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Original Article

An Experimental Analysis of Poly-Lactic Acid (PLA) Filament Manufacturing for the 3D Printer Using Taguchi and Analysis of Variance (ANOVA)

Manoj Kumar Poddar[1], Saroj Kumar Sarangi[2]

[1,2]*Department of Mechanical Engineering, National Institute of Technology, Bihar, India.*

[1]*Corresponding Author : manojp.phd19.me@nitp.ac.in*

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Abstract *- The 3D printing technology known as Fused Deposition Modelling (FDM) for fabricating three-dimensional objects using a filament as the input substance. Poly-Lactic Acid (PLA) is a superior alternative for several petroleum-based polymers due to its ability to break down naturally, compatibility with living organisms, and favourable thermal and mechanical characteristics. The investigation started by feeding a PLA pellet into an extruder machine, which functioned at an extrusion temperature between 175ºC to 185ºC, with a screw speed varying from 3 rpm to 5 rpm. This study focuses on optimizing the filament extrusion process parameters in manufacturing PLA filament by using the taguchi method. The experiments were meticulously planned using a Taguchi method of L9 orthogonal array for two factors at three levels each. A tensile test was conducted to examine the mechanical performance of PLA filament for 3D printing. Data from tensile testing are analyzed using a regression model and Analysis of Variance (ANOVA). The findings indicate that the interactions between extrusion temperature and Screw speed significantly influence the mechanical* strength. *The results suggest that the tensile strength of PLA filaments ranged from 19.88 to 27.22 MPa. These results will provide a significant dataset for future researchers using PLA material as a filament in 3D printing for further investigation.*

Keywords *- Poly-Lactic Acid (PLA), Taguchi, ANOVA, Filament, Extruder machine, 3D-printing.*

1. Introduction

A filament is used as the raw material in Fused Deposition Modelling (FDM), a 3D printing technique, to create three-dimensional models [9]. Poly-Lactic Acid (PLA) is a superior substitute for other petro-polymers because of its ability to break down naturally, compatibility with living organisms, and favourable thermal and mechanical characteristics [1]. Currently, the issue of plastic waste derived from petroleum-based polymers is a worldwide concern due to its widespread contamination and pollution of the environment [1, 5, 10]. Numerous things rely on plastics, such as transportation, building supplies, electrical components, and consumer goods [3, 11].

Biodegradable polymer plastics may replace petro-polymer-based polymers, including Polyethene (PE), Polypropylene (PP), and Polyamide (PA). The most common biodegradable polymers today are Poly-Glycolic Acids (PGA), Poly-Lactic Acids (PLA), Poly-Caprolactone (PCL), Poly-Hydroxybutyrate (PHB), and Poly-Hydroxybutyrate-co-Hydroxyvalerate (PHBV) [1, 4]. PLA has shown sufficient mechanical qualities and strength for various therapeutic applications. In addition, PLA has been the material of choice for a number of additional tools, including forceps, scalpel handles, hemostats, and needle drivers. The usefulness of using bulk thermoplastics that can be 3D printed into any desired product has been shown by the Covid-19 pandemic [18].

The production of PLA begins with the fermentation of natural/corn starch, which is converted into L-lactic acid oligomers. These oligomers are then subjected to catalytic depolymerization under specific pressure conditions to get pure lactic acid with a minimum of 95% L-actic acid content. By using stannous octoate-Sn(oct)2 as a catalyst, the monomer of lactic acid undergoes polymerization to form Poly-Lactic Acid (PLA), a material with a high molecular weight [2, 6-8].

Poly-Lactic Acid (PLA) is a semi-crystalline polymer derived from pure L-lactic acid and D-lactic acid. Its melting Temperature (Tm) is approximately 175ºC, and its glass transition Temperature (Tg) falls within the range of 50 to 60ºC [13-15]. In its granular form, PLA is a versatile raw material used for various manufacturing processes such as injection moulding, film extrusion, blow moulding, thermoforming, and fibre spinning.

It can also be used for filament production, specifically for FDM-based 3D printing [5, 11]. Creating PLA filament for 3D printing involves extrusion, where the PLA material grains are uniformly combined at high temperatures [11, 12]. The production of PLA filament with a specific diameter often involves using a filament extruder machine. This machine takes in poly-lactic acid in the form of granules and pellets as its input material [17, 20].

Filament quality, including continuity, homogeneity, diameter, and mechanical properties, is essential in fabricating 3-dimensional objects using the FDM technique [14, 9]. 3D printing is an expanding technology that is used globally. The process of 3D printing necessitates the use of filament, and the price of the finished 3D printed product is directly related to the cost of the filament [9, 24]. To enhance the quality and production rate of the filament for 3D printing, the process parameters of the extruder machine must be optimized [16, 22]. Recently, considerable research has been performed to examine the mechanical characteristics and manufacturing of PLA filaments for FDM 3D printers.

Yubo Tao et al. [25] studied the production of WF/PLA composite filaments and assessed their characteristics using the FDM technique. The filaments were compatible with 3D printing and exhibited improved microstructure of PLA fracture surfaces when combined with Wood Fibre (WF). The initial resistance to deformation was enhanced, whereas the initial temperature at which thermal deterioration begins lowered marginally.

Wenjie Liu et al. [26] examined preparing PLA filaments for 3D printing using a desktop extruder. The findings demonstrated that generating filaments that met the necessary qualifications was possible under appropriate circumstances. Optimal printing performance was attained by utilizing a build layer thickness of 0.1mm, an extruder temperature of 220°C, and a speed of 60mm/s.

Ana Pilar Valerga et at. [27] investigation indicates that the PLA filament exhibits more fluidity as the extrusion temperatures rise, leading to more significant dimensional variations. However, enhanced mechanical durability is attained at temperatures up to 220◦C. The material's structural integrity is affected by its storage environment, whereby dry circumstances lead to enhanced strength but reduced toughness of PLA.

