Research Article

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Enhancing Drilling Performance in Natural Fiber-Reinforced Biocomposites Using Taguchi Method for Sustainable Manufacturing

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ABSTRACT

The current research work focuses on optimizing drilling parameters for Sesbania rostrata fiber-reinforced polycaprolactone (PCL) biocomposites using the Taguchi method and ANOVA to improve hole quality, particularly to minimize delamination. The Taguchi L9 orthogonal array was employed with three factors: spindle speed (300, 750, and 1800 rpm), feed rate (0.05, 0.12, and 0.25 mm/rev), and drill size (4, 8, and 10 mm). The experimental results showed that drill size had the most significant effect on thrust force, with a contribution rate of 99.29%, whereas spindle speed primarily influenced delamination, contributing 67.65%. Optimal parameters were determined to be a spindle speed of 300 rpm, a feed rate of 0.25 mm/rev, and a drill size of 10 mm. These findings are significant for industries using biocomposites, offering sustainable solutions with enhanced machining performance.

Keywords: Sesbania rostrata fiber; Polycaprolactone biopolymer; Orthogonal array; Taguchi design; Drilling properties.

1. INTRODUCTION

Material sustainability refers to the practice of using resources in ways that do not deplete them for future generations, ensuring their availability and health over the long term. This entails careful material selection, use, and management to minimize environmental impact and promote ecological balance. Sustainable materials are typically renewable, recyclable, or biodegradable, reducing the carbon footprint and waste. When choosing materials, putting sustainability first leads to choosing natural fiber-reinforced biocomposites. These are a better choice for the environment than traditional composites made from non-renewable materials like synthetic fibers and petrochemical-based resins. Natural fibers and biodegradable polymers combine to create the biocomposites. The material possesses some ideal properties, such as being lightweight, low price, acoustic and thermal insulation, excellent mechanical strength, and being environment-friendly. Additionally, the use of natural fibers reduces the carbon footprint of the material, as these plants absorb CO_2 during their growth, locally available materials, and indirectly improve the rural economy. According to (Raja *et al.* 2021; Manu *et al.* 2022), the utilization of natural fibers not only reduces the carbon footprint of the material but also enhances the rural economy. Biocomposites are a better choice for industries like aerospace, automobile, structural, construction, sports, and packing because they are sustainable materials. Riveting and bolting methods combine several parts and components to produce an intricate biocomposite-based product. When developing products based on biocomposite materials, the joint strength between the parts is as important as the strength of the individual part. According to (Bajpai *et al.* 2013; Helmi Abdul Kudus *et al.* 2021), joint strength is a crucial factor in the development of biocomposite-based products.

The most common machining method for making holes in biocomposite parts to enable bolt and rivet joints is conventional drilling. Because biocomposite materials are isotropic and heterogeneous, drilling mechanisms present unique challenges compared to metals and alloys. Moreover, abrasiveness and hard fiber cause noteworthy damage around the drilled holes, such as delamination, fiber peel-up, and fiber pull-out. Drilling operations have damaged biocomposite components, leading to their rejection in the industry. Many researchers analyzed the reason for the formation of delamination and surface roughness in drilled holes based on drilling parameters like drilling speed, feed rate, and drill bit size. They optimized these parameters to minimize damage (Lotfi *et al.* 2020; Madhan Kumar *et al.* 2022; Benyettou *et al.* 2022).

(Lotfi *et al.* 2020) examined the relationship between drilling parameters and delamination on flax-reinforced polylactic acid biocomposites. They concluded that enhancing the drilling speed decreased delamination and thrust force, but trust force and delamination increased while augmenting the feed rate and drill diameter. The authors applied ANOVA analysis to validate the experimental result and identified 3000 rpm as the optimal drilling speed and 0.11 mm/rev as the optimum feed rate. According to (Madhan Kumar *et al.* 2022), the best drill settings, viz., speed, drill diameter, and feed rate, to reduce delamination and surface roughness on bagasse particles reinforced with polylactic acid biocomposite is 2000 rpm, 9 mm, and 97 mm/min, respectively. They concluded that the delamination and surface roughness values were significantly influenced by the drilling speed and feed rate. (Benyettou *et al.* 2022) experimented with drilling 10 mm holes in biocomposites made of 30 wt.% palm fiber with iso-polyester. They varied the spindle speeds (560, 1120, and 2240 rpm) and feed rates (40, 80, and 200 mm/min) to examine the surface condition of the drilled hole, specifically its circularity, cylindricity, and delamination. The drilling parameters' interaction was evaluated by the ANOVA analysis, which was compared with the experimental findings. They concluded that, for the best circularity and cylindricity, the ideal cutting speed and feed rate were 1200 rpm, 80 mm/min, and 560 rpm, 80 mm/min, respectively.

