PREDICTION OF TORQUE IN DRILLING WOVEN JUTE FABRIC REINFORCED EPOXY COMPOSITES USING THE ADAPTIVE NETWORK-BASED FUZZY INFERENCE SYSTEM AND RESPONSE SURFACE METHODOLOGY

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Jute fiber reinforced epoxy (JREp) composites were prepared by the compression moulding technique by varying the fiber content (0, 20, 30 and 40 wt%). Fabricated JREp composites were subjected to a drilling study to observe the impact of factors such as spindle speed (rpm), feed rate (mm/min) and fiber content (wt%) on the output response – torque. A set of experiments were designed and conducted as per Taguchi's Design of Experiment. The obtained torque results were found in the range from 14.84 to 32.28 N-m. The minimum value of torque was achieved for the composite drilled using an HSS twist drill (90°-point angle) at a high spindle speed (3000 rpm), with low feed rate (25 mm/min) on low fiber loaded JREp composite (20JREp). ANOVA analysis showed that the developed regression model was fairly significant and torque was mainly influenced by the feed rate. Mathematical models were developed for drilling JREp composites using response surface methodology (RSM) and adaptive neuro fuzzy inference system (ANFIS), and compared for their efficacy. The coefficient of determination (R^2) values for RSM and ANFIS were 0.9778 and 0.9982, respectively, which conveys that both models were beneficial to predict the torque. The average checking error percentage (0.0000222) was obtained for the ANFIS model trained using 'gbellmf' membership function with 100 epochs. FESEM images of the drilled surface were captured to analyse the mode of failure endured by the JREp composites.

Keywords: drilling, regression, ANFIS, RSM, jute-epoxy, FESEM, torque

INTRODUCTION

In recent decades, novel materials made from natural fibers have been attracting growing interest to replace man-made or synthetic fibers for various engineering applications. The advantages of natural fibers consist in their unique properties, such easy processing, less pollution, superior strength, environmental friendliness and industrial sustainability. Moreover, the global demand for eco-friendly fibers has paved the way to synthesizing novel composite materials as part of the waste to wealth concept.[1,2] Recent research outcomes have underscored the importance of studying the drilling of composite materials, and, as of now, it can be clearly said that composite machining is brimming as a new important research area.[3,4] Simple engineered composite materials can be directly fabricated by employing primary manufacturing processes, but for producing complex composite products, it is essential to adopt primary and secondary manufacturing processes. For instance, to produce composite based aerospace parts, several shape components are essentially required to be assembled to execute the complete assembly. Conventional drilling is a machining operation that is famously employed for producing holes on the components to facilitate the complete assembly process.

Machining of composite materials meets many challenges and scientists have tried to address problems in different ways. Drilling in fiber reinforced polymer composites (FRPC) leads to different types of damage, such as fiber pull-outs, matrix fracture, delamination, burrs around the holes, chipping, matrix burning, and spalling, *etc*. These aforesaid damages occurring during drilling may lead to catastrophes because of the premature failure of the composite structure.[5] Many innovative research works have been reported on drilling of FRPCs. Bajpai *et al*.[6] reported that, compared to the cutting speed, drill point angle has a substantial effect on the drill forces when drilling sisal fiber reinforce polypropylene (PP) composites. Debnath *et al*.[7] investigated the drilling behavior of sisal/epoxy and sisal/PP composites. Their results revealed that the torque value obtained for sisal/PP composites was relatively lower than that of sisal/epoxy composites. The thrust force decreases with spindle speed and linearly increases with feed rate. The chips of sisal/PP were continuous and of the ring type when a step drill was employed at low speed and feed rate. The dimensional stability of natural fiber-reinforced hybrid composites due to the chemical treatments of fibers has been investigated. Singh *et al*.[8] have found that tool geometry is the major factor causing drill damages in composites. The effects on input parameters on the tool wear and drilling forces in drilling coir-polyester composites have also been studied.[9] Latha *et al*.[10] confirmed in drilling GFRP composites that feed rate and drill diameter play a major impact on thrust forces, however, the spindle speed factor had the least effect. The combined effect of drill point angle, spindle speed and feed rate on the delamination factor and thrust force during drilling of CFRP has also been reported.[11] Venkateshwaran *et al*.[12] studied the drilled hole quality produced on banana/epoxy composites using an image processing technique. The study showed that feed rate was the most significant factor affecting the delamination of the composites.

The manufacturing process has the objective to produce good quality products with minimum effort, and the only way to achieve this is by means of experiments. However, finding the optimal solutions takes a large number of trials, which eventually consumes time and incurs high costs. Thus, for minimizing the trials, a prior well-thought design, involving analysis of the data is crucial. Therefore, the statistical approach is employed for planning the experiments and analysing the data for minimizing the error. Various modeling techniques have been established.

