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Research Article

Optimization of drilling parameters for Spanish cherry fiber reinforced hybrid composites using Taguchi analysis

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Abstract:

Natural fiber-reinforced composites have gained significant attention in engineering applications due to their sustainability, lightweight nature, and mechanical properties. However, machining these materials, particularly drilling, presents challenges such as delamination, fiber pull-out, and surface roughness, which impact component integrity. Limited research exists on optimizing drilling parameters for Spanish cherry fiber-reinforced hybrid composites to minimize machining defects. This study aims to optimize drilling parameters—drill bit diameter, spindle speed, and feed rate—using the Taguchi L27 approach to enhance machining performance. The composite was fabricated using Spanish cherry fiber, vetiver fiber, and coir pith in a polyester resin matrix through compression molding. Experimental trials analyzed the effects of process parameters on thrust force (TF) and surface roughness (SR), supported by ANOVA and regression analysis. Results indicate that spindle speed has a significant influence on TF and SR, followed by drill bit diameter and feed rate. The optimal setting (8 mm drill bit, 1480 rpm spindle speed, 160 mm/min feed rate) achieved minimal TF (3.82 kgf) and SR (8.76 μm). Water absorption increased with exposure time, with a maximum rate of 7.58% at 192 hours. These findings provide insights for improving composite machining and enhancing structural integrity. Future research should explore the effects of tool wear and alternative machining strategies.

