Experimental investigation and optimization of delamination factors in the drilling of jute fiber–reinforced polymer biocomposites with multiple estimators

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Received: 11 May 2021 / Accepted: 28 June 2021 / Published online: 13 July 2021
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Abstract
Currently, the manufacture of composite structures often requires material removal operations using a cutting tool. Indeed, since biocomposites are generally materials that do not conduct electricity, electro-erosion cannot be utilized. As a result, the processes that can be used not only the unconventional method of abrasive water jet but also conventional machining, such as drilling. Delamination factors ($F_d$) are widely recognized for controlling the damaged area (delamination) induced by drilling in industry. As discussed in the literature, several approaches are available to evaluate and quantify the delamination surrounding a hole. In this context, the objective of this study is to compare the three $F_d$ evaluation methods that have been most frequently used in previous investigations. To this end, three spindle and feed speeds and three Brad and Spur drills (BSD) tool diameters were selected ($L_{27}$) for drilling 155-g/m² density jute fabric–reinforced polyester biocomposites. The desirability function (DF) was further made to optimize the drilling parameters. The response surface methodology (RSM) and artificial neural networks (ANNs) were applied to validate the results obtained experimentally as well as to predict the behavior of the structure depending on the cutting conditions.

Keywords Drilling/machining · Composite delamination · Statistical properties/methods · RSM/ANN · Genetic algorithm optimization

1 Introduction

Natural fibers are biodegradable materials and are often considered neutral with respect to CO₂ emissions into the atmosphere because their biodegradation only produces a certain amount of carbon dioxide [1]. Biocomposites made of natural fibers are therefore easier to recycle. Moreover, if their matrix is biodegradable, these materials are also compostable after grinding when the material is too degraded [2]. Biocomposites are mainly used in several fields, such as construction, sports, and transport [3, 4]. On the other hand, the manufacturing processes and implementations of these biomaterials are poorly controlled because of the natural origin of the biofibers. Consequently, to better understand the behavior of biocomposites, in-depth scientific studies have been conducted by several researchers [5, 6]. Currently, a wide variety of plant fibers are currently used as reinforcements for different matrices [7, 8], such as sisal [9], jute [10], Agave americana L. [11], flax [4, 12–14], Washingtonia filifera [15], date palm [16, 17], and pineapple [18].

To date, in several studies, the machining process has been investigated during the drilling of polymer matrix composites reinforced synthetic fibers (glass, aramid, and carbon) to study the interaction mechanisms between the cutting tools and the material and to determine the most influential machining parameters with respect to the behavior of the fibers; thus, the most suitable process can be chosen [19–27]. On the other
hand, there have been a number of studies in the literature that address the machining of biocomposites [28–54] as well as comparative studies between biocomposites and glass fiber composites for example [55]. However, the milling process [56, 57] and orthogonal cutting [58, 59] have been much less studied.

Chandramohan and Rajesh [60] showed that the drill geometry has an effect on the drilling torque. These researchers relied on the drilling torque results of two types of drills for the prediction of the drilling torque when machining biocomposites. Indeed, the drilling torque with a multisided drill was greater than that with a twist drill at a low spindle speed. The effect of the drill geometry on the drilling quality of laminated composites has been the subject of much research [61]. In investigations on the drilling of flax fiber–reinforced plastics (FFRPs) using drills of different geometries, Rezghi Maleki et al. [62] found that due to the difference in the cutting mechanism, the type of drill used had a great influence on the thrusting force and thereby on the delamination size. Furthermore, their ANOVA showed that the choice of drill bit had a great impact on the delamination factor (67.27%) and surface roughness (74.44%). However, the tool geometry has been shown to have less impact on the residual tensile strength of FFRP composites [63].

Bajpai and Singh [30] experimentally investigated the drilling behavior of the polypropylene (PP) matrix–reinforced sisal fiber biocomposite (sisal/PP). In this study, the effect of cutting parameters (spindle speed, feed speed, and tool geometry) and drill geometry (twist drill and tool trepanation) was investigated. The investigation, using ANOVA, showed that the influence of the tool geometry is more important than other parameters. In other work presented by Bajpai et al. [31], the drilling performance of the biodegradable biocomposite sisal and Grewia optiva–reinforced polylactic acid (PLA) was studied using tool geometries, namely, twist, Jo, and parabolic drills with 8-mm-diameter solid carbide. The RSM method was used to optimize the cutting parameters in terms of the drilling thrust force and torque and drilling-induced damage. This study showed that the geometry of the tools is an important factor influencing the forces and damage induced by drilling. Davim and Reis [64] experimentally studied the influence of the tool material and geometry, such as a straight shank drill bit and Brad and Spur drill. Their work focused on producing less entry and exit delamination on carbon-reinforced epoxy composite laminates. Chaudhary and Gohil [35] conducted an experimental study of the drilling performance, e.g., the thrust force, torque, and exit delamination factor, on bidirectional cotton fiber–reinforced polyester biocomposites by varying the cutting parameters, namely, the spindle speed and feed speed geometry of a 10-mm-diameter drill. In addition, the tests were carried out with the aid of the Taguchi orthogonal method ($L_{27}$) to optimize the cutting forces and damage using a one-way analysis (ANOVA) method. A comparative study developed by Durão et al. [55] between two composite materials (epoxy matrix–reinforced glass and sisal fibers) was conducted to analyze the effect of the two different tungsten carbide drill tool geometries (6 mm in diameter). The machining operation was realized with a classical helical drill and a Brad-type (BSD) tool. In addition, the experiments were carried out at a constant spindle speed of 2800 rev/min with two feed rates (0.05 and 0.2 mm/rev). From this work, the authors concluded that a maximum thrust force and delamination extension depend on drilling conditions, tool geometry, and material and for higher feed rates, thrust force and delamination extension are superior. Venkateshwaran and ElayaPerumal [36]
investigated the influence of drilling conditions (spindle speed and feed speed) using a constant 10-mm-diameter HSS (high-speed steel) drill on the exit delamination factor damage of an epoxy matrix–reinforced short banana fiber green biocomposite. The damage was analyzed using the ultrasonic C-scan technique. Moreover, the obtained results were evaluated using ANOVA. Ismail et al. [39] studied the drilling behavior of different drill tool diameters on biodegradable composite laminates made of natural hemp fibers by varying the spindle speed and feed speed. The Taguchi method according to the $L_{16}$ array design was chosen. These authors concluded that the optimal results for delamination and sur-

### Table 1 Process parameters available in open literature for drilling of jute fiber–reinforced polymer composites

| Matrix       | Fiber                        | Fiber content (% w/w) | Cutting parameters | Tool material | Drill diameter d (mm) | Feed rate f (mm/rev) | Spindle speed N (rpm) | References |
|--------------|------------------------------|-----------------------|--------------------|---------------|-----------------------|----------------------|-----------------------|------------|
| Epoxy        | Unidirectional jute          | -                     |                    | HSS twist drills | 6, 8, 10              | 50, 150, 250 (mm/min) | 1000, 2000, 3000     | [49]       |
| Polyester    | Treated and untreated jute   | 30                    |                    | HSS twist drill | 6                     | 0.03, 0.06, 0.09, 0.12 | 9,42, 15.07, 20.72, 26.36 (m/min) | [50]       |
| Epoxy and polyester | Treated and untreated jute fabric | 30 | | HSS twist drill | 6 | 0.03, 0.06, 0.09, 0.12 | 500, 800, 1100, 1400 | [51] |
| Polypropylene| Jute fabric                  | 30, 40, 50            |                    | Twist drills, Jo drills, parabolic drills | 8 | 0.05, 0.12, 0.19 | 900, 1800, 2800 | [52] |
| Epoxy        | Jute fabric                  | 43                    |                    | HSS twist drill; CoroDrill 854, N$_2$OC; CoroDrill 856, N$_2$OC Brad & Spur, coated carbide | 6, 9, 12 | 0.04, 0.06, 0.08 | 1000, 2000, 3000 | [67] |
| Polyester    | Glass-sisal-jute             | -                     |                    | HSS twist drill; CoroDrill 854, N$_2$OC Brad & Spur, coated carbide | 6, 9, 12 | 0.04, 0.06, 0.08 | 1000, 2000, 3000 | [67] |
| Vinyl-ester  | Untreated Vetiver-jute-glass  | -                     |                    | Twist drills, 60°, 90°, 120°, 150° | 10 | 0.1, 0.2, 0.3, 0.4 | 500, 1000, 1500, 2000 | [68] |
| Vinyl-ester  | Treated (NaOH) Vetiver-jute-glass | - | | Twist drills, 60°, 90°,120°, 150° | 10 | 0.1, 0.2, 0.3, 0.4 | 500, 1000, 1500, 2000 | [69] |
| Epoxy        | Glass-flax-jute              | -                     |                    | Drill bit carbide | 6, 8, 10 | 0.1, 0.2, 0.3 | 600, 1200, 1800 | [70] |
| Polyester    | Short jute fiber 5, 10 and 15 mm | 40 | | Brad and Spur drills twist drills | 5, 7, 10 | 0.1, 0.2, 0.3 | 600, 1200, 1800 | [28] |
| Epoxy        | Jute fabric (210 g/m$^2$)    | 40                    |                    | Brad and Spur drills, Twist drills (HSS), Twist drills (HSS-TiN) | 5, 7, 10 | 0.1, 0.2, 0.3 | 600, 1200, 1800 | [46] |
| Polyester    | Jute fabric and steel fibers | 40                    |                    | HSS, 90°, 120°, 150° | 8, 10,12 | 0.1, 0.2, 0.3 | 500, 1250, 2000 | [71] |
| Polypropylene| Unidirectional Jute          | 30                    |                    | HSS, Co-HSS | 2, 3, 4 | 0.1, 0.2, 0.3 | 600, 1200, 2700 | [72] |
| Epoxy        | Jute and flax fabric         | -                     |                    | HSS, HSS-TiN, WC | 4 | 0.01, 0.015, 0.020 | 2500, 5000, 7500 | [56] |
| Polyester    | Jute fabric (155 g/m$^2$)    | 30                    | Brad and Spur drills | 5, 7, 10 | 0.1, 0.2, 0.3 | 600, 1200, 1800 | [28] |

