Journal of Natural Fibers

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/wjnf20

Quality Evaluation and Predictive Analysis of Drilled Holes in Jute/Palm/Polyester Hybrid Bio-Composites Using CMM and ANN Techniques

Salah Amroune, Abdelmalek Elhadi, Mohamed Slamani, Mustapha Arslane, Ahmed Belaadi, Mahmood M. S. Abdullah, Hamad A. Al-Lohedan, Tarek Bidi, Herbert Mukalazi & Amar Al-Khawlani

To cite this article: Salah Amroune, Abdelmalek Elhadi, Mohamed Slamani, Mustapha Arslane, Ahmed Belaadi, Mahmood M. S. Abdullah, Hamad A. Al-Lohedan, Tarek Bidi, Herbert Mukalazi & Amar Al-Khawlani (2025) Quality Evaluation and Predictive Analysis of Drilled Holes in Jute/Palm/Polyester Hybrid Bio-Composites Using CMM and ANN Techniques, Journal of Natural Fibers, 22:1, 2495929, DOI: 10.1080/15440478.2025.2495929

To link to this article: https://doi.org/10.1080/15440478.2025.2495929

Published online: 26 Apr 2025.

JOURNAL OF NATURAL FIBERS
2025, VOL. 22, NO. 1, 2495929
https://doi.org/10.1080/15440478.2025.2495929

Quality Evaluation and Predictive Analysis of Drilled Holes in Jute/Palm/Polyester Hybrid Bio-Composites Using CMM and ANN Techniques

Salah Amroune[a,b], Abdelmalek Elhadi[a,b], Mohamed Slamani[a,b], Mustapha Arslane[a,b], Ahmed Belaadi[c], Mahmood M. S. Abdullah[d], Hamad A. Al-Lohedan[d], Tarek Bidi[a,b], Herbert Mukalazi[e], and Amar Al-Khawlani[f]

[a]Mechanical Department, Faculty of Technology, University of Msila, Msila, Algeria; [b]Materials and Structural Mechanics Laboratory (LMMS), University of M'sila, Msila, Algeria; [c]Department of Mechanical Engineering, Faculty of Technology, University 20 August 1955-Skikda, El-Hadaiek Skikda, Algeria; [d]Department of Chemistry, College of Science, King Saud University, Riyadh, Saudi Arabia; [e]Department of Mathematics and Statistics, Kyambogo University, Kampala, Uganda; [f]Jiangsu Optoelectronic Functional Materials and Engineering Research Center, School of Chemistry and Chemical Engineering, Southeast University, Nanjing, China

ABSTRACT

In this study, the evaluation of 75 holes drilled in a hybrid bio-composite jute/palm/polyester plate and controlled by a coordinate measuring machine (CMM) is essential to ensure the quality, dimensional precision, and geometric conformity of the plate. This rigorous process is necessary to meet industrial standards for circularity and cylindricity, which are essential criteria for high-performance applications. Additionally, the integration of artificial neural network (ANN) techniques has revolutionized this approach by enabling precise predictions of key parameters such as delamination, circularity, and cylindricity. In this study, the ANN was trained with 52 samples (70%), while 8 samples (10%) were used for validation and 15 others (20%) for testing at different stages. The results show the influence of feed rate on the delamination factor (Fd) ($R^2 = 0.98$), circularity error ($R^2 = 0.99$), and cylindricity error ($R^2 = 0.98$). This predictive approach significantly improves the reliability and efficiency of the evaluation process.

摘要

在这项研究中，对在混合生物复合黄麻/棕榈/聚酯板上钻的75个孔进行评估，并由坐标测量机（CMM）控制，对于确保板的质量、尺寸精度和几何一致性至关重要. 这种严格的过程对于满足圆度和圆柱度的工业标准是必要的，这是高性能应用的基本标准. 此外，人工神经网络（ANN）技术的集成通过精确预测分层、圆度和圆柱度等关键参数，彻底改变了这种方法. 在这项研究中，ANN用52个样本（70%）进行训练，8个样本（10%）用于验证，另外15个样本（20%）用于不同阶段的测试. 结果表明，进料速率对分层系数（Fd）（R2 = 0.98）、圆度误差（R2 = 0.99）和圆柱度误差（R2 = 0.98）的影响. 这种预测方法显著提高了评估过程的可靠性和效率.

KEYWORDS
Coordinate measuring machine (CMM); inspection; drilled holes; cylindricity; circularity; artificial neural network (ANN)

关键字
坐标测量机（CMM）; 检查; 钻孔; 圆柱度; 循环性; 人工神经网络

CONTACT Ahmed Belaadi ahmedbelaadi1@yahoo.fr Department of Mechanical Engineering, Faculty of Technology, University 20 August 1955-Skikda, El-Hadaiek Skikda, Algeria; Herbert Mukalazi hmukalazi@kyu.ac.ug Department of Mathematics and Statistics, Kyambogo University, Kampala, Uganda

Introduction

Composite materials have attracted a great deal of interest in recent years (Blythe et al. 2024; Chai et al. 2023; Chai, Gunaratne, et al. 2024; Chai, Wang, et al. 2024; Shevtsov et al. 2024). However, environmental concerns have led to growing interest in the development of degradable materials using natural fibers (Gheribi et al. 2024; Kir et al. 2024; Ladaci et al. 2024; Teyar et al. 2024). Natural fiber-reinforced composite materials are increasingly being used in the field of machining. Among the commonly employed fibers are those from palm trees (Fnides et al. 2024), Washingtonia filifera (Lekrine et al. 2022), Yucca Treculeana L. Leaf (Belaadi et al. 2022), Flax (Amroune, Belaadi, Bourchak, et al. 2022; Amroune, Belaadi, Dalmis, et al. 2022; Bedjaoui et al. 2019; Belaadi, Amroune, and Bourchak 2020; Makhlouf et al. 2022), Syagrus Romanzoffiana palm (Ferfari et al. 2024) and others (Hachaichi et al. 2022; Saada, Amroune, et al. 2024; Tablit et al. 2024). They are also used in the automotive sector (Benyettou et al. 2023a; da Silva et al. 2021; Maleki et al. 2019; Pailoor, Narasimha Murthy, and Sreenivasa 2021; Ravikumar et al. 2022).

The meticulous inspection of holes drilled in a hybrid jute/palm/polyester composite plate using a Coordinate Measuring Machine (CMM) is a complex and essential procedure for detailed evaluation of the shape, dimensions, and overall quality of this crucial element in the composite materials industry. The composite plate has unique and varied qualities since it is made of a blend of palm and jute fibers embedded in polyester. In order to ensure adherence to the necessary standards and specifications, maintaining accurate dimensional control is therefore both difficult and essential (Benyettou et al. 2023b; Benyettou, Amroune, Slamani, et al. 2022; Elhadi, Amroune, Slamani, Arslane, et al. 2024; Rajmohan, Palanikumar, and Kathirvel 2012; Srinivasan et al. 2021). An essential part of the inspection procedure is determining how round the holes are. The degree to which a form resembles a perfect circle is known as its circularity. The CMM uses high-precision sensors that precisely measure several sites surrounding the drilled holes in order to analyze this feature (Saif et al. 2023). This detailed examination makes it possible to determine whether the hole's shape closely resembles the perfect circular shape needed for a composite plate (Elhadi, Amroune, Slamani, Jawaid, et al. 2024; Elhadi, Slamani, et al. 2024). The performance and general quality of the plate can be greatly impacted by even a small departure from the circular shape (Saleem et al. 2013; Zhu et al. 2017; Zitoune, Krishnaraj, and Collombet 2010). Similarly, the evaluation of cylindricity is an equally crucial step. Although the composite plate is not a conventional cylindrical shape, the CMM checks the alignment of the different constituent parts around the hole. The precision of this theoretical cylindrical shape is essential to ensure the functionality and compatibility of the plate in its final application (Gao et al. 2015). To carry out this inspection, the CMM uses sophisticated sensors and specialized software to collect detailed data on the dimensions, shape, and specific geometry of each hole. This data is then thoroughly analyzed to determine if the composite plate meets the stringent circularity and cylindricity standards required by industrial applications (Larue, Brown, and Viala 2015).

The importance of this control process is not limited to compliance with standards but also to ensuring the final quality and performance of the composite plate. Meticulous inspection helps ensure the reliability, durability, and safety of products in various industrial sectors such as aerospace, automotive, construction, and many others (Kanyilmaz et al. 2022). Thus, every step of the CMM inspection, from circularity control to cylindricity control, is of paramount importance in the validation and certification of the hybrid composite plate for use in critical and demanding applications (Mahmood, Qureshi, and Talamona 2018; Sheth and George 2018). A study on the delamination of biocomposites conducted by Belaadi et al. (2020), combines experiments, statistical analyses, and modeling approaches to optimize drilling parameters and reduce defects in the biocomposites studied. The results confirm that selecting appropriate cutting parameters and using robust models such as artificial neural networks (ANN) allows for optimizing the drilling process of biocomposites while minimizing defects such as delamination.

This study investigates the creative use of artificial neural network (ANN) techniques to forecast three important quality indicators in hybrid bio-composite materials: cylindricity, circularity, and delamination. This method uses artificial neural networks (ANNs) to deliver real-time, data-driven insights on the geometric accuracy and structural integrity of composite plates, in contrast to standard evaluation approaches that only use direct measurements. The use of machine learning algorithms to predict possible flaws and deviations is what makes this research distinctive and enables producers to put proactive quality control measures into place. Predictive modeling decreases manufacturing time and material waste while also improving assessment accuracy and efficiency. The results of the study are especially pertinent to high-stakes sectors like aerospace and automotive, where composite materials' performance, safety, and dependability are critical. This work pushes the limits of composite design and quality assurance by developing the use of ANN in material characterization, providing a progressive method for maximizing the performance of bio-composite materials in demanding applications.