Iulian Antoniac et at. [28] Investigates the progress of Mg-filled PLA filaments for AM-based material extrusion, demonstrating its appropriateness for the production of implant screws. The text also covers the topics of material characterization, parameter settings, and the use of vitamin E. The study highlights the need to maintain a consistent filament width and stickiness in 3D printing procedures.

Harshit K. Dave et al. [29] created a new PLA filament for FDM machines to study its tensile properties and monitor the whole process, from filament production to printing the final part. This research investigates the influence of raster width, angle, and layer thickness on the tensile strength of specimens produced using 3D printing. The angle of the raster has the most significant impact, followed by the breadth and thickness of the layer.

Orellana Barrasa et al. [30] studied how extruder temperature, ageing, and printing speed affect the mechanical, thermal, physical, and fractographical properties of PLA-printed parts using material extrusion. It also aimed to simulate printed structures and identify the factors that influence the properties of 3D-printed PLA filament.

Chil-Chyuan Kuo et al. [31] studied recycled PLA waste plastic to create 3D printing filaments using the Taguchi technique. The filaments are cost-effective. The recommended process parameters consist of a temperature of 184°C, a feed rate of 490mm/min, a cooling distance of 57.5mm, and the inclusion of 40% recycled material.

Orellana-Barrasa et al. [32] investigate the mechanical properties of PLA for its use in medical prostheses. Their research also explores the potential of PLA storage to prevent ageing. This study unveils a significant finding that freezing PLA at temperatures of -24◦C or below may effectively prevent its ageing for up to nine months without causing any harm to the material.

S. Hamat et al. [33] experimented to study the effects of process parameters on filament manufacturing for 3D printing. The experiment included selecting four different extrusion temperatures and speeds. Combining 175°C to 180°C and 4 to 5 rpm resulted in the maximum tensile strength. The DOE approach was effectively used, producing filament with exceptional strength and precise control over filament diameter.

Grubbs J. et al. [34] discussed a systematic approach to optimize the process of Fused Filament Fabrication (FFF) to increase its use with different materials. The study focuses on utilizing PLA as a specific example and intends to improve the practicality of FFF in 3D printing.

Recent papers still lack sufficient experimental data, necessitating future studies to enhance our comprehension of the ideal process parameter settings for making PLA filament for FDM 3D printers and the characterization of filaments. The current research examines how an extruder machine's process parameters impact the filament's tensile properties. However, there is a lack of information about the comprehensive relationship between extrusion parameters and tensile properties.

A novel approach through taguchi design of experiment techniques is presented to analyze the tensile strength of PLA filament for 3D printing. The present research aims to optimize the filament extrusion process parameters in manufacturing PLA filament by using the taguchi method. The experiments were meticulously planned using a Taguchi method of L9 orthogonal array for two factors at three levels each. A tensile test was performed to analyze the mechanical characteristics of PLA filament for 3D printing, taking into account variations in extrusion temperature and screw speed. The data from tensile testing is analyzed using Analysis of Variance (ANOVA) and a regression model.

2. Materials and Methods

2.1. Materials

The materials used for filament making were Poly-Lactic Acid (PLA) pallets of spherical shape manufactured by Corbion, a bio-based chemical company, and supplied in India by Rivika Bio Industry Pvt. Ltd., Gujarat. Compared to oil-based polymers, PLA, a biobased polymer created from renewable resources, significantly decreases carbon impact. PLA is a transparent, amorphous, low-flow, high-viscosity PLA resin that works well for fibre spinning, thermoforming, and film extrusion [23].

2.2. Filament Extruder Machine

The PLA filament was manufactured using the Wellzoom desktop filament extruder, as shown in Figure 3, which is equipped with a filament auto winder. This machine operates on the extrusion process and utilizes a single screw extruder. It can accommodate nozzle diameters of 1.75 mm and 3.00 mm, with this study's 1.75 mm nozzle diameter. The specifications of the machine can be found in Table 2.

2.3. Preparation of PLA Filament

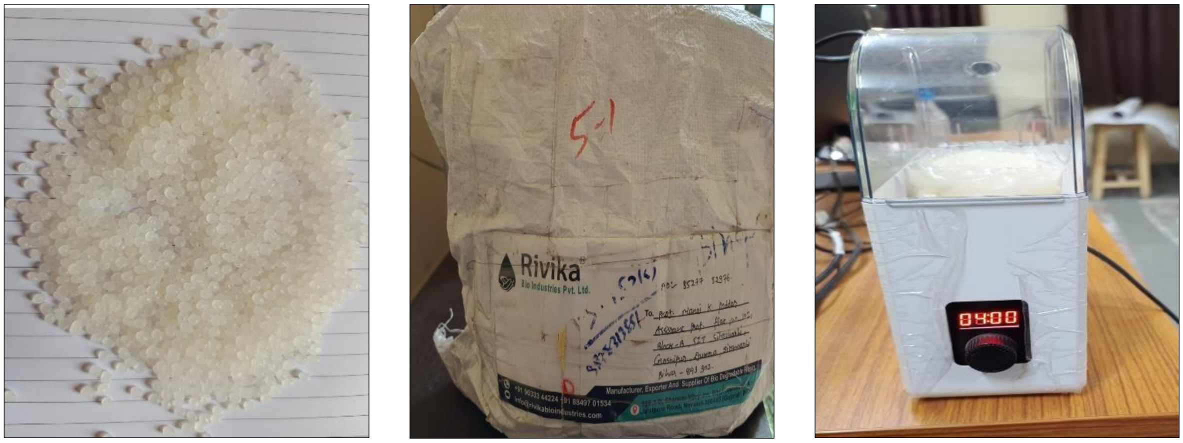
The primary components of a filament extruder machine include a cylindrical barrel, helical screw, heater, and electric motor. PLA Pellets are consistently and automatically dispensed by gravity from a hopper and pushed into the heater. The pellets soften and melt, then are mechanically propelled through a die nozzle, creating a seamless filament strand. The speed control switch regulates the flow, and an air fan cools the filament after exiting the die. The winder spools the filaments.