Sesbania rostrata fiber is taken out from the stem of the Sesbania rostrata (SR) plant. The SR plants are cultivated as an intercrop in the turmeric field to increase the soil nitrogen level and give shading to the turmeric plant. Both SR plants contribute to the growth rate of the turmeric plants. In Erode and Karur Districts, Tamil Nadu, India, farmers have cultivated more than 1000 acres of SR plants, ensuring a plentiful supply of fibers without disrupting the primary functions of the plants. (Raja *et al.* 2023) and (Krishnan *et al.* 2024) investigated the mechanical and thermal characterization of novel SR fibers reinforced with polycaprolactone biocomposites.

The Taguchi method is a powerful optimization technique that uses orthogonal arrays to study a large number of variables in a small number of experiments. This method reduces the number of experimental runs and attains valid conclusions for the experimentation (Kurt *et al.* 2009). In a dry drilling process study, researchers used the Taguchi method to optimize cutting parameters for surface finishing and hole diameter precision. Another study observed that the speed and drill point angle significantly influence delamination damage during basalt fiber composite drilling. Similarly, researchers use the Taguchi L27 orthogonal array and analysis of variance to study the influence of machining parameters on overcut and MRR. Taguchi analysis determines the optimal level of parameters, and confirmation tests validate it. (Krishnamoorthy *et al.* 2012) investigated the delamination factor at the hole entrance and exit while drilling CFRP composite material by using HSS drills with different point angles. ANOVA is a statistical tool used to analyze differences in average performance between groups, detecting the significance of variables and their interactions (Zerti *et al.* 2017).

Our review reveals that very few studies have focused on polycaprolactone biocomposites to determine the optimal drilling parameters. Therefore, the current study utilizes Taguchi and ANOVA techniques to evaluate the impact of drilling parameters on thrust force and delamination factor in Sesbania rostrata natural fiber-reinforced polycaprolactone biocomposite, using MINITAB for statistical analysis.

2. MATERIALS AND METHODS

2.1. Natural Fiber Extraction

Fig. 1: Sesbania rostrata plant in the turmeric field

Sesbania rostra plant's stems were collected from turmeric fields (Fig. 1) at Kodumudi, Tamil Nadu, India. The skins from the stems were peeled out using a knife and immersed in the water for 10 days at room temperature. Due to microbial degradation, the cellular tissues and gummy substances surrounding the fibers were dissolved in the water. The fibers were separated from the water and it was washed with running water to remove the skinny substances on the fiber. The fibers were dried in sunlight for two days to remove the absorbed moisture content.

2.2. Biocomposite Samples Preparation

The strips from polycaprolactone (PCL) (Fig. 2) were purchased from Bhejo, Mumbai, India. The biocomposite samples were prepared on the ratio of 20 wt. % SR fiber /80 wt. % PCL matrix by using compression molding techniques. The PCL strips were arranged on the mold and 5 mm chopped SR fiber was spread over it and again PCL strips were placed over the spread fibers. The mold was pressurized by 15 kN load along with heating at 70 °C for 50 minutes. The prepared biocomposite panel was removed from the mold after cooling down to room temperature. The sample was cut into a size of 150 mm length, 45 mm width, and 3 mm thickness.