Drilling quality of the FRPC depends on several factors, as reported by some researchers.[13-15] In this context, several authors reported on regression models, which are mainly applied to draw the relationships between input parameters and the output response chosen.[16-20] From the last decade, several researchers have attempted the ANFIS (Adaptive Neuro-Fuzzy Inference system) predictive model, which is basically an integration of the properties of fuzzy logic and artificial neural networks.[21] ANFIS overcomes the demerits associated with the latter one, and hence it is applicable in solving numerous practical problems.[22] As far as drilling of a material is concerned, the ANFIS based model may be applied to predict desired output responses, such as thrust force, surface roughness, life of the tool, delamination factor and torque. Kumaran *et al*.[23] presented the usefulness of the ANFIS model for predicting the experimental values of surface roughness in abrasive waterjet machining of carbon fiber reinforced plastics. ANFIS predicted results showed good accuracy, matching with the experimental ones, and proved the model's efficacy in predicting cutting force in turning PEEK composites, as reported by Ozden *et al*.[24] Azmi[25] predicted the tool wear and feed force using the ANFIS model with a higher confidence level, when drilling glass fiber reinforced polymer composite. Material removal rate and surface roughness have also been predicted effectively by the ANFIS model for machining LM6/SiC/dunite hybrid metal matrix composites using the wire electrical discharge machining process.[26] Marani *et al*.[27] proposed that the ANFIS model can not only predict the surface roughness and cutting force during the machining of Al–20 Mg_2Si metal matrix composites, but also minimize the repetition of experiments.

Our literature survey has clearly shown that the ANFIS model has not been implemented for measuring the drilling performance of jute reinforced epoxy (JREp) composites so far. Hence, the present research work aims to improve the quality of holes produced in JREp composites upon drilling by means of predicting the optimal parameters. Prediction of the torque was performed using ANFIS and RSM regression models and further validated by comparing with experimental results.

Table 1
Chemical composition of jute fiber compared with other natural fibers[28]

Fiber	Cellulose (wt%)	Hemicelluloses (wt%)	Lignin (wt%)	Wax (wt%)	Moisture (wt%)	Ash (wt%)
Jute (*Corchorus*)	64.4	12	11.8	0.5	10	-
Acacia nilotica L.	56.46	14.14	8.33	0.85	-	4.93
Common reed fiber	64.56	12.57	10.84	-	-	-
Piliostigma racemosa	60.3	0.27	30.76	-	-	-
Shwetark	69.65	0.2	16.82	-	-	-
Sida rhombifolia	75.09	15.43	7.48	0.49	12.02	4.07
Acacia leucophloea	68.09	13.60	17.73	0.55	8.83	0.08
Cyperus pangorei	68.50	-	17.88	0.17	9.19	-
Saharan aloe vera	67.4	8.2	13.7	0.24	5.8	-
Heteropogon contortus	64.87	19.34	13.56	0.22	7.4	-
Furcraea foetida	68.35	11.46	12.32	0.24	5.43	6.53
Coccinia grandis L.	62.35	13.42	15.61	0.79	5.64	4.38
Ficus religiosa	55.58	13.86	10.13	0.72	9.33	4.86
Dichrostachys cinerea	72.4	13.08	16.89	0.57	9.82	3.97
Ziziphus mauritiana	43	10.2	5.1	-	7.9	-
Phaseolus vulgaris	62.17	7.04	9.13	-	6.1	-

Table 2
Properties of jute fiber compared with other plant-based fibers[29]

Fiber	Density (g/cc)	Elongation percentage (%)	Tensile strength (MPa)	Young's Modulus (GPa)
Jute	1.3	1.5–1.8	393–773	26.5
Cotton	1.5–1.6	7.0–8.0	400	5.5–12.6
Flax	1.5	2.7–3.2	500–1500	27.6
Hemp	1.47	2–4	690	70
Kenaf	1.45	1.6	930	53
Sisal	1.5	2.0–2.5	511–635	9.4–22
Coir	1.2	30	593	4.0–6.0

EXPERIMENTAL

Materials

In this study, jute yarns were procured from local vendors, in Sathyamangalam, Tamil Nadu, India. The matrix material, epoxy resin (VBR 8912 grade) and its hardener (VBR1209), were purchased from Vasavibala Resins Private Ltd., Chennai, Tamil Nadu, India. Jute yarns were woven into irregular basket woven fabric with the help of a tabletop handloom machine (ERGO G2). The areal density of the woven fabric was 475 GSM, and it was used as a reinforcement member in the epoxy matrix (phase) for preparing jute reinforced epoxy (JREp) composites. The chemical composition of the jute fiber and its physico-mechanical properties, compared with those of other cellulosic fibers, are shown in Tables 1 and 2, respectively.

Fabrication of JREp composites

The fabrication of the JREp composite was accomplished by means of the hand layup process, followed by curing in the compression moulding machine. Four layers of jute woven fabrics (known wt%) were stacked in a bottom mild steel mould of dimension 300 mm × 300 mm × 4 mm. On each layer, epoxy resin (known wt%) was poured for uniformly wetting the fabric. A stainless steel roller was used for spreading the resin evenly on the fabric. This step was repeated until all the layers of jute fabric were stacked. Teflon sheets were placed on the top and bottom of the mould for ease of removing the cured laminates. The bottom mould containing the stacked jute with epoxy was closed with the help of the top mould and subjected to continuous pressure (24 hours) in the compression moulding machine for a room temperature curing process. Once the JREp laminates were cured, they were taken out and specimens with required dimensions were cut. In this way, JREp composites with different fiber loadings (20, 30, and 40 wt%) were prepared, and their composition and denotation are shown in Table 3. The fabrication of the JREp composites is illustrated in Figure 1.