CS solid carbide; CSC TiN-coated solid carbide; HSS high-speed steel; BSD Brad and Spur drill

### Table 2 Different delamination measuring equations [74–78]

| Method estimation | Assessment parameter | Formula |
|-------------------|----------------------|---------|
| $Fd_1$            | Delamination factor (diameter) | $F_d = \frac{D_{max}}{D_{nom}}$ |
| $Fd_2$            | Delamination factor (area) | $F_d = \frac{A_{max}}{A_0}$ |
| $Fd_3$            | Delamination factor (area) | $F_d = \frac{A_d}{A_0}$ |

$A_0$ Drilled area (hole area), $A_d$ delamination area in the vicinity of the drilled hole, $A_{max}$ delamination area related to $D_{max}$, $D$ nominal diameter of drilled hole, $D_{max}$ maximum diameter of delamination, $F_d$ conventional delamination factor
face roughness were obtained at a lower spindle speed and feed speed. In a similar work, Abilash and Sivapragash [41] studied the effect of experimental drilling parameters using the Taguchi method ($L_{18}$ array design). In this work, the force output, torque, and delamination were studied by drilling holes in green biodegradable composite polyester laminates reinforced with natural fibers treated with bamboo. ANOVA was adopted to determine which drilling parameters were statistically significant. Athijayamani et al. [37] studied the drilling behavior of polyester-reinforced sisal and Roselle fiber hybrid green composites. The fibers were treated using an alkali treatment of 10% NaOH for different durations. A constant drill (8-mm HSS) was used to perform the drilling process. The obtained results suggest that a better dimensional stability was reached by using a 30% by weight of fiber treatment for 8 h. Recently, Lotfi et al. [14] examined the drilling performance of a developed high-strength of natural fiber–reinforced composites (NFRC) laminate (flax/PLA) and evaluated the influence of the cutting parameters, feed rate, and spindle speed using two drills (HSS twist drill and carbide drill) on the generation of the minimum drilling force and drilling-induced damage. The authors concluded that the lowest damage with a good quality of the hole of the flax/PLA biocomposite is achieved with the HSS twist drill, a spindle speed of 2550 rpm and a feed rate of 0.08 mm/rev. In addition, this drill demonstrated better hole quality than carbide drills and results in a nearly 60% lower thrust force. In other recent work, Parthipan et al. [65] conducted interesting research that focused on the effect of drilling parameters such as the spindle speed, feed rate, and drilling diameters on jute/polyester staple fiber biocomposites to estimate the

![Fig. 2 Typical holes drilled on jute fabric/polyester biocomposites for three test (#3, #12, and #21): a entrance, b exit and typical damage in drilling, and c determination of different parameters for calculation the delamination factors at the drill and resulting image obtained with ImageJ software](image-url)
influence of the delamination factor $F_d$. In other recent work by Belaadi et al. [46], an artificial neural network (ANN) model was developed to evaluate the direct and interaction effects of cutting parameters to analyze delamination. In their experiments, epoxy matrix jute fabric sheets were drilled three times for each cutting condition, and the hole exit damage was measured using a high-resolution scanner. The resulting image was subsequently processed by ImageJ software to calculate the delamination factor. The results revealed that delamination is sensitive to each cutting parameter and that a combination of a high spindle speed and a low feed rate can minimize it. Furthermore, the regression analysis established a very good match between the predicted and experimental values of the delamination factor. This model establishes a nonlinear relationship between the drilling parameters and the delamination factor.

### Table 4 Experimental results for delamination factor of the drilled holes at the exit

| Experiment number | Input variables | Output variables |
|-------------------|-----------------|-----------------|
|                  | $f$ (mm/min)    | $N$ (rev/min)   | $d$ (mm) | $F_{d1}$ | $F_{d2}$ | $F_{d3}$ |
| 1                 | -1              | -1              | -1       | 50       | 355     | 5       | 1.12    | 1.12    | 1.02    |
| 2                 | 0               | -1              | -1       | 108     | 355     | 5       | 1.45    | 1.54    | 1.14    |
| 3                 | 1               | -1              | -1       | 190     | 355     | 5       | 1.64    | 2.17    | 1.44    |
| 4                 | -1              | 0               | -1       | 50       | 710     | 5       | 1.18    | 1.25    | 1.08    |
| 5                 | 0               | 0               | -1       | 108     | 710     | 5       | 1.46    | 1.75    | 1.17    |
| 6                 | 1               | 0               | -1       | 190     | 710     | 5       | 1.53    | 2.18    | 1.38    |
| 7                 | -1              | 1               | -1       | 50       | 1400    | 5       | 1.13    | 1.38    | 1.01    |
| 8                 | 0               | 1               | -1       | 108     | 1400    | 5       | 1.24    | 1.68    | 1.09    |
| 9                 | 1               | 1               | -1       | 190     | 1400    | 5       | 1.30    | 1.90    | 1.38    |
| 10                | -1              | -1              | 0        | 50       | 355     | 7       | 1.66    | 1.90    | 1.28    |
| 11                | 0               | -1              | 0        | 108     | 355     | 7       | 1.83    | 2.11    | 1.37    |
| 12                | 1               | -1              | 0        | 190     | 355     | 7       | 1.85    | 2.77    | 1.40    |
| 13                | -1              | 0               | 0        | 50       | 710     | 7       | 1.72    | 1.59    | 1.11    |
| 14                | 0               | 0               | 0        | 108     | 710     | 7       | 1.85    | 1.61    | 1.30    |
| 15                | 1               | 0               | 0        | 190     | 710     | 7       | 1.89    | 1.68    | 1.56    |
| 16                | -1              | 1               | 0        | 50       | 1400    | 7       | 1.59    | 2.10    | 1.29    |
| 17                | 0               | 1               | 0        | 108     | 1400    | 7       | 1.83    | 2.29    | 1.49    |
| 18                | 1               | 1               | 0        | 190     | 1400    | 7       | 1.82    | 2.66    | 1.64    |
| 19                | -1              | -1              | 1        | 50       | 355     | 10      | 1.33    | 2.35    | 1.38    |
| 20                | 0               | -1              | 1        | 108     | 355     | 10      | 1.47    | 2.90    | 1.52    |
| 21                | 1               | -1              | 1        | 190     | 355     | 10      | 1.49    | 2.94    | 1.78    |
| 22                | -1              | 0               | 1        | 50       | 710     | 10      | 1.43    | 2.68    | 1.54    |
| 23                | 0               | 0               | 1        | 108     | 710     | 10      | 1.45    | 2.90    | 1.73    |
| 24                | 1               | 0               | 1        | 108     | 710     | 10      | 1.51    | 2.96    | 1.82    |
| 25                | -1              | 1               | 1        | 50       | 1400    | 10      | 1.73    | 2.88    | 1.68    |
| 26                | 0               | 1               | 1        | 108     | 1400    | 10      | 1.76    | 2.87    | 1.71    |
| 27                | 1               | 1               | 1        | 190     | 1400    | 10      | 1.84    | 3.07    | 2.02    |