Table 1. Physical properties of PLA pallets [23]

Parameters	Values
Density	1.24 g/cm^3
Melt Flow Index ISO 1133-A (190°C/2.16kg)	3 g/10 min
Appearance	Crystalline White Pellets
Melting Temperature	155°C
Glass Transition Temperature	60°C

Table 2. Specification of Wellzoom desktop filament extruder

Parameters	Value
Extrude Speed (mm/min)	300– 650
Diameter (mm)	1.75 and 3.00 (2 nozzles)
Material Extruding	PLA, ABS, PVA, Wood-Plastic, etc.
Working Temperature (°C)	Upto 300 (maximum)
Temperature Control Accuracy (°C)	+/- 1
Power Required (W)	150
Power Supply	220V AC, 50 or 110V AC, 50Hz
Size (mm)	502 x 135 x 252



(a) **(b)** **(c)**

Fig. 1 (a) PLA pallets, (b) 5 Kg packet supply by Rivika Bio Industry, and (c) Pallets dried at 80°C for 4 to 6 hrs.

After that, the filament was connected to a puller to gather the product. The winder was then configured to spool the filaments after the puller had maintained the filament diameters within the desired diameter range for ten to twelve minutes [24, 17]. Once removed from their packing, PLA pallets were dried at 80°C for 4 to 6 hours, as shown in Figure 1(c). Before beginning the filament extrusion process, pre-drying is crucial. Hydrolysis of the PLA polymer caused by moisture during melt processing lowers the mechanical performance of the finished product. The preparation of the PLA filament workflow is shown in Figure 2.

2.4. Experimental Plan

Experiments have been carried out in a filament extruder machine, as shown in Figure 3. The workpiece material used is Poly-Lactic Acid (PLA) in pallet form, as shown in Figure 1(a). The goal of the present study is to apply the Taguchi method and ANOVA analysis to examine the impact of filament extruder machine process factors, such as extrusion temperature and screw speed, on the tensile strength and diameter of PLA filament. For this experiment, three different levels of process factors for extrusion temperature and screw speed were selected.

Table 3 contains the values of the process parameters' level. The Taguchi technique developed the experiment design for two factors at three levels. The array chosen was the L_9, which has nine rows with two columns at three levels, as shown in Table 4. Taguchi's design of trials was utilized to optimize process parameters [19, 20]. The Signal-to-Noise (S/N) ratio is a quality indicator used to analyze the influence of input factors on responses.

The present study's output response (Tensile Strength) is a quality attribute of the 'larger the better' type. Equation 1 calculated the responses' (S/N) ratio. After that, a linear regression method is used to identify the link between the responses and the process factors with the help of Statistical Software Minitab-2021 and Microsoft Excel 2013 within the given range of process parameters [21].

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right) \tag{1}$$

Where, n is the number of repeated experiments; S/N is signal-to-noise; and y is the output response value.