Table 3
Composition of JREp composites

Composite code	Weight fraction of constituents (wt%)		Layers of fabric used	Density of JREp composites (g/cc)		Void (%)
	Epoxy resin	Jute fiber		Theoretical	Experimental	
Neat epoxy	100	0	-	1.220	1.160	4.91
20JREp	80	20	4	1.175	1.142	2.809
30JREp	70	30	4	1.222	1.154	5.565
40JREp	60	40	4	1.264	1.212	4.114

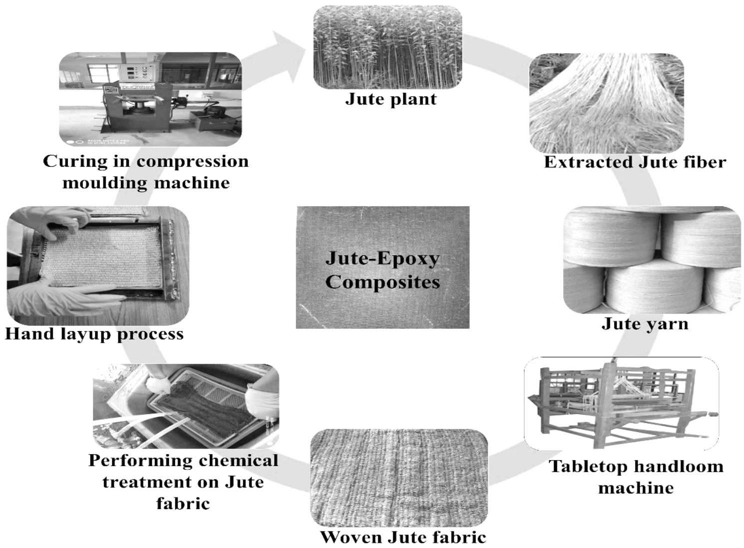

Figure 1: Preparation of JREp composite

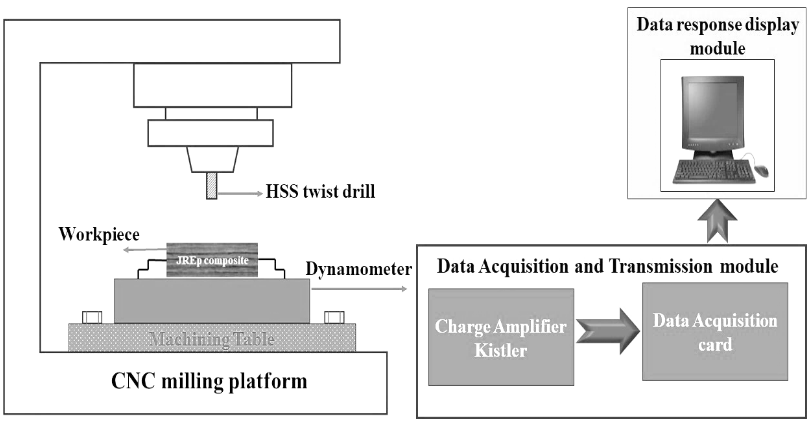

Figure 2: Drilling setup used in the present study

Drilling test

Drilling was performed on the JREp composites. The test was executed using a 6 mm diameter HSS twist drill in a vertical CNC machine. The drilling parameters, namely fiber content of the JREp composite (20, 30 and 40 wt%), spindle speed (1000, 2000, and 3000 rpm), and feed rate (25, 50, and 75 mm/min), were varied. For the aforesaid input parameters, torque is the output response selected, as it mainly influences the delamination damage around the drilled holes. Therefore, by identifying the suitable combination of selected inputs, torque can be controlled and minimized and thus the delamination damages. JREp laminate of the dimension 150 cm × 200 cm was firmly fixed on the force dynamometer (Kistler, Germany) and this whole setup with utmost care was placed in the fixture to prevent any disturbances. Drilling signals of the torque responses were recorded via a dynamometer and their numerical values were obtained by analysing through the acquisition system. The drilling setup for producing holes in the JREp composite is illustrated in Figure 2.

Design of Experiments (DoEs)

Taguchi's orthogonal arrays (TOAs) competently analyses process parameters by reducing the actual experiments and thus it saves time, material, and costs by avoiding redundant tests. The implementation of a Taguchi-based experimental approach can simplify the data collection, analysis, and interpretation process, aligned with the research purpose. Design of Experiments (DOEs) extracts maximum information from the minimal experimental data by means of variable combinations, as suggested in the design layout. In this investigation, various factor combinations (spindle speed, feed rate, and fiber content) were considered in order to understand the drilling behaviour of the JREp composites. The study employs L_{27} OA experimental design, for assessing spindle speed, feed rate, and fiber loadings at three levels each, as indicated in Table 4. The recorded torque during drilling the JREp composites is shown in Table 5, which served as the main variable. Subsequently, the interaction effects of the process parameters were analysed.

