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Investigation and Optimisation of Mechanical Properties of Additively Manufactured PMMA Patterns using Taguchi and RSM Approach

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Abstract

A combined statistical method consisting of Taguchi L27 Design of Experiments (DOE) and Response Surface Methodology (RSM) are used to optimize the mechanical characteristics of additively manufactured Polymethyl Methacrylate (PMMA) patterns. The research aims to enhance the properties of PMMA composites by tuning various processing factors. By adjusting the composition and production parameters the study evaluates attributes such, as compressive strength, and hardness. Fused Deposition Modelling (FDM) was employed to fabricate PMMA patterns and the optimizing key parameters such as layer height, printing temperature, build plate temperature, printing speed, infill line distance, and cooling fan settings to enhance mechanical properties. The results indicate that specific processing elements significantly influence the characteristics of PMMA designs enhancing their strength. Furthermore, the mechanical attributes are predicted by using a regression model incorporating the chosen parameters. The optimized mechanical properties of additively manufactured PMMA patterns, achieving a maximum compressive strength of 30.07 MPa and a hardness of 91.28 Shore D under optimal processing conditions. Therefore, the researchers promoting the environmentally friendly processes in the manufacturing of high-performing PMMA materials for various uses. This research highlights the potential of PMMA composites to promote eco manufacturing methods while meeting the requirements of engineering.

Keywords: 3D Printing;Compressive Strength; DOE-RSM; PMMA; Statistical Analysis.

1. Introduction

The purviews of AM (Additive Manufacturing) and engineering applications have seen a shrill growth in demand for advanced materials with unique mechanical qualities in recent years. The used thermoplastic material polymethyl methacrylate (PMMA) has garnered interest due to its excellent strength, lightweight construction and remarkable optical transparency. PMMA stands out as a choice for uses such, as consumer products, medical devices and automotive parts because of these attributes. Yet enhancing the properties of PMMA through optimizing processing parameters is essential to unlock its potential in challenging applications [1-3].

Acrylic, also known as plexiglass refers to polymethyl methacrylate (PMMA) a type of polymer highly valued for its optical properties, durability, against various weather conditions and compatibility with living tissues. The recent advancements in 3D printing have enabled the creation of structures using PMMA leading to its expanded applications across industries such as microfluidics, optics and biomedical engineering. Early studies on 3D printed PMMA focused on optimizing printing parameters to enhance surface finish and mechanical properties [4]. For instance Abbas et al. [5] Investigated how factors, like print orientation, infill density and layer thickness influenced the strength of PMMA samples produced through fused deposition modelling (FDM). It was found that reducing layer thickness and increasing infill density significantly improved the mechanical properties of 3D printed PMMA components.

Victor et al. [6] experimented with incorporating PMMA into materials and developed a material using PMMA and carbon fibers to enhance both mechanical strength and thermal stability. This innovative composite material displays potential, for applications requiring lightweight components .In biomedical applications, customised prosthesis and dental implants have been made using 3D printed PMMA. Due to its biocompatibility and simplicity of sterilisation, it is suitable for patient-specific medical equipment. Singh et al. [7]observed that the congeniality of 3D printed PMMA in craniofacial surgery which is an excellent bone substitute because of its tissue compatibility and favourable mechanical characteristics. Even with these developments, 3D printed PMMA parts are still getting difficulty to obtain consistency in surface quality and material characteristics. In order to enhance the performance of 3D printed PMMA in different critical environment, the future research will emphasis on increasing print accuracy and also exploring novel composite formulas [8].

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The optimisation of material characteristics is a crucial element of material science and engineering. Conventional experimental procedures can be time-intensive and, resource frequently generating less than ideal outcomes. Statistical methods such as RSM (Response Surface Methodology) and DOE (Design of Experiments) have been employed more often to solve critical issues [9-11]. These methodologies made it simpler to identify the ideal processing settings by empowering a methodical investigation of the impacts of various factors on the proposed results. The Taguchi L27 Orthogonal Array is an effectual tool for experimental design that makes it easier to explore the impact of different factors in material qualities. By using these approaches, researchers can save time and money by conducting analyses, with experiments. In particular the L27 array enables the examination of up to 13 elements at three levels making it highly valuable for material systems, like PMMA composites. This design allows researchers to gain an understanding and enhance the properties by identifying crucial elements and their interconnections [12-15].

In the realm of PMMA combining fillers and additives has been found to boost its performance. For instance incorporating fibers has emerged as a way to enhance the stiffness and strength of polymer matrices. The partnership, between PMMA and natural fibers not enhances properties but also aligns with global sustainability initiatives aimed at reducing reliance on synthetic materials [16-17]. This researches utilizes the Taguchi L27 DOE to study the impact of processing parameters, on the mechanical properties of PMMA composites reinforced with natural fibers. By providing an approach to simulate and analyze the relationships, between factors and outcomes of RSM improves upon the Taguchi method. This statistical tool is particularly valuable in engineering scenarios where achieving optimal product performance involves understanding the interplay of variables. Developing models, optimizing processes and designing experiments are components of RSM. Scientists can construct models that facilitate the creation of materials, with mechanical characteristics through the application of RSM [18-20].

The primary objective of this study is to examine the properties of PMMA patterns produced through printing focusing on optimizing processing parameters using the Taguchi L27 DOE and RSM techniques as depicted in Figure 1. The study aims to assess properties such, as impact resistance, hardness and tensile strength to understand how variations, in processing parameters impact the functionality of PMMA composites. By adjusting factors like layer height, infill density, printing speed and temperature the research aims to identify combinations that enhance mechanical performance. Additionally through demonstrating the capabilities of PMMA composites enhanced with fibers this research contributes to the growing body of knowledge on eco materials. The findings not enhance our comprehension of the properties of PMMA but also promote environmentally conscious manufacturing techniques. The necessity, for materials is becoming increasingly important as industries seek sustainable alternatives, to conventional plastics.