### Table 5 Mathematical models for different estimator delamination factors

| RSM response | $F_{d1}$ | $F_{d2}$ | $F_{d3}$ |
|--------------|----------|----------|----------|
|              | $-1.909324+7.86866 \times 10^{-3} f-6.23020 \times 10^{-4} \times N+0.87873 \times d-7.06429 \times 10^{-7} \times f \times N-3.01359 \times 10^{-8} \times f \times d+1.07601 \times 10^{-4} \times N \times d-1.46448 \times 10^{-7} \times f^{2}-2.28431 \times 10^{-8} \times N^{2}-0.059233 \times d^{2}$ |
|              | $0.12200+0.012543 \times f-1.07049 \times 10^{-3} \times N+0.14591 \times d-2.36589 \times 10^{-7} \times f \times N-6.7351 \times 10^{-8} \times f \times d+3.07495 \times 10^{-7} \times N \times d-6.93560 \times 10^{-9} \times f^{2}+7.00806 \times 10^{-7} \times N^{2}+9.40370 \times 10^{-7} \times d^{2}$ |
|              | $0.70471+1.64052 \times 10^{-3} f-2.69733 \times 10^{-4} \times N+0.047514 \times d+2.9233 \times 10^{-7} \times f \times N-2.6833 \times 10^{-5} \times f \times d+5.07080 \times 10^{-3} \times N \times d-3.02775 \times 10^{-6} \times f^{2}-1.81812 \times 10^{-8} \times N^{2}+9.11111 \times 10^{-1} \times d^{2}$ |
Most of the damage induced by the drill during the drilling process is located in the internal or external region of the biocomposite, where the evaluation of the latter is a difficult task. To quantify the size, shape, and region of the delamination area, it is essential to use microstructural analysis supported by image processing software. The visual inspection technique

| Table 6 | ANOVA for the response surface quadratic model for different delamination factors |
|---------|-----------------------------------------------------------------------------------|
| Source  | DF    | SS   | MS    | F value | P value | Cont. % | Remarks |
| a) ANOVA for delamination factor $F_d_1$ |       |      |       |         |         |         |         |
| Model   | 9     | 1.41 | 0.16  | 36.46   | < 0.0001 |         | Significant |
| $f$     | 1     | 0.19 | 0.19  | 43.47   | < 0.0001 | 12.02   | Significant |
| $N$     | 1     | 0.017 | 0.017 | 3.94    | 0.0634   | 0.18    |         |
| $d$     | 1     | 0.26 | 0.26  | 60.12   | < 0.0001 | 60.77   | Significant |
| $f \times N$ | 1 | 8.367E-003 | 8.367E-003 | 1.94 | 0.1814  | 0.09    |         |
| $f \times d$ | 1 | 0.034 | 0.034 | 7.93    | 0.0119   | 0.36    | Significant |
| $N \times d$ | 1 | 0.25 | 0.25  | 57.66   | < 0.0001 | 2.66    | Significant |
| $f \times N \times d$ | 1 | 0.029 | 0.029 | 6.69    | 0.0192   | 0.31    | Significant |
| Error   | 17    | 0.073 | 4.309E-003 |       |         | 7.98    | Significant |
| Total   | 26    | 1.49 |       |         |         |         |         |
| b) ANOVA for delamination factor $F_d_2$ |       |      |       |         |         |         |         |
| Model   | 9     | 8.38 | 0.93  | 15.61   | < 0.0001 |         | Significant |
| $f$     | 1     | 1.24 | 1.24  | 20.83   | 0.0003   | 13.19   | Significant |
| $N$     | 1     | 0.055 | 0.055 | 0.92    | 0.3515   | 0.59    |         |
| $d$     | 1     | 6.03 | 6.03  | 100.99  | < 0.0001 | 64.15   | Significant |
| $f \times N$ | 1 | 0.094 | 0.094 | 1.57    | 0.2268   | 1.00    |         |
| $f \times d$ | 1 | 0.17 | 0.17  | 2.81    | 0.1122   | 1.81    |         |
| $N \times d$ | 1 | 0.020 | 0.020 | 0.34    | 0.5675   | 0.21    |         |
| $f \times N \times d$ | 1 | 6.465E-003 | 6.465E-003 | 0.11 | 0.7461  | 0.07    |         |
| Error   | 17    | 1.01 | 0.060 |       |         | 0.20    |         |
| Total   | 26    | 9.40 |       |         |         |         |         |
| c) ANOVA for delamination factor $F_d_3$ |       |      |       |         |         |         |         |
| Model   | 9     | 1.77 | 0.20  | 41.58   | < 0.0001 |         | Significant |
| $f$     | 1     | 0.51 | 0.51  | 106.87  | < 0.0001 | 5.43    | Significant |
| $N$     | 1     | 0.063 | 0.063 | 13.29   | 0.0020   | 0.67    | Significant |
| $d$     | 1     | 1.16 | 1.16  | 244.16  | < 0.0001 | 58.34   | Significant |
| $f \times N$ | 1 | 1.439E-003 | 1.439E-003 | 0.30 | 0.5887  | 0.02    |         |
| $f \times d$ | 1 | 2.708E-004 | 2.708E-004 | 0.057 | 0.8139  | 0.00    |         |
| $N \times d$ | 1 | 0.055 | 0.055 | 11.65   | 0.0033   | 0.59    | Significant |
| $f \times N \times d$ | 1 | 1.232E-003 | 1.232E-003 | 0.26 | 0.6166  | 0.01    |         |
| Error   | 17    | 0.081 | 4.737E-003 |       |         | 0.00    |         |
| Total   | 26    | 1.85 |       |         |         |         |         |

a) $SD_0 = 0.066$, mean = 1.56, coefficient of variation = 4.21%, predicted residual error of sum of squares (PRESS) = 0.21, $R^2 = 95.07\%$, $R^2$ adjusted = 92.47%, $R^2$ predicted = 85.60%, adequate precision = 20.749

b) $SD_0 = 0.24$, mean 2.19, coefficient of variation = 11.13%, predicted residual error of sum of squares (PRESS) = 2.25, $R^2 = 89.21\%$, $R^2$ adjusted = 83.49%, $R^2$ predicted = 76.07%, adequate precision = 12.8777

c) $SD_0 = 0.069$, mean 1.42, coefficient of variation = 4.85%, predicted residual error of sum of squares (PRESS) = 0.18, $R^2 = 96.65\%$, $R^2$ adjusted = 93.35%, $R^2$ predicted = 90.14%, adequate precision = 24.004
creates special problems for quantifying the delamination of biocomposites. From the literature review, it can be stated that few research studies have discussed the area of drilling of natural fiber biocomposites. In other words, there is still an important field of research in the field of machining biocomposites. In this context, this study focuses on the effect of drilling machining parameters on the delamination factor ($F_d$) of woven jute fabric/
polyester (WJFP)–reinforced biocomposites. For comparison, different expressions for the evaluation of the delamination damage factor in drilling were used. A tool with different diameters was chosen, such as a wood drill (Brad and Spur), to estimate the influence and the simultaneous interaction of the input parameters on the $F_d$ factor. Moreover, the response surface methodology (RSM) and artificial neural networks (ANNs) are applied for $F_d$ data to estimate the influence and interaction of the machining parameters at the exit of the drilling.
delamination. Additionally, optimization functions such as the desirability based on the RSM, genetic algorithm (GA), and function (fmincon) were used to confirm the optimal combination of cutting parameters (feed rate \( f \), spindle speed \( N \), and drill diameter \( d \)) for the biocomposite studied in this work.

### 2 Materials and methods

#### 2.1 Biocomposites manufacturing

In the present study, the reinforcement consisted of bidirectional jute fibers (Fig. 1) with a basis weight of 155 g/m² (28 ×...
23 threads/100 mm) and unsaturated polyester resin with a density of 1.410 kg/m³. Hence, the average diameter of jute yarn measured varies between 550 and 1000 μm. These yarns are produced with a surface angle torsion range 10 to 13° and a linear density of 27,021 tex (g/1000 m). In addition, the tensile strength is 91.69 MPa, the mean strain is 2.18 %, and tensile modulus is 3163 MPa [28]. The polyester resin and jute fabric were supplied locally. The average mechanical characteristics of the unsaturated polyester resin, namely, a 32 MPa tensile strength, a 2.7% elongation, and a Young’s modulus equal to 1.12 GPa, were described by Belaadi et al. [28]. The biocomposite samples (jute/polyester) were developed using the contact molding and hand lay-up process while the woven fabric was previously fabricated and then cut to dimensions of 280 mm × 280 mm. The woven fabric used in this study is a multiple yarns comprise a woven fabric, crossing each other at right angles to form the grain. The obtained biocomposite samples were rectangular sheets, which were 280 mm in length, 280 mm in width, and approximately 5.5±0.2 mm in thickness, consisting of five layers are of the same orientation (0/90). Furthermore, the fiber content of the biocomposite laminates was 30 wt%. The processing of the unsaturated polyester resin, whose proportions are approximately 1 to 1.5% by mass, was carried out by catalysis and polymerization. The mixture (fiber/matrix) was cured and kept in the mold for 24 h under standard atmospheric pressure (1 bar) and at an ambient temperature of 26°C until the end of the polymerization. To allow the mixture to polymerize, the plates were kept in open air for 15 days to ensure complete polymerization of the resin. The samples were finally postcured at a temperature of 60°C in an oven for 5 h. The specimens for the drilling experiments were cut to the following dimensions, namely, 260 × 90 × 5.5 mm³, using a diamond saw with water lubrication to avoid excessive heating during cutting. Subsequently, the specimens were air-dried at room temperature (23°C) for 20 days.