Table 4
Control factors and their levels

Control factors	Levels			Units
	I	II	III	
Spindle speed (A)	1000	2000	3000	rpm
Feed rate (B)	25	50	75	mm/min
Fiber content (C)	25	35	45	wt%

Table 5
Drilling results of JREp composites

Trial No	Levels of factors			Torque
	A	B	C	(N-m)
1	1000	25	25	21.610
2	1000	25	35	22.100
3	1000	25	45	23.840
4	1000	50	25	24.450
5	1000	50	35	26.660
6	1000	50	45	27.820
7	1000	75	25	26.250
8	1000	75	35	28.570
9	1000	75	45	32.280
10	2000	25	25	16.985
11	2000	25	35	17.371
12	2000	25	45	21.081
13	2000	50	25	19.668
14	2000	50	35	21.995
15	2000	50	45	22.952
16	2000	75	25	24.615
17	2000	75	35	26.452
18	2000	75	45	28.980
19	3000	25	25	14.846
20	3000	25	35	15.183
21	3000	25	45	18.425
22	3000	50	25	17.284
23	3000	50	35	19.329
24	3000	50	45	20.170
25	3000	75	25	22.618
26	3000	75	35	24.120
27	3000	75	45	26.250

RSM and ANFIS models

In this study, RSM and ANFIS modelling techniques were employed and their respective models were developed by using Design Expert and MATLAB software.

RSM is applied to establish the relationship among the various input parameters and explores the effect of these process parameters on the selected responses, (*i.e.* torque in this study). The relationship between the control parameters of drilling JREp composites and the response (torque) is shown by Equation (1):

$$f_u = \psi(x_{1u}, x_{2u}, x_{3u}, \ldots x_{ku}) + \varepsilon_u \quad (1)$$

where u = 1, 2, 3, … k, and k represents factorial experiment number; x_{iu} denotes the level of the i^{th} factor in the u^{th} experiment. The function ψ is called the response surface. The residual ε_u measures the experimental error in corresponding u^{th} observation.

The second order polynomial equation, that is, the quadratic response surface has two variables and is given in Equation (2):

$$f_u = \beta_0 + \beta_1 x_{1u} + \beta_2 x_{2u} + \beta_{11} x_{1u}^2 + \beta_{22} x_{2u}^2 + \beta_{12} x_{1u} x_{2u} + \varepsilon_u \quad (2)$$

where β_0, β_1, β_2 … are the regression coefficient of the input variable (x).

The quadratic model indicated in Equation (2) was created for expecting the approximation of output variable by the values received through experiments. Further, its efficacy was validated by ANOVA. Finally, model fitness was checked by the coefficient of determination (R^2) value.

ANFIS integrates a neural network and a fuzzy logic concept.[15] ANFIS technique is attributed to the hybrid learning procedures, it employs a multilayer feedforward network. By means of directional links, multi-layers of nodes are interconnected. Thus, the error in the system can be reduced by suitably varying input parameters.[20] The magnitude of each input control factors in the ANFIS system is defined by the membership function (MF) and its curves are graphically indicated. Several membership functions are available, which is opted for the apropos input factors with output response variables. For the present study, Gaussian membership functions namely, gbellmf,' 'gaussmf,' and 'gauss2mf,' have been selected. Various iterations were performed during ANFIS training, and based on the input parameters given, nearly 27 fuzzy rules were generated. The proposed system converged with the minimum root mean square error value of 0.0000222 at 100^{th} epochs.

ANFIS parameters and their respective membership functions are given in Table 6. There are mainly two types of fuzzy inference systems (FIS): Mamdani FIS and Sugeno FIS. The latter technique is employed and its architecture is shown in Figure 3. The validation of the drill input parameters in Sugeno FIS is depicted in Figure 4. Equations (4) and (5) are used to determine the performance factors for evaluating the effectiveness of the ANFIS model employed. The root means square error (RMSE) and the mean absolute error (MAE) of the predicted and experimental values can be computed using Equations (3) and (4), respectively:

$$RMSE = \sqrt{\frac{\sum (j-k)^2}{m}} \quad (3)$$

$$MAE = \frac{\sum |j-k|}{m} \quad (4)$$

where m, j and k are the number of patterns, the set of actual and predicted output, respectively.

The coefficient of determination (R^2) was determined for understanding the effectiveness of the mathematical model used and its value generally ranges from 0 to 1. Equation (5) was utilized for calculating the R^2 value, providing an insight into the relationship between one term's performance and its prediction on the performance of another term.

$$R^2 = 1 - \frac{\sum (j-k)^2}{\sum (j-\bar{k})^2} \quad (5)$$

where $\bar{k}$ is the mean of the predicted output.

The accuracy of the performance factors calculated is at 10^{-4}. The model with minimum average checking error is preferred, which gives good results.

Table 6
ANFIS information of membership function for drilling JREp composites

Sl. No	Parameters	Membership functions		
		gbellmf	gaussmf	gauss2mf
1	Number of nodes	78	78	78
2	Linear	27	27	27
3	Non-linear	27	27	27
4	Total number of parameters	54	54	54
5	Number of fuzzy rules	27	27	27

