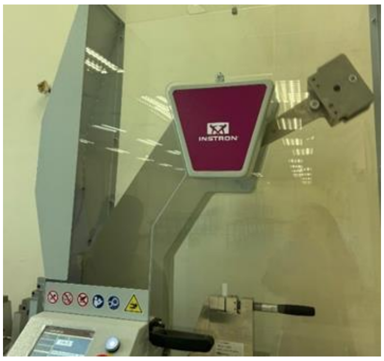


Fig. 9: A pendulum impactor strike the specimen

2.5.3 Flexural Test

Flexural testing was conducted Universal Mechanical Testing Machine (Model: LLOYD instruments LR30K) as shown in Figure 10 to evaluate the bending strength and stiffness of 3D-printed polypropylene specimens. The setting for the speed used in this study was 5mm/min with the thickness of 3.2mm.

Fig. 10: The sample is being positioned in the universal testing machine

3. Result and Discussion

3.1 Experimental Run

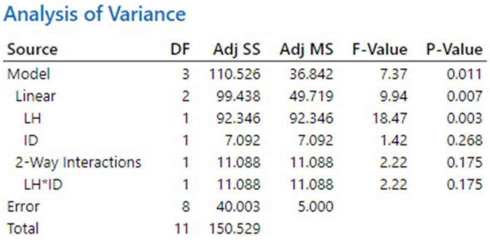
The 3D-printed specimens were fabricated using a fused filament fabrication (FFF) 3D printer. Other printing parameters, such as nozzle temperature, bed temperature, and print speed, were kept constant to ensure consistency. After fabrication, bending strength was measured using a three-point bending test, tensile strength and impact test was evaluated using a universal testing machine as shown in Table 3.

Table 3: Experimental Run and Mechanical Test Results

StdOrder	RunOrder	CenterPt	LH	ID	Tensile (MPa)	Impact (J/m^2)	Bending (MPa)
1	7	1	0.10	50	20.166	1220	503.57
2	12	1	0.15	50	22.687	3350	502.12
3	1	1	0.10	100	19.542	2140	504.87
4	4	1	0.15	100	27.212	1950	502.95
5	5	1	0.10	50	19.246	920	503.42
6	3	1	0.15	50	27.303	2130	502.47
7	2	1	0.10	100	17.458	1830	507.74
8	8	1	0.15	100	29.162	4880	504.28
9	6	1	0.10	50	21.265	3050	503.88
10	10	1	0.15	50	21.564	5190	504.63
11	9	1	0.10	100	22.522	1830	501.38
12	11	1	0.15	100	25.560	2130	504.62

3.2 Full Factorial Design Analysis

The Analysis of Variance (ANOVA) results provide valuable insights into the influence of layer height (LH) and infill density (ID) on the mechanical properties of 3D-printed specimens. In Figure 11 for the tensile test, the model was statistically significant, with a P-value of 0.011, indicating that the combination of LH and ID significantly affects tensile strength. Among the factors, LH had the most substantial impact, as its P-value of 0.003 confirmed its significance, whereas ID showed no significant influence with a P-value of 0.268. The interaction between LH and ID was also insignificant, suggesting that their combined effect does not meaningfully affect tensile strength.

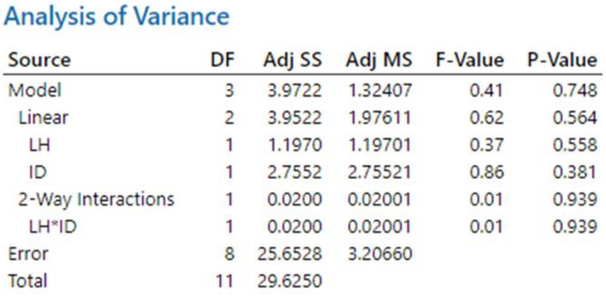


Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	110.526	36.842	7.37	0.011
Linear	2	99.438	49.719	9.94	0.007
LH	1	92.346	92.346	18.47	0.003
ID	1	7.092	7.092	1.42	0.268
2-Way Interactions	1	11.088	11.088	2.22	0.175
LH*ID	1	11.088	11.088	2.22	0.175
Error	8	40.003	5.000		
Total	11	150.529			

Fig. 11: Analysis of Variance (ANOVA) for Tensile test

Similarly, In Figure 12 the impact test results indicated no significant effects of the individual factors or their interaction on the impact strength. Although LH showed a borderline effect with a P-value of 0.085, it was not statistically significant under the experimental conditions. The influence of ID was negligible, with a high P-value of 0.809, demonstrating its minimal impact on the material's ability to absorb impact forces. The combined effect of LH and ID was also insignificant.