2.2 Drilling experimental procedures

The drilling tests were performed using a MOMAC universal milling machine equipped with a 1400-rpm spindle with a feed rate of 4.6 to 1040 mm/rev [28, 46]. During the drilling phase, to limit the bending of the parts to avoid amplifying the defects at the exit of the hole, a solid steel support was placed...
under the composite parts. To carry out the drilling tests, the geometry of the workpiece was $260 \times 90 \times 5.5 \text{ mm}^3$, and Fig. 1 shows a workpiece fixation system. In this study, all the features (geometry, material, and type) of the three drills are the same except for their diameters (5 mm, 7 mm, and 10 mm). The drilling of the holes in this study was performed in a single phase. To ensure a well-sized hole and prevent the wear of the drilling tool, the drill bit was renewed every four to five operations. The drilling operations were performed dry, without coolant. The spindle speeds were 355, 710, and 1400 rpm, and three feed rates were chosen (50, 108, and 190 mm/min). The cutting parameters were selected following a literature review presented in Table 1.
were considered (Table 3). Table 4 shows the values of the response parameters $F_{d1}$, $F_{d2}$, and $F_{d3}$ determined under different experimental configurations. The experimental design of this study was an orthogonal ($L_{27}$) central composite design (CCD) array using Design-Expert version 10. This design was adopted to limit the number of experiments, and thus, the experimental expense and time was reduced.

### 3 Results and discussion

#### 3.1 Influence of the drilling parameters on the delamination factor

The condition of the drilled holes at the exit and entrance (#3, #12, and #21) with feed rates of 50, 108, and 190 mm/min, and a spindle speed of 355 rpm was examined (Fig. 2a and b). The machined jute/unsaturated polyester fiber composites were digitally imaged with a standard scanner with a resolution of 4800 pixels. Image processing software was used to create two concentric circles. The damage caused by drilling the holes in the composite is related to the delamination factor. The choice of cutting parameters and the fiber fabric used during the design process is a fundamental concern for delamination. Indeed, the determination of the delamination factor $F_d$ of biocomposite using Brad and Spur drills (BSD) is related to many factors, such as the feed rate, spindle speed, and tool diameter. Additionally, it is appropriate to determine the different parameters for the calculation of the delamination factors performed on the drills and to analyze the image obtained through this calculation (Fig. 2c).

#### 3.2 Response surface methodology and ANOVA for delamination factor

The response surface analysis method was used to process the experimental results to find the correlation that exists between delamination and the different parameters of the drilling. Indeed, the response surface methodology (RSM) is a mathematical and statistical approach that is generally used in engineering sciences and cutting operations [79] based on an empirical approach that aims to find the relationship between input and output parameters, such as the delamination $F_d$, by changing the different cutting parameters when drilling the biocomposites. The mathematical equations of the regression are reported in Table 5 for the different delamination factors obtained by Design-Expert software, which recommended the quadratic models. These models are second-order mathematical models based on the RSM. Figure 3 shows the relationship between the probability of the residuals and the predicted and experimental values of the delamination $F_d$ for $F_{d1}$, $F_{d2}$, and $F_{d3}$. For the $F_d$ delamination residuals, the normal probability curve shown in Fig. 3a–c indicates that

### Table 9 Comparison between RSM and ANN approach for different $F_d$

| Order | $F_{d1}$ | $F_{d2}$ | $F_{d3}$ |
|-------|---------|---------|---------|
|       | EXP     | RSM     | ANN     | EXP     | RSM     | ANN     | EXP     | RSM     | ANN     |
| 1     | 1.12    | 1.24    | 1.12    | 1.12    | 1.25    | 1.15    | 1.02    | 1.05    | 1.09    |
| 2     | 1.45    | 1.46    | 1.45    | 1.54    | 1.67    | 1.54    | 1.14    | 1.17    | 1.21    |
| 3     | 1.64    | 1.60    | 1.68    | 2.17    | 2.19    | 2.17    | 1.44    | 1.37    | 1.39    |
| 4     | 1.18    | 1.19    | 1.18    | 1.25    | 1.15    | 1.25    | 1.08    | 1.04    | 1.01    |
| 5     | 1.46    | 1.39    | 1.46    | 1.75    | 1.52    | 1.51    | 1.17    | 1.16    | 1.12    |
| 6     | 1.53    | 1.52    | 1.66    | 2.18    | 1.97    | 1.86    | 1.38    | 1.38    | 1.35    |
| 7     | 1.13    | 1.07    | 1.13    | 1.38    | 1.45    | 1.38    | 1.01    | 1.01    | 1.08    |
| 8     | 1.24    | 1.25    | 1.25    | 1.68    | 1.73    | 1.68    | 1.09    | 1.15    | 1.17    |
| 9     | 1.30    | 1.33    | 1.31    | 1.90    | 2.05    | 1.90    | 1.38    | 1.38    | 1.35    |
| 10    | 1.66    | 1.62    | 1.66    | 1.90    | 1.72    | 1.90    | 1.28    | 1.20    | 1.22    |
| 11    | 1.83    | 1.81    | 1.83    | 2.11    | 2.07    | 2.11    | 1.37    | 1.31    | 1.32    |
| 12    | 1.85    | 1.90    | 1.85    | 2.77    | 2.47    | 2.47    | 1.40    | 1.51    | 1.51    |
| 13    | 1.72    | 1.65    | 1.65    | 1.59    | 1.64    | 1.41    | 1.11    | 1.22    | 1.18    |
| 14    | 1.85    | 1.82    | 1.86    | 1.61    | 1.94    | 1.61    | 1.30    | 1.35    | 1.32    |
| 15    | 1.89    | 1.89    | 1.81    | 1.68    | 2.28    | 1.78    | 1.56    | 1.56    | 1.53    |
| 16    | 1.59    | 1.68    | 1.59    | 2.10    | 1.99    | 2.10    | 1.29    | 1.27    | 1.31    |
| 17    | 1.83    | 1.82    | 1.83    | 2.29    | 2.19    | 2.40    | 1.49    | 1.40    | 1.44    |
| 18    | 1.82    | 1.85    | 1.81    | 2.66    | 2.40    | 2.49    | 1.64    | 1.63    | 1.64    |
| 19    | 1.33    | 1.31    | 1.34    | 2.35    | 2.57    | 2.71    | 1.38    | 1.43    | 1.49    |
| 20    | 1.47    | 1.44    | 1.47    | 2.90    | 2.80    | 2.90    | 1.52    | 1.55    | 1.61    |
| 21    | 1.49    | 1.46    | 1.54    | 2.94    | 3.04    | 2.94    | 1.78    | 1.74    | 1.77    |
| 22    | 1.43    | 1.45    | 1.33    | 2.68    | 2.53    | 2.72    | 1.54    | 1.52    | 1.58    |
| 23    | 1.45    | 1.56    | 1.44    | 2.90    | 2.70    | 2.90    | 1.73    | 1.64    | 1.73    |
| 24    | 1.51    | 1.56    | 1.51    | 2.96    | 2.88    | 2.96    | 1.82    | 1.84    | 1.90    |
| 25    | 1.73    | 1.70    | 1.73    | 2.88    | 2.94    | 2.88    | 1.68    | 1.66    | 1.60    |
| 26    | 1.76    | 1.79    | 1.76    | 2.87    | 3.02    | 2.96    | 1.71    | 1.80    | 1.75    |
| 27    | 1.84    | 1.75    | 1.85    | 3.07    | 3.06    | 3.07    | 2.02    | 2.02    | 1.97    |
the residuals form a straight line, implying that the errors are correctly distributed. These results demonstrate that the fit of the model is excellent. Thus, the results obtained show satisfactory agreement of the regression model since the predicted values are statistically identical to the experimental values as shown in Fig. 3d–f with a 95% confidence level. The significance synthesis of the results revealed that the quadratic model is statistically significant for the delamination analysis. In Table 6, the results of the ANOVA quadratic model for $F_{d1}$, $F_{d2}$, and $F_{d3}$ are presented; however, the model terms $f$, $d$, $N^2$, and $d^2$ are significant and $N \times d$ is not significant for $F_{d2}$ while $N$ and $f \times N$ are also significant for BSD only. The $R^2$ coefficient and adjusted $R^2$ coefficient corresponding to delamination are 95.07% and 95.47% for $F_{d1}$, 89.21% and 83.49% for $F_{d2}$, and 96.65% and 93.35% for $F_{d3}$, respectively. Indeed, it is important to note that the low values of the $F_{d2}$ correlation coefficients recorded in this work is mainly due to the high variation of the values obtained by the formula 2 in Table 2 which is mainly based on the damage area. Thus, it is clear that this regression model provides a perfect fit between the responses and the independent factors. In this study, to confirm the effect of the cutting-related parameters on the responses, the statistical tools called “p-value” and “F-value” (the ratio of the mean square to the mean square and the ratio of the mean square to the mean square of the experimental error, respectively) are described. If the $p$ values are less than 0.05 ($p$ value < 0.05), then the conditions required by the model are significant. The present analysis is performed at a 5% significance level, i.e., for a 95% confidence level. According to ANOVA, the models were highly statistically significant ($p < 0.0001$). In addition, the $F$ values for $F_{d1}$, $F_{d2}$, and $F_{d3}$ are 36.46, 15.61, and 41.58, respectively. Due to the larger $F$ value, it appears that the drill diameter ($d$) is the most significant parameters for the delamination of composites $F_{d1}$, $F_{d2}$, and $F_{d3}$ compared to spindle speed ($N$). However, for $F_{d1}$, the model terms $f$, $d$, $f \times d$, $N \times d$, $f \times f$, and $d \times d$ are significant, while only the terms $f$ and $d$ are significant for $F_{d2}$, and $f$, $N$, $d$, and $N \times d$ influence $F_{d3}$. The most important variable influencing the response value of the delamination factors is the drill diameter. Then, the second variable influencing the response value is the feed rate. Therefore, it appears that the diameter of the drill is the main parameter that affects the delamination factor followed by the feed rate but the spindle speed influenced only for $F_{d3}$. In addition, the percentage contribution of the d-factor shows also that the drill diameter is more significant for $F_{d1}$, $F_{d2}$, and $F_{d3}$ than the feed rate and cutting the speed. In addition, the percentage contribution shows also that the drill diameter is more significant for $F_{d1}$, $F_{d2}$, and $F_{d3}$ than the feed rate and spindle speed.
3.3 2D surface plots for the delamination factor