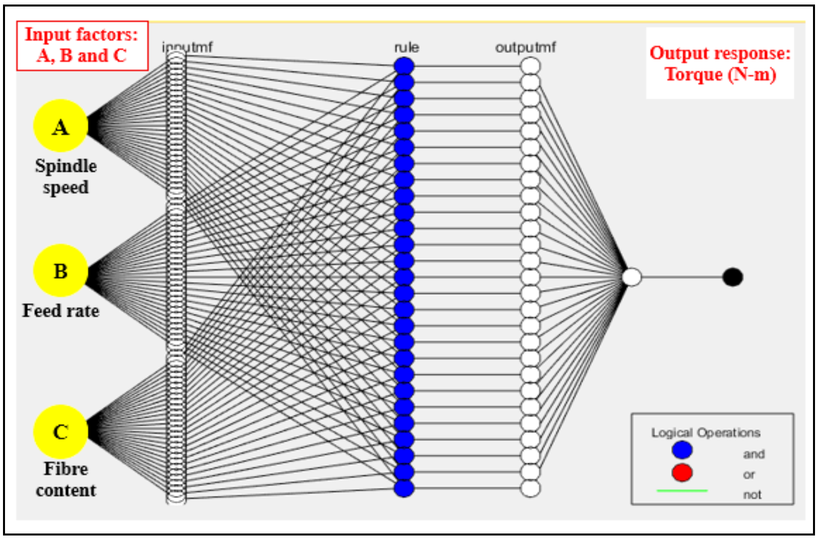

Figure 3: ANFIS architecture employed for drilling JREp composites

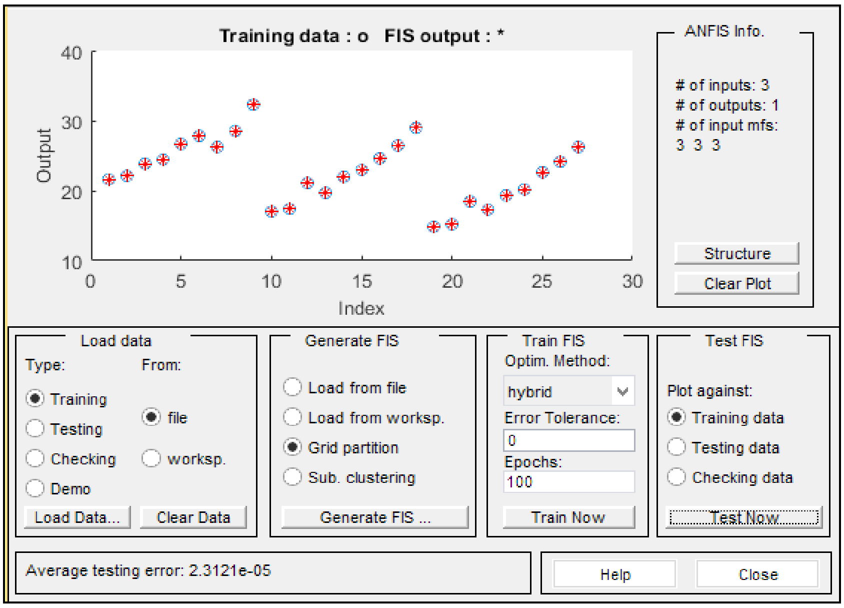

Figure 4: Validation of input drill parameters with Sugeno model in MATLAB (R2017a)

RESULTS AND DISCUSSION

Drilling of JREp composites

Composite materials have to endure various stages of machining process before becoming a useful product. During the drilling of the composite material, maintaining high surface quality of the holes with minimum damage is vital and challenging, and can be achieved, if the machining conditions are wisely selected.

In this study, the drilling operation was performed on the JREp composites to analyse the output response torque for the following input factors: spindle speed, feed rate and fiber loading. We obtained a total of 27 combinations in accordance with the L_{27} TOA operated at three levels. From Table 5, it is evident that the first nine trials are conducted by the setting up spindle speed (A) at 1000 rpm. Subsequently, the speed is increased to 2000 rpm for the next nine trials and further raised to 3000 rpm for the remaining trials. The feed rate (B) is altered after every three trials, starting from 25 mm/min, then progressing to 50 mm/min, and finally reaching 75 mm/min. Notably, each trial showcases distinct fiber loading (C), as indicated in Table 5.

Experimental results show that the torque value exhibited by the JREp composites ranges from 14.84 to 32.28 N-m. Torque values increase with an increase in the fiber content and hence lower fiber loaded JREp composites containing 20 wt% of jute fiber is preferred over other composites. This may be attributed to the resistance offered by the higher fiber loading during the drilling action, which might have resulted in higher thrust force. Furthermore, the torque value decreases with an increase spindle speed and feed rate. Thus, for producing holes with good surface finish and less delamination in JREp composites, higher spindle speed and lower feed rate is preferred.

Experimental results demonstrate that the selected input factors and their combinations have a significant effect on the torque, which is generated during drilling JREp composites. Results clearly conveyed that torque can be minimized in drilling JREp composites, provided the drilling is performed on 20 wt% jute fiber filled epoxy composites (20JREp) by setting spindle speed and feed rate at higher and lower level, respectively. Thus, by implementing these conditions, delamination in JREp composites can be minimized as the thrust force and the torque produced are minimal.

The obtained experimental results were used to build the RSM and ANFIS models for analyzing not only their predicting ability, but also to find the best modelling approach. ANOVA analysis was used to find out the most significant factor affecting the output responses. In this study, linear, 2FI, and quadratic RSM models have been developed in order to understand their efficacy in predicting the torque value generated during drilling of JREp composites.

The RSM model generated using the Design Expert software is shown in Table 7, and its corresponding equation – in Table 8. It is clearly noted that the R^2 value of the quadratic model is found higher among the other models. Figure 5 and Figure 6 present the normal probability plot and correlation between predicted and actual torque values, respectively. From these plots, it is evident that torque values are distributed normally and predicted torque values are found closer to the real ones and thus, it can be inferred that the developed RSM quadratic model is suitable.