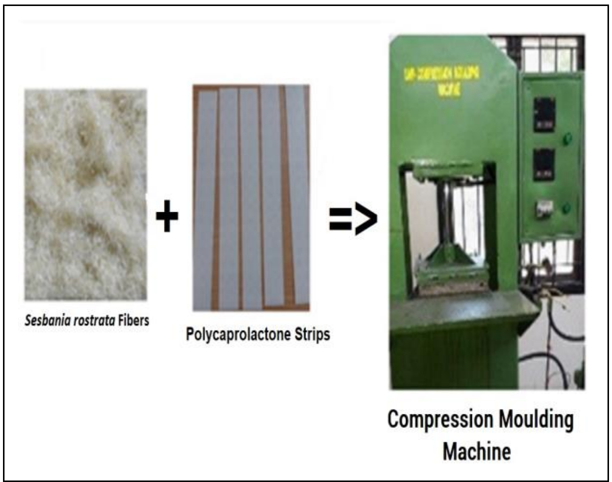

Fig. 2: Preparation of Biocomposite samples

2.3. Machining of Biocomposite

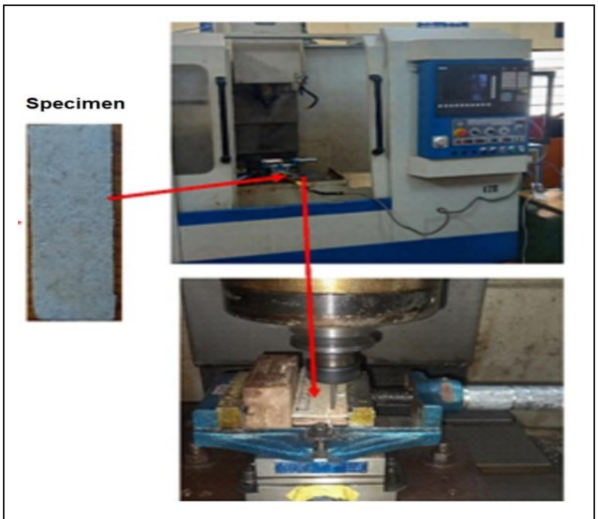

Fig. 3: Drilling machine setup

The drilling was carried out in Bharat Fritez Werner CNC Machining Centre, Model-BMV 40T20, Bangalore, India. A High-speed Steel 4 mm/8 mm/10 mm twist drill was used to drill the holes. Kistler Multicomponent Dynamotor, Guindy, Chennai, Tamil Nadu was fitted along the machine to measure the drilling tool's thrust force while machining. The sample was properly held on the machine vice and holes were drilled by following the settings presented in Table 1. The thrust force for each machining operation was recorded.

2.4. Experiment based on the Taguchi method

Taguchi's experimental design method is a statistical tool that allows for studying multiple variables with a limited number of experiments. The Taguchi method employs orthogonal arrays to determine the optimal levels of control factors. The traditional method of process optimization, which involves studying one variable at a time, is time-consuming. The Taguchi method, on the other hand, allows for the estimation of main effects in an unbiased fashion with a minimum number of experimental runs [8]. The signal-to-noise (S/N) ratio measures quality characteristics deviating from desired values. The formula for calculating the S/N ratio is "smaller is better" for smaller values, "nominal is best" for minimum variation, and "higher is better" for larger values.

In this study, the objective was to minimize delamination damage, and the S/N ratio was calculated using the "smaller the better" approach, represented by a general Eqn. 2 [9]. In this study, the machining process parameters of speed, feed, and drill bit size were considered. Table 1 displays the number of factors and their corresponding levels. According to Taguchi’s design of experiments, for three factors and three levels, the L9 Taguchi orthogonal array was selected. The results of this study will provide insights into optimizing the selected process parameters for improved performance

$$\frac{S}{N} = -10\ log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Y^2{}_i\right) \quad ..... (1)$$

Table 1: Levels of the variables used in the experiment

	Variables		
Level	**A: Spindle speed (rpm)**	**B: Feed rate (mm/rev)**	**C: Drill size (mm)**
1	300	0.05	4
2	750	0.12	8
3	1800	0.25	10
1	300	0.05	4