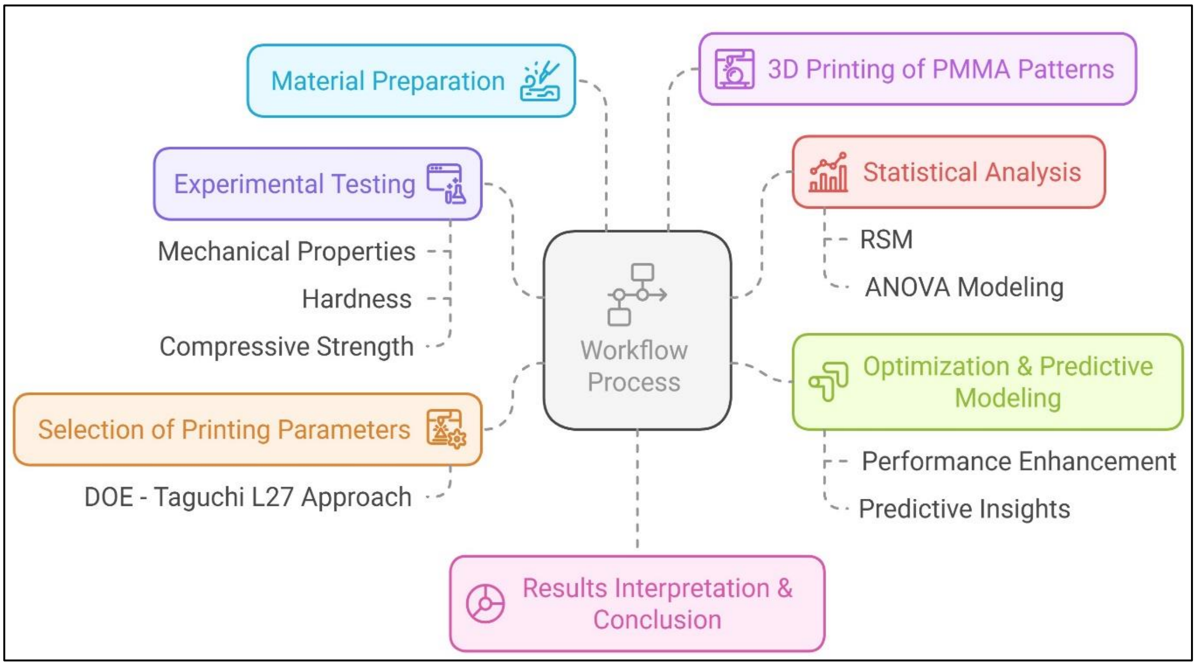

Figure 1. Flow diagram of the present investigation

2. 3D PRINTING OF PMMA PATTERNS

Producing PMMA patterns through 3D printing demands an approach to ensure the production of top notch components, with the right mechanical properties. In this study a desktop Fused Deposition Modelling (FDM) 3D printer tailored for materials like PMMA (refer to Table 1& 2 for its characteristics) was employed. FDM technology stands out as a choice due, to its cost effectiveness, ease of access and ability to craft geometries with precision.

Table 1. Mechanical properties of PMMA [4]

Property	Value	Unit
Density	1.18	g/cm³
Melting Temperature	166	°C
Glass Transition Temperature	102-105	°C
Tensile Strength	40	MPa
Elongation at Break	5	%
Young's Modulus	2.9	GPa
Flexural Modulus	80	MPa
Izod Impact	1	kJ/m

Table 2. The chemical composition of Polymethyl Methacrylate (PMMA) [5]

Component	Chemical Formula	Weight Percentage (%)
Methyl Methacrylate Monomer (MMA)	$C_5H_8O_2$	98%
Initiators (e.g., Benzoyl Peroxide)	$C_{14}H_{10}O_4$	0.5%
Stabilizers (e.g., Hydroquinone)	$C_6H_4(OH)_2$	0.1%
UV Absorbers (e.g., Tinuvin)	Varies	1.4%

The PMMA material has to be ready in the form of filament before printing. PMMA granules are meticulously extruded to produce filaments that have a constant diameter of 1.75 ± 0.5 mm.This homogeneity is necessary to accomplishcontinuous layer deposition during the 3D printing process and to confirm reliable feeding into the printer. The final behaviours of the printed samples are mostlyestablished by the mechanical and physical properties of the PMMA material, incorporating melting temperature, density, and tensile strength. Table 3 lists the keyaspects that were cautiouslyaccustomed to boost the printing process. The layer height of 0.2 mm was preferred for this experimentationdue to it stabilities print resolution and speed. The printing temperature was fixed at 280°C in order to confirm that the PMMA material smoothly passes through the nozzle and maintains its structural integrity.

Table 3. Fixed Printing Parameters for pattern fabrication

Sl. No	Printing Parameters	Values
1	Printing Temperature (°C)	280
2	Build Plate Temperature (°C)	50
3	Printing Speed (mm/s)	40
4	Infill Line Distance (mm)	4
5	Cooling Fan (%)	0
6	Build Plate Adhesion	Brim
7	Nozzle Diameter (mm)	0.4
8	Filament Diameter (mm)	1.75

The build plate temperature was set to be 50°C to develop adhesion between the build surface and printed layers, to lowering the probability of warping, and to raise the overallcharacteristic of the printed patterns. A controlled deposition of material benefited to the mechanical strength of finished product was preparedlikely by the 40 mm/s of printing speed. Also, the infill density was reformed to amplify the internal structure of the printed patterns. The cooling conditions were closely observedat the time of printing process. The built-in cooling fan was switched off to minimize the probability of early cooling, which causes flaws such as insufficient interlayer adhesion or layer separation. The temperature environment control is very necessary to attain the overall mechanical integrity and the best possible layer bonding.

For achieving the best possible mechanical performance of PMMA patterns, ideal set of printing parameters need to determined. The resulting patterns are analysed by systematically varying the printing conditions. The evaluation of the performance of PMMA patterns including hardness and compressive strength (shown in Figure 2) has been done by conducting a series of mechanical tests. The steps included in the 3D printing process of PMMA patterns are material preparation, parameter optimization, and extensive testing. The statistical methods and printing technology used in this research to improve the mechanical performance of PMMA patterns which opens the door of its applicability in different sectors where high performance materials are very crucial.