1. Introduction

Natural fiber-reinforced composites (NFRCs) have emerged as a sustainable alternative to synthetic fiber-reinforced composites, offering a balance between mechanical performance, environmental benefits, and cost-effectiveness[1,2]. With the growing emphasis on eco-friendly materials in industries such as automotive, aerospace, construction, and marine engineering, NFRCs have gained widespread attention for their lightweight nature, high strength-to-weight ratio, and biodegradability[3]. Unlike synthetic fibers such as carbon and glass, natural fibers—derived from plant sources like jute, hemp, coir, and flax—offer renewability, low density, and reduced environmental impact[4]. Among various natural fibers, Spanish cherry fiber, extracted from the leaves and fruit of the Spanish cherry tree (Mimusops elengi), has demonstrated promising mechanical properties, including high tensile strength and biodegradability, making it a viable reinforcement material in polymer composites.The adoption of natural fiber-reinforced polymer composites (NFRPCs) has significantly increased over the past two decades due to their ability to address sustainability concerns while maintaining structural integrity. Composites reinforced with jute, sisal, flax, and coir have been widely studied, revealing enhanced tensile strength, impact resistance, and flexural properties when combined with polymer matrices such as polyester, epoxy, and polypropylene. However, NFRCs exhibit inherent anisotropic behavior, variability in fiber properties, and lower thermal resistance, leading to challenges in their machining, particularly in drilling operations.The reviewed literature, presented in Table 1, highlights the advancements in natural fiber composite (NFC) drilling, with a focus on optimizing the process, minimizing defects, and developing innovative machining methods. Parameters have been optimized through Taguchi, ANOVA, and RSM studies, which have demonstrated that higher feed rates lead to increased delamination and that optimal spindle speeds result in improved precision. Other techniques, such as microwave-assisted and abrasive waterjet drilling, show better quality of machining [16]. However, there is no research on Spanish cherry fiber composites, and quantification of delamination through image analysis has not been explored. The current research bridges the gap by maximizing the HSS drilling parameters of Spanish cherry fiber composites.The Spanish cherry fiber, a relatively unexplored and potentially useful reinforcement material, is derived from Mimusops elengi, a natural fiber. This fiber exhibits good mechanical characteristics, including high tensile strength, biodegradability, and thermal stability, making it a suitable candidate for polymer reinforcement. Spanish cherry fiber, when combined with other natural fibers such as vetiver and coir pith, can be used to form balanced composites with enhanced mechanical strength, rigidity, and durability. The concept of hybridization has been identified as a possible solution to the shortcomings of single-fiber composites, leveraging the complementary characteristics of various fibers. For example, Spanish cherry offers tensile strength and biodegradability, whereas vetiver provides rigidity and moisture resistance, and coir pith offers structural reinforcement. When combined with these fibers and placed in a polyester resin matrix, they can form a superior composite with potential for sustainable industrial use.Although it has potential, the machining behavior of Spanish cherry fiber-reinforced composites has not been extensively explored in the literature. Although jute, banana, hemp, and flax have been extensively researched, there has been very little research on Spanish cherry fiber, especially in composite hybrids. Its drilling performance has not been systematically studied, and this knowledge gap is a significant inhibitor to its further acceptance and industrial application. To achieve successful adoption in real-world applications, the optimal machining parameters that minimize defects and enhance machining efficiency must be determined.The current literature on drilling NFRCs emphasizes the importance of selecting the optimal process parameters to minimize machining defects. Design of experiments (DOE) methods, such as Taguchi optimization, analysis of variance (ANOVA), and response surface methodology (RSM), have been used to facilitate the systematic study of the effects of variables like drill bit diameter, spindle speed, and feed rate. The results have consistently shown that increased feed rates lead to increased delamination, while optimum spindle speeds result in precision and minimized damage. Microwave-assisted drilling and abrasive waterjet drilling have also been introduced, offering benefits such as reduced heat-affected areas, minimized burr development, and higher-quality holes compared to standard high-speed steel (HSS) drilling.However, although these studies offer useful information about machining natural fibers, the majority of them have focused on standard fibers and have not covered hybrid composites reinforced with Spanish cherry fiber. Additionally, despite the thorough recognition of delamination as a severe drilling flaw, quantitative technologies like image-based analysis are not fully utilized in natural fiber composite research[14,17]. It is this gap that suggests specific research needs to be conducted on Spanish cherry fiber-reinforced hybrid composites, which may not respond to machining in the same way as other composites due to their heterogeneous microstructure and composition[18].One of the key issues in NFRC drilling is the trade-off between thrust and surface roughness to achieve good hole quality [19]. The thrust force is excessive, resulting in delamination at the entry and exit points and the separation of the fiber layers, which leads to a loss of load-bearing capacity. Similarly, the worst surface finish, characterized by high roughness, adversely affects both dimensional accuracy and mechanical reliability[20,21]. NFRCs have a heterogeneous microstructure, where the fibers and resin matrices react differently to mechanical loads, resulting in complex interactions during drilling and necessitating the optimization of parameters. Additionally, natural fibers are inherently hydrophilic, which can be problematic in terms of longevity. Fiber swelling, weakening of the fiber-matrix interface, and ultimate loss of mechanical properties are caused by water absorption[22]. Thus, the moisture absorption behavior should also be considered when performing a thorough study of NFRC machining to ensure stable long-term performance.Although NFRCs have been extensively studied, there is a lack of research on hybrid composites, which include Spanish cherry fiber. Most of the literature focuses on individual-fiber composites (e.g., jute, hemp, or flax), whereas methods of hybridization aimed at improving mechanical and machining properties are not studied as extensively[23–25]. In the case of