3. RESULTS AND DISCUSSION

3.1. Analysis of the experimental results

Delamination, a damage caused by fiber-reinforced composite materials during drilling, is measured using a Toolmaker’s microscope with an accuracy of 0.01 mm. The delamination factor (Fd) is calculated by using the maximum diameter covered by the surface damage (Dmax) and the nominal diameter (Dnom) (Eqn. 2). Two mechanisms of delamination occur during drilling: peel-up delamination at the entrance and push-out delamination at the exit. Peel-up delamination occurs at the specimen's entrance, while push-out delamination occurs at the specimen's exit due to inter-ply failure. Fig. 4 provides a scheme for determining the delamination factor, which directly indicates surface damage due to drilling operations.

$$F_d = \frac{D_{max}}{D_{nom}} \quad \text{........ (2)}$$

The Taguchi technique is a systematic method for selecting optimal cutting parameters, focusing on the S/N ratio, which measures predictable performance. The highest S/N ratio results in the best values with minimal variance.

Table 2 displays the experimental results for the thrust force and delamination factor of each sample. Eqn. 2 was used to convert the experimental results into the signal-to-noise (S/N) ratio. Tables 3 and 4 provide the S/N values for the thrust force and delamination factor, respectively. Figures 5 and 6 depict the primary effect plot for all responses.

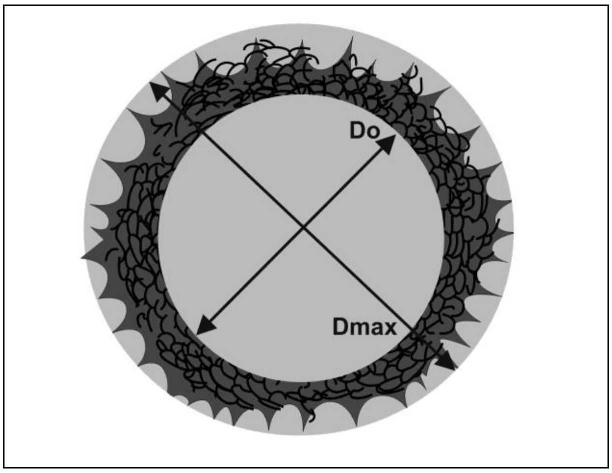

Fig. 4: Scheme for determination of the delamination factor

Table 2. Experimental results from the Taguchi analysis

Spindle speed (rpm)	Feed rate (mm/rev)	Drill size (mm)	Thrust force (N)	Delamination factor (Fd)	S/N ratio of Thrust force (N)	S/N ratio of Fd
300	0.05	4	28.47	1.32	-29.09	-2.41
300	0.12	8	131.46	1.39	-42.38	-2.87
300	0.25	10	191.68	1.5	-45.65	-3.52
750	0.05	8	124.79	1.30	-41.92	-2.25
750	0.12	10	174.71	1.35	-44.85	-2.61
750	0.25	4	27.21	1.34	-28.69	-2.54
1800	0.05	10	155.13	1.2	-43.81	-1.58
1800	0.12	4	23.96	1.2	-27.59	-1.58
1800	0.25	8	118.54	1.29	-41.48	-2.22

Table 3 displays the response table for the S/N ratio of thrust force. Based on the information provided in Table 3 and Fig. 5, it is evident that the size of the drill has the greatest impact on the thrust force during the drilling operation, followed by the spindle speed and feed rate. The optimum process parameters for thrust force, as indicated in Fig. 5, are a drill size of 10 mm at Level 3, a spindle speed of 300 rpm at Level 1, and a feed rate of 0.25 mm/rev at Level 3.

Table 3. Response table for S/N ratios of Thrust force (N)

Level	Spindle speed (rpm)	Feed rate (mm/rev)	Drill size (mm)
1	-39.04	-38.28	-28.46
2	-38.49	-38.27	-41.93
3	-37.63	-38.61	-44.77
Delta	1.41	0.34	16.31
Rank	2	3	1

Based on the data shown in Table 4 and Fig. 6, it can be concluded that the spindle speed has the greatest influence on the delamination factor, followed by the feed rate and drill size. The optimal situation for the delamination factor, as shown in Fig. 6, is achieved by setting the spindle speed to Level 1 (300 rpm), the feed rate to Level 3 (0.25 mm/rev), and the drill size to Level 3 (10 mm).