The results in Fig. 4 provide a mapping of the response surfaces obtained for delamination at the exit of composites machined by BSD drills as a function of the feed rate ($f$), spindle speed ($N$), and diameter ($d$). For a constant diameter, the delamination $Fd_1$ does not exceed 1.10 when $f$ is between 50 and 58 mm/min and $N$ from 1241 to 1400 rev/min, but it exceeds 1.5 when $f$ is between 123 and 190 mm/min and $N$ from 355 to 773 rev/min (Fig. 4a). For $Fd_2$, notably, the delamination does not exceed 1.2 when $f$ is between 50 and 57 mm/min and $N$ is between 459 and 992 rev/min, while it exceeds 2.0 when $f$ is between 185 and 190 mm/min and $N$ is between 355 and 658 rev/min and from 1330 to 1400 rev/min (Fig. 4d). For tool $Fd_3$, we also note that the delamination does not exceed 1.1 for $f$ between 50 and 78 mm/min and $N$ from 355 to 1400 rev/min, but it exceeds 1.3 when $f$ is between 164 and 190 mm/min and $N$ from 355 to 1400 rev/min (Fig. 4g). Figures 4d–f show for a constant spindle speed how the feed rate and drill diameter significantly affect delamination $Fd_1$, $Fd_2$, and $Fd_3$ using the BSD drills. Delamination is less than 1.2 for $Fd_1$ when $f$ is between 50 and 88 mm/min and $d$ is between 5 and 5.4 mm, less than 1.5 for $Fd_2$ when $f$ is between 50 and 58 mm/min and $d$ is between...
5 and 5.2 mm, and less than 1.2 for $Fd_1$ when $f$ is between 50 and 126 mm/min and $d$ is between 5 and 6.5 mm. It also appears that the delamination is greater than 1.8 for $Fd_1$ when $f$ is between 50 and 190 mm/min and $d$ is between 6.6 and 10 mm, greater than 3 for $Fd_2$ when $f$ is between 90 and 190 mm/min and $d$ is between 9.8 and 10 mm, and greater than 1.8 for $Fd_3$ when $f$ is between 112 and 190 mm/min and $d$ is between 8.5 and 10 mm. The effect of drill tool diameter and spindle speed on delamination at a constant feed rate is shown in Fig. 4g–h. The delamination is less than 1.2, 1.5, and 1.1 for $Fd_1$, $Fd_2$, and $Fd_3$, respectively, when $d$ and $N$ are between 5–5.2 mm and 721–1400 rev/min for $Fd_1$, 5–6.4 mm and 355–1400 rev/min for $Fd_2$, and 5–5.7 mm and 355–1400 rev/min for $Fd_3$. Furthermore, it is also observed that the $Fd$ value exceeds 1.8, 2.5, and 1.6 when $d$ and $N$ are between 7.9–9.2 mm and 1295–1400 rev/min for $Fd_1$, 6–10 mm and 720–1400 rev/min for $Fd_2$, and 9.8–10 mm and 1295–1400 rev/min for $Fd_3$, respectively. These results are fully consistent with those observed by Belaadi et al. [28, 46] for epoxy/jute fabric biocomposites under identical cutting conditions. In the case where the drill diameter is kept constant, the $Fd$ factor increases with increasing feed rate. In this work, $Fd_1 (\approx 1.12$ to 1.89) produces lower $Fd$ values than $Fd_2 (\approx 1.12$ to 3.07) and $Fd_3 (\approx 1.01$ to 2.02). Therefore, the comparison of

![Fig. 9 Comparison between 3D surface plots of delamination factor for $Fd_2$ versus $f$, $N$, and $d$ of biocomposites elaborated a–e RSM and d–f ANN models](image)
this study with the literature is difficult because several studies show that the delamination factor is influenced by many factors such as machining conditions, geometry of the cutting tool, type of material to be machined, and more particularly, the manufacturing process of biocomposite materials. Indeed, as a comparison, we mention the values of $Fd$ calculated by the first formula in the works of Sridharan et al. [51] and Belaadi et al. [28] which are respectively in the range of $1.2 - 1.8$ (for HSS-twist drill) and $Fd = 1.02 - 1.89$ (for BSD tool). However, the $Fd$ found by the three estimation formulas in this work is $1.12 - 1.89$ for $Fd_1$, $1.12 - 3.07$ for $Fd_2$, and $1.02 - 2.02$ for $Fd_3$. Indeed, the values of $Fd$ thus obtained from this investigation are quasisimilar with a small variation compared to the results of the literature [28, 51]. This may be due mainly to the matrices used (PE [51] and epoxy [28]), the drilling tool, the type of woven jute fabric reinforcement (treated [51] and untreated [28]), and the cutting parameters used in their research.

### 3.4 Prediction of the delamination factor by neural networks

The input layer integrates the data into the network model, and the output layer provides the response. For the prediction of
the delamination factor, a multilayer perceptron consisting of an input layer, a hidden layer, and an output layer was used. The ANN network model was designed using the MATLAB Neural Network Toolbox version R2015a. The use of neural network modeling offers a powerful solution capable of simulating the behavior of all nonlinear systems [80]. The ANN model training method in this investigation was based on the LM (Levenberg–Marquardt) algorithm, which associates both the principles of the quasiNewton algorithm and steepest descent back propagation, adapted to solve nonlinear least squares problems and curve adjustment. Of the total data, 80% of the datasets were chosen as training sets for \( Fd_1 \) and 75% for \( Fd_2 \) and \( Fd_3 \), and 20% of the remaining total data were used for testing and validation for \( Fd_1 \) and 25% for \( Fd_2 \) and \( Fd_3 \). For models \( Fd_1 \), \( Fd_2 \), and \( Fd_3 \), the input layer contains three neurons; the hidden layers contain ten, eleven, and eleven neurons, respectively, while the output layer contains one neuron (Fig. 5). The choice of the number of neurons in the hidden layers is based on the principle of reducing the error with an increasing number of hidden nodes [81].