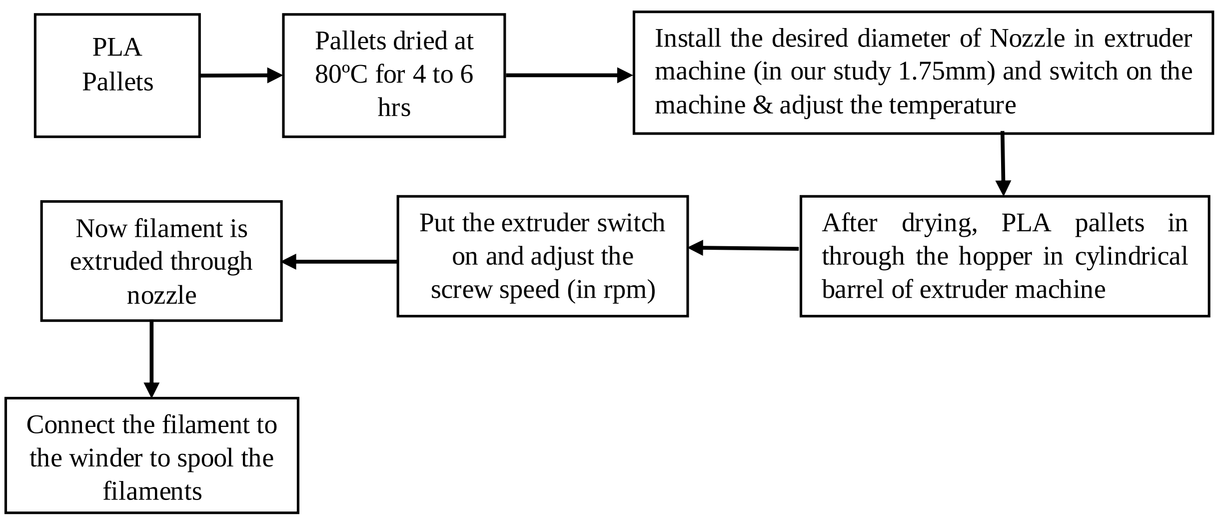


Fig. 2 Filament-making workflow

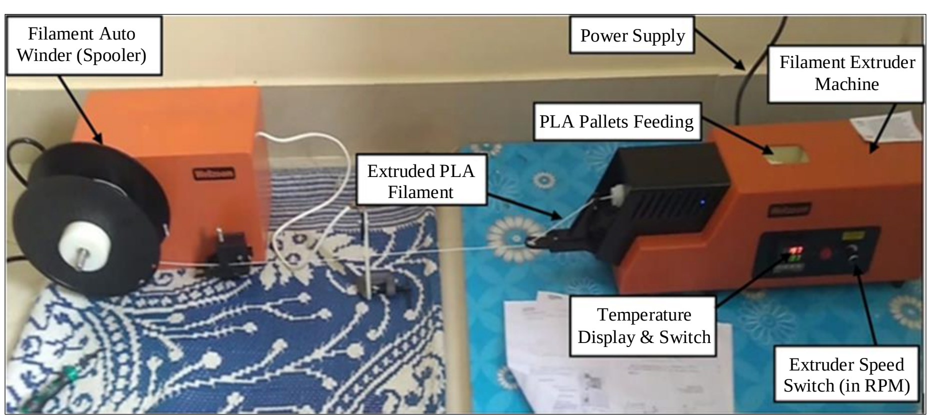
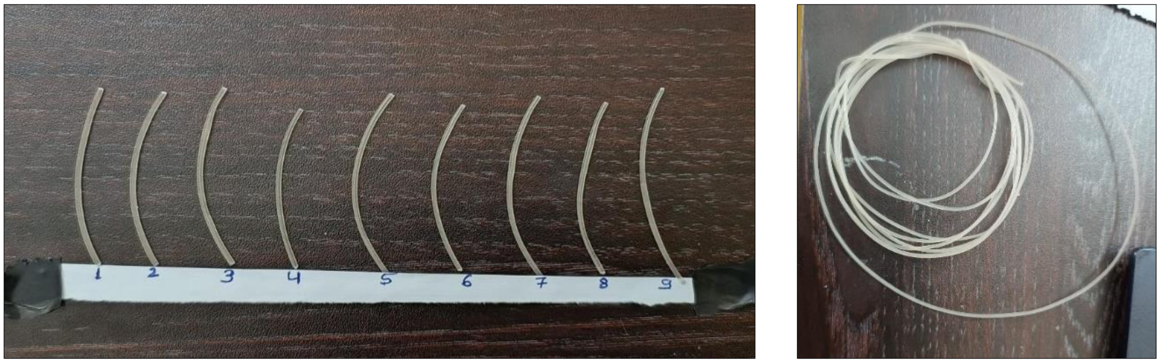


Fig. 3 Preparation of PLA filament by using filament extruder machine in the present study



(a) **(b)**

Fig. 4 Prepared filaments (a) As per Taguchi L9 experiment, and (b) PLA filament.

Table 3. Process parameters and their levels

Symbol	Parameters / Factors	Unit	Level 1	Level 2	Level 3
A	Screw speed	RPM	3	4	5
B	Extrusion Temperature	°C	175	180	185

Table 4. Experimental plan (Taguchi L9) and observed responses

Run	(A) Screw Speed (RPM)	(B) Extrusion Temperature (°C)	Responses		S/N Ratio for Tensile Strength
			Maximum Tensile Strength (MPa)	Average Diameter of Filament (mm)	
1	3	175	22.74	1.78	27.14
2	3	180	24.66	1.68	27.84
3	3	185	19.88	1.54	25.97
4	4	175	24.22	1.81	27.68
5	4	180	26.23	1.72	28.38
6	4	185	19.98	1.58	26.01
7	5	175	25.23	1.85	28.04
8	5	180	27.22	1.75	28.70
9	5	185	20.68	1.62	26.31

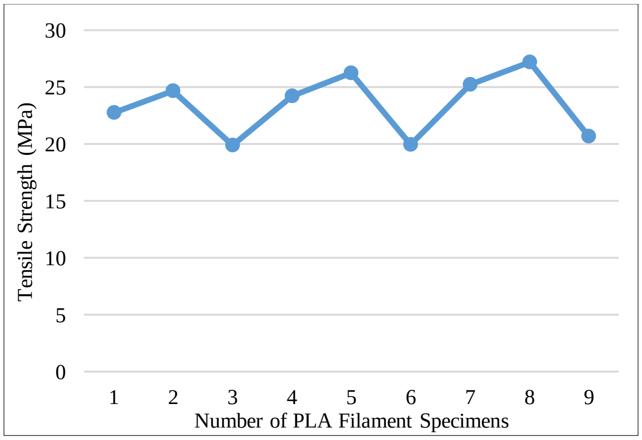


Fig. 5 Graph of tensile strength of PLA filament specimens

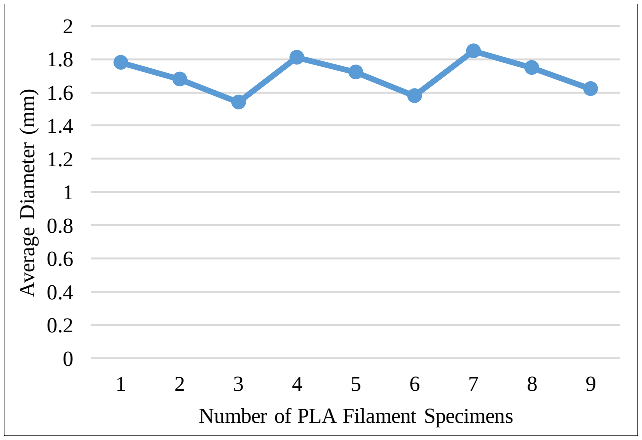
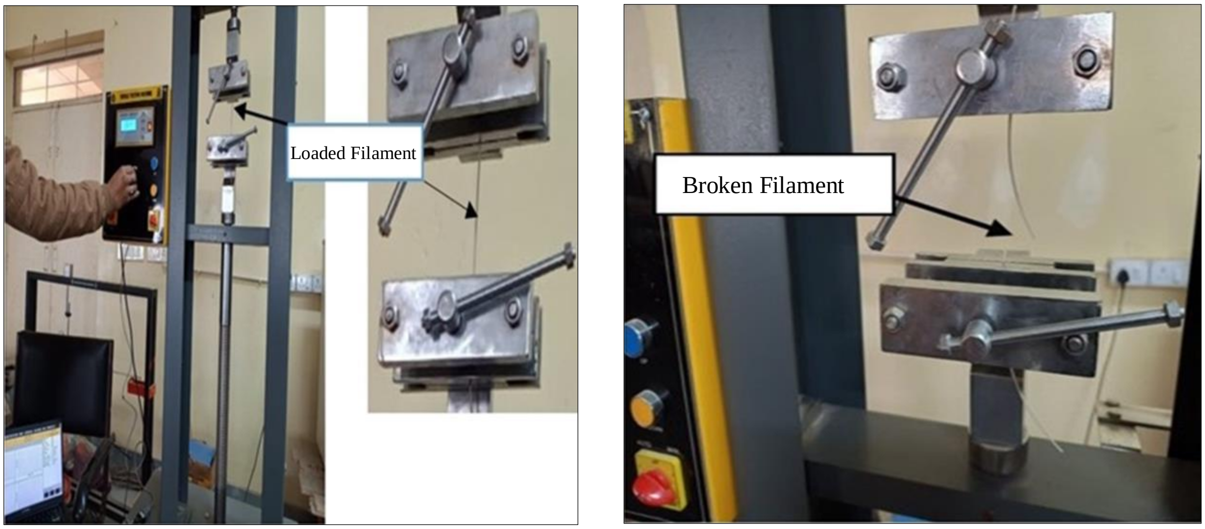