Table 7
Summary of RSM models for torque

Source	Standard deviation	R^2	Adjusted R^2	Predicted R^2	PRESS*
Linear	0.95	0.9597	0.9544	0.9434	29.15 (suggested)
2FI	0.92	0.9668	0.9569	0.9304	35.87
Quadratic	0.83	0.9775	0.9656	0.9396	31.14

*Prediction error sum of squares

Table 8
RSM model for torque

Response	Model expression	R^2
Torque (N-m)	$21.59-3.08*A+3.82*B+1.86*C+0.42*AB-0.13*AC+0.34*BC+0.64A^2+0.61B^2+0.36C^2$	0.9775

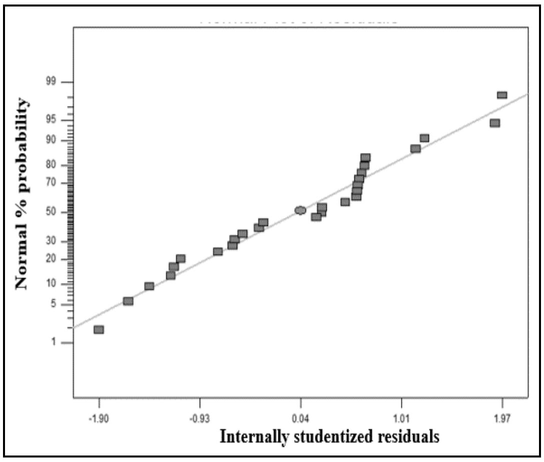

Figure 5: Normal probability graph

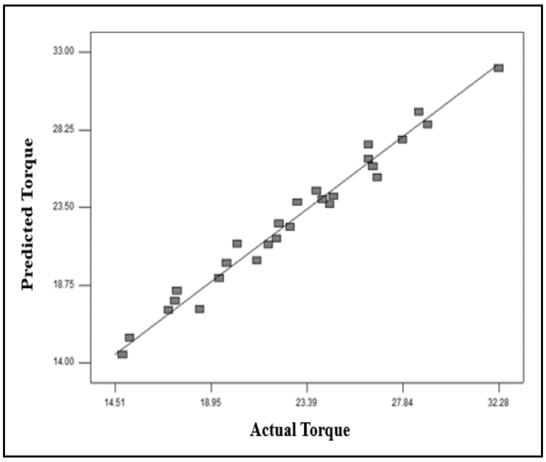

Figure 6: Correlation graph for torque

Table 9
Information of ANFIS model chosen for drilling JREp composites

Model parameters	Membership functions		
Chosen membership function	gbellmf	gaussmf	gauss2mf
No. of epochs	100	100	100
Error (%)	2.18657E-05	2.37581E-05	2.22387E-05