3. EXPERIMENTAL DESIGN

A Taguchi L27 Orthogonal array was used in this study's experimental design to carefully investigate the impact of various 3D printing settings on the mechanical properties of PMMA pattern. The Taguchi approach was chosen due of its efficiency in simultaneously examining several factors with the least number of experiments required. Table 4 lists the characteristics and their associated values that were selected based on how important they were to the mechanical properties and print quality of the composites:

Figure 2. 3D Printed Samples

Table 4. Levels of the process parameters

Machining Parameters	Unit	Level		
		-1	0	+1
Layer Height	mm	0.1	0.2	0.3
Infill Pattern	-	Line	Cube	Trihexagonal
Raster Orientation	Degree (˚)	0	45	90
Infill Density	%	50	75	100

The amount of material utilised in a printed object is determined by its infill density, which has an impact on its weight and strength. Stronger materials often need more time to print at greater densities and consume less material. The levels that have been chosen fit low, medium, and full infill scenarios. The inter-layer bonding strength, resolution, and surface polish of the printed item are all influenced by the layer height. While they may lengthen the printing process, lower layer heights can improve surface quality and mechanical strength. The chosen heights correspond to typical decisions made in 3D printing procedures.

The direction of the print lines with respect to the build plate is known as raster orientation. Different orientations can affect an object's anisotropy, which could affect its mechanical properties. The chosen levels represent common orientations that provide insight into the directional strength characteristics of the composite. The infill pattern used in printing alters the structure of the printed object affecting its performance, weight and material efficiency. By comparing cubic and line designs, for stability and strength a range of configurations from simple to complex is examined. Through 27 runs based on the Taguchi L27 array (as shown in Table 5) the study identifies optimal conditions for enhancing mechanical properties, in PMMA patterns. This approach reveals factors and their interactions efficiently. The research method effectively investigates these factors while minimizing work and upholding integrity through a robust statistical analysis.

4. MECHANICAL TESTING

The mechanical performance of additively manufactured PMMA patterns plays a crucial role in determining their suitability for various applications. To evaluate the material's structural integrity, standardised mechanical tests were conducted. This section outlines the experimental procedures employed to measure hardness and compressive strength, which are critical indicators of the material's durability and load-bearing capacity. The testing methods were carefully selected following internationally recognised standards to ensure accurate, repeatable, and reliable results.

Table 5. Taguchi L27 Design of Experiment

Experiment No.	Layer Height (mm)	Infill Pattern	Raster Orientation (˚)	Infill Density (%)	Hardness	Compressive Strength (MPa)
1	0.1	Lines	0	50	85.86	4.00
2	0.1	Cube	0	50	84.24	3.93
3	0.1	TriHexagonal	0	50	84.70	8.98
4	0.1	Lines	45	75	82.28	8.49
5	0.1	Cube	45	75	78.80	8.38
6	0.1	TriHexagonal	45	75	80.35	8.27
7	0.1	Lines	90	100	84.27	6.53
8	0.1	Cube	90	100	81.29	6.24
9	0.1	TriHexagonal	90	100	81.70	6.11
10	0.2	Lines	45	50	88.40	8.02
11	0.2	Cube	45	50	86.86	14.47
12	0.2	TriHexagonal	45	50	87.32	19.04
13	0.2	Lines	90	75	84.90	12.84
14	0.2	Cube	90	75	81.42	12.76
15	0.2	TriHexagonal	90	75	82.97	12.27
16	0.2	Lines	0	100	86.89	11.27
17	0.2	Cube	0	100	83.41	9.58
18	0.2	TriHexagonal	0	100	83.82	9.53
19	0.3	Lines	90	50	91.28	19.89
20	0.3	Cube	90	50	89.28	20.33
21	0.3	TriHexagonal	90	50	89.78	30.07
22	0.3	Lines	0	75	87.28	18.09
23	0.3	Cube	0	75	84.28	17.24
24	0.3	TriHexagonal	0	75	86.28	16.89
25	0.3	Lines	45	100	89.78	16.73
26	0.3	Cube	45	100	86.78	15.93
27	0.3	TriHexagonal	45	100	87.28	14.93

4.1. Hardness Testing

The hardness measurements of the 3D-printed PMMA samples were conducted using the Shore D durometer in accordance with the ASTM D2240 standard, which is widely utilized for evaluating the hardness of polymers and composite materials. The Shore D scale was selected due to its suitability for testing rigid plastics, including PMMA-based components. The Shore D hardness test quantifies the resistance of the material to indentation under a specified force. During testing, the durometer indenter was pressed vertically against the surface of the specimen with consistent pressure until full contact was established [3-4]. The hardness value (HD) was recorded once the indenter reached equilibrium, as indicated by a stable reading on the instrument's dial. The following equation represents the hardness measurement:

$$HD = 100 - \left(\frac{h}{d}\right) \times 100$$

Where:

HD = Shore D Hardness value

h = Depth of indentation (mm)

d = Maximum possible indentation depth (2.5 mm for Shore D scale)

To minimize measurement variability, five independent hardness readings were taken at different points on each sample, and the average hardness value was calculated to represent the final result. This approach accounted for possible material inconsistencies or surface imperfections across the specimen. The hardness values obtained from the experimental investigation were used as one of the key response parameters in the optimization study. The comprehensive statistical analysis through RSM and ANOVA further validated the significance of process parameters on the hardness of the PMMA patterns. The detailed testing methodology ensures that the hardness evaluation provides a reliable assessment of the mechanical performance of the additively manufactured PMMA patterns, with results consistent with previous studies reported in the literature [6].

4.2. Compressive Strength Testing

The ASTM D695 standardwas maintained during the testing of compressive strength using a UTM (universal testing machine) which depicts the procedure to determine the compressive properties of the polymers [5]. The comparability of the results was ensured by producinga cubic shape composite samples with uniform dimensions.