Materials and methods

The material used is a hybrid composite in plate form, consisting of reinforcements including bidirectional jute fibers (15% by weight) and unidirectional palm fibers (15% by weight), with an unsaturated polyester matrix. The plate measures 250 × 120 x 9 mm^3 and comprises six layers of palm fibers and six layers of jute fibers, manufactured through contact molding. Drilling tests were conducted using a CNC milling machine equipped with a spindle rotating at 8000 rpm. Three drills with a diameter of 8 mm and a point angle of 118° were used: high-speed steel (HSS), 5% cobalt-coated high-speed steel (HSS-Co5) and solid carbide (Figure 1). The cutting parameters were selected after a thorough analysis, involving five spindle speeds (1194 rpm, 1592.35 rpm, 1990.44 rpm, 2388.53 rpm

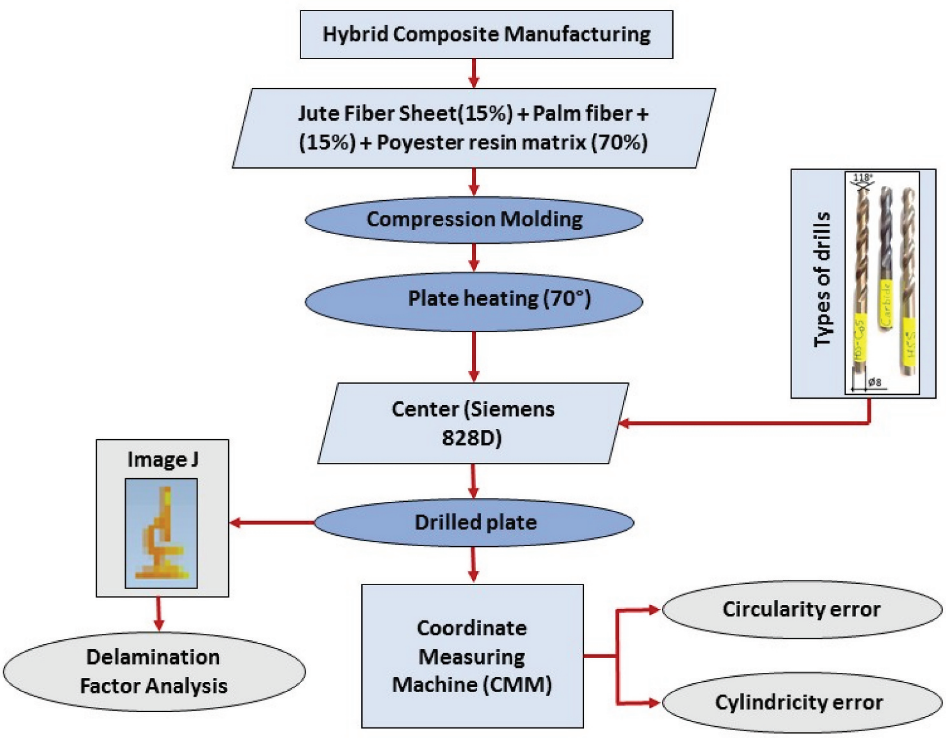


Figure 1. Equipment used for drilling and hole quality assessment of hybrid composite plate.

and 2786.62 rpm) and five feed (0.04 mm/rev, 0.08 mm/rev, 0.12 mm/rev, 0.16 mm/rev and 0.2 mm/rev). Each drill bit created 25 holes, totaling 75 on the plate. The plate was secured to a wooden base and tightly clamped to prevent any bending or damage during drilling, ensuring better hole quality. The quality of the holes was assessed based on delamination, circularity, and cylindricity by digitizing images of the holes resulting from the drilling operation (Figure 2).

The delamination factor is defined by the following formula: $F_d = Dmax/Dd$, where Dmax represents the maximum delamination diameter and Dd refers to the drill bit diameter, meaning the actual hole diameter, measured in millimeters.

Regarding circularity and cylindricity, these were evaluated by measuring the damaged area using two concentric circles and determining circularity and cylindricity errors with a coordinate measuring machine (CMM).

The Siemens SINUMERIK 828D CNC control (Figure 3) is specifically designed for turning and milling operations, compatible with various machine tools such as vertical and horizontal machining centers, turning centers with counter spindle, rotary tools, and Y-axis capability.

After each test, the composite plate's surface profile was examined using a *Euromex* microscope at a magnification of 4× (Figure 4a). This approach allowed for measuring the delamination length (Ld) in the tool entry zone of the workpiece when delamination was detected or confirming its absence.

Using a Coordinate Measuring Machine (CMM) presented in Figure 4b, circularity and cylindricity were accurately measured, ensuring high precision and reliability in the evaluation of geometric features. The CMM system employs advanced probing techniques to capture detailed data points on the surface of the measured components. This data is then analyzed to assess the roundness and cylindricity, providing critical insights into the quality and performance of the parts.

Previous studies that used twist drills provide guidance for the selection of cutting parameters and drill materials for machining natural fiber-reinforced composites, such as those reinforced with jute, cotton, palm, and sisal fibers. These studies have demonstrated how crucial it is to select suitable machining settings in order to reduce flaws like delamination and fiber pull-out (Benyettou et al. 2023b; da Silva et al. 2021; Maleki et al. 2019; Pailoor, Narasimha Murthy, and Sreenivasa 2021; Ravikumar et al. 2022).

(a) (b)

Figure 2. (a) plate fastening system (b) plate with 75 holes.

Figure 3. Siemens SINUMERIK 828D numerical control.

The ANN configuration is shown in Figure 5, with the delamination factor as the output and spindle speed, feed, and drill materials as inputs. Using MATLAB and the Levenberg-Marquardt algorithm (19 epochs, 5 training sets), the model was trained (70% of 52 samples), validated (15% of 8 samples), and tested (15% of 15 samples). ANN is a popular research tool for simulating how feed affects delamination in composites (Benyettou, Amroune, Mohamed, et al. 2022; Heraiz et al. 2024; Saada, Farsi, et al. 2024; Saada, Zaoui, et al. 2024). By modeling the nonlinear relationships between cutting parameters and delamination, ANNs enable accurate predictions and optimization of cutting conditions to reduce defects. This is especially beneficial in industries relying on composites for their superior mechanical properties.

Multi-factor ANOVA (Analysis of Variance) is a statistical technique used to examine the influence of multiple independent variables (factors) on a dependent variable. It assesses whether these factors

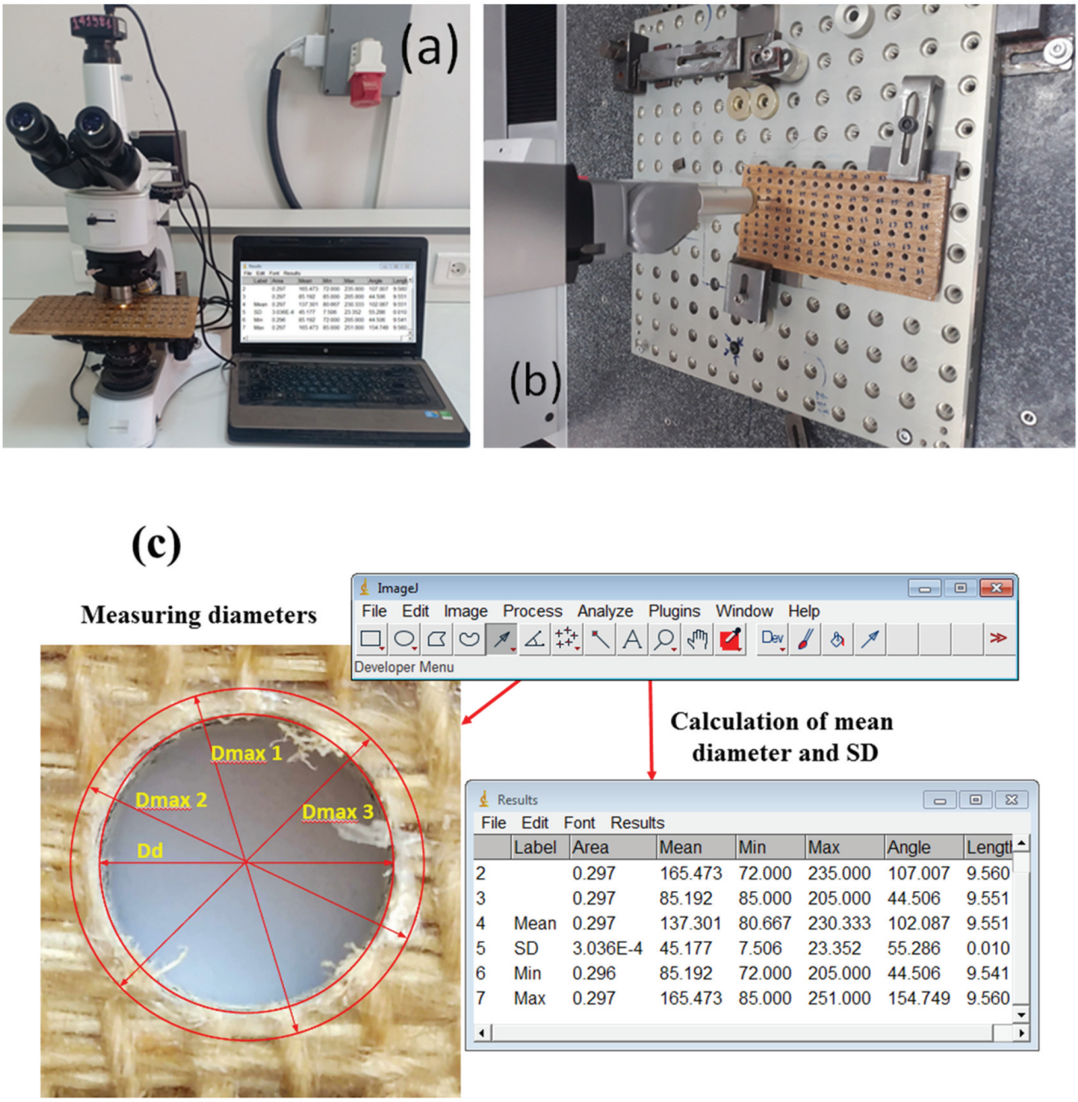


Figure 4. (a) Profile observation of the composite plate using a microscope, (b) Measurement of circularity and cylindricity by CMM and (c) Measuring diameters ImageJ.