Table 7 shows the ANN architectures and the MSE and \( R \) values for training, validation, and testing of \( Fd_1 \), \( Fd_2 \), and \( Fd_3 \). In fact, these neurons are linked together by weights. Figures 6 a–i correspond to the predictions of \( Fd \) delamination through the neural network against the experimental test results for \( Fd_1 \), \( Fd_2 \), and \( Fd_3 \) for the training, test, and validation data sets. The ANN prediction is in perfect agreement with the experimental results. Thus, according to the results, the capability of the ANN models developed for \( Fd_1 \), \( Fd_2 \), and \( Fd_3 \) can satisfactorily interpret the data, and this approach is a good way to predict the delamination factor (Table 8). Furthermore, the results indicate that the model is an effective and applicable way to measure the delamination factor of composites made from jute/polyester fabric.

### 3.5 Comparison of the RSM and ANN models

Figure 7 and Table 9 present a comparison of the results predicted by the ANN and RSM models with those obtained experimentally. Figures 8, 9, and 10 show a comparison between the 3D surface plots of the delamination factor as a function of \( f \), \( N \), and \( d \) of the composite obtained with the RSM and ANN models. Both models are further showing a representation of the experimentally obtained results. According to the results of Fig. 11, the maximum absolute percentage of the error in the prediction by the ANN model of the delamination factors \( Fd_1 \), \( Fd_2 \), and \( Fd_3 \) is 6.99%, 8.71%, and 4.89%, while by the RSM model, this percentage is 7.58%, 9.36%, and 7.14%, respectively. Therefore, we can conclude that the ANN model provides a more accurate prediction than the RSM model. Since these error rates are low, we can say that the optimization process is appropriate and that the model predicts the responses with high accuracy.

### 3.6 Optimization of the responses

Figures 12 and 13 show the mapping and distribution of the desirability contour and ramp function for \( Fd_1 \), \( Fd_2 \),

### Table 10

| Condition       | Goal     | Lower limit | Upper limit |
|-----------------|----------|-------------|-------------|
| Feed rate, \( f \) (mm/min) | Is in range | 50          | 190         |
| Spindle speed, \( N \) (rev/min) | Is in range | 355         | 1400        |
| Drill, \( d \) (mm) | Is in range | 5           | 10          |
| \( Fd_1 \)      | Minimize | 1.011       | 1.782       |
| \( Fd_2 \)      | Minimize | 1.011       | 1.782       |
| \( Fd_3 \)      | Minimize | 1.089       | 2.029       |
and $Fd_3$ and their combination in Figure 13d. Determining the cutting parameters and minimizing the delamination factors are the main objectives of the optimization. Table 10 shows the cutting parameters used in the optimization process as well as the optimized values of the factors, and the responses obtained are shown in Table 11. The selection of the 10 trials was conducted because of the high desirability factor. These first 10 trials show that at a low feed rate, a small tool diameter, and a high spindle speed, the reduction of the delamination factor is appropriate with desirability factors of 1.00, 0.98, and 1.00 for $Fd_1$, $Fd_2$, and $Fd_3$, respectively (Fig. 13a–c). The optimal drilling conditions according to Table 11 ($f = 50$ mm/min, $N = 1085.89$ rev/min, and $d = 5.00$ mm) resulted in minimal delamination for $Fd_1$, $Fd_2$, and $Fd_3$ with the following values, i.e., 1.13, 1.23, and 1.02, respectively. To solve the optimization problem through the genetic algorithm (GA) and to find a minimum of the multivariable nonlinear constraint function (fmincon) using MATLAB software V. R2015a, the models generated with the ANN
Fig. 13  Ramp function graph of multiobjective optimization for different \( F_d \) method evaluated \( a \) \( F_d_1 \) data, \( b \) \( F_d_2 \) data, \( c \) \( F_d_3 \) data, and \( d \) combination data.
method were chosen. The results of this optimization of the input parameters and $F_{d1}$, $F_{d2}$, and $F_{d3}$ are presented in Table 12. Indeed, these results for $F_{d1}$ show that the response parameters from the GA and fmincon produce almost similar. Finally, a comparison of the response parameters $F_{d1}$, $F_{d2}$, and $F_{d3}$ with those predicted by the GA and fmincon algorithms are 1.11, 1.15, and 1.01 for RSM, 1.04, 1.70, and 1.59 for the fmincon function and 1.10, 1.84, and 1.65 for the GA respectively, thus validating the relevance of the models and the concordance of the results with those obtained by the GA and fmincon [28].

Indeed, for $F_{d2}$ and $F_{d3}$, the results of GA and fmincon are almost similar, but they differ from those obtained by RSM.

### 4 Conclusion

The present study focuses on the optimization of the delamination factor during the orthogonal drilling of a material consisting of a bidirectional jute/polyester fabric matrix using the BSD tool. Models via artificial neural networks (ANNs) and the response surface methodology (RSM) were developed to predict the delamination factor determined by different methods. A three-level factorial design was applied to generate the input–output data used to develop the ANN and RSM models. The two models were compared in terms of the performance based on their predictive accuracy through the realization of the surface curves corresponding to the direct and interaction links of the parameters related to the drilling operations. The main conclusions drawn from the present study are as follows:

- From the effects of the interaction of the cutting parameters during the drilling process, it is apparent that the combination of a low feed rate and small tool diameter is necessary to reduce the delamination factor.
- The delamination factor is influenced by the diameter of the drill as well as the size of the feed rate while the spindle speed has no influence on the delamination factor.
- The contributions of the different elements of the optimal drilling condition to $F_{d1}$, $F_{d2}$, and $F_{d3}$ are the drill diameter (60.77%, 64.15%, and 58.34%), feed rate (12.02%, 13.19%, and 5.43%), and spindle speed (0.18%, 0.59%, and 0.67%), respectively.
- This optimization is considered to be of good robustness, as the overall desirability factor is 97%. In addition, a comparison of the response parameters with those predicted by the GA, fmincon algorithms, and RSM validated the adequacy of the models, which are in perfect agreement with the literature.
The percentage of the maximum absolute error for the ANN model prediction of the delamination factors $F_{d1}$, $F_{d2}$, and $F_{d3}$ is 6.99%, 8.71%, and 4.89%, compared to 7.58%, 9.36%, and 7.14% for the RSM model, respectively.

The agreement between the ANN and RSM models, used to predict cutting parameters in drilling processes, and the experimental data is very high. A comparison of the experimental results with those predicted by the RSM and ANN models reveals that the ANN models are more accurate and generate excellent results.

Nomenclature
- ANOVA, Analysis of variance; DOF, Degrees of freedom; SS, Sum of squares; MS, Mean squares; Cont.% Contribution ratio (%); F value, Fisher value; P value, Probability value; SD, Standard deviation; GA, Genetic algorithms; RSM, Response surface methodology; ANN, Artificial neural network; DF, Desirability function; BSD, Brad and Spur drills; HSS, High-speed steel

Acknowledgements
The authors gratefully acknowledge the Direction Générale de la Recherche Scientifique et du Développement Technologique, Algérie (DGRSDT) for their support in this work.

Author contribution
Bachir Adda: Conceptualization, investigation, and writing — review and editing. Messaouda Boumaaza: Conceptualization, investigation, and writing — review and editing. Mostefa Bourchak: Investigation and writing — review and editing.

Data availability
Not applicable.

Declarations

Ethics approval
The work contains no libelous or unlawful statements, does not infringe on the rights of others, or contains material or instructions that might cause harm or injury.

Consent to participate
The authors consent to participate.

Consent for publication
The authors consent to publish.

Competing interests
The authors declare no competing interests.