Spanish cherry composites, the relationship between the drill bit diameter, spindle speed, and the feed rate and thrust force, as well as the surface roughness, is not clearly understood. Additionally, the long-term stability of these composites when subjected to moisture has not been thoroughly researched. Such a deficiency in thorough knowledge leads to uncertainty in the use of Spanish cherry composites in the industry, particularly where high accuracy in machining and stability in the presence of fluctuating environmental factors are required.The current study, as a way of filling these gaps, methodically explores the performance of Spanish cherry fiber-reinforced hybrid composites in drilling. The study employs a Taguchi L27 experimental design to investigate the impact of three key variables —drill bit diameter, spindle speed, and feed rate —on thrust force (TF) and surface roughness (SR). ANOVA and regression modeling are then performed to establish the significance of each parameter, its contribution, and to construct predictive models of TF and SR. Moreover, the water absorption characteristic of the composite is tested with longer exposure periods to determine its moisture resistance and long-term stability.The work objectives include examining the effects of drill bit diameter, spindle speed, and feed rate on thrust force and surface roughness during drilling of Spanish cherry fiber-reinforced hybrid composites. Determine the best machining parameters that yield the lowest thrust force and surface roughness, leading to improved hole quality and high-quality machining. In order to examine the behavior of water absorption of the composite during long-term exposure, to determine its application to long-term durability and mechanical reliability. Generate a Predictive model of thrust force and surface roughness based on regression analysis, and thus be able to predict machining results at different combinations of parameters.Through the accomplishment of these goals, the study contributes to the machining knowledge of NFRCs in several ways. It provides a structured survey of drilling parameters for Spanish cherry fiber composites, addressing a significant gap in the existing literature. Combining statistical optimization with experimental validation makes the study's results very strong and applicable in practice. Moreover, the absorption behavior of water provides information on the material's long-term stability, which is essential in the context of use in wet or salty environments. Industrially, the findings of this research will be used to justify the use of Spanish cherry fiber-reinforced hybrid composites in lightweight structures, automotive parts, and other sustainable engineering processes. The machining parameters will be optimized to minimize material wastage, reduce defects caused by machining, and maximize the reliability of the final products. By doing so, the research will align with the larger sustainability objectives, as it will help encourage the use of renewable, biodegradable, and environmentally friendly materials.

2. Materials and Methods

The present study investigated the drilling behavior of Spanish cherry fiber-reinforced hybrid composites, focusing on the effects of drill bit diameter, spindle speed, and feed rate on thrust force (TF) and surface roughness (SR). The composites were fabricated using Spanish cherry fiber, vetiver fiber, and coir pith in a polyester resin matrix, followed by a controlled drilling process using the Taguchi L27 experimental design. The methodology encompassed composite preparation, drilling experimentation, machining parameter selection, and response measurement to determine the optimal machining conditions. The primary raw materials used in this study included Spanish cherry fiber (SCF), vetiver fiber (VF), and coir pith (CP), which were reinforced into a polyester resin matrix. The Spanish cherry fiber was sourced from *Mimusops elengi*, a naturally occurring plant known for its high tensile strength, biodegradability, and thermal resistance. The vetiver fiber and coir pith were selected for their high rigidity, moisture resistance, and reinforcing properties. The properties of the fibers are shown in Table 2. The fiber composition consisted of 40% SCF, 25% VF, and 13% CP, while the matrix phase was composed of 14% polyester resin, 6% cobalt activator, and 2% catalyst. The fibers were initially cleaned, dried, and pulverized using a mechanical crusher to ensure uniform particle size distribution. The moisture content of SCF was reduced to 3.0%, while the vetiver fiber and coir pith were oven-dried at 60°C for 24 hours to achieve optimal processing conditions.

The composite fabrication process employed a compression molding technique, which involved preparing fiber-resin mixtures, heating them, and molding under controlled pressure. The fiber mixture was mechanically stirred with polyester resin, followed by the addition of cobalt as an initiator and a catalyst to facilitate polymerization. The prepared composite mixture was transferred into a steel mold, ensuring a uniform distribution of fibers (Figure 1 Fiber arrangement and compression molding process). The mold was placed into a hydraulic compression molding machine operated at 145°C and 25 kg/cm² pressure for 6 minutes under heating and 30 minutes under compression without heat. The fabricated composite sheets were post-cured at room temperature for 24 hours, after which they were cut into the required specimen sizes for drilling experiments.

The drilling experiments were conducted using a vertical milling machine (Model: FEELER-FV1000A), which ensured precise control of spindle speed, feed rate, and depth of cut. The composite specimens were firmly clamped onto the machine table, and drilling was performed using high-speed steel (HSS) twist drill bits with diameters of 6 mm, 8 mm, and 10 mm. The drilling setup is shown in Figure 2.

The experimental design followed the Taguchi L27 orthogonal array, allowing systematic variation of process parameters while minimizing the number of experimental runs. The machining parameters considered in this study included drill bit diameter (DBD: 6, 8, and 10 mm), spindle speed (SS: 740, 1480, and 2220 rpm), and feed rate (FR: 80, 160, and 240 mm/min). The response variables measured were thrust force (TF) and surface roughness (SR), as these significantly influence the machining quality of fiber-reinforced composites.