Fig. 6 Graph of average diameter of PLA filaments under nine different conditions



(a) (b)

Fig. 7 Tensile testing of (a) Loaded filament specimen, and (b) Broken filament during testing.

2.5. Tensile Testing

The tensile strength of the manufactured PLA filaments was evaluated in compliance with ISO 527-3: 2019 [30] using a Universal Testing Machine (UTM). Figure 7 illustrates how universal testing equipment outfitted with a 30 KN load cell and a steady crosshead speed of 2 mm/min was used to evaluate tensile strength.

3. Results and Discussion

3.1. Optimization

The experimental results obtained for 3D printing of PLA specimens as per Taguchi experimental design are summarised in Table 4. As shown in Figure 5, the findings indicate that the PLA filament's tensile strength varied from 19.88 to 27.22 MPa. Taguchi optimization using S/N ratio analysis determines the best set of process factors. The S/N ratio was selected to be 'larger is better' since the study's primary goal is to enhance the tensile strength of PLA filament, which aids in the uninterrupted feeding of the filament without any breakage during 3D printing.

The best levels are determined by calculating the mean values of the S/N ratios for each response at every level. The larger the S/N ratios, the more favourable quality attributes. Table 5 displays the response table for the tensile strength S/N ratio. Extrusion temperature rank in this case is 1 (delta = 2.21), while screw speed is ranked second (delta = 0.70). The rank determines the element with the most effect on the replies. The optimum printing parameters for the tensile strength of PLA filament based on S/N ratios were an extrusion temperature of 180°C and a 5 rpm screw speed, as shown in Table 6. Under these optimal process conditions, the average diameter of the PLA filament measured was 1.75 mm, which closely matches the intended diameter value. As shown in Figure 4, nine filament specimens were made according to the experimental plan in Table 4.

The average diameters of the filament specimens are presented in the plot shown in Figure 6. Figure 8 displays the primary effects charts for the S/N ratios of tensile strength with extrusion parameters such as screw speed and extrusion temperature, respectively. A higher S/N ratio indicates a more minor variance and a smaller range in the tensile strength around the intended value. The relative significance of the process variables on tensile properties is established. So, the best possible combination of process factors can be determined more accurately.

Table 5. Response table for S/N ratio of tensile strength (larger is better)

Level	Screw Speed	Extrusion Temperature
1	26.98	27.62
2	27.36	**28.30**
3	**27.68**	26.10
Delta	0.70	2.21
Rank	2	1

Table 6. Optimized results

Parameters	Screw Speed	Extrusion Temperature	Maximum Tensile Strength	Diameter of PLA Filament
Optimized Values	5 rpm	180°C	27.22 Mpa	1.75mm

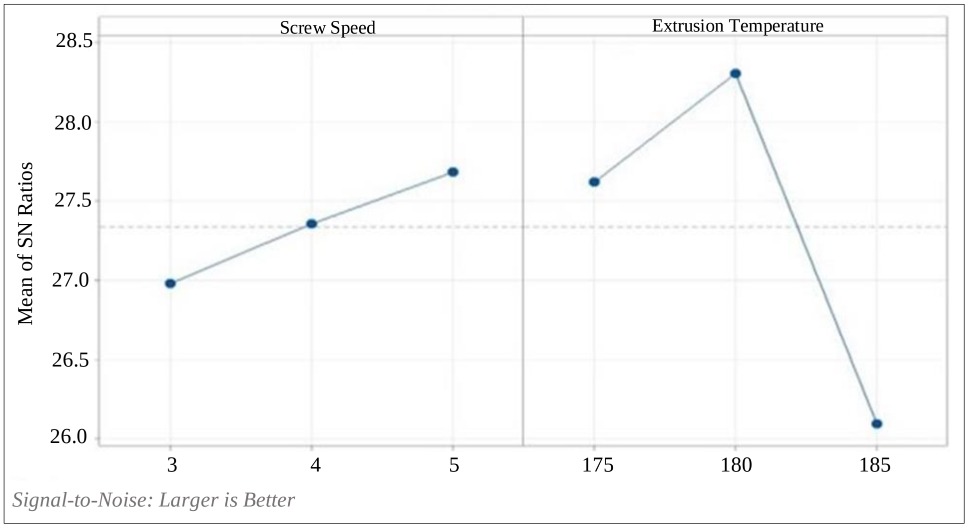


Fig. 8 Main effect plot for S/N ratio of tensile strength (MPa)