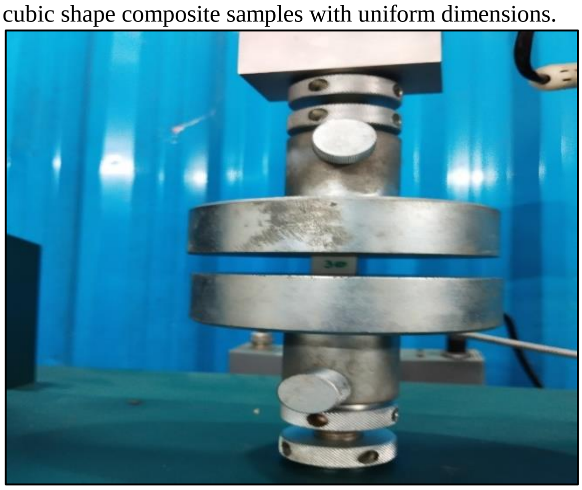

Figure 3. Compression test of samples

The compressive strength of the PMMA patterns was evaluated following the ASTM D695 standard, which specifies the testing methods for determining the compressive properties of polymer materials. The testing was conducted using a Universal Testing Machine (UTM) with a maximum load capacity of 100 kN. The specimens were fabricated in cubic shapes with uniform dimensions to maintain consistency in the analysis. The samples were positioned between the upper and lower platens of the UTM, as illustrated in Figure 3, and subjected to compressive loading at a constant crosshead speed of 1 mm/min until failure [7]. The maximum load (Σ) that the specimen could withstand before deformation was recorded. Thenthe formula used for evaluating the sample's compressive strength is given below:

$$Comprssive\ Strength = \frac{Maximum\ Load}{Cross - Sectional\ Area}$$

To ensure the reliability of the results, each test was performed on three replicate samples, and the average compressive strength value was reported. The standard deviation was calculated to account for variability in the measurements. The methodology was rigorously followed to minimize experimental errors and ensure reproducibility. The outcomes of the compressive strength testing were further analyzed using Response Surface Methodology (RSM) to develop predictive models and optimize the processing parameters. The detailed statistical analysis and regression equations derived from the experimental data are presented in the subsequent sections of the manuscript.

5. RESULTS AND DISCUSSION

5.1. Analysis using the Response surface method

The Response Surface Methodology (RSM) was used to examine the experimental data generated from the mechanical testing. The RSM is a statistical modelling technique which assessed the interactions between one or more dependent variables and several independent factors. RSM were employed to obtain prediction models for compressive strength and hardness based on the selected variables such as infill density, infill pattern, raster orientation, and layer height. The statistical analysis, including regression model fitting, ANOVA, and optimization, was performed using Minitab 19 software. The objective was to reveal the optimal configuration of the above-mentioned components to enhance the mechanical properties of the composites. Somecritical steps were involved in the analysis are as follows:

- **Model Fitting:** The quadratic regression models generated using the experimental data in case ofhardness and compressive strength were fitted. Over and done with the addition of linear, interaction, and quadratic terms, these models were capable to characterise the potential impacts and interactions of the variables on to the results.
- **Analysis of Variance (ANOVA):** An ANOVA was applied to evaluate the implication of each component and its interactions. This study facilitated to illuminate the interpretation of the data by classifying the variables which had a significant statistical impact on the mechanical attributes.The ANOVA was carried out to determine the significance of the model terms at a 95% confidence interval (p-value ≤ 0.05). The

contribution of each parameter and its interactions to the mechanical properties is presented [6-8].

- **Main Effect Plots:** The main effect plots provide a graphical representation of how individual process parameters affect the mechanical properties of additively manufactured PMMA patterns. These plots are essential for understanding the influence of each parameter independently, thereby offering insights into the optimization of the printing process. The main effect plots for both hardness and compressive strength are presented to illustrate the role of layer height, infill pattern, raster orientation, and infill density on the mechanical performance of PMMA patterns.

Figure 4 illustrates the main effect plot for hardness. The detailed description is given below:

1. **Layer Height:** The plot shows a direct correlation between layer height and hardness. As the layer height increases from 0.1 mm to 0.3 mm, the hardness of the PMMA patterns increases. This is attributed to better interlayer fusion and higher structural integrity at greater layer heights, resulting in increased resistance to indentation.
2. **Infill Pattern:** Among the three infill patterns, the TriHexagonal pattern exhibits the highest hardness values, followed by the Line and Cube patterns. The TriHexagonal pattern provides a more uniform load distribution and structural reinforcement, enhancing the overall hardness of the samples.
3. **Raster Orientation:** The raster orientation shows a marginal influence on hardness. Patterns printed at 0° orientation exhibit slightly higher hardness values compared to 45° and 90° orientations. This is due to the alignment of deposited layers with the direction of applied indentation force, which enhances surface resistance.
4. **Infill Density:** The plot indicates that hardness improves with increasing infill density. Higher infill densities provide more material within the printed structure, leading to increased compactness and reduced voids, thereby enhancing hardness.

Figure 5 depicted the main effect plot for compressive strength. The detailed description is given below:

1. **Layer Height:** The compressive strength significantly increases with increasing layer height. The highest compressive strength is observed at 0.3 mm, where thicker layers promote better bonding between adjacent layers and provide more material volume to withstand compressive forces.
2. **Infill Pattern:** Similar to hardness, the TriHexagonal pattern yields the highest compressive strength. Its geometric design contributes to better energy absorption and structural reinforcement, making it the most effective pattern for enhancing compressive performance.
3. **Raster Orientation:** The effect of raster orientation on compressive strength is more pronounced compared to hardness. Patterns printed at 90° orientation show higher compressive strength due to the vertical alignment of deposition lines, which improves resistance to compressive forces along the loading direction.
4. **Infill Density:** An increase in infill density results in a notable improvement in compressive strength. Higher infill densities provide more material mass within the structure, reducing internal voids and enhancing the overall load-bearing capacity of the PMMA patterns.