The thrust force (TF) generated during drilling was measured using a Kistler 9257B piezoelectric dynamometer, which recorded real-time force data continuously. The dynamometer was calibrated before each experiment to ensure accurate force measurements. The recorded TF values were analyzed using signal-to-noise (S/N) ratio analysis, following the smaller-the-better criterion, as lower TF values are desirable for minimizing machining-induced defects.

The surface roughness (SR) of the drilled holes was evaluated using a Mitutoyo SJ-201 surface roughness tester, which measured the average roughness (Ra) over a 10 mm scan length. Three measurements were taken at different positions within each drilled hole, and the average SR value was recorded. The effects of drill bit diameter, spindle speed, and feed rate on SR were analyzed to identify optimal conditions for achieving a smooth drilled surface with minimal fiber pull-out and matrix cracking.

The Taguchi method was employed to systematically evaluate the influence of drilling parameters on TF and SR. The L27 orthogonal array was chosen as it efficiently handles three control factors at three levels, reducing the number of required experimental runs while maximizing statistical efficiency. The signal-to-noise (S/N) ratio was computed for each experimental condition using Equation 1, where n is the number of observations and y is the measured response:

$$S/N = -\log_{10}\left[\frac{1}{n}\sum y^2\right] \quad \text{eq (1)}$$

Analysis of variance (ANOVA) was performed to determine the statistical significance of the machining parameters. The p-values (<0.05) indicated significant effects, and the percentage contribution of each parameter was analyzed. Regression models were developed to establish predictive equations for TF and SR, ensuring robust optimization of machining conditions.

To evaluate the moisture resistance of the composite, water absorption tests were conducted in accordance with ASTM D570 standards. Composite specimens were immersed in distilled water at room temperature, and the water uptake was recorded at 24, 48, 72, 120, and 192 hours. The percentage water absorption (WA%) was calculated using Equation 2, where W_0 is the initial dry weight and W□ is the wet weight after exposure time t:

$$WA(\%) = \frac{W_t - W_0}{W_0} \times 100 \quad \text{eq (2)}$$

Figure 3 illustrates the water absorption behavior, showing an increasing trend in moisture uptake with exposure time. The highest absorption rate of 7.58% was recorded at 192 hours, attributed to fiber swelling and matrix degradation. These findings underscore the significance of surface treatment and fiber-matrix bonding in enhancing the composite's moisture resistance. Table 3 summarizes the drilling parameters and their respective levels, while Table 4 presents the response variables (TF and SR) measured for different experimental runs.

The materials and methods adopted in this study provided a systematic approach to analyzing the drilling characteristics of Spanish cherry fiber-reinforced hybrid composites. The Taguchi-based experimental design enabled an efficient evaluation of machining parameters, while ANOVA and regression modeling ensured statistical validation. The findings contribute to the optimization of drilling conditions for NFRCs, promoting their industrial applicability in sustainable engineering applications.

The raw materials used in this study included Spanish cherry fiber, vetiver, and coir pith, while the matrix ingredients consisted of polyester resin, cobalt, and a catalyst. Table 1 lists the properties of the natural fibers used in the research. The matrix and reinforcing materials are composed of the following: 40% are fibers from Spanish cherry, 25% are vetiver fiber, 13% are coir pith, 14% are polyester resin, 6% are cobalt, and 2% are catalyst. A compression molding machine with a pressing speed of 25 mm/s, a maximum pressing capacity of 25 tons, a heating range of 145 °C, and an operating pressure of 25 kg/cm² was used in the investigation. The vinyl ester resin was cured using methyl ethyl ketone peroxide, and the polyester resin was cured using a cobalt activator.

3. Results and discussion

Several investigations have demonstrated a substantial correlation between the thrust force, torque, and surface roughness generated during composite drilling. The composite is drilled using different geometrical drill bits, and the thrust force and torque are assessed. Thrust force, torque, and surface roughness were measured using three different drill bits. Table 3 presents the experimental values and corresponding signal-to-noise (S/N) ratios.