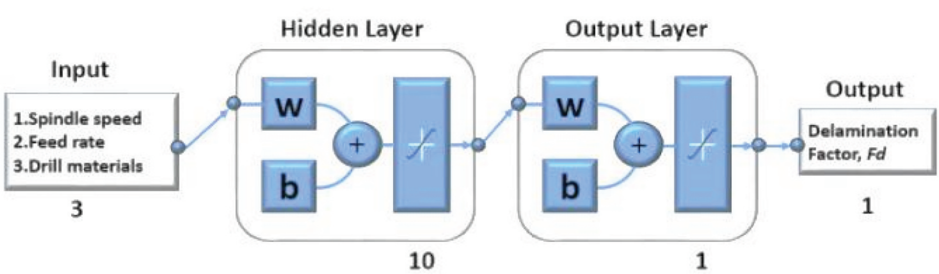


Figure 5. Diagrammatic depiction of ANN modeling.

have significant effects and whether interactions exist between them. In this study, a three-factor ANOVA is employed to evaluate how feed rate, cutting speed, and drill type affect three response variables: delamination, circularity, and cylindricity. The goal is to identify whether these factors have a statistically significant impact on the response variables and to detect any potential interactions among them. The statistical model considers the main effects of each factor, interactions between two factors, and the overall interaction among all three factors. Before analyzing the results, it is crucial to ensure that key assumptions – such as residual normality, variance homogeneity, and observation independence – are met. Once these conditions are satisfied, the analysis will help determine the significance of the main effects and interactions. If interactions are found to be significant, this would suggest that the influence of one factor depends on the levels of the other factors.

Results and discussion

Circularity

Figure 6 presents a detailed analysis of the relationship between circularity error and feed, illustrating how circularity evolves as the feed varies. The graph provides a comprehensive view of the circularity data collected for different types of drills, including non-coated high-speed steel (HSS), cobalt-coated HSS, and carbide drills. A clear and consistent trend emerges from the data: as the feed increases, the circularity error also rises. This indicates that higher feed negatively impact the precision of the drilled holes, leading to deviations from the ideal circular shape.

The observed trend is consistent across all drill types tested in the study, suggesting that the relationship between feed and circularity error is a fundamental characteristic of the drilling process in hybrid composite materials. While the magnitude of the error may vary slightly depending on the specific drill type, the overall pattern remains the same. For instance, non-coated HSS drills, which generally produce less delamination, still exhibit increased circularity errors at higher feed, similar to cobalt-coated HSS and carbide drills.

This finding underscores the importance of carefully controlling feed during the drilling process to minimize circularity errors and maintain the dimensional accuracy of the holes. By optimizing feed, manufacturers can improve the quality of drilled holes in hybrid composite plates, ensuring they meet the stringent standards required for high-performance applications. The insights gained from this analysis contribute to a better understanding of the factors influencing hole quality and provide valuable guidance for optimizing drilling parameters in industrial settings.

Figure 7a displays the circularity measurements captured using the Coordinate Measuring Machine (CMM). The graph includes both the nominal (theoretical) and measured values along the x and y axes, providing a clear comparison between the expected and actual dimensions of the drilled holes. Additionally, the standard deviation is presented, offering insights into the variability and consistency of the measurements. This comprehensive representation allows for a detailed evaluation of the circularity accuracy and the precision of the drilling process.

Cylindricity

Figure 7b presents cylindricity measurements collected with a *Hexagon Metrology* coordinate measuring machine (CMM). The data includes both the nominal (theoretical) and measured values along the x and y axes, alongside the standard deviation, which provides an indication of measurement consistency and variability. These measurements are systematically organized into tables, serving as the foundation for plotting curves that illustrate the relationship between cylindricity and cutting speed. By analyzing these curves, the study evaluates how cylindricity evolves with changes in cutting speed, offering valuable insights into the impact of this parameter on the dimensional accuracy of the drilled holes.

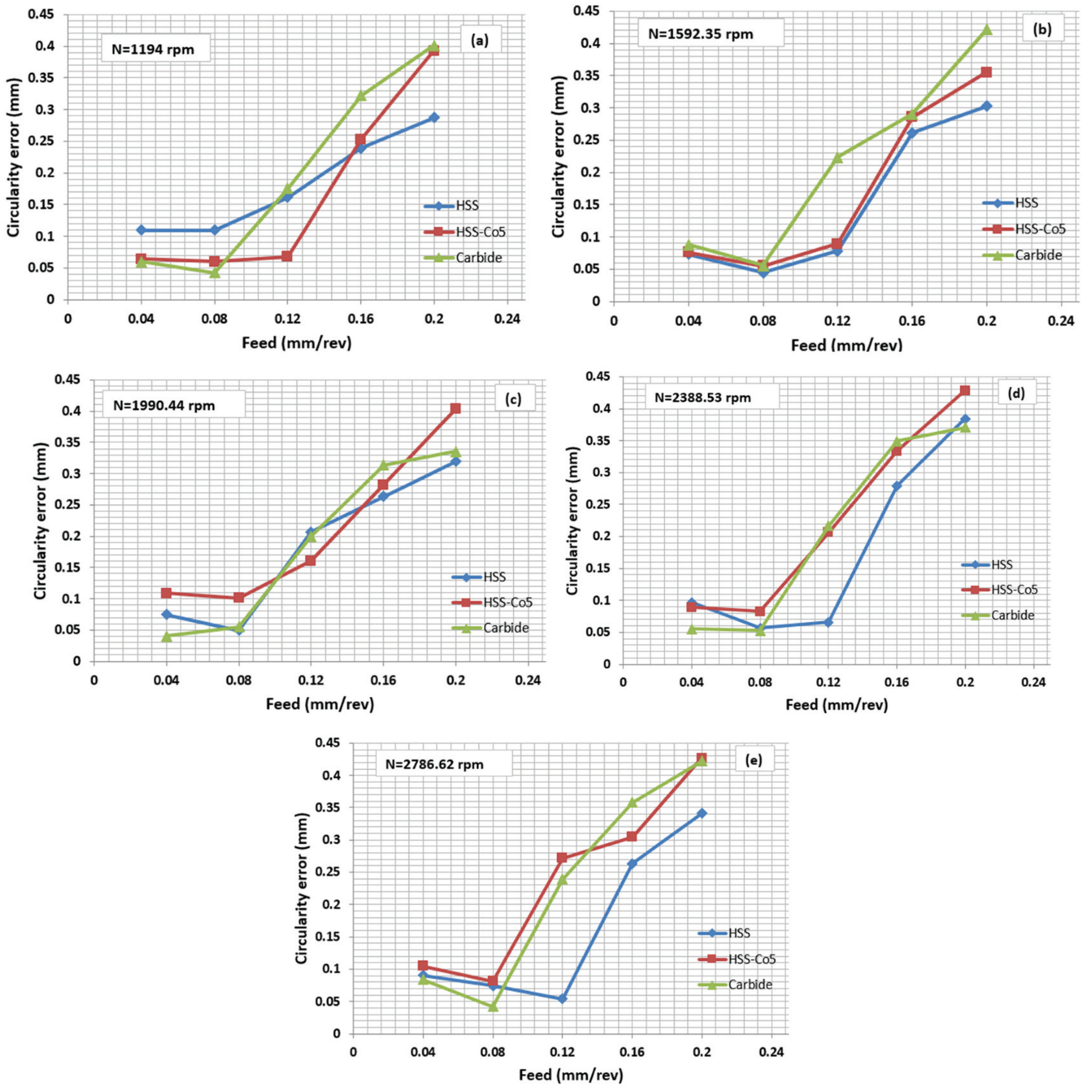
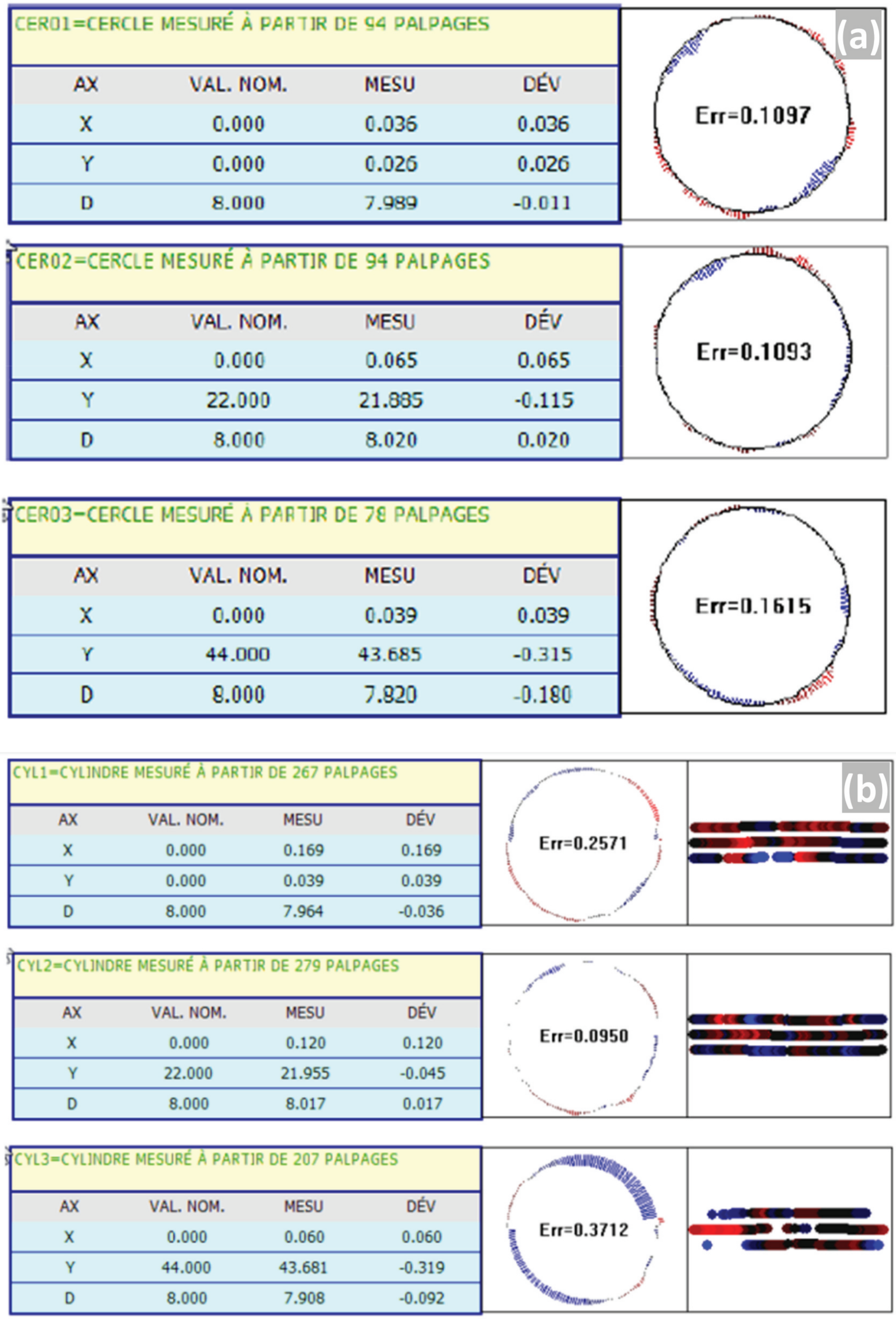