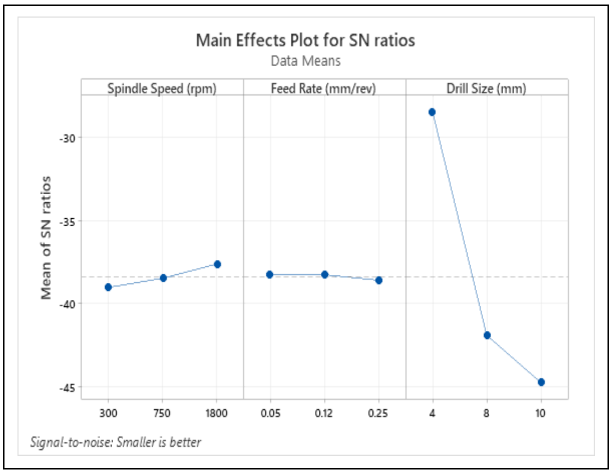

Fig. 5: Main effect plot for S/N ratios of Thrust force (N)

3.2. Analysis of Variance (ANOVA)

The appropriateness of the model was assessed by doing an ANOVA study using Minitab, a statistical software. The results from all experimental runs were evaluated using a 95% confidence level to assess the impact of the chosen variable. Tables 5 and 6 indicate the significance of each parameter, including spindle speed, feed rate, and drill size, for each response.

Table 4: Response table for S/N ratios of Delamination factor (Fd)

Level	Spindle speed (rpm)	Feed rate (mm/rev)	Drill size (mm)
1	-2.934	-2.081	-2.179
2	-2.466	-2.353	-2.445
3	-1.795	-2.760	-2.571
Delta	1.139	0.679	0.392
Rank	1	2	3

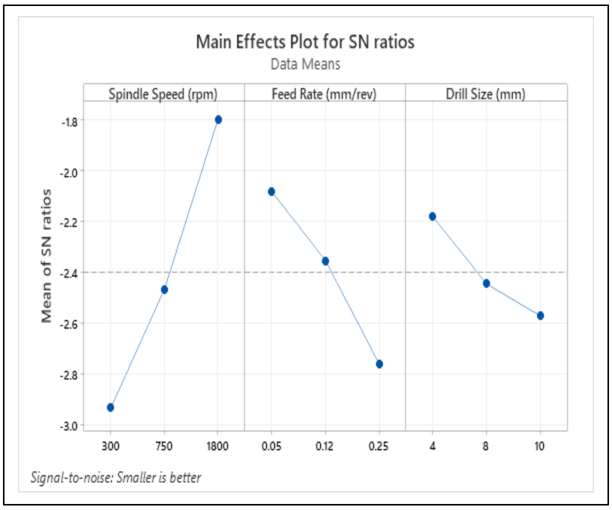

Fig. 6: Main effect plot for S/N ratios of Delamination factor (Fd)

According to the findings (Table 5), the drill size has the most significant impact on the thrust force, followed by the spindle speed and feed rate. Table 6 shows that spindle speed and feed rate have the greatest influence on the delamination factor, with drill size being the next most significant component. The ANOVA (Table 5) reveals that the drill size primarily influences the thrust force. The drill size has a higher contribution rate (99.29%) compared to the spindle speed (0.66%) and feed rate (0.05%). Spindle speed significantly affects thrust force more than feed rate.

Table 5: Analysis of Variance (ANOVA) of Thrust force (N)

Source	DF	Seq SS	Adj SS	Adj MS	Contribution (%)
A: Spindle speed (rpm)	2	3.036	3.036	1.518	0.66
B: Feed rate (mm/rev)	2	0.224	0.224	0.112	0.05
C: Drill size (mm)	2	455.610	455.610	227.805	99.29

Based on the findings of the ANOVA (Table 6), it can be deduced that the delamination factor is predominantly impacted by the spindle speed, with the feed rate having a secondary influence. The contribution of spindle speed (67.65%) exceeds that of feed rate (24.0%) and drill size (8.25%). The feed rate has a more significant impact on the delamination factor than the drill size.