3.1 Parametric effect on thrust force

Table 5 displays the thrust force determined during drilling of the natural composite. The minimum thrust force of 1.67 kgf was obtained at parametric conditions 6 mm, 740 rpm, and 80 mm/min, and the maximum thrust force of 4.35 kgf was recorded at 8 mm, 1480 rpm, and 240 mm/min. The S/N ratio assessment was used to evaluate the impact of the input variables on the result. The thrust force S/N ratios are presented in Table 5, indicating that feed rate, drill bit diameter, and spindle speed have the greatest impact on thrust force. The thrust force ANOVA findings are displayed in Table 6. The p-value in the ANOVA was lower than 0.05, which indicates the proposed model is adequate [12]. Using Design Expert software, a quadratic model was created to determine the interaction between the various drilling variables and the thrust force. Equation (3) provides the regression equation for thrust force. The regression coefficient and adjusted coefficient of the investigation were 95.03% and 92.39%, respectively. Compared to drill bits of other diameters, the drill bit with a 6 mm diameter produces less thrust force. When drilled at a spindle speed of 740 rpm and a feed rate of 80 mm/min, the lowest thrust force was noted.

$$F = -4.98 + 0.660d + 0.004208N + 0.01771f - 0.0250(d^2) - 0.000001(N^2) - 0.000020(f^2) + 0.000035(d \times N) - 0.000550(d \times f) - 0.000001(N \times f)$$

Equation (3)

Where,

f- feed rate

d- drill bit diameter

N- spindle speed

F- thrust force

Figure 4 shows that the thrust force increases as the drill bit diameter, feed rate, and spindle speed rise; however, at extremely high spindle speed levels, it tends to decrease. Although a smaller drill bit diameter (6 mm) removes less material per revolution, it usually requires less force to advance through the workpiece, resulting in lower thrust forces [26].

The more material is removed with every revolution using larger drill bit sizes (10 mm), higher thrust forces are typically required. The drill bit rotates more slowly at a low spindle speed (740 rpm), which reduces the cutting motion. The longer period of contact between the drill bit and the workpiece, caused by this slower spin, may help reduce friction by allowing for greater heat dissipation. However, due to the increased resistance encountered during drilling, the drill bit may remain in the material for a longer period as a result of the slower rotational speed[27]. This could lead to an increase in thrust forces. The drill bit achieves a moderate rotational velocity at a medium spindle speed (1480 rpm), which allows for effective material removal without excessive dwell time. High spindle speeds (2,220 rpm) enable the drill bit to rotate quickly, resulting in high cutting velocities and effective material removal rates. Drill bits that rotate quickly can remove material more effectively and spend less time in the material, which can minimize frictional forces and perhaps lessen thrust forces [28]. However, an overly high spindle speed produces excessive heat, which can cause problems such as melting or scorching the natural composite material. Reduced thrust forces are typically the result of the low feed rate (80 kgf), as the cutting action is less vigorous. By allowing for more regulated chip production and evacuation, the slower advancement reduces the chance of chip jamming and the resulting increases in thrust force. Medium thrust force is produced by drilling at a moderate feed rate of 160 kgf, which offers a reasonable balance between productivity and machining quality. It retains control over chip formation and evacuation while enabling effective material removal. The increased heat and friction produced at a higher feed rate (240 kgf) could cause problems, such as melting or charring of the natural composite material.

3.2. Parametric effect on surface roughness

From the experimental table, it was observed that the parametric setting of d: 10 mm, N: 1480 rpm, and f: 160 mm/min yields the minimum SR of 5.3 μm. The parametric setting with 8 mm of DBD, 2220 of SS, and 80 mm/min of FR showed a maximum SR value of 15.5 µm. The S/N response graph for surface roughness is shown in Table 7. The response table indicates that feed rate and spindle speed are the next most important parameters for surface roughness, following drill bit diameter. According to the p-values listed in Table 8, which are all lower than 0.05 with a 95% confidence level, the results are statistically significant. Hence, the developed model is adequate. Equation (4) represents the thrust force model equation. From the mathematical results, the regression and adjusted regression coefficients were 99.22% and 98.81%, respectively, which shows the empirical model is adequate. The graph showed that the SR increases as the feed rate and drill bit diameter increase, but it reduces when the spindle speed rises.