Figure 6. Evolution of circularity as a function of the feed.

Figure 8 illustrates the relationship between cylindricity and feed, depicting how cylindricity evolves as the feed changes. Cylindricity, a critical parameter that reflects both the roundness and straightness of a drilled hole, exhibits a complex pattern in its progression. The figure reveals that cylindricity generally increases with higher feed across different types of drill bits. This indicates a positive correlation between feed and cylindricity, meaning that as the feed rises, the drilled holes tend to become less round and less straight, compromising their dimensional accuracy. This trend is consistent for all drill bits tested in the study, underscoring the significant influence of feed on the quality of the drilled holes. The findings emphasize the need for precise control and optimization of feed during the drilling process to achieve the desired levels of cylindricity. By carefully managing feed, manufacturers can minimize deviations in roundness and straightness, ensuring that the drilled holes meet the stringent quality standards required for high-performance applications. This analysis highlights the critical role of feed in maintaining the structural integrity and functionality of hybrid composite materials in industrial settings. This observation was identified by (Varikkadinmel et al.



CER01=CERCLE MESURÉ À PARTIR DE 94 PALPAGES

AX	VAL. NOM.	MESU	DÉV
X	0.000	0.036	0.036
Y	0.000	0.026	0.026
D	8.000	7.989	-0.011

CER02=CERCLE MESURÉ À PARTIR DE 94 PALPAGES

AX	VAL. NOM.	MESU	DÉV
X	0.000	0.065	0.065
Y	22.000	21.885	-0.115
D	8.000	8.020	0.020

CER03=CERCLE MESURÉ À PARTIR DE 78 PALPAGES

AX	VAL. NOM.	MESU	DÉV
X	0.000	0.039	0.039
Y	44.000	43.685	-0.315
D	8.000	7.820	-0.180

CYL1=CYLINDRE MESURÉ À PARTIR DE 267 PALPAGES

AX	VAL. NOM.	MESU	DÉV
X	0.000	0.169	0.169
Y	0.000	0.039	0.039
D	8.000	7.964	-0.036

CYL2=CYLINDRE MESURÉ À PARTIR DE 279 PALPAGES

AX	VAL. NOM.	MESU	DÉV
X	0.000	0.120	0.120
Y	22.000	21.955	-0.045
D	8.000	8.017	0.017

CYL3=CYLINDRE MESURÉ À PARTIR DE 207 PALPAGES

AX	VAL. NOM.	MESU	DÉV
X	0.000	0.060	0.060
Y	44.000	43.681	-0.319
D	8.000	7.908	-0.092

Figure 7. (a) Circularity and (b) Cylindricity values measured by CMM.

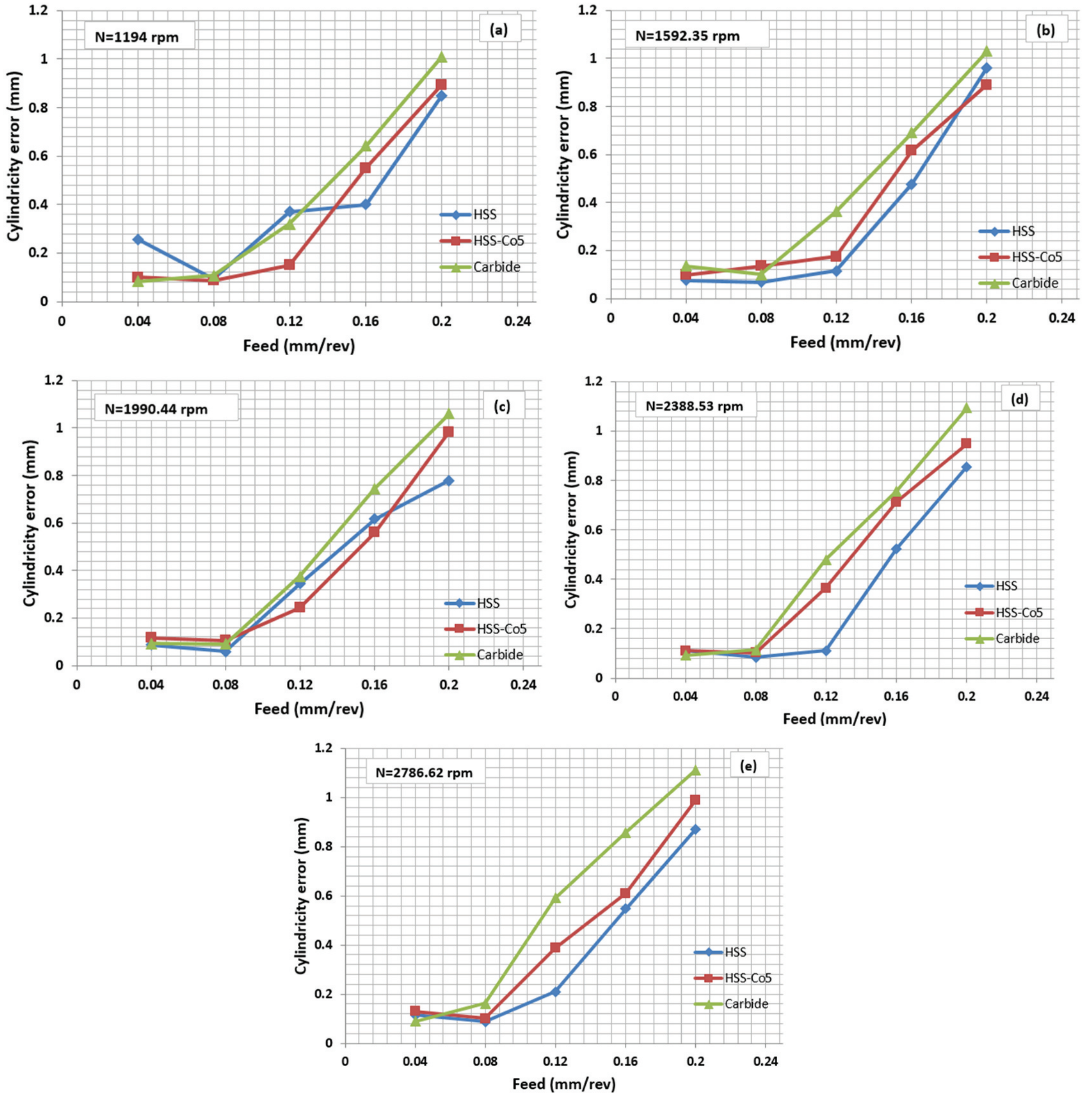


Figure 8. Evolution of cylindricity as a function of the feed.

2024) in his study on the machinability of sustainable Basalt/PBS composites. In his research, he thoroughly analyzed the influence of cutting parameters on the machining quality of these composite materials and highlighted the significant impact of these parameters on the final characteristics of the machined parts, particularly regarding the cylindricity and dimensional accuracy of the drilled holes.