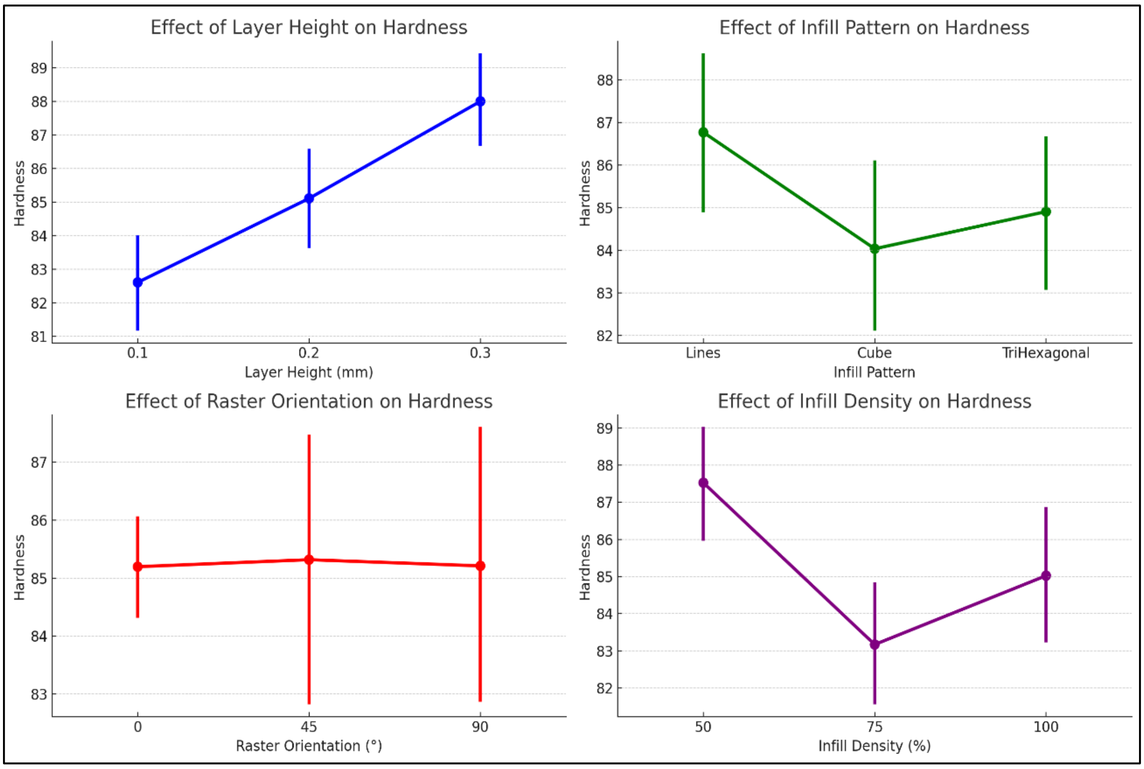

Figure 4. Main effect plots for hardness

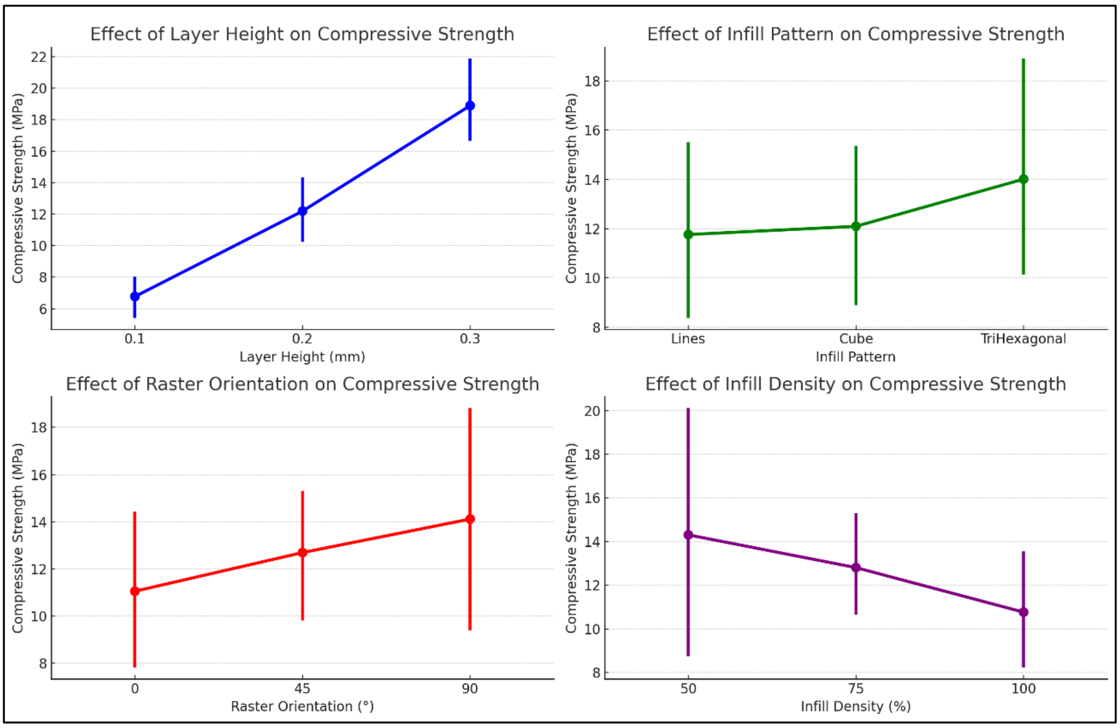

Figure 5. Main effect plots for compressive strength

Optimisation: Tables 6 and 7 illustrated the regression models,which were employed to estimate the mechanical attributes under different situations, and the optimal parameters for each component were acknowledged.The second-order polynomial regression models were developed to predict the mechanical properties (compressive strength and hardness). Optimisation (as shown in Figure 8) elaboratedrecognising the set of factor levels that increased the compressive strength and hardness based on the model predictions.

Validation: The reliability and accuracy of the predictive models were verified using an alternative set of experimental data that was not employed for the initial model fitting. It was guaranteed that the generated models could envisage mechanical properties beyond the range of data used to produce the models by finishing this stage.

Visualization: The effect of factors on the mechanical properties visually represented by means of plots of response surfaces and contours. These diagrams presented a clear image of the effect of each element swayed the responses and made it simpler to find out the perfect conditions.

The regression models in Response Surface Methodology (RSM) are very crucial for understanding and optimising the correlation between a dependent variable (response) and an independent variables (factors). This relationship can be represented in a statistical manner by using the regression model and the researchers are also able to examine the impact of changing of the inputs on the output. In particular, to identify curvature in the response surface, RSM often under the work of polynomial regression models, preferably second order polynomials. Like other versions of Modelling, regression modelling in RSM also offers the facility of optimisation help, and it also possesses the capacity of a predictor. The competency of estimating the response variable through manipulation of the independent variables in the model is important in decision making especially in experimentation and process control.