$$SR = -9.04 + (10.322d) - (0.02313N) - 0.06614f - 0.06115d^2 + 0.000008N^2 + 0.000231f^2 + 0.000112(d \times N) - 0.001265(d \times f) - 0.000003(N \times f)$$ **Equation (4)**

$R^2 = 99.22\%$,

$R^2(Adjusted\ = 98.81\%$

The effect of the drilling variable on surface roughness is illustrated in Figure 5. From the graph, it was observed that a drill bit diameter of 6 mm exhibited a roughness value of 10.45µm. This concentrated cutting pressure enables precise, controlled cuts while minimizing chip recutting and material deformation [29,30]. This accuracy lowers heat production and vibrations, resulting in softer surfaces. At the drilled surface with a 8 mm drill bit diameter, a roughness of 12.5 µm was observed. Because the bit has a larger cutting surface and disrupts the material more than small bits, it may cause more vibrations and less precise cutting. The 10 mm diameter reduces the roughness value to 9.26 µm. The larger diameter reduces friction and prevents material from re-cutting or spreading, thereby improving chip removal performance. Surface roughness is reduced, and the cut is smoother as a result of the enhanced stability and efficient chip evacuation. A smoother, less textured surface with fewer discernible ridges or defects would be shown in the SEM image. The surface would seem smoother and more even, reflecting less roughness[31].

As spindle speed increases, roughness initially increases, but it then decreases further as the spindle speed continues to rise. At a spindle speed of 740 rpm, the surface roughness was 11.65µm. When the sliding speed was increased to 1480 rpm, the roughness decreased drastically to 7.84 µm. Surface roughness was minimal at intermediate spindle speeds, as the speed was precisely regulated to produce heat and cutting force. This speed makes the cutting process steadier by minimizing tool wear and vibrations. It also enables effective chip removal with minimal friction, leading to a better surface finish [32]. At higher speeds, roughness values then increased to 12.72 µm. At greater spindle speeds, the high temperature buildup causes the matrix material to deteriorate, resulting in fiber pull-out and matrix cracking. This causes the roughness to grow to 12.72 µm. The roughness is exacerbated by higher vibrations from high-speed tools, which also lead to uneven drilling, resulting in poorer surface roughness.

The surface roughness value decreased to 9.75µm as the feed rate was increased to 160 mm/min. At the lowest feed rate (80 mm/min), the roughness values were high. It may be attributed to increased tool material rubbing and friction, which can cause heat accumulation and likely composite surface spreading. Slower feed rates result in vibration and tool deflection, which can make the cutting process more unstable and lead to a rougher surface. Furthermore, increasing the feed rate to 240 mm/min resulted in an increase in roughness to 10.67µm. Increasing the feed rate may result in increased surface roughness because of the increased cutting forces that induce more fiber pull-out and displacement. The increased removal rate may lead to insufficient chip elimination, potentially resulting in debris formation and uneven cutting[33].

***Table 1** Literature review on the machining of natural fiber-reinforced polymers*

Ref.	Fiber Type	Machining Process	Optimization/ Analysis Method	Key Findings
[5]	Natural Fiber Composites	Image Analysis for FVC Prediction	CNN & Ensemble ML	Achieved 2.72% error in FVC prediction; promoted low-resource ML models for composites analysis.
[6]	Kenaf, Sisal, Aloe Vera	Radial Drilling (HSS drill)	Cutting Speed & Feed Rate Variation	Higher delamination in PVC-based composites vs. vinyl ester-based composites performed better.
[7]	Date Palm Fiber	Drilling (10 mm drill, varied feed & spindle speed)	RSM & ANOVA	Higher feed rate increased delamination, and higher spindle speed reduced it.
[8]	Aramid Fiber	Bionic Stepped Drilling	Tool Design &	Beetle-mimic drill tools reduced