Delamination

Figure 9 depicts the influence of feed f on delamination factor F_d for the three drills. This figure demonstrates that the feed parameter has a notable effect on the delamination factor, with an increase in feed leading to higher delamination factors. The curves show nearly linear trends. It was also observed that the drill material plays a significant role in the delamination factor: non-coated HSS drills caused less delamination compared to cobalt-coated HSS (HSS Co5) drills and carbide drills. It has also been observed that the delamination factor values sometimes converge

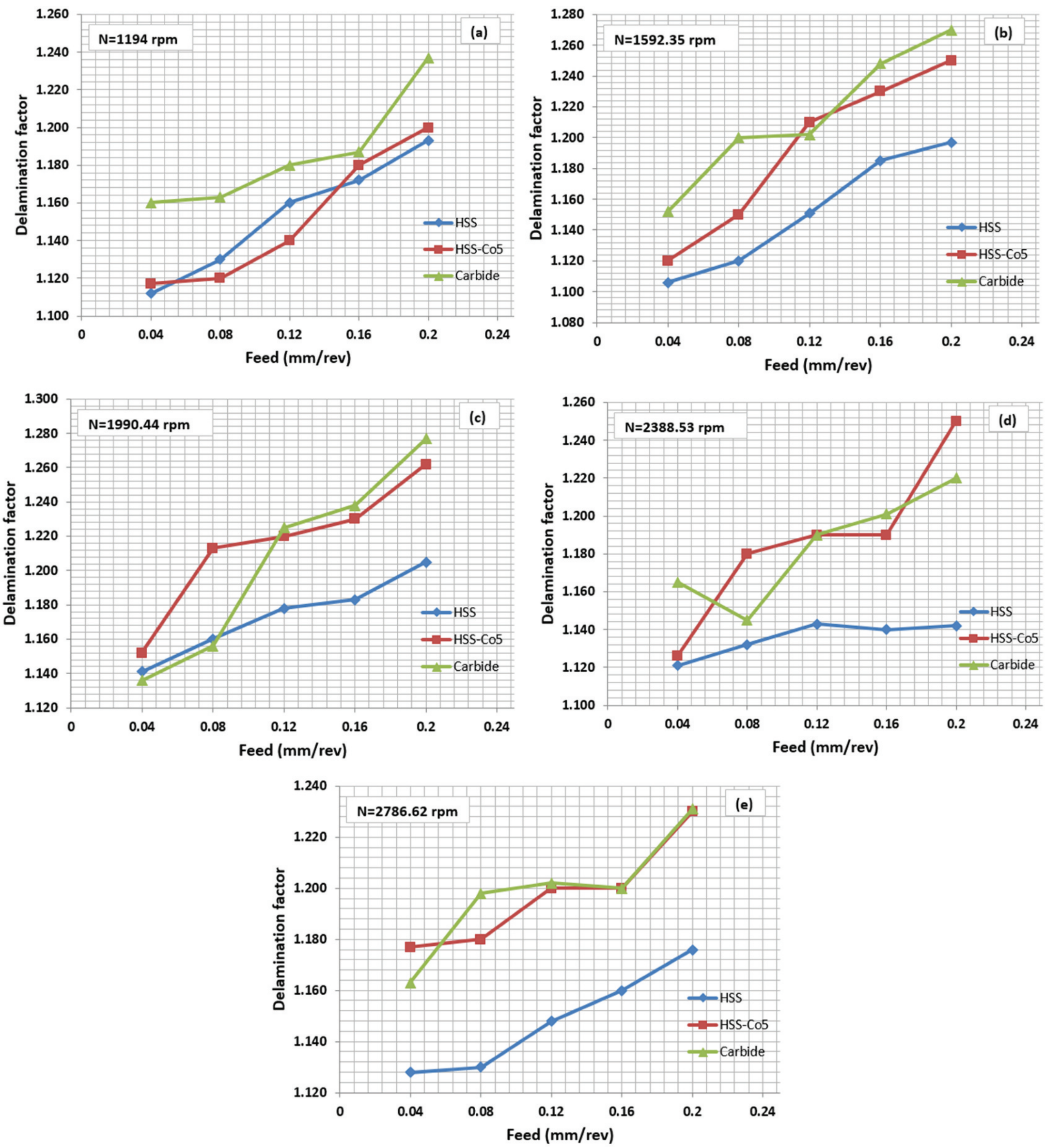


Figure 9. Influence of feed f on delamination factor F_d.

and become identical at high speeds of rotation, such as 2388.53 rpm and 2786.62 rpm. There is a noticeable difference between the delamination factor values for the solid carbide drill at feed of 0.04, 0.08, and 0.12 mm/rev at a rotation speed of 1194 rpm, and for the uncoated HSS drill at feed of 0.12, 0.16, and 0.2 mm/rev at a corresponding rotation speed of 1990.44 rpm. The smallest delamination factor value observed is 1.1075, obtained with the uncoated HSS drill at a feed of 0.04 mm/rev and a rotation speed of 1592.35 rpm. In contrast, the highest value is 1.3387, recorded with the solid carbide drill at a feed of 0.2 mm/rev and a rotation speed of 2786.62 rpm. A high feed can lead to vibrations, material deformations, excessive heating, and risks such as fiber pull-out, delamination, and irregularities on the hole walls. High-Speed Steel (HSS) drills tend to cause less delamination and provide better drilling quality compared to coated HSS and carbide drills. This is due to HSS's ductility, which allows it to absorb vibrations and mechanical stresses more effectively during drilling. In contrast, coated HSS and carbide drills are harder and more rigid, leading to a more aggressive cutting action. This increased rigidity results in higher cutting forces, which can promote delamination and deteriorate hole quality.

Artificial neural network (ANN)

Figure 10 illustrates the effect of feed on delamination, with a coefficient of determination ($R^2 = 0.98$). This shows that a higher feed leads to greater delamination values, thereby increasing the risk of delamination. This figure shows the comparison between the experimental values and the expected values for the ANN for the delamination factor, as well as the residual between them, making it clear that these values are very close with a very small error margin. This is consistent with the results obtained in the work of (Benyettou et al. 2023b), who compared different drills and drilling parameters to determine the optimal conditions for minimizing delamination in cellulosic fiber-reinforced biocomposites using the ANN tool.

Figure 11 shows the influence of the feed (*f*) on the circularity error between the experimental values and the expected values for the ANN, as well as the residual between them. It is evident that these values are very close, with a very small error margin and an R^2 value of 0.99, which is very close to 1, indicating a strong correlation between the experimental and ANN results.

Figure 12 shows the influence of the feed *f* on the cylindricity error between the experimental values and the expected values for the ANN, as well as the residual between them. It is evident that these values are very close, with a very small error margin and an R^2 of 0.98 for training and 0.97 for validation.

Multi-Factor ANOVA (analysis of variance)

Table 1 presents the results of the three-factor analysis of variance, examining the impact of feed (F), cutting speed (N), and drill type on three response variables: delamination, circularity, and cylindricity.

Effects on delamination

The results show that all three factors significantly influence delamination. The feed ($p = .003$) and drill type ($p = .005$) have a particularly strong impact, while cutting speed ($p = .016$) also has an effect, although slightly less pronounced.

Effects on circularity

Regarding circularity, the feed ($p = .001$) and drill type ($p = .003$) play a crucial role, whereas cutting speed ($p = .175$) does not have a significant effect. This indicates that circularity is more influenced by feed rate and drill type than by cutting speed.

Effects on cylindricity

The analysis reveals that only the feed rate ($p = .000$) has a significant effect on cylindricity. In contrast, neither cutting speed ($p = .159$) nor drill type ($p = .331$) appear to have an influence.

Overall, the feed rate is the most influential factor, affecting all three response variables. Drill type plays a role in reducing delamination and improving circularity but has no significant effect on cylindricity. Finally, cutting speed only affects delamination. To refine these conclusions and optimize machining parameters, a more in-depth analysis of the interactions between factors could be conducted.

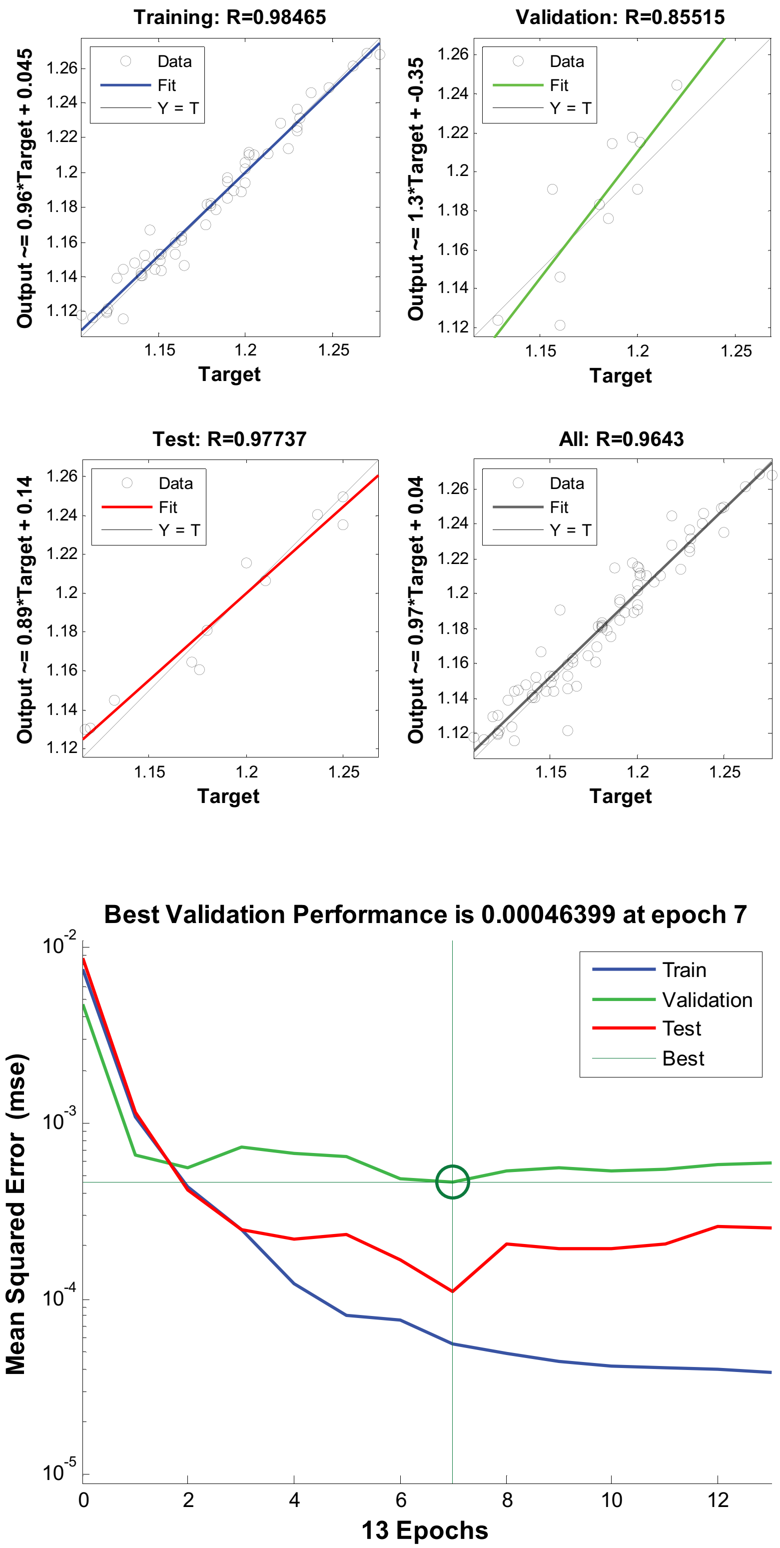


Figure 10. Influence of feed f on delamination factor F_d.