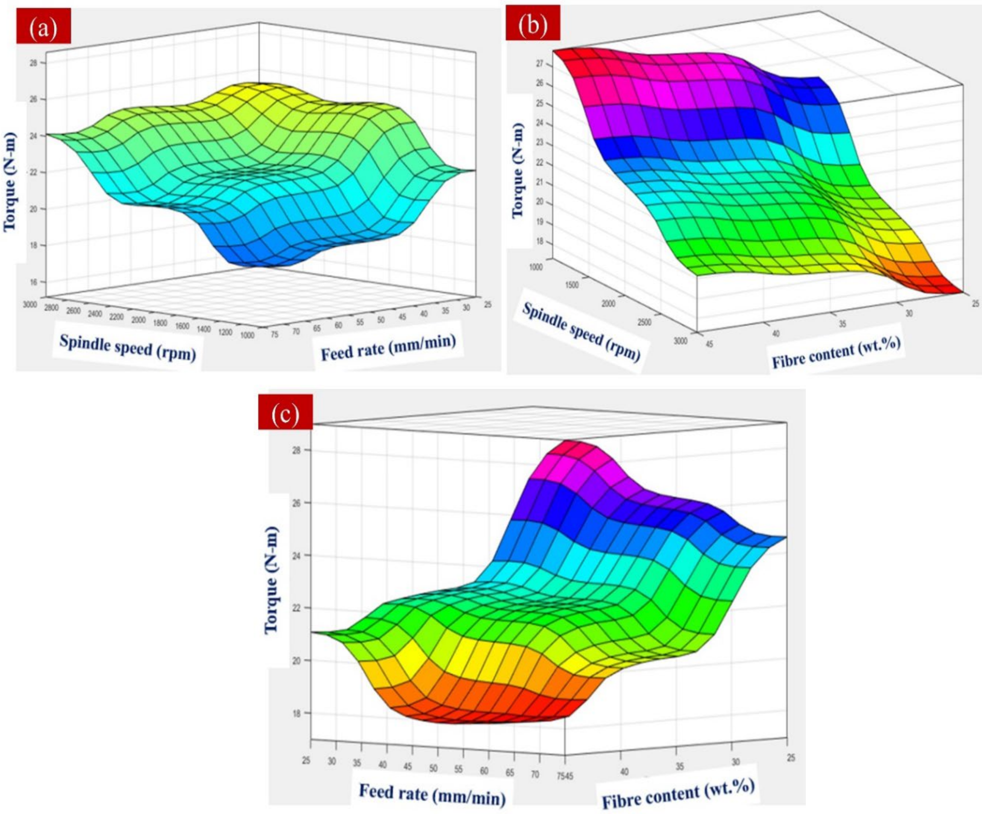

Figure 7: ANFIS three dimensional graphs for the response torque

Modelling of the torque can also be performed using the ANFIS technique. Typical results obtained from the ANFIS are shown in Table 9. From the table, it is evident that the ANFIS model trained under 'gbellmf" with 100 epochs has given the least error in predicting the torque response among the three membership functions. Hence, 'gbellmf' ANFIS model is suitable for modelling the input parameters for drilling JREp composites. Figure 7 depicts the ANFIS surface plots of torque obtained for JREp composites. The graphs clearly explain the interaction effects of spindle speed and feed rate, feed rate and fiber content, and spindle speed and fiber content on the output response torque. From the obtained plots, it can be inferred that the torque response can be effective, provided drilling is performed on the 20JREp composites at higher spindle speed with lower feed rate.

The significant factors affecting the torque response is presented by means ANOVA and shown in Table 10. The F-value of 82.06 and the R^2 value of 0.9775 reveal that the model is significant. ANOVA results showed that all the three input parameters are significant and influence the torque, but, amongst them, feed rate is found to be dominant, followed by spindle speed and fiber content. Moreover, it is observed that, torque is minimum at higher spindle speed when drilling 20JREp composite. During the drilling of JREp composite at high speed, heat generation is highly prominent, owing to friction occurring between the drill bit and the reinforcement component. The developed heat is sufficient to melt the polymer and softened polymer helps in easing removal, resulting in the generation of lower thrust force and torque while producing the holes. However, during the drilling of JREp composite at lower spindle speed, the composite experiences low strain rates and consumes longer machining time, which results in higher drilling forces, in contrary to the high-speed drilling condition. From Figure 8, it is observed that the following combinations: low fiber-JREp composite and lower feed rate, and lower feed rate with high spindle speed lead to decreased torque value. Thus, torque can be under control when the 20JREp composite is chosen to drill at higher spindle speed and lower feed rate.

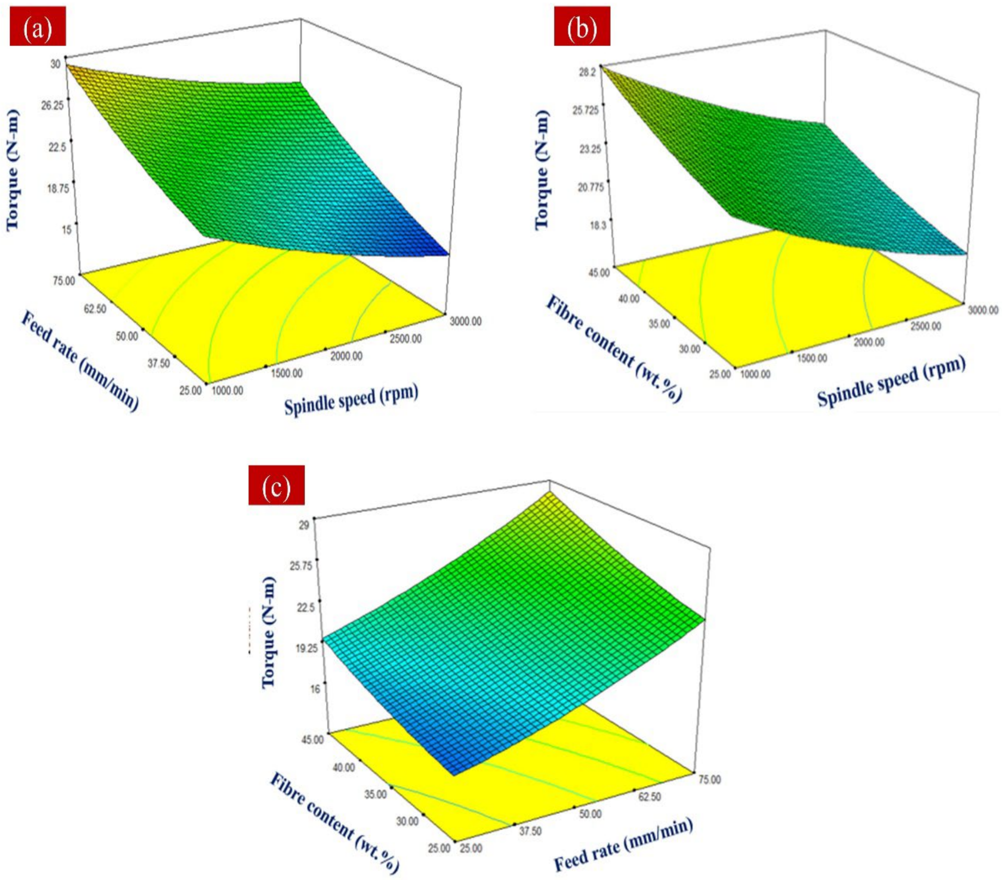

Figure 8: RSM graphs for response torque

Table 10
ANOVA for torque in drilling JREp composites

Source	SS	DF	Mean square	F value	P value Prob > F	
Regression model	503.82	9	55.98	82.06	< 0.0001	significant
A-Spindle speed	170.23	1	170.23	249.53	< 0.0001	
B-Feed rate	262.17	1	262.17	384.28	< 0.0001	
C-Fiber content	62.23	1	62.23	91.22	< 0.0001	
AB	2.07	1	2.07	3.03	0.0996	
AC	0.20	1	0.20	0.29	0.5989	
BC	1.42	1	1.42	2.08	0.1679	
A^2	2.50	1	2.50	3.66	0.0728	
B^2	2.21	1	2.21	3.24	0.0897	
C^2	0.80	1	0.80	1.17	0.2943	
Residual	11.60	17	0.68			
Cor. Total	515.42	26				