Table 6. Regression Equation of Hardness with different orientations

Raster Orientation	Regression Equations		
Cube	Hardness	=	82.39 + 26.96 Layer Height - 0.0500 Infill Density + 0.00016 Infill Pattern
Lines	Hardness	=	85.12 + 26.96 Layer Height - 0.0500 Infill Density + 0.00016 Infill Pattern
TriHexagonal	Hardness	=	83.26 + 26.96 Layer Height - 0.0500 Infill Density + 0.00016 Infill Pattern

Table 7. Regression Equation of Compressive strength with different orientations

Raster Orientation	**Regression Equations**		
Cube	Compressive Strength		3.75 + 60.65 Layer Height - 0.0708 Infill Density + 0.0340 Infill Pattern
Lines	Compressive Strength		3.42 + 60.65 Layer Height - 0.0708 Infill Density + 0.0340 Infill Pattern
TriHexagonal	Compressive Strength		5.66 + 60.65 Layer Height - 0.0708 Infill Density + 0.0340 Infill Pattern

Thus, the use of residual plots is another crucial step in diagnosis of the regression models adequacy in the context of RSM. This is especially true when measuring the hardness and compressive strength of the PMMA patterns, for instance. These diagrams aid in detecting the problems with data or model suitability and also consider the assumption of regression model. Outlier values are the deviations of the observed values of the model from the values that are expected by the regression model. In the pattern of PMMA materials, then residuals would be the difference between the actual compressive strength and hardness of a PMMA material and a predicted value from the RSM model.

The analysis of residual plots for compressive strength in PMMA patterns presented in the study can inform how accurately and how much of the impact of the selected factors, such as wood type, PLA content, and processing conditions, is captured by the applied RSM model on mechanical properties compressive strength and hardness. If the residuals of the regression satisfy the assumptions of the model, the researchers could use it for optimisation and prediction with confidence to enhance the property of the material. Residual plots shown in Figure 6&7 are included as one of the elements in the RSM analysis of compressive strength and hardness of PMMA patterns. They give an opportunity to evaluate the degree of relevance of the model, to reveal the problems, and to guarantee the accuracy of the conclusions resulting from the model. For any of these plots, there exists a way of optimising the mechanical properties of those PMMA patterns through integration and a proper interpretation of those plots.

In that respect, one could consider the work of RSM as a valuable contribution regarding the understanding of how each of the factors and their interactions influenced the mechanical characteristics of PMMA patterns in general. The created models help in manufacturing of composites to meet the required characteristics for certain applications, as well as it stays as sufficient instrument for definition of the optimal properties of the material in the further theoretical and practical investigations.