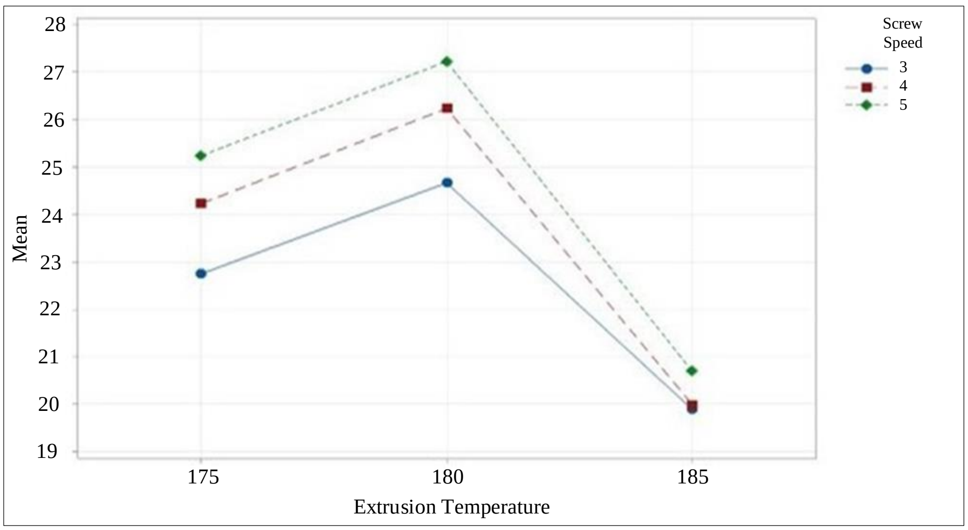


Fig. 9 Interaction plots for tensile strength

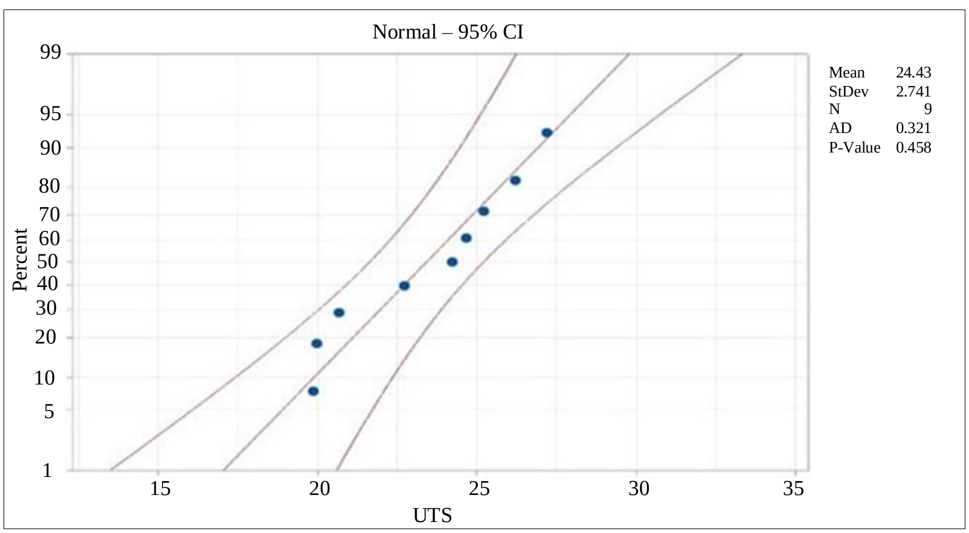


Fig. 10 Normal probability plots of tensile strength

3.2. Analysis of Tensile Strength

Figure 9 displays the interaction plots for tensile properties concerning two factors considered in the present study. This interaction plot's non-parallel lines strongly correlate with the extrusion process parameters and tensile properties. Plots of probabilities assess the distribution of experimental data from PLA filament tensile testing; Figure 10 illustrates that the experimental data on tensile strength closely corresponds to the fitted line.

The normal probability plots demonstrate that every data point exhibits a uniform distribution and is closely aligned with a linear pattern. With a 95% confidence level, an ANOVA was performed to evaluate the main effect of process factors of the extruder on tensile strength. The findings for tensile strength are shown in Table 7. The extrusion temperature was shown to be the primary determinant of mechanical strength in this research; other parameters, such as screw speed, was the slightest influence on the mechanical strength.

Table 7. ANOVA for the response (tensile strength)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	2	28.324	47.11%	28.324	14.162	2.67	0.148
Screw Speed	1	5.704	9.49%	5.704	5.704	1.08	0.340
Extrusion Temperature	1	22.620	37.62%	22.620	22.620	4.27	0.084
Error	6	31.800	52.89%	31.800	5.300	-	-
Total	8	60.125	100.00%	-	-	-	-

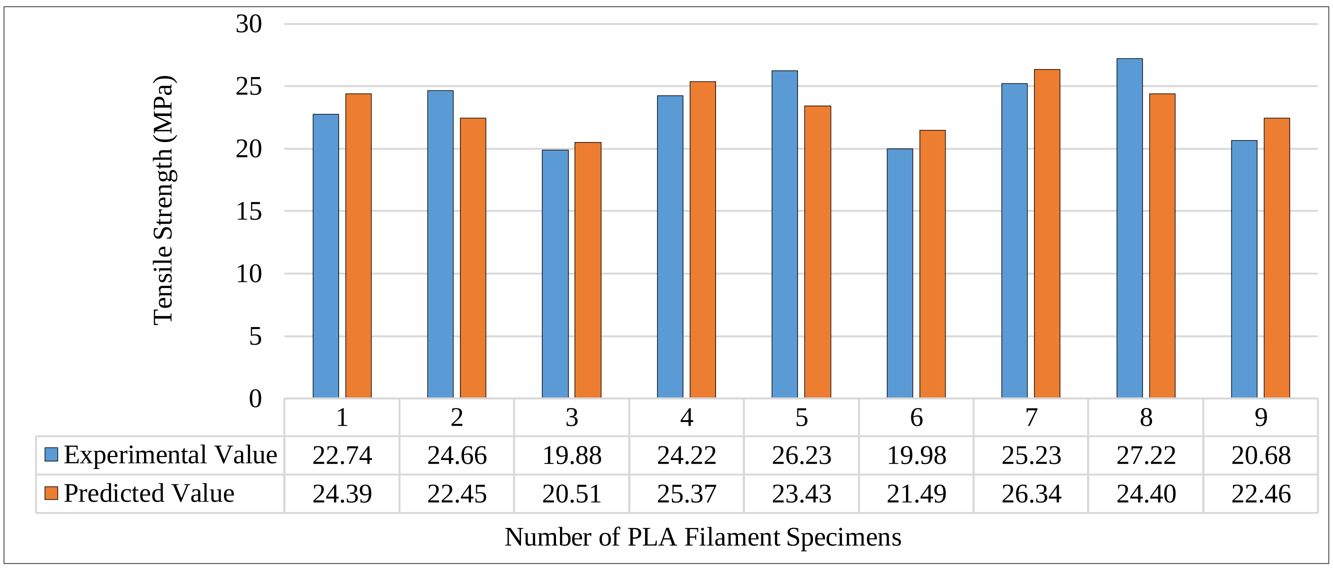


Fig. 11 Regression fit plot of experimental vs. Predicted values for tensile strength