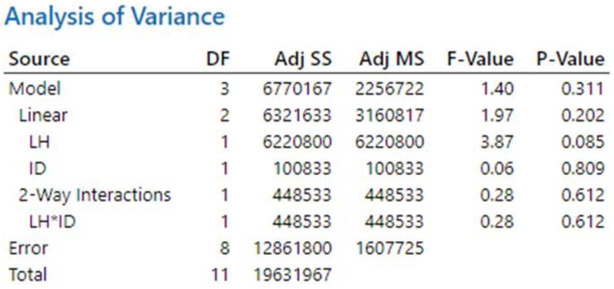


Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	3.9722	1.32407	0.41	0.748
Linear	2	3.9522	1.97611	0.62	0.564
LH	1	1.1970	1.19701	0.37	0.558
ID	1	2.7552	2.75521	0.86	0.381
2-Way Interactions	1	0.0200	0.02001	0.01	0.939
LH*ID	1	0.0200	0.02001	0.01	0.939
Error	8	25.6528	3.20660		
Total	11	29.6250			

Fig. 12: Analysis of Variance (ANOVA) for Charpy Impact test

In contrast, in Figure 13 the ANOVA for the flexural bending test revealed that the overall model and individual factors were not statistically significant, as shown by a high P-value of 0.748. Neither LH nor ID, nor their interaction, contributed significantly to flexural properties. This suggests that changes in these parameters within the tested range do not influence the stiffness or bending strength of the specimens.



Analysis of Variance

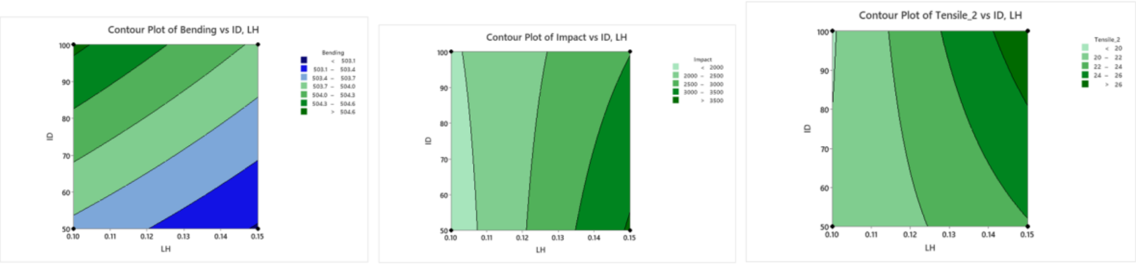
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	6770167	2256722	1.40	0.311
Linear	2	6321633	3160817	1.97	0.202
LH	1	6220800	6220800	3.87	0.085
ID	1	100833	100833	0.06	0.809
2-Way Interactions	1	448533	448533	0.28	0.612
LH*ID	1	448533	448533	0.28	0.612
Error	8	12861800	1607725		
Total	11	19631967			

Fig. 13: Analysis of Variance (ANOVA) for Flexural test

In conclusion, the ANOVA findings highlight that layer height significantly influences tensile strength, but its effects on flexural and impact properties are limited. Infill density, on the other hand, has minimal impact across all tested mechanical properties. These results underscore the importance of parameter selection depending on the specific mechanical property being optimized in 3D printing applications.

3.3 Contour Plot Mechanical Testing

The analysis of Figures 14 highlights the impact of layer height (LH) and infill density (ID) on three critical mechanical properties: flexural strength, impact resistance, and tensile strength. These parameters play a pivotal role in determining the overall performance of 3D-printed parts, offering valuable insights for parameter optimization. In Figure 14 (a), the flexural strength, represented as Bending, increases with both LH and ID. The highest flexural strength values are observed in the top-right corner of the plot (LH > 0.14 and ID > 90). This trend indicates that a combination of higher layer height and infill density enhances the part's resistance to bending forces, making it more mechanically robust under flexural stress. In Figure 14 (b) illustrates the relationship between LH, ID, and impact resistance. The darkest green regions, representing the highest impact values, are concentrated in the top-right corner (LH > 0.15 and ID > 100). Higher LH improves interlayer bonding, while increased ID provides greater structural integrity. This synergy results in superior energy absorption and toughness, critical for applications requiring high durability. Similarly, Figure 14 (c) demonstrates the effect of LH and ID on tensile strength. Increasing either parameter enhances the material's ability to withstand tensile loads, with the highest tensile strength values observed in the top-right corner. Larger LH improves bonding between printed layers, while higher ID increases the internal material volume, enhancing strength and load-bearing capacity. In conclusion, the findings confirm that optimizing LH and ID significantly improves mechanical properties. This optimization is vital for producing 3D-printed parts with superior flexural, impact, and tensile performance, ensuring reliability for demanding applications such as biomedical implants.