	(AFRP)		ANOVA	delamination and burrs; a 45° rake angle was optimal.
[9]	Palm & Jute Fiber	Conventional Drilling	Bootstrap Regression	Lower spindle speeds produced more precise holes, and circularity & cylindricity errors were analyzed.
[10]	Various FRPs	Review of Drilling Defects	Literature Survey	Delamination, fuzzing, and matrix/fiber burning are critical defects in drilling NFRCs.
[11]	Banana Fiber	Microwave Drilling (2.45 GHz)	FEM + Experimental	Drilling in 4-6 sec, minimized heat-affected zone (HAZ).
[12]	Jute & Silk	Taguchi Optimization	ANOVA & Taguchi	Hybrid jute-silk laminates reduced delamination vs. pure jute or silk.
[13]	Basalt Fiber	Abrasive Water Jet (AWJ) Drilling	Multi-Objective Optimization	AWJ drilling reduced delamination and burrs compared to conventional drilling.
[14]	NFCs	NDT for Drilling-Induced Delamination	Image Processing	Flatbed scanner-based imaging accurately quantified delamination.
[15]	Sisal & Coir	Drilling	Roundness, Delamination, Taper Angle Analysis	Hybrid nanocomposites minimized drilling defects.

Table 2 *Properties of natural fibers used*

Properties	**Spanish cherry**	**Vetiver**	**Coir**
Density (g/cm^3)	0.9	1.2	1.3
Tensile Strength (MPa)	353 -683	234 – 636	128 – 166
Young's Modulus (GPa)	12.0 – 24.5	10.8.0 – 43.8	3.0 – 5.0
Elongation at Break (%)	1.1 – 1.3	1.6 – 2.4	2.8 – 6.4

Figure 1 *Fiber arrangement and compression molding process*

Figure 2: *Vertical milling machine setup used for the drilling experiments*

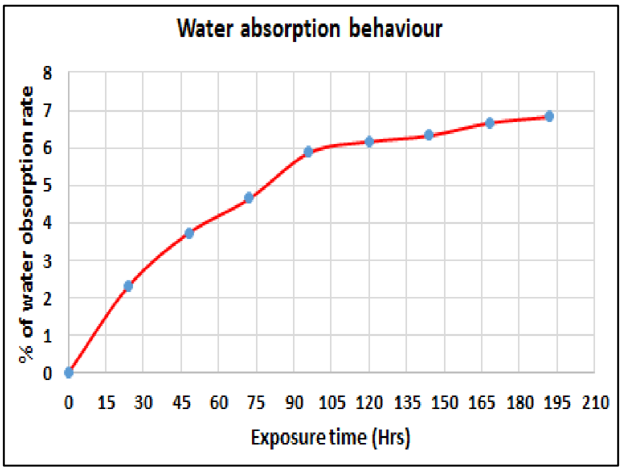

Figure 3: *Water absorption behavior of Spanish cherry fiber-reinforced hybrid composite over time.*

Table 3: *Process parameters chosen for analysis*

Parameter	**Level 1**	**Level 2**	**Level 3**
Drill Bit Diameter (mm)	6	8	10
Spindle Speed (rpm)	740	1480	2220
Feed Rate (mm/min)	80	160	240

Table 4: *Experimental results of thrust force (TF) and surface roughness (SR)*

Exp. No	**Drill Bit (mm)**	**Spindle Speed (rpm)**	**Feed Rate (mm/min)**	**TF (kgf)**	**SR (µm)**
1	6	740	80	1.67	12.3
2	8	1480	160	3.82	8.76
3	10	2220	240	4.35	9.74

Table 5: *Response table for S/N ratio on thrust force*

Level	Drill bit Diameter (mm)	Spindle speed (rpm)	Feed rate (mm/min)
1	-8.415	-8.231	-8.450
2	-10.084	-11.172	-10.158
3	-11.009	-10.106	-10.900
Delta	2.594	2.941	2.451
Rank	2	1	3

Table 6: *ANOVA table for thrust force*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Drill bit diameter	2	3.665	3.6651	1.832	45.44	0.000
Spindle speed	2	4.798	4.7985	2.399	59.49	0.000
Feed rate	2	3.155	3.1559	1.577	39.12	0.000
Residual Error	20	0.806	0.8066	0.040		
Total	26	12.426				