3.3. Analysis of the Effects of Process Parameters

The diameter of filaments produced by the extruder machine is shown in Table 4. When the screw speed is constant, a rise in extrusion temperature results in a reduction in filament diameter. The diameter of the PLA filaments grows as the screw speed of the extruder rises, but the extrusion temperature stays constant. This might be caused by a rise in speed, leading to a significant build-up of PLA material at the extruder nozzle opening, resulting in the observed high filament diameter. The tensile strength of the filaments is crucial for ensuring smooth filament feeding without breaking during 3D printing. The filament's tensile strength ranged from 19.88 to 27.22 MPa, as seen in Table 4.

An extrusion temperature of 185°C and a screw speed of 3 rpm resulted in the lowest tensile strength of 19.88 MPa. In comparison, an extrusion temperature of 180°C and a screw speed of 5 rpm led to the maximum tensile strength of 27.22 MPa, slightly surpassing the findings of the previous study by S. Hamat et al. [33].

The optimum printing parameters for tensile strength of PLA filament based on taguchi S/N ratios were extrusion temperature 180°C and 5 rpm screw speed. Under these optimal process conditions, the average diameter of the PLA filament measured was 1.75 mm, which closely matches the desired diameter value.

3.4. Regression Analysis for Tensile strength

The linear equation for tensile strength is derived using Statistical Software Minitab-2021 and Microsoft Excel 2013 within the specified range of process parameters [21]. Equation 2 represents the relationship between the extrusion process parameters and the tensile strength. These expressions help determine the characteristics of the response variable for specific input process parameters of the extrusion machine when producing the PLA filament. The deviation between the experimentally observed responses obtained using the Taguchi approach and the projected outcomes is seen in Figure 11. Using an extrusion machine, the graph compares the experimental and projected ultimate tensile strength values for PLA filaments. Regression equation for tensile strength is,

$$\text{Tensile Strength (TS)} = 89.4 + 0.975\ A - 0.388\ B \quad (2)$$

Where, A = Screw speed, and B = Extrusion temperature

4. Conclusion

The experimental study aimed to analyze the tensile properties of manufactured PLA filaments and identify the optimum combination of process parameters for the filament extruder machine. This would enhance the tensile properties and quality of the PLA filament, ensuring it can be fed smoothly without any breakage during 3D printing. The tensile strength of the manufactured PLA filaments was examined according to ISO 527-3: 2019 standard; by considering the three different values of extrusion temperature (175, 180 and 185ºC) and screw speed (3, 4 and 5 rpm). This study aimed to optimize the extrusion parameters in manufacturing PLA filament by using the Taguchi method. Tensile test data are analyzed using the Analysis of Variance (ANOVA) and regression models. The manufactured PLA filaments exhibited various tensile strength values, ranging from 19.88 to 27.22 MPa. The optimal setting of extrusion parameters for tensile strength of the filament based on S/N ratios was extrusion temperature 180°C and 5 rpm screw speed.

Under these optimal process conditions, the average diameter of the PLA filament measured was 1.75 mm, which closely matches the desired diameter value. According to the results of the ANOVA analysis, the extrusion temperature was shown to have the most significant impact on the mechanical strength. The changing screw speed has the most negligible impact on the mechanical strength. The probability plots demonstrate that every data point exhibits a strong linear alignment and is evenly distributed. A regression model was used to determine linear mathematical correlations between a filament extrusion machine's tensile strength and process parameters. Essentially, these results will provide a significant dataset for future researchers who are using PLA material as a filament in 3D printing for further investigation.

References

[1] Tianyi Ke, and Xiuzhi Sun, "Physical Properties of Poly (Lactic Acid) and Starch Composites with Various Blending Ratios," *Cereal Chemistry*, vol. 77, no. 6, pp. 761-768, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[2] Saara Inkinen et al., "From Lactic Acid to Poly (Lactic Acid) (PLA): Characterization and Analysis of PLA and Its Precursors," *Biomacromolecules*, vol. 12, no. 3, pp. 523-532, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[3] Randal L. Shogren, Gordon Selling, and J.L. Willett, "Effect of Orientation on the Morphology and Mechanical Properties of PLA/Starch Composite Filaments," *Journal of Polymers and the Environment*, vol. 19, pp. 329-334, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[4] Mamata Singhvi, and Digambar Gokhale, "Biomass to Biodegradable Polymer (PLA)," *RSC Advances*, vol. 3, pp. 13558-13568, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[5] Jean-Marie Raquez et al., "Polylactide (PLA)-Based Nanocomposites," *Progress in Polymer Science*, vol. 38, no. 10-11, pp. 1504-1542, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[6] Kazunari Masutani, and Yoshiharu Kimura, "PLA Synthesis. From the Monomer to the Polymer," *RSC Polymer Chemistry Series (Chapter 1)*, 2015. [Google Scholar] [Publisher Link]