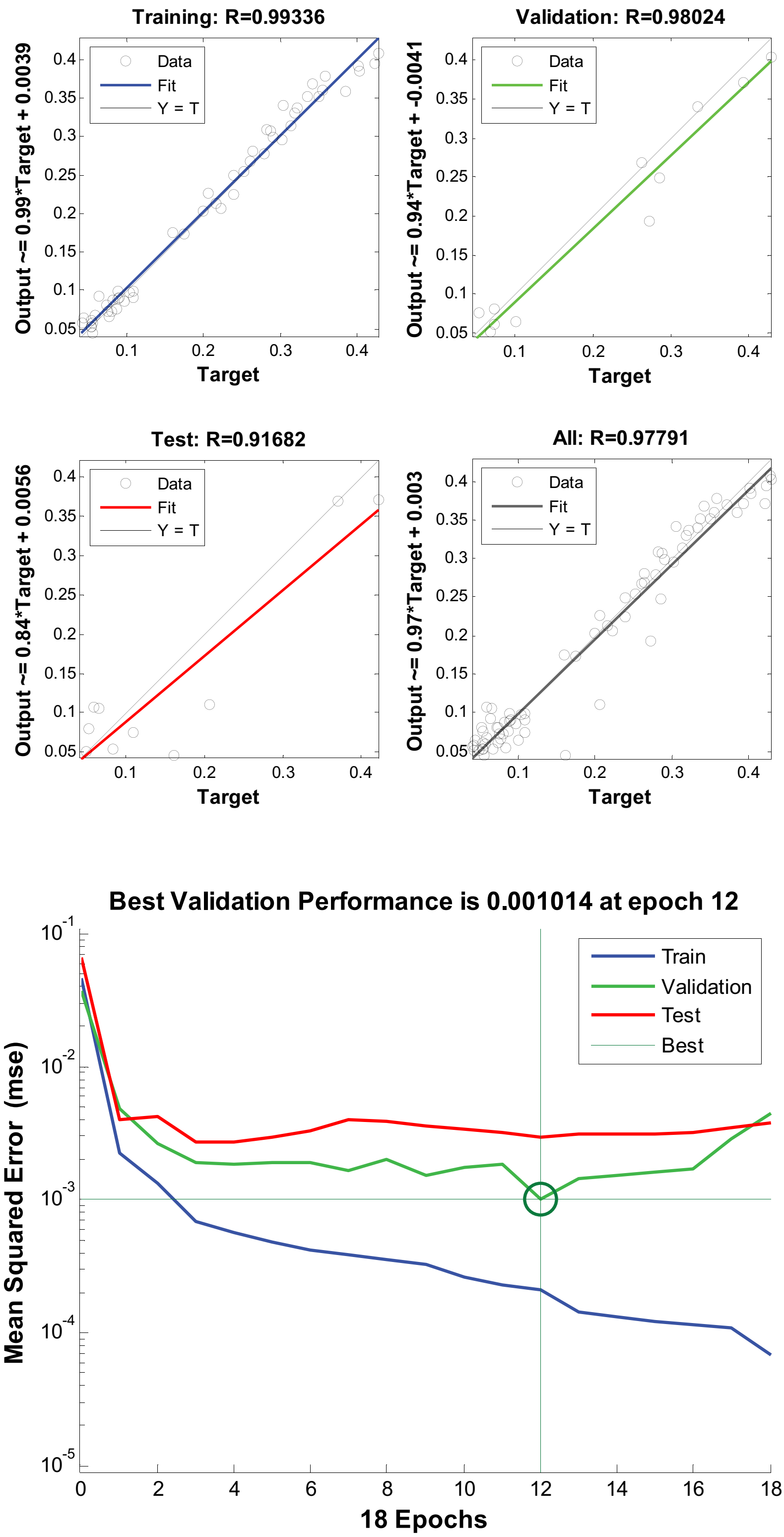


Figure 11. Influence of feed f on circularity error.

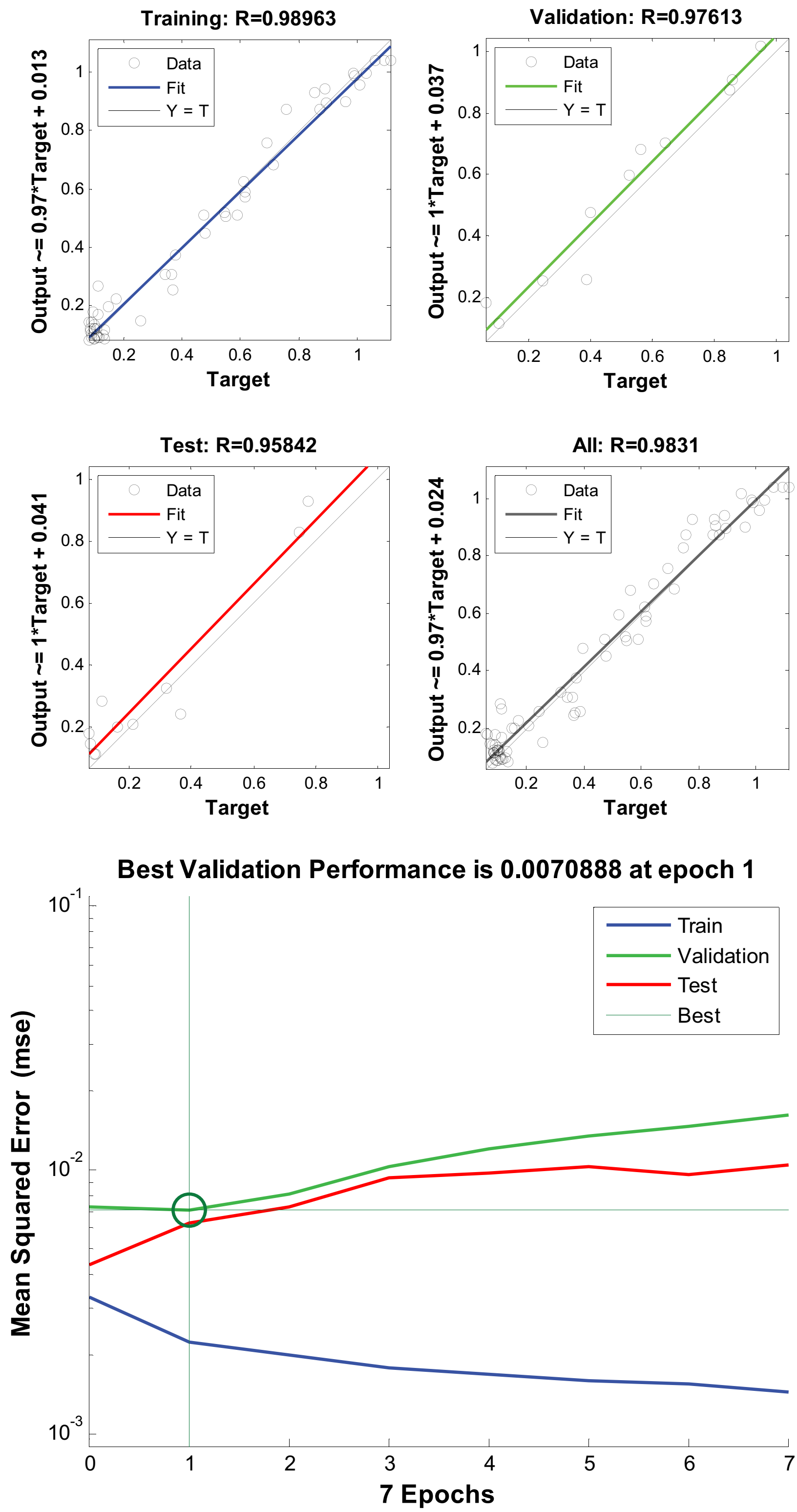


Figure 12. Influence of feed f on cylindricity.

Table 1. Multi-factor ANOVA (analysis of variance).