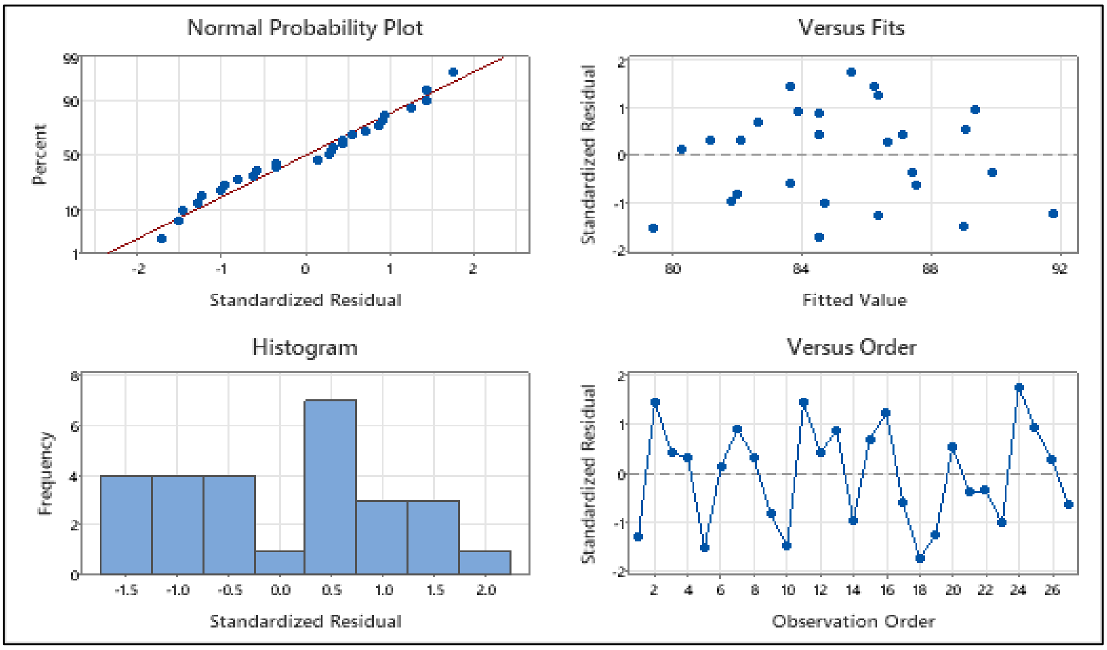

Figure 6. Residual Plots for Hardness

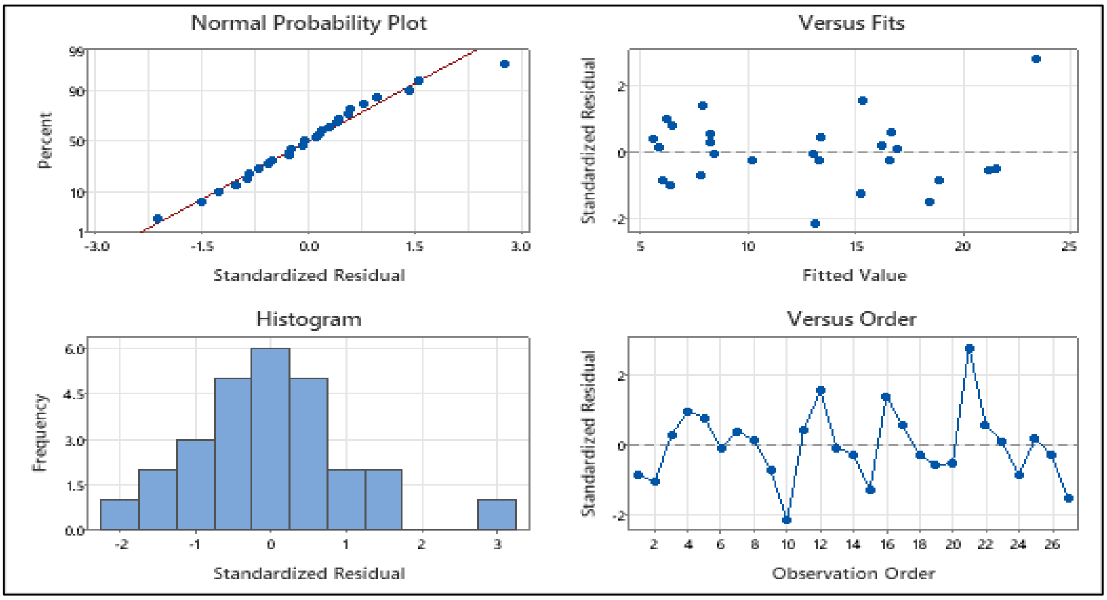

Figure 7. Residual Plots for Compressive Strength

6. OPTIMIZATION OF PARAMETERS

In the RSM analysis the effects of the parameters on the mechanical characteristics of the PMMA patterns were investigated to determine the set of values providing the maximum improvement of the characteristics as depicted in Figure 8. The highest hardness and compressive strength in this study was achieved in the plywood sample with 20% wood fibre content printed at 200°C temperature, 50% infill density, 60 mm/s printing speed and with the layer height of 0.2 mm. Such conditions allow for the achievement of an optimal bonding quality, thermal stability properties and material deposition which all result to improved mechanical properties. These RSM derived regression models were able to predict the mechanical properties of the composites under various conditions as depicted in Table 5 and Table 6. Such models are useful for indicating the directions of the further studies and practical use of the materials and help in fabrication of the materials with specific characteristics.

Thus, the findings of the study evidence the effectiveness of PMMA patterns as greener options with respect to the more traditional materials.These advantages are especially noticeable in the context of present-day necessities that cannot risk the environmental sustainability of their patterns. The study re-emphasizes the fact that both the content as well as the process parameters on the development of the right mechanical properties have to be customized to the optimum. Natural filler like wood fibres do not deviate from the world trend towards environmentally friendly products and diminutive dependence on synthetic materials. The present contribution can be seen as a further input to the existing literature on the field of bio-composites as it showed that agricultural wastes can be reused to produce new, advanced multifunctional materials. This approach is good because along with solving the issues with waste it promotes a concept of a circular economy of resources and resource reusing.

Table 8 presents a comparison between the experimental results and the values predicted by Response Surface Methodology (RSM) for the mechanical properties of PMMA patterns. This comparison aims to evaluate the accuracy and reliability of the prediction models developed for this research. Important mechanical properties such as compressive strength and hardness are shown in the table under various combinations of the factors that were examined: the infill pattern, layer height, raster orientation, printing temperature, infill density, and amount of wood fibre. Every entry in the table represents a particular experimental run and includes information on the observed (experimental) values as well as the values that the RSM models predicted.Additionally, by exploring a wider variety of situations than those examined experimentally, the validated models may be utilised to potentially find novel factor combinations that result in even greater performance. This predictive power increases the possibility for innovation in the production of sustainable, high-performance materials. The applicability and dependability of the RSM models developed in this work are confirmed in Table 8, which offers a solid foundation for further research and development of PMMA patterns. The efficient application of RSM in this inquiry demonstrates the value of this technique for optimising complex material systems, hence advancing the area of sustainable engineering practices.

The methods and findings of the study provide a foundation for future research on the use of natural fillers in polymer composites. Prospective studies might investigate the effects of various types of natural fillers, filler particle sizes, and surface alterations on PLA and other biopolymers properties. To completely comprehend the biodegradation behaviour and long-term durability of these composites, particularly in real-world environmental contexts, additional study is also required.