References
1. Atagur M, Seki Y, Oencu O, Sever K, Seki Y, Sarikanat M, Altay L (2020) Evaluating of reinforcing effect of Ceratonia Siliqua for polypropylene: tensile, flexural and other properties. Polym Test 89:106607. https://doi.org/10.1016/j.polymertesting.2020.106607
2. Sarasis F, Tiriollo J, Lampani L, Sasso M, Mancini E, Burgstaller C, Calzolari A (2019) Static and dynamic characterization of agglomerated cork and related sandwich structures. Compos Struct 212:439–451. https://doi.org/10.1016/j.composites.2019.01.054
3. Belaadi A, Bourchak M, Aouici H (2016) Mechanical properties of vegetal yam: statistical approach. Compos Part B Eng 106:139–153. https://doi.org/10.1016/j.compositesb.2016.09.033
4. Belaadi A, Amroune S, Bourchak M (2019) Effect of eco-friendly chemical sodium bicarbonate treatment on the mechanical properties of flax fibres: Weibull statistics. Int J Adv Manuf Technol 106:1753–1774. https://doi.org/10.1007/s00170-019-04628-8
5. Zhou Y, Fan M, Chen L (2016) Interface and bonding mechanisms of plant fibre composites: an overview. Elsevier Ltd
6. Rajmohan T, Vinayagamoorthy R, Mohan K (2019) Review on effect machining parameters on performance of natural fibre-reinforced composites (NFRCs). J Thermoplast Compos Mater 32:1282–1302. https://doi.org/10.1177/0954409718796541
7. Dutta S, Kim NK, Das R, Bhattacharyya D (2019) Effects of sample orientation on the fire reaction properties of natural fibre composites. Compos Part B Eng 157:195–206. https://doi.org/10.1016/j.compositesb.2018.08.118
8. Merli R, Preziosi M, Acampora A, Lucchetti MC, Petrucci E (2020) Recycled fibers in reinforced concrete: a systematic literature review. J Clean Prod 248:119207. https://doi.org/10.1016/j.jclepro.2019.119207
9. Chrief M, Belaadi A, Bouakba M, Bourchak M, Meddour I (2020) Behaviour of lignocellulosic fibre-reinforced cellular core under low-velocity impact loading: Taguchi method. Int J Adv Manuf Technol 108:223–233. https://doi.org/10.1007/s00170-020-05393-9
10. Boumaaza M, Belaadi A, Bourchak M (2020) The effect of alkaline treatment on mechanical performance of natural fibres-reinforced plaster: optimization using RSM. J Nat Fibers 1–21. https://doi.org/10.1080/15440478.2020.1724236
11. Jaouadi M, M’saﬁli S, Sakli F (2009) Optimization and characterization of pulp extracted from the Agave Americana L. Fibers. Text Res J 79:110–120. https://doi.org/10.1177/0040517508090781
12. Bedjaoui A, Belaadi A, Amroune S, Madi B (2019) Impact of surface treatment of flax fibers on tensile mechanical properties accompanied by a statistical study. Int J Integr Eng 6:10–17
13. Lotfi A, Li H, Dao DV (2019) Effect of drilling parameters on delamination and hole quality in drilling flax ﬁber reinforced biocomposites BF - sustainable design and manufacturing 2018. In: Howlett RJ, Setchi R, Vlacic L (eds) Dao D. Springer International Publishing, Cham, pp 71–81
14. Lotfi A, Li H, Dao DV (2020) Analytical and experimental investigation of the parameters in drilling flax/poly(lactic acid) bio-composite laminates. Int J Adv Manuf Technol 109:503–521. https://doi.org/10.1007/s00170-020-05668-1
15. Benzannache N, Belaadi A, Boumaaza M, Bourchak M (2021) Improving the mechanical performance of biocomposite plasater: Washingtonian filifira ﬁbres using the RSM method. J Build Eng 33:101840. https://doi.org/10.1016/j.jobe.2020.101840
16. Benzidane R, Sereir Z, Bennegadi ML, Doumalin P, Poilâne C (2018) Morphology, static and fatigue behavior of a natural UD composite: the date palm petiole ‘wood’. Compos Struct 203:110–123. https://doi.org/10.1016/j.compstruct.2018.06.122
17. Djoudi T, Heicini M, Scida D, Djebbloun Y (2019) Physico-mechanical characterization of composite materials based on date palm tree ﬁbers physico-mechanical characterization of composite materials based on date palm tree ﬁbers. J Nat Fibers 0:1–14. https://doi.org/10.1080/15440478.2019.1658251, 18
18. Mercy JL, Sivashankari P, Sangeetha M, Kavitha KR, Prakash S (2020) Genetic optimization of machining parameters affecting thrust force during drilling of pineapple ﬁber composite plates – an experimental approach. J Nat Fibers 1–12. https://doi.org/10.1080/15440478.2020.1788484
19. Zhang H, Zhu P, Liu Z, Qi S, Zhu Y (2020) Research on prediction method of mechanical properties of open-hole laminated plain woven CFRP composites considering drilling-induced delamination damage. Mech Adv Mater Struct 0:1–16. https://doi.org/10.1080/15376494.2020.1745969
20. Feito N, Díaz-Álvarez J, López-Puente J, Miguelez MH (2018) Experimental and numerical analysis of step drill bit performance when drilling woven CFRPs. Compos Struct 184:1147–1155. https://doi.org/10.1016/j.composites.2017.10.061

21. Fernández-Pérez J, Cantero JL, Díaz-Álvarez J, Miguélez MH (2017) Influence of cutting parameters on tool wear and hole quality in composite aerospace components drilling. Compos Struct 178:157–161. https://doi.org/10.1016/j.composites.2017.06.043

22. Feito N, Díaz-Álvarez J, López-Puente J, Miguelez MH (2016) Numerical analysis of the influence of tool wear and special cutting geometry when drilling woven CFRPs. Compos Struct 138:285–294. https://doi.org/10.1016/j.composites.2015.11.065

23. Feito N, Díaz-Álvarez A, Cantero JL, Rodríguez-Millán M, Miguelez H (2016) Experimental analysis of special tool geometries when drilling woven and multidirectional CFRPs. J Reinf Plast Compos 35:33–55. https://doi.org/10.1177/0731684415612931

24. Díaz-Álvarez J, Olmedo A, Santistbe C, Míguez MH (2014) Theoretical estimation of thermal effects in drilling of woven carbon fiber composite. Materials (Basel) 7:4442–4454. https://doi.org/10.3390/ma7064442

25. Díaz-Álvarez A, Rodríguez-Millán M, Díaz-Álvarez J, Miguélez MH (2018) Experimental analysis of drilling induced damage in aramid composites. Compos Struct 202:1136–1144. https://doi.org/10.1016/j.composites.2018.05.008

26. Bayraktar Ş, Turgut Y (2020) Determination of delamination in drilling of carbon fiber reinforced carbon matrix composites/Al 6013-T651 stacks. Measurement 154:107493. https://doi.org/10.1016/j.measurement.2020.107493

27. Geng D, Liu Y, Shao Z, Lu Z, Cai J, Li X, Jiang X, Zhang D (2019) Delamination formation, evaluation and suppression during drilling of composite laminates: a review. Compos Struct 216:168–186. https://doi.org/10.1016/j.composites.2019.02.099

28. Belaadi A, Laoucie H, Bourchak M (2020) Mechanical and drilling performance of short jute fibre-reinforced polymer biocomposites: statistical approach. Int J Adv Manuf Technol 106:1989–2006. https://doi.org/10.1007/s00170-019-04761-4

29. Chattanya S, Singh I (2018) Ecofriendly treatment of aloe vera fibers for PLA based green composites. Int J Precis Eng Manuf - Green Technol 5:143–150. https://doi.org/10.1007/s40684-018-0015-8

30. Bajpai PK, Singh I (2013) Drilling behavior of sisal fibre-reinforced polypolypropylene composite laminates. J Reinf Plast Compos 32:1569–1576. https://doi.org/10.1177/0731684413492866

31. Bajpai PK, Debnath K, Singh I (2015) Hole making in natural poly lacytic acid laminates: an experimental investigation. J Thermoplast Compos Mater 30:1–17. https://doi.org/10.1177/0892705715575094

32. Debnath K, Sisodia M, Kumar A, Singh I (2016) Damage-free hole making in fiber-reinforced composites: an innovative tool design approach. Mater Manuf Process 31:1400–1408. https://doi.org/10.1080/10426941.2016.1140191

33. Debnath K, Singh I, Dwivedi A (2014) Drilling characteristics of sisal fiber-reinforced epoxy and polypolypropylene composites. Mater Manuf Process 29:1401–1409. https://doi.org/10.1080/10426941.2014.941870

34. Debnath K, Singh I, Dwivedi A (2017) On the analysis of force during secondary processing of natural fiber-reinforced composite laminates. Polym Compos 38:164–174. https://doi.org/10.1002/pc.23572

35. Chaudhary V, Gohil PP (2016) Investigations on drilling of bidirectional cotton polyester composite. Mater Manuf Process 31:960–968. https://doi.org/10.1080/10426941.2015.1059444

36. Venkateshwaran N, ElayaPerumal A (2013) Hole quality evaluation of natural fiber composite using image analysis technique. J Reinf Plast Compos 32:1188–1197. https://doi.org/10.1177/0731684413486847

37. Athiyanayami A, Thiruchirambalam M, Natarajan U, Pazhanivel B (2010) Influence of alkali-treated fibers on the mechanical properties and machinability of rosselle and sisal fiber hybrid polyester composite. Polym Compos 31:723–731. https://doi.org/10.1002/pc.20853