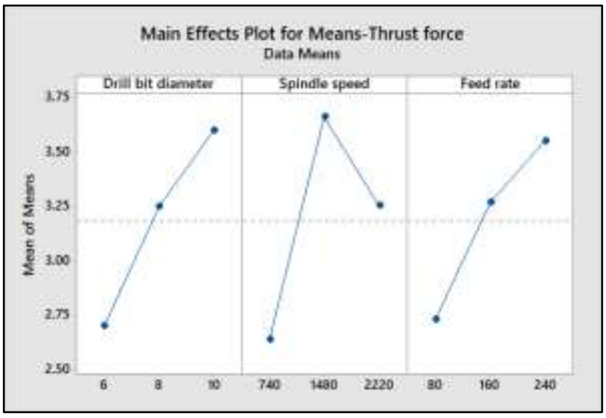

Figure 4: *Parametric effect on thrust force*

Table 7: *Response table for S/N ratio on thrust force*

Level	Drill bit Diameter (mm)	Spindle speed (rpm)	Feed rate (mm/min)
1	-20.18	-21.25	-21.21
2	-21.80	-17.71	-19.46
3	-19.00	-22.02	-20.30
Delta	2.80	4.30	1.74
Rank	2	1	3

Table 8*: ANOVA table for thrust force*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Drill bit diameter	2	48.427	48.427	24.2135	180.6	0.000
Spindle speed	2	118.19	118.19	59.0958	440.7	0.000
Feed rate	2	18.690	18.690	9.3450	69.70	0.000
Residual Error	20	2.681	2.681	0.1341		
Total	26	187.99				

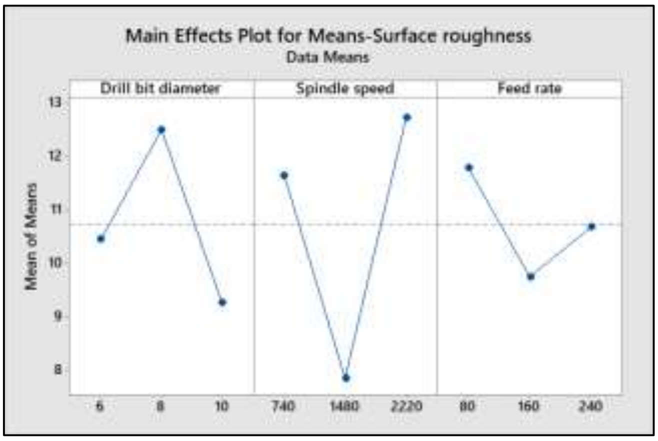

Figure 5: *Parametric effect on surface roughness*

4. Conclusions

In this investigation, the Taguchi technique was used to analyze the drilling of epoxy resin composites reinforced with Spanish cherry fiber. Various drilling variables, including drill bit diameter, spindle speed, and feed rate, were involved in achieving the desired drilled characteristics (TF and SR). At optimal parametric settings of 8 mm, 1480 rpm, and 160 mm/min, the suitable thrust force and surface roughness are 3.82 kgf and 8.76 µm, respectively. The results of the S/N ratio table reveal that the variable most impacted by TF and SR was spindle speed, followed by drill bit diameter and feed rate. The p-values indicated in the ANOVA table show the significance of the variable; the resulting p-values were lower than 0.05 (95% confidence level). Thus, the models developed for TF and SR were adequate. It was observed that the TF increases with the increase of DBD, SS, and FR; however, TF decreases when the spindle speed is increased to 2220 rpm. SR decreases with the increase of SS and FR, but initially, SR increases with the increase of the DBD to 8 mm. Further, by increasing the SS and FR to a higher level, SR increases. The water absorption report showed that as exposure time increases, the water absorption rate also increases. The minimum and maximum water absorption rates recorded over 24 hours and 192 hours were 2.62% and 7.58%, respectively. It was concluded that the optimal parametric setting showed better thrust force and surface roughness, while a minimum water absorption rate was observed at the lowest exposure time.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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