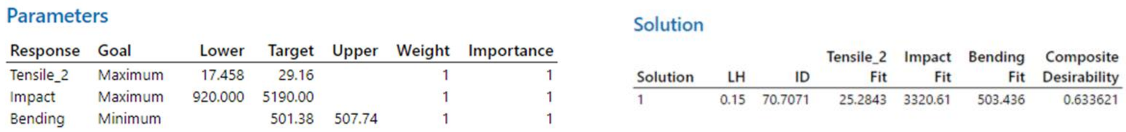


(a) (b) (c)

Fig. 14: Contour Plot (a) Bending (b) Impact (c)Tensile

3.4 Optimization Response

The optimization process was guided by specific parameter goals and their respective ranges, weights, and importance levels, ensuring that the material achieved an ideal balance of mechanical properties. The three primary response variables—Tensile_2, Impact, and Bending—each had distinct objectives to align with the desired material performance as shown in Figure 15. The Load Factor (LH) is optimized at 0.15, indicating that a relatively low value supports the desired outcomes. The Input Dimension (ID) is set at 70.7071, reflecting a precise configuration that enhances overall material performance. The desirability score of 0.633621 suggests that the optimized parameters meet the criteria to a significant extent, though there is potential for further refinement to approach an ideal score of 1.0. These results underscore the material's practicality for applications requiring high mechanical resilience.



Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Tensile_2	Maximum	17.458	29.16		1	1
Impact	Maximum	920.000	5190.00		1	1
Bending	Minimum		501.38	507.74	1	1

Solution

Solution	LH	ID	Tensile_2 Fit	Impact Fit	Bending Fit	Composite Desirability
1	0.15	70.7071	25.2843	3320.61	503.436	0.633621

(a) (b)

Fig. 15: Optimize response (a) Parameter Goal for Optimized Response (b) Optimized Parameter

4. Conclusion

In conclusion, this study successfully identified the optimal parameters for fused filament fabrication (FFF) 3D printing using polypropylene (PP) in biomedical applications. By employing a Design of Experiments (DOE) approach, the influence of layer height and infill density on the mechanical properties of 3D-printed parts was systematically analyzed. The results highlighted the critical role of these parameters in achieving the desired strength, flexibility, and durability essential for biomedical use. Mechanical testing, including tensile, Charpy impact, and flexural tests, confirmed that the optimized printing parameters significantly enhance the material's structural integrity and performance. The repeatability of results across multiple print runs validated the reliability of the identified setup, ensuring consistent quality and functionality of the printed parts. This study underscores the importance of parameter optimization in FFF 3D printing to meet the stringent requirements of biomedical applications. The findings not only provide a pathway for producing high-quality, mechanically robust 3D-printed parts but also serve as a valuable foundation for future advancements in additive manufacturing technologies for healthcare solutions.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurul Nadhirah Aulolazmi, Khairu Kamarudin, Raman.FNA, Mohd Khairuddin M.S, Radin Khairul Faizi, Che Rusoh.M.I.H, Zulkifli.N.S;* ***data collection****: Nurul Nadhirah Aulolazmi;* ***analysis and interpretation of results:*** *Nurul Nadhirah Aulolazmi, Khairu Kamarudin, Raman.FNA, Mohd Khairuddin M.S, Radin Khairul Faizi, Che Rusoh.M.I.H, Zulkifli.N.S;* ***draft manuscript preparation:*** *Nurul Nadhirah Aulolazmi, Khairu Kamarudin, Raman.FNA, Mohd Khairuddin M.S, Radin Khairul Faizi, Che Rusoh.M.I.H, Zulkifli.N.S. All authors reviewed the results and approved the final version of the manuscript.*

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