38. Ramesh M, Sri Ananda Atrey T, Aswin US et al (2014) Processing and mechanical property evaluation of banana fiber reinforced polymer composites. Procedia Eng 97:563–572. https://doi.org/10.1016/j.proeng.2014.12.284

39. Ismail SO, Dhakal HN, Dimla E, Beaugrand J, Popov I (2016) Effects of drilling parameters and aspect ratios on delamination and surface roughness of lignocellulosic HFRP composite laminates. J Appl Polym Sci 133. https://doi.org/10.1002/app.42879

40. De Oliveira LA, Dos Santos JC, Panzera TH et al (2018) Investigations on short coil fibre-reinforced composites via full factorial design. Polym Compos 26:391–399. https://doi.org/10.1002/pc.20853

41. Ahilash N, Sivapragash M (2016) Optimizing the delamination failure in bamboo fiber reinforced polymer composite. J King Saud Univ - Eng Sci 28:92–102. https://doi.org/10.1016/j.jsues.2013.09.004

42. Díaz-Álvarez A, Díaz-Álvarez J, Santistbe C, Míguez MH (2019) Experimental and numerical analysis of the influence of drill point angle when drilling biocomposites. Compos Struct 209:700–709. https://doi.org/10.1016/j.composites.2018.11.018

43. Babu GD, Babu KS, Gowd BUM (2012) Effects of drilling parameters on delamination of hemp fiber reinforced composites. Int J Mach Eng Res Dev 2:1–8

44. Azuan SAS (2013) Effects of drilling parameters on delamination of coconut meat husk reinforced polymer composites. Adv Environ Biol 7:1097–1100. https://doi.org/10.1007/978-3-642-38345-8_6

45. Roy Choudhury M, Srinivas MS, Debnath K (2018) Experimental investigations on drilling of lignocellulosic fiber reinforced composite laminates. J Manuf Process 34:51–61. https://doi.org/10.1016/j.jmapro.2018.05.032

46. Belaadi A, Boumaza M, Amroune S, Bourchak M (2020) Mechanical characterization and optimization of delamination factor in drilling bidirectional jute fibre-reinforced polymer biocomposites. Int J Adv Manuf Technol 111:2073–2094. https://doi.org/10.1007/s00170-020-06217-6

47. Rao YS, Mohan NS, Shetty N, Shivamurthy B (2019) Drilling and structural property study of multi-layered fiber and fabric reinforced polymer composite - a review. Mater Manuf Process 34:1549–1579. https://doi.org/10.1080/10426941.2019.1666522

48. Azuan SAS, Juraidi JM, Muhamad WMW (2012) Evaluation of delamination in drilling rice husk reinforced polyester composites. Appl Mech Mater 232:106–110. https://doi.org/10.4028/www.scientific.net/AMM.232.106

49. Aravind S, Umanath K (2015) Delamination in drilling of natural fibre reinforced polymer composites produced by compression moulding. Appl Mech Mater 767:796–800. https://doi.org/10.4028/www.scientific.net/AMM.766.767.796

50. Sridharan V, Muthukrishnan N (2013) Optimization of machinability of polyester/modified jute fabric composite using grey relational analysis (GRA). Procedia Eng 64:1003–1012. https://doi.org/10.1016/j.proeng.2013.09.177

51. Sridharan V, Raja T, Muthukrishnan N (2016) Study of the effect of matrix, fibre treatment and graphene on delamination by drilling jute / epoxy nanohybrid composite. Arab J Sci Eng 41:10–14. https://doi.org/10.1007/s13369-015-2005-2

52. Yallew TB, Kumar P, Singh I (2015) A study about hole making in woven jute fabric-reinforced polymer composites. Proc IMechE Part L J Mater Des Appl 0:1–11. https://doi.org/10.1177/1464420715587750, 230
53. Monteiro SN, Terrones LAH, D’Almeida JRM (2008) Mechanical performance of coir fiber/polyester composites. Polym Test 27:591–595. https://doi.org/10.1016/j.polymertesting.2008.03.003

54. Jayabal S, Natarajan U (2011) Drilling analysis of coir – fibre reinforced polyester composites. Bull Mater Sci 34:1563–1567. https://doi.org/10.1007/s12034-011-0359-y

55. Durão LMP, Gonçalves DJS, Tavares JMRS, de Albuquerque R (2019) Analysis of orthogonal cutting of jute and flax fiber reinforced composites. J Nat Fibers:1–15. https://doi.org/10.1080/15440478.2020.1764435

56. Rezghi Maleki H, Hamedi M, Kubouchi M, Arao Y (2019) Drilling delamination outcomes on glass and sisal reinforced plastics. Mater Sci Forum 730–732:301–306. https://doi.org/10.4028/www.scientific.net/MSF.730-732.301

57. Çelik YH, Alp MS (2020) Determination of milling performance of jute and flax fiber reinforced composites. J Nat Fibers:1–15. https://doi.org/10.1080/15440478.2020.1764435

58. Vinayagamoorthy R (2012) Analysis of cutting forces during milling of natural fibered composites using Fuzzy logic. Int J Compos Mater Manuf

59. Chegani F, El M, Chebbi A (2021) Cutting behavior of flax fibers as reinforcement of bio-composite structures involving multiscale hygrometric shear. Compos Part B 211:108660. https://doi.org/10.1016/j.compositesb.2021.108660

60. Díaz-Alvarez A, Díaz-Alvarez J, Cantero JL, Santieste C (2020) Analysis of orthogonal cutting of bio-composites. Compos Struct 234:111734. https://doi.org/10.1016/j.compositesstructure.2019.111734

61. Chandramohan D, Rajesh S (2014) Study of machining parameters on natural fiber particle reinforced polymer composite material. Acad J Manuf Eng:12

62. Vinayagamoorthy R, Rajeswari N, Sivanarasimha S, Balasubramanian K (2015) Fuzzy based optimization of thrust force and torque during drilling of natural hybrid composites. In: Applied Mechanics and Materials. Trans Tech Publ, pp 812–817

63. Vinayagamoorthy R, Rajeswari N, Sivanarasimha S, Balasubramanian K (2015) Fuzzy based optimization of thrust force and torque during drilling of natural hybrid composites. In: Applied Mechanics and Materials. Trans Tech Publ, pp 265–269

64. Ramnath BV, Sharavanan S, Jeykrishnan J (2017) Optimization of process parameters in drilling of fibre hybrid composite using Taguchi and grey relational analysis. In: IOP Conference Series: Materials Science and Engineering. IOP Publishing, p 12003

65. Vinayagamoorthy R (2017) Parametric optimization studies on drilling of sandwich composites using the Box–Behnken design. Mater Manuf Process 32:645–653. https://doi.org/10.1080/10426914.2016.1232811

66. Palloor S, Murthy HNN, Sreenivasa TN (2021) Drilling of in-line compression molded jute / polypropylene composites. J Nat Fibers 18:91–104. https://doi.org/10.1080/15440478.2019.1612309

67. Babu J, Sunny T, Paul NA, Mohan KP, Philip J, Davim JP (2016) Assessment of delamination in composite materials: a review. Proc Inst Mech Eng Part B J Eng Manuf 230:1990–2003. https://doi.org/10.1177/0954405415619343

68. Vigneshwaran S, John KM, Deepak Joel Johnson R, Uthayarajakumar M, Arumugaprabhu V, Kumaran ST (2020) Conventional and unconventional machining performance of natural fibre-reinforced polymer composites: a review. J Reinm Plast Compos 40:553–567. https://doi.org/10.1177/0731684420959103

69. Mohan NS, Kulkarni SM, Ramachandra A (2007) Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials. J Mater Process Technol 186:265–271. https://doi.org/10.1016/j.jmatprocess.2006.12.043

70. Mudhukrishnan M, Hariharan P, Palanikumar K (2020) Measurement and analysis of thrust force and delamination in drilling glass fiber reinforced polypropylene composites using different drills. Meas J Int Meas Confed 149:106973. https://doi.org/10.1016/j.measurement.2019.106973

71. Chen W-C (1997) Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. Int J Mach Tools Manuf 37:1097–1108. https://doi.org/10.1016/S0890-6955(96)00095-8

72. Majumber A (2010) Comparison of ANN with RSM in predicting surface roughness with respect to process parameters in Nd:YAG laser drilling. Int J Eng Sci Technol 2:5175–5186

73. Karnik SR, Gaitonde VN, Davim JP (2008) A comparative study of the ANN and RSM modeling approaches for predicting burr size in drilling. Int J Adv Manuf Technol 38:868–883

74. Benardos PG, Vosniakos G-C (2003) Predicting surface roughness in machining: a review. Int J Mach Tools Manuf 43:833–844. https://doi.org/10.1016/S0890-6955(03)00059-2

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