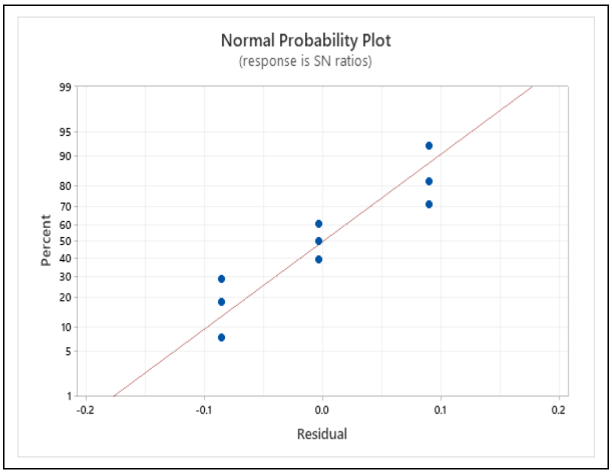

Fig. 7: Normal probability plot of Thrust force (N)

Table 6: Analysis of variance (ANOVA) of Delamination factor (Fd)

Source	DF	Seq SS	Adj SS	Adj MS	Contribution (%)
A: Spindle speed (rpm)	2	1.96788	1.96788	0.98394	67.65
B: Feed rate (mm/rev)	2	0.70101	0.70101	0.35050	24.10
C: Drill size (mm)	2	0.23995	0.23995	0.11997	8.25

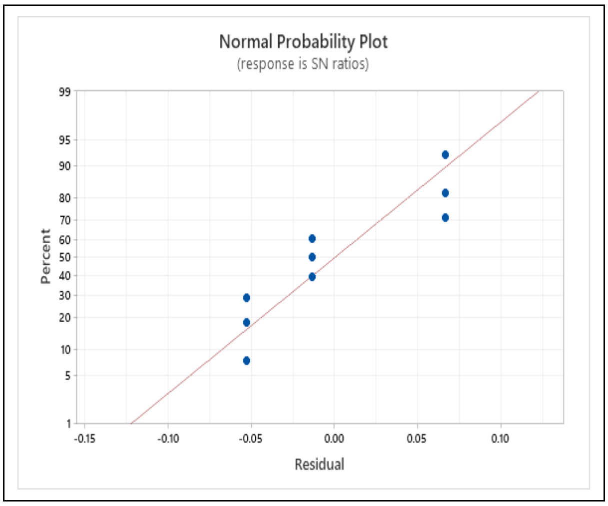

Fig. 8: Normal probability plot of Delamination factor (Fd)

The normal probability plots of the residuals, as depicted in Figures 7 and 8, demonstrate that the majority of the residuals exhibit a linear pattern. This observation is consistent with the findings reported by (Mohan *et al.* 2007). The experimental results of thrust force in drilling

Sesbania rostra fiber-reinforced composites were used to construct a multi-variable linear regression model that relates thrust force to process factors in drilling composites. This study will provide valuable insights for companies on the selection of process parameters in drilling Sesbania rostra fiber-reinforced composite materials. The aim is to enhance the quality of drilled holes by minimizing delamination.

4. CONCLUSION

The study provides valuable insights for industries using natural Sesbania rostrata fiber-reinforced polycaprolactone (PCL) biocomposites, especially in sustainable manufacturing applications such as automotive, aerospace, and construction. Taguchi and ANOVA techniques reduce experimental time and material waste, improving the precision and durability of biocomposite parts. Further research could explore the effects of other machining parameters or fiber types to expand applicability across different biocomposite materials. Spindle speed, feed rate, and drill size have a significant impact on thrust force and delamination, which influence the quality of drilled holes in biocomposite materials. The conclusions drawn from this work are as follows:

- The minimum thrust force can be achieved by selecting the best combination level of C3A1B3 (smaller the better) - a spindle speed of 300 rpm, a feed rate of 0.25 mm/rev, and a drill size of 10 mm.
- The minimum delamination factor can be achieved by selecting the best combination level of A1B3C3 (smaller the better) - spindle speed of 300 rpm, the feed rate of 0.25 mm/rev, and the drill size of 10 mm.
- The ANOVA results reveal that drill size was found to be the most influential factor for minimizing thrust force, contributing 99.29%, while spindle speed played the dominant role in reducing delamination, contributing 67.65%.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Bajpai, P. K. and Singh, I., Drilling behavior of sisal fiber-reinforced polypropylene composite laminates, *J. Reinf. Plast. Compos.*, 32(20), 1569–1576 (2013). https://doi.org/10.1177/0731684413492866

Benyettou, R., Amroune, S., Slamani, M., Seki, Y., Dufresne, A., Jawaid, M. and Alamery, S., Assessment of induced delamination drilling of natural fiber reinforced composites: a statistical analysis, *J. Mater. Res. Technol.*, 21, 131–152 (2022). https://doi.org/10.1016/j.jmrt.2022.08.161

Helmi Abdul Kudus, M., Ratnam, M. M. and Akil, H. M., Factors affecting hole quality during drilling of natural fiber-reinforced composites: A comprehensive review, *J. Reinf. Plast. Compos.*, 40(9–10), 391–405 (2021). https://doi.org/10.1177/0731684420970650

Krishnamoorthy, A., Rajendra Boopathy, S., Palanikumar, K. and Paulo Davim, J., Application of grey fuzzy logic for the optimization of drilling parameters for CFRP composites with multiple performance characteristics, *Measurement*, 45(5), 1286–1296 (2012). https://doi.org/10.1016/j.measurement.2012.01.008

Krishnan, R., Muthusamy, K., Shanmugam, S. K. M. and Kadhiresan, S., Development of novel sustainable biocomposite from polycaprolactone and *Sesbania rostrata* fiber, *Polym Compos.*, 1-15 (2024). https://doi.org/10.1002/pc.28825

Kurt, M., Bagci, E. and Kaynak, Y., Application of Taguchi methods in the optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling processes, *Int. J. Adv. Manuf. Technol.*, 40(5–6), 458–469 (2009). https://doi.org/10.1007/s00170-007-1368-2

Lotfi, A., Li, H. and Dao, D. V., Drilling Behavior of Flax/Poly(Lactic Acid) Bio-Composite Laminates: An Experimental Investigation, *J. Nat. Fibers*, 17(9), 1264–1280 (2020). https://doi.org/10.1080/15440478.2018.1558158

Madhan Kumar, A. and Jayakumar, K., Mechanical and drilling characterization of biodegradable PLA particulate green composites, *J. Chinese Inst. Eng.*, 45(5), 437–452 (2022).
https://doi.org/10.1080/02533839.2022.2061602

Manu, T., Nazmi, A. R., Shahri, B., Emerson, N. and Huber, T., Biocomposites: A review of materials and perception, *Mater. Today Commun.*, 31, 103308 (2022).
https://doi.org/10.1016/j.mtcomm.2022.103308

Mohan, N. S., Kulkarni, S. M. and Ramachandra, A., Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials, *J. Mater. Process. Technol.*, 186(1–3), 265–271 (2007).
https://doi.org/10.1016/j.jmatprotec.2006.12.043

Raja, K., A, K., Senthil Kumar, M. and P S, S., Investigation of Mechanical Properties and Drilling Parameters of Sesbaniarostrata Fiber Reinforced Polycaprolactone Biodegradable Polyester Resin Composites, In: (2023).
https://doi.org/10.4271/2023-28-0073

Raja, K., Senthilkumar, P., Nallakumarasamy, G. and Natarajan, T., Effect of Eco-Friendly Chemical Treatment on the Properties of Sesbania Rostrata Fiber, *J. Nat. Fibers*, 18(12), 2241–2253 (2021).
https://doi.org/10.1080/15440478.2020.1725712

Zerti, O., Yallese, M. A., Khettabi, R., Chaoui, K. and Mabrouki, T., Design optimization for minimum technological parameters when dry turning of AISI D3 steel using Taguchi method, *Int. J. Adv. Manuf. Technol.*, 89(5–8), 1915–1934 (2017).
https://doi.org/10.1007/s00170-016-9162-7