Response	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Delamination	F	4	0.06428	0.016071	45.61	0.003
	N	4	0.01161	0.002902	8.24	0.016
	Drill	2	0.02871	0.014356	40.74	0.005
	Error	64	0.02255	0.000352		
	Total	74	0.12715			
circularity	F	4	1.08792	0.271981	169.43	0.001
	N	4	0.01054	0.002634	1.64	0.175
	Drill	2	0.0203	0.010148	6.32	0.003
	Error	64	0.10273	0.001605		
	Total	74	1.22149			
cylindricity	F	4	8.05341	2.01335	333.1	0
	N	4	0.04132	0.01033	1.71	0.159
	Drill	2	0.20263	0.10132	16.76	0.331
	Error	64	0.38683	0.00604		
	Total	74	8.68419			

Conclusions

This study underscores the necessity of stringent quality assessment in the drilling of hybrid jute/palm/polyester bio-composite plates to ensure dimensional accuracy and geometric conformity. The use of a coordinate measuring machine (CMM) enabled precise evaluation of key parameters such as circularity and cylindricity, ensuring compliance with strict industrial standards.

Additionally, integrating artificial neural network (ANN) techniques significantly enhanced the predictive capabilities of the evaluation process. The ANN model exhibited high accuracy in predicting delamination, circularity errors, and cylindricity errors, achieving R^2 values of 0.98, 0.99, and 0.98, respectively. These findings highlight the strong correlation between feed rate and machining defects, emphasizing the necessity of optimizing cutting conditions to minimize quality issues. Notably, feed rate has a linear impact on the delamination factor, with the lowest value (1.1075) observed using an uncoated HSS drill at 0.04 mm/rev and 1592.35 rpm, while the highest (1.3387) occurred with a carbide drill at 0.2 mm/rev and 2786.62 rpm, demonstrating the critical role of parameter selection. By enhancing the reliability and efficiency of quality control, this approach supports the broader adoption of bio-composite materials in high-performance sectors such as aerospace and automotive industries. The lightweight, durable, and sustainable properties of these composites make them highly suitable for advanced engineering applications where precision and safety are paramount. Future research could focus on further optimizing drilling parameters and incorporating more advanced machine learning models to improve predictive accuracy. The combination of precise measurement techniques and intelligent modeling marks a significant advancement in the quality assurance of hybrid bio-composites, fostering their widespread application in next-generation industrial technologies.

Acknowledgments

The authors acknowledge the financial support through Researchers Supporting Project number (RSPD2025R688), King Saud University, Riyadh, Saudi Arabia.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Salah Amroune http://orcid.org/0000-0002-9565-1935
Ahmed Belaadi http://orcid.org/0000-0002-6059-3974

Highlights

- The study assesses drilled holes in bio-composites using a CMM.
- CMM sensors ensure precise quality checks.
- ANN predicts quality, reducing manual work.
- Bio-composites are light, sustainable, and efficient.
- Precision ensures high standards in industrial use.

References

Amroune, S., A. Belaadi, M. Bourchak, A. Makhlouf, and H. Satha. 2022. "Statistical and Experimental Analysis of the Mechanical Properties of Flax Fibers." *Journal of Natural Fibers* 19 (4): 1387–1401. https://doi.org/10.1080/15440478.2020.1775751.

Amroune, S., A. Belaadi, R. Dalmis, Y. Seki, A. Makhlouf, and H. Satha. 2022. "Quantitatively Investigating the Effects of Fiber Parameters on Tensile and Flexural Response of Flax/Epoxy Biocomposites." *Journal of Natural Fibers* 19 (6): 2366–2381. https://doi.org/10.1080/15440478.2020.1817831.

Bedjaoui, A., A. Belaadi, S. Amroune, and B. Madi. 2019. "Impact of Surface Treatment of Flax Fibers on Tensile Mechanical Properties Accompanied by a Statistical Study." *International Journal of Integrated Engineering* 11 (6): 10–17.

Belaadi, A., S. Amroune, and M. Bourchak. 2020. "Effect of Eco-Friendly Chemical Sodium Bicarbonate Treatment on the Mechanical Properties of Flax Fibres: Weibull Statistics." *International Journal of Advanced Manufacturing Technology* 106 (5): 1753–1774. https://doi.org/10.1007/s00170-019-04628-8.

Belaadi, A., S. Amroune, Y. Seki, O. Yasin Keskin, S. Köktaş, M. Bourchak, A. Dufresne, H. Fouad, and M. Jawaid. 2022. "Extraction and Characterization of a New Lignocellulosic Fiber from Yucca Treculeana L. Leaf as Potential Reinforcement for Industrial Biocomposites." *Journal of Natural Fibers* 19 (15): 12235–12250. https://doi.org/10.1080/15440478.2022.2054895.

Belaadi, A., M. Boumaaza, S. Amroune, and M. Bourchak. 2020. "Mechanical Characterization and Optimization of Delamination Factor in Drilling Bidirectional Jute Fibre-Reinforced Polymer Biocomposites." *International Journal of Advanced Manufacturing Technology* 111 (7): 2073–2094. https://doi.org/10.1007/s00170-020-06217-6.

Benyettou, R., S. Amroune, M. Slamani, and A. KILIÇ. 2023a. "Investigation of Machinability of Biocomposites: Modeling and ANN Optimization." *Academic Journal of Manufacturing Engineering* 21 (1): 97–104.

Benyettou, R., S. Amroune, M. Slamani, and A. KILIÇ. 2023b. "Investigation of Machinability of Biocomposites: Modeling and ANN Optimization." *Academic Journal of Manufacturing Engineering* 21 (1).

Benyettou, R., S. Amroune, S. Mohamed, Y. Seki, and A. Dufresne. 2022. "Experimental Investigation of the Absorption Behavior of Date Palm Fiber Reinforced Iso-Polyester Composites: Artificial Neuron Network (ANN) Modeling." *Journal of Natural Fibers* 19 (17): 15902–15918. https://doi.org/10.1080/15440478.2022.2136323.

Benyettou, R., S. Amroune, M. Slamani, Y. Seki, A. Dufresne, M. Jawaid, and S. Alamery. 2022. "Assessment of Induced Delamination Drilling of Natural Fiber Reinforced Composites: A Statistical Analysis." *Journal of Materials Research and Technology* 21: 131–152. https://doi.org/10.1016/j.jmrt.2022.08.161.

Blythe, A., B. Fox, M. Nikzad, B. Eisenbart, and B. Xian Chai. 2024. "Stiffness Retention in Cyclic-Loaded CFRP Composites Produced via Novel Automatic Tape Laying." *Journal of Composites Science* 8 (3): 92.

Chai, B. X., M. Gunaratne, M. Ravandi, J. Wang, T. Dharmawickrema, A. Di Pietro, J. Jin, and D. Georgakopoulos. 2024. "Smart Industrial Internet of Things Framework for Composites Manufacturing." *Sensors (Switzerland)* 24 (15): 4852.

Chai, B. X., J. Wang, T. Kim Mai Dang, M. Nikzad, B. Eisenbart, and B. Fox. 2024. "Comprehensive Composite Mould Filling Pattern Dataset for Process Modelling and Prediction." *Journal of Composites Science* 8 (4): 153.

Chai, B. X., B. Eisenbart, M. Nikzad, B. Fox, A. Blythe, P. Blanchard, and J. Dahl. 2023. "A Novel Heuristic Optimisation Framework for Radial Injection Configuration for the Resin Transfer Moulding Process." *Composites Part A, Applied Science and Manufacturing* 165:107352. https://doi.org/10.1016/j.compositesa.2022.107352.

da Silva, R. Vilarim, H. Voltz, A. Itman Filho, M. Xavier Milagre, and C. de Souza Carvalho Machado. 2021. "Hybrid Composites with Glass Fiber and Natural Fibers of Sisal, Coir, and Luffa Sponge." *Journal of Composite Materials* 55 (5): 717–728. https://doi.org/10.1177/0021998320957725.

Elhadi, A., S. Amroune, M. Slamani, M. Arslane, and M. Jawaid. 2024. "Assessment and Analysis of Drilling-Induced Damage in Jute/Palm Date Fiber-Reinforced Polyester Hybrid Composite." *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-023-05251-0.

Elhadi, A., S. Amroune, M. Slamani, M. Jawaid, U. Koklu, and T. Bidi. 2024. "Evaluation of Drilling by Induced Delamination of Hybrid Biocomposites Reinforced with Natural Fibers: A Statistical Analysis by RSM." *Journal of Composite Materials* 58 (23): 2515–2530. https://doi.org/10.1177/00219983241271035.

Elhadi, A., M. Slamani, S. Amroune, M. Arslane, J.-F. Chatelain, M. Jawaid, and T. Bidi. 2024. “Precision Drilling Optimization in Jute/Palm Fiber Reinforced Hybrid Composites.” *Measurement* 236:115066. https://doi.org/10.1016/j.measurement.2024.115066.

Ferfari, O., A. Belaadi, M. Boumaaza, S. Amroune, H. Alshahrani, and M. Ka Khan. 2024. “Mechanical Properties and Statistical Analysis of Syagrus Romanzoffiana Palm Cellulose Fibers.” *Journal of Composite Materials* 58 (6): 755–778. https://doi.org/10.1177/00219983241231833.

Fnides, M., S. Amroune, A. Belaadi, K. Saada, B. Xian Chai, M. M. S. Abdullah, I. M. H. Alshaikh, D. Ghernaout, and A. Al-Khawlani. 2024. “Modeling and Optimizing the Alkaline Treatment Process to Enhance the Date Palm Fibers’ Tensile Mechanical Properties Using RSM.” *Journal of Natural Fibers* 21 (1): 2384663. https://doi.org/10.1080/15440478.2024.2384663.

Gao, W., S. W. Kim, H. Bosse, H. Haitjema, Y. L. Chen, X. D. Lu, W. Knapp, A. Weckenmann, W. T. Estler, and H. Kunzmann. 2015. “Measurement Technologies for Precision Positioning.” *CIRP Annals* 64 (2): 773–796. https://doi.org/10.1016/j.cirp.2015.05.009.