[7] Anders Sodergard, and Mikael Stolt, "Properties of Lactic Acid Based Polymers and their Correlation with Composition," *Progress in Polymer Science*, vol. 27, no. 6, pp. 1123-1163, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[8] Kajsa M. Stridsberg, Maria Ryner, and Ann-Christine Albertsson, "Controlled Ring-Opening Polymerization: Polymers with Designed Macromolecular Architecture," *Degradable Aliphatic Polyesters*, pp. 41-65, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[9] V. Mirón et al., "Manufacturing and Characterization of 3D Printer Filament Using Tailoring Materials," *Procedia Manufacturing*, vol. 13, pp. 888-894, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Satya P. Dubey et al., "Progress in Environmental-Friendly Polymer Nanocomposite Material from PLA: Synthesis, Processing and Applications," *Vacuum*, vol. 146, pp. 655-663, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[11] Justine Muller, Chelo Gonzalez-Martínez, and Amparo Chiralt, "Combination of Poly(Lactic) Acid and Starch for Biodegradable Food Packaging," *Materials*, vol. 10, no. 8, pp. 1-22, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[12] Ana Pilar Valerga et al., "Influence of PLA Filament Conditions on Characteristics of FDM Parts," *Materials*, vol. 11, no. 8, pp. 1-13, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[13] Gianluca Cicala et al., “Polylactide (PLA) Filaments a Biobased Solution for Additive Manufacturing: Correlating Rheology and Thermomechanical Properties with Printing Quality,” *Materials*, vol. 11, no. 7, pp. 1-13, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[14] K. Jamshidi, S.H. Hyon, and Y. Ikada, “Thermal Characterization of Polylactides,” *Polymer*, vol. 29, no. 12, pp. 2229-2234, 1988. [CrossRef] [Google Scholar] [Publisher Link]

[15] Akbar Hanif Dawam Abdullah et al., “Fabrication and Characterization of Poly Lactic Acid (PLA)-Starch Based Bioplastic Composites,” *IOP Conference Series: Materials Science and Engineering*, vol. 553, pp. 1-11, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[16] Luis Enrique Solorio-Rodriguez, and Alejandro Vega-Rios, “Filament Extrusion and Its 3D Printing of Poly (Lactic Acid)/Poly(Styrene-co-Methyl Methacrylate) Blends,” *Applied Sciences*, vol. 9, no. 23, pp. 1-17, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Fengze Wang et al., “Fabrication and Characterization of PCL/HA Filament as a 3D Printing Material Using Thermal Extrusion Technology for Bone Tissue Engineering,” *Polymers*, vol. 14, no. 4, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Vincent DeStefano, Salaar Khan, and Alonzo Tabada, “Applications of PLA in Modern Medicine,” *Engineered Regeneration*, vol. 1, pp. 76-87, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ala’aldin Alafaghani, and Ala Qattawi, “Investigating the Effect of Fused Deposition Modeling Processing Parameters Using Taguchi Design of Experiment Method,” *Journal of Manufacturing Processes*, vol. 36, pp. 164-174, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Isksioui Hamza, El Gharad Abdellah, and Oubrek Mohamed, “Experimental Optimization of Fused Deposition Modeling Process Parameters: A Taguchi Process Approach for Dimension and Tolerance Control,” *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Paris, France, pp. 1-11, 2018. [Google Scholar] [Publisher Link]

[21] Jackson Pasini Mairing, “The Effect of Advance Statistics Learning Integrated Minitab and Excel with Teaching Teams,” *International Journal of Instruction*, vol. 13, no. 2, pp. 139-150, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[22] Herianto, S.I. Atsani, and H. Mastrisiswadi, “Recycled Polypropylene Filament for 3D Printer: Extrusion Process Parameter Optimization,” *IOP Conference Series: Materials Science and Engineering*, vol. 722, pp. 1-8, 2020. [Google Scholar] [Publisher Link]

[23] Product Data Sheet, 2022. [Online]. Available: https://www.totalenergies-corbion.com/media/03xnhcab/pds-luminy-lx175-20220722.pdf

[24] Mamta H. Wankhade, and Satish G. Bahaley, “Design and Development of Plastic Filament Extruder for 3D Printing,” *IRA International Journal of Technology & Engineering*, vol. 10, no. 3, pp. 23-40, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[25] Yubo Tao et al., “Development and Application of Wood Flour-Filled Polylactic Acid Composite Filament for 3D Printing,” *Materials*, vol. 10, no. 4, pp. 1-6, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[26] Wenjie Liu et al., “Fabrication of PLA Filaments and its Printable Performance,” *IOP Conference Series: Materials Science and Engineering*, vol. 275, 2017. [Google Scholar] [Publisher Link]

[27] Ana Pilar Valerga et al., “Influence of PLA Filament Conditions on Characteristics of FDM Parts,” *Materials*, vol. 11, no. 8, pp. 1-13, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[28] Iulian Antoniac et al., “Magnesium Filled Polylactic Acid (PLA) Material for Filament Based 3D Printing,” *Materials*, vol. 12, no. 5, pp. 1-13, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[29] Harshit K. Dave et al., “Investigation on Tensile Strength and Failure Modes of FDM Printed Part Using In-House Fabricated PLA Filament,” *Advances in Materials and Processing Technologies*, vol. 8, no. 1, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[30] Jaime Orellana Barrasa et al., “Characterisation and Modelling of PLA Filaments and Evolution with Time,” *Polymers*, vol. 13, no. 17, pp. 1-19, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[31] Chil-Chyuan Kuo, Jia-You Chen, and Yuan-Hao Chang, “Optimization of Process Parameters for Fabricating Polylactic Acid Filaments Using Design of Experiments Approach,” *Polymers*, vol. 13, no. 8, pp. 1-19, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[32] Jaime Orellana-Barrasa et al., “Natural Ageing of PLA Filaments, Can it be Frozen?,” *Polymers*, vol. 14, no. 16, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] S. Hamat et al., “Influence of Filament Fabrication Parameter on Tensile Strength and Filament Size of 3D Printing PLA-3D850,” *Materials Today: Proceedings*, vol. 74, no. 3, pp. 457-461, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[34] Jack Grubbs, Bryer C. Sousa, and Danielle L. Cote, “Establishing a Framework for Fused Filament Fabrication Process Optimization: A Case Study with PLA Filaments,” *Polymers*, vol. 15, no. 8, pp. 1-26, 2023. [CrossRef] [Google Scholar] [Publisher Link]