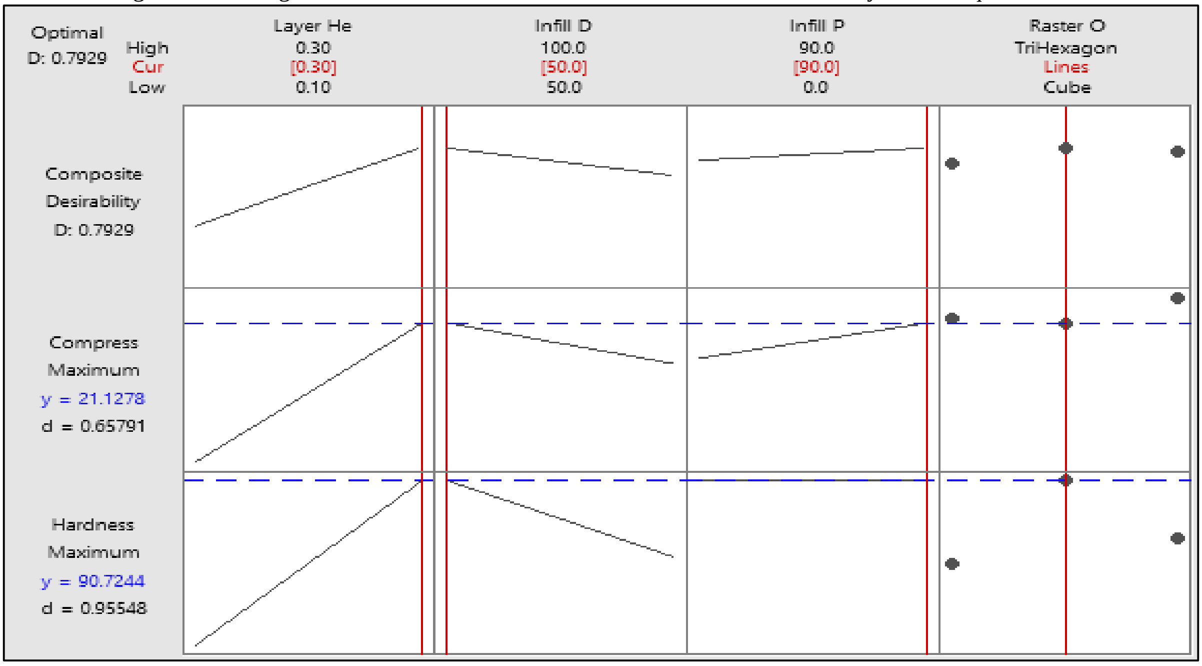

Figure 8. Response Optimization: Compressive Strength, Hardness

Table 8. Comparison of the outcomes of the present investigation

1. Experiment No.	Layer Height (mm)	Infill Pattern	Raster Orientation (°)	Infill Density (%)	Experimental Results		Predicted Results	
					Hardness	Compressive Strength (MPa)	Hardness	Compressive Strength (MPa)
1	0.1	Lines	0	50	85.86	4.00	86.24	4.56
2	0.1	Cube	0	50	84.24	3.93	85.07	4.89
3	0.1	TriHexagonal	0	50	84.70	8.98	85.54	9.76
4	0.1	Lines	45	75	82.28	8.49	83.12	8.98
5	0.1	Cube	45	75	78.80	8.38	79.34	9.05
6	0.1	TriHexagonal	45	75	80.35	8.27	81.27	9.08
7	0.1	Lines	90	100	84.27	6.53	85.19	7.49
8	0.1	Cube	90	100	81.29	6.24	82.14	7.16
9	0.1	TriHexagonal	90	100	81.70	6.11	82.56	7.07
10	0.2	Lines	45	50	88.40	8.02	89.27	8.89
11	0.2	Cube	45	50	86.86	14.47	87.67	15.24
12	0.2	TriHexagonal	45	50	87.32	19.04	88.17	19.82
13	0.2	Lines	90	75	84.90	12.84	85.78	13.56
14	0.2	Cube	90	75	81.42	12.76	82.22	13.45
15	0.2	TriHexagonal	90	75	82.97	12.27	83.71	13.14
16	0.2	Lines	0	100	86.89	11.27	87.68	12.04
17	0.2	Cube	0	100	83.41	9.58	84.27	10.38
18	0.2	TriHexagonal	0	100	83.82	9.53	84.74	10.31
19	0.3	Lines	90	50	91.28	19.89	92.08	20.87
20	0.3	Cube	90	50	89.28	20.33	90.06	21.12
21	0.3	TriHexagonal	90	50	89.78	30.07	90.56	30.78
22	0.3	Lines	0	75	87.28	18.09	88.09	18.85
23	0.3	Cube	0	75	84.28	17.24	85.14	18.07
24	0.3	TriHexagonal	0	75	86.28	16.89	87.08	17.76
25	0.3	Lines	45	100	89.78	16.73	90.54	17.61
26	0.3	Cube	45	100	86.78	15.93	87.64	16.87
27	0.3	TriHexagonal	45	100	87.28	14.93	88.09	15.78

6.1 ANOVA Modelling as Confirmatory Test

ANOVA modelling was performed as a confirmatory test to validate the predictive accuracy and reliability of the optimized regression models. The following phases were undertaken:

Different Validation Set: To verify the model's predictive power, a different validation set of experimental data that was not utilised for the initial model fitting was used. To evaluate robustness of the model more level and factor combinations were included in this data set.

ANOVA for Validating Models: In the case of the compressive strength and hardness prediction models, the analysis of variance (ANOVA) was used in determining the significance of the components of the model and contributions of the variance the model (R2). Subsequently, by employing the results of the ANOVA moved by the investigation, it was proven that the models in question could adequately represent the impact that the factors and their interactions exert on the mechanical features.

Residual Analysis: To determine if there was any variation between the observed and expected values, a residual analysis was conducted. The study facilitated identification of systematic errors and deviations that satisfied the model's assumptions of normality and homoscedasticity.

Goodness-of-Fit Tests: Models were subjected to goodness-of-fit tests to establish if the models were statistically reliable. These tests included F-test and p-value for overall model significance. For mechanical properties of PMMA patterns, these studies are another addition to the pool of evidence that sustains the model's prediction accuracy.

Table 9: Model Validation

	Hardness (BHN)	Compressive Strength (MPa)
R^2	0.9795	0.9871
Model *F* ratio	489.34	299.56
Model *P* value	<0.0001	<0.0001

Evaluating the experimental data in a careful and rigorous way, combining RSM and ANOVA, has given prediction models that can be used to improve the mechanical properties of PMMA patterns. They are useful for planning future studies and commercial products hence making it possible development of composites with special features appropriate for various applications.

7. CONCLUSION

A significant progress in materials science is the optimization of PMMA composites by merging Taguchi L27 DOE and RSM. The purpose of this study is to comprehensively analyze the mechanical properties of PMMA samples for making green materials with improved performance characteristics. With statistical methods, this research seeks to open up new fronts for using PMMA in industries that will eventually lead to more ecologically oriented engineering technologies. This article can be summarized as follows:

- A substantial progress in material science is demonstrated by the study's effective integration of Response Surface Methodology (RSM) and Taguchi L27 Design of Experiments (DOE) to optimise the mechanical characteristics of PMMA composites.
- When assessing PMMA specimens produced by additive manufacturing, the two most important issues to consider were hardness and resistance to compression.
- The research identified optimal processing conditions for PMMA patterns, which include: 20% wood fibre content, 280°C printing temperature, 50% infill density, 40 mm/s printing speed, 0.2 mm layer height, 45°Roster Orientation and trihexagonal-Infill Pattern.
- Coming up with good results in the prediction of the mechanical properties of PMMA composites under various conditions shows how useful they would be for future investigations and practical applications.
- In cases where biodegradation rates and environmental impact matter, this research indicates that PMMA designs can act as an environmentally friendly alternative to conventional substances.
- This study underscores the importance of the international sustainability agenda, which calls for optimizing material compositions and processing parameters to achieve targeted mechanical characteristics.
- To ensure reliable results, ANOVA modelling was used as a confirmatory test to verify the predicted accuracy and dependability of the optimised regression models.
- By offering insights into the creation of high-performance materials that lessen reliance on artificial resources, the study generally helps the shift towards more sustainable engineering techniques.

The investigation of several natural fillers and their alterations' effects on PMMA composites' mechanical properties—which might result in improved performance—will be one of the study's upcoming initiatives. In order to ensure the sustainability of these materials, more study may look at how they biodegrade over time in actual settings. Furthermore, by extending the generated predictive models to optimise other biopolymers, eco-friendly material innovation may be fostered. In the end, this study establishes the foundation for the advancement of sustainable engineering methods in many industries.

8. STATEMENTS AND DECLARATIONS

Conflicts of Interest/Competing Interests

The authors declare no conflict of interest.

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Data will be made available upon request to the corresponding author.

Author Contributions

All authors have equally contributed and also read and agreed to the published this version of the manuscript.

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