Gheribi, H., S. Teyar, M. Boumaaza, A. Belaadi, B. Xian Chai, M. M. S. Abdullah, A. A. Gelgelu, and I. Klimkina. 2024. “Statistical Study of the Mechanical Behavior of the New Fiber from the Strelitzia Juncea Plant Fibers: Application in Ecological Yarns.” *Journal of Natural Fibers* 21 (1): 2396905. https://doi.org/10.1080/15440478.2024.2396905.

Hachaichi, A., S. Nekkaa, S. Amroune, M. Jawaid, O. Y. Alothman, and A. Dufresne. 2022. “Effect of Alkali Surface Treatment and Compatibilizer Agent on Tensile and Morphological Properties of Date Palm Fibers-Based High Density Polyethylene Biocomposites.” *Polymer Composites* 43 (10): 7211–7221. https://doi.org/10.1002/pc.26784.

Heraiz, H., C. Farsi, H. Makri, S. Amroune, A. Belaadi, K. Saada, M. Zaoui, and M. Ismail Beddiar. 2024. “Assessment of Mechanical and Physicochemical Properties of Palm Fiber Composites: Effect of Alkaline Treatment and Volume Alterations.” *Journal of Composite Materials* 58 (15): 1789–1800. https://doi.org/10.1177/00219983241246614.

Kanyilmaz, A., A. Gökhan Demir, M. Chierici, F. Berto, L. Gardner, S. Yagnanna Kandukuri, P. Kassabian, et al. 2022. “Role of Metal 3D Printing to Increase Quality and Resource-Efficiency in the Construction Sector.” *Additive Manufacturing* 50:102541. https://doi.org/10.1016/j.addma.2021.102541.

Kir, M., M. Boudiaf, A. Belaadi, M. Boumaaza, M. Bourchak, and D. Ghernaout. 2024. “Extracting and Characterizing of a New Vegetable Lignocellulosic Fiber Produced from C. Humilis Palm Trunk for Renewable and Sustainable Applications.” *International Journal of Biological Macromolecules* 281:136495. https://doi.org/10.1016/j.ijbiomac.2024.136495.

Ladaci, N., A. Saadia, A. Belaadi, M. Boumaaza, B. Xian Chai, M. M. S. Abdullah, A. Al-Khawlani, and D. Ghernaout. 2024. “ANN and RSM Prediction of Water Uptake of Recycled HDPE Biocomposite Reinforced with Treated Palm Waste W. Filifera.” *Journal of Natural Fibers* 21 (1): 2356697. https://doi.org/10.1080/15440478.2024.2356697.

Larue, J.-F., D. Brown, and M. Viala. 2015. “How Optical CMMs and 3D Scanning Will Revolutionize the 3D Metrology World.” In *Integrated Imaging and Vision Techniques for Industrial Inspection: Advances and Applications*, edited by Z. Liu, H. Ukida, P. Ramuhalli, and K. Niel, 141–176. London: Springer London.

Lekrine, A., A. Belaadi, A. Makhlouf, S. Amroune, M. Bourchak, H. Satha, and M. Jawaid. 2022. “Structural, Thermal, Mechanical and Physical Properties of Washingtonia Filifera Fibres Reinforced Thermoplastic Biocomposites.” *Materials Today Communications* 31:103574. https://doi.org/10.1016/j.mtcomm.2022.103574.

Mahmood, S., A. J. Qureshi, and D. Talamona. 2018. “Taguchi Based Process Optimization for Dimension and Tolerance Control for Fused Deposition Modelling.” *Additive Manufacturing* 21: 183–190. https://doi.org/10.1016/j.addma.2018.03.009.

Makhlouf, A., A. Belaadi, S. Amroune, M. Bourchak, and H. Satha. 2022. “Elaboration and Characterization of Flax Fiber Reinforced High Density Polyethylene Biocomposite: Effect of the Heating Rate on Thermo-Mechanical Properties.” *Journal of Natural Fibers* 19 (10): 3928–3941. https://doi.org/10.1080/15440478.2020.1848737.

Maleki, R., M. H. Hadi, M. Kubouchi, and Y. Arao. 2019. “Experimental Study on Drilling of Jute Fiber Reinforced Polymer Composites.” *Journal of Composite Materials* 53 (3): 283–295. https://doi.org/10.1177/0021998318782376.

Pailoor, S., H. N. Narasimha Murthy, and T. N. Sreenivasa. 2021. “Drilling of In-Line Compression Molded Jute/Polypropylene Composites.” *Journal of Natural Fibers* 18 (1): 91–104. https://doi.org/10.1080/15440478.2019.1612309.

Rajmohan, T., K. Palanikumar, and M. Kathirvel. 2012. “Optimization of Machining Parameters in Drilling Hybrid Aluminium Metal Matrix Composites.” *Transactions of Nonferrous Metals Society of China* 22 (6): 1286–1297. https://doi.org/10.1016/S1003-6326(11)61317-4.

Ravikumar, P., G. Rajeshkumar, P. Manimegalai, K. R. Sumesh, M. R. Sanjay, and S. Siengchin. 2022. “Delamination and Surface Roughness Analysis of Jute/Polyester Composites Using Response Surface Methodology: Consequence of Sodium Bicarbonate Treatment.” *Journal of Industrial Textiles* 51 (1_suppl): 360S–377S. https://doi.org/10.1177/15280837221077040.

Saada, K., S. Amroune, A. Belaadi, M. Zaoui, I. M. H. Alshaikh, and D. Ghernaout. 2024. “Enhancing the Mechanical Characteristics of Eco-Friendly Composite Materials: Taguchi and RSM Optimization.” *Journal of Natural Fibers* 21 (1): 2427704. https://doi.org/10.1080/15440478.2024.2427704.

Saada, K., C. Farsi, S. Amroune, M. Fnides, M. Zaoui, and H. Heraiz. 2024. “Examining the Bending Test Properties of Bio-Composites Strengthened with Fibers Through a Combination of Experimental and Modeling Approaches.” *Journal of Composite Materials* 58 (12): 1483–1499. https://doi.org/10.1177/00219983241240819.

Saada, K., M. Zaoui, S. Amroune, R. Benyettou, A. Hechaichi, M. Jawaid, M. Hashem, and I. Uddin. 2024. “Exploring Tensile Properties of Bio Composites Reinforced Date Palm Fibers Using Experimental and Modelling Approaches.” *Materials Chemistry and Physics* 314:128810. https://doi.org/10.1016/j.matchemphys.2023.128810.

Saif, Y., Y. Yusof, A. Zafiah M Rus, A. M. Ghaleb, S. Mejjaouli, S. Al-Alimi, D. Hissein Didane, K. Latif, A. Zuhra Abdul Kadir, and H. Alshalabi. 2023. “Implementing Circularity Measurements in Industry 4.0-Based Manufacturing Metrology Using MQTT Protocol and Open CV: A Case Study.” *PLOS ONE* 18 (10): e0292814.

Saleem, M., L. Toubal, R. Zitoune, and H. Bougherara. 2013. “Investigating the Effect of Machining Processes on the Mechanical Behavior of Composite Plates with Circular Holes.” *Composites Part A, Applied Science and Manufacturing* 55: 169–177. https://doi.org/10.1016/j.compositesa.2013.09.002.

Sheth, S. M., and P. M. George. 2018. “Investigation of Machining Process Parameters in the Context of Geometric Dimensioning and Tolerancing.” (GD&T), Thesis., Gujarat Technological University. Ahmedabad, 2018. [Online].

Shevtsov, S., S. Hsyung Chang, I. Zhilyaev, B. Xian Chai, and N. Snezhina. 2024. “Numerical Study of Thin-Walled Polymer Composite Part Quality When Manufactured Using Vacuum Infusion with Various External Pressure Controls.” *Polymers* 16 (5): 654.

Srinivasan, S., S. Thirumurugaveerakumar, N. Nagarajan, N. Mohammed Raffic, and K. Ganesh Babu. 2021. “A Review of Optimization Techniques in Machining of Composite Materials.” *Materials Today: Proceedings* 47: 6811–6814. https://doi.org/10.1016/j.matpr.2021.05.136.

Tablit, S., R. Krache, S. Amroune, M. Jawaid, A. Hachaichi, A. Safwan Ismail, and A. Meraj. 2024. “Effect of Chemical Treatments of Arundo Donax L. Fibre on Mechanical and Thermal Properties of the PLA/PP Blend Composite Filament for FDM 3D Printing.” *Journal of the Mechanical Behavior of Biomedical Materials* 152:106438. https://doi.org/10.1016/j.jmbbm.2024.106438.

Teyar, S., H. Gheribi, M. Boumaaza, A. Belaadi, B. Xian Chai, M. M. S. Abdullah, I. M. H. Alshaikh, A. Al-Khawlani, and D. Ghernaout. 2024. “Analyzing the Strelitzia Juncea Cellulosic Fibers Mechanical Properties’ Experimental Data Using Various Statistical Methods.” *Journal of Natural Fibers* 21 (1): 2394142. https://doi.org/10.1080/15440478.2024.2394142.

Varikkadinmel, B., D. Kaushik, A. Mahajan, and I. Singh. 2024. “Machinability of Basalt/PBS Sustainable Composites: A Comprehensive Experimental Analysis.” *Materials & Manufacturing Processes* 39 (14): 2033–2047. https://doi.org/10.1080/10426914.2024.2390362.

Zhu, Z., S. Sui, J. Sun, J. Li, and Y. Li. 2017. “Investigation on Performance Characteristics in Drilling of Ti6Al4V Alloy.” *International Journal of Advanced Manufacturing Technology* 93 (1): 651–660. https://doi.org/10.1007/s00170-017-0508-6.

Zitoune, R., V. Krishnaraj, and F. Collombet. 2010. “Study of Drilling of Composite Material and Aluminium Stack.” *Composite Structures* 92 (5): 1246–1255. https://doi.org/10.1016/j.compstruct.2009.10.010.