FESEM images (Fig. 9 (a-c)) of drilled holes in JREp composites show fiber fracture, debonding, micro-crack propagation, drilled debris and matrix damages in the proximity of the fiber region. Figure 9 (c) clearly reveals that the drilled surface is quite rough, as it is evident due to the projections of the jute fibers after heavy fracture, owing to high thrust force developed during the drilling action. It is evident that debonding between the jute fiber and the epoxy matrix is prominent and may be attributed to poor adhesion between fiber and matrix, which can be overcome by chemical treatment. It is also interesting to note that less damage is observed on the matrix surface when the JREp composite is drilled at higher spindle speed with lower feed rate**.** This may be due to the softening of the epoxy matrix as a result of high temperature generated between the drill bit and the reinforcement member. Thus, if the JREp composite is not impregnated uniformly by epoxy resin, brittleness of the material is evident and leads to more fiber fracture around the drilled holes, resulting in higher roughness, as may be seen in Figure 9 (a). From the FESEM analysis, it can be deduced that heavy fiber breakage and protrusion in the drilled JREp composites are mainly attributed to the high thrust force and torque developed during the drilling action. This implies that the holes are produced with poor surface finish may not be suitable for the required application. Thus, proper selection of drilling parameters is vital for producing high-quality drilled holes in JREp composites.

Table 11
R-Sq values of RSM and ANFIS models for JREp composites

Response	R-Sq values	
	RSM model	ANFIS model
Torque (N-m)	0.9775	0.9982

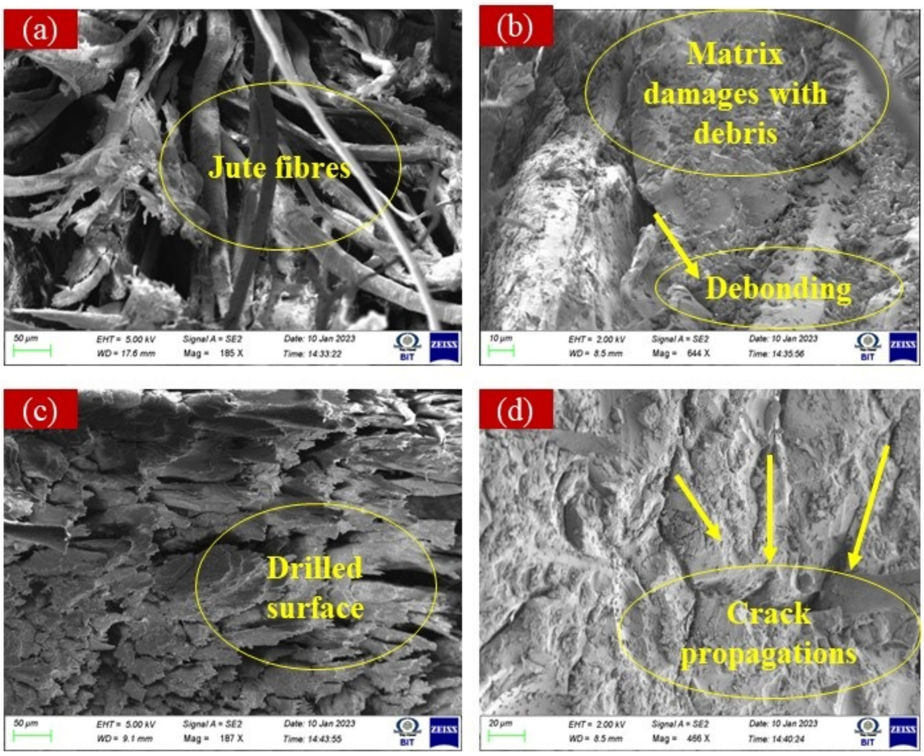

Figure 9: FESEM images of the drilled surface of 20JREp composites

In this work, two types of modeling techniques are employed and their effectiveness is compared in Table 11. The R^2 values of RSM and ANFIS are found to be 0.9775 and 0.9982, respectively, which indicates both models strongly agree with each other. The developed models were implemented and analysed by performing confirmation tests. The drilling conditions chosen for conducting confirmations tests lie within the factors and levels considered in this work. A comparison of experimental torque values, and those predicted by ANFIS and RSM is depicted in Figure 10. It clearly conveys that the ANFIS and RSM models effectively predicted the experimental results. The values shown in Table 10 explain the predicting ability of the developed models. Thus, these models can predict the torque value generated while drilling JREp composites for chosen parameters considered. The confirmation test revealed that the experimentally obtained torque values are consistent with those predicted by ANFIS and RSM models, as illustrated in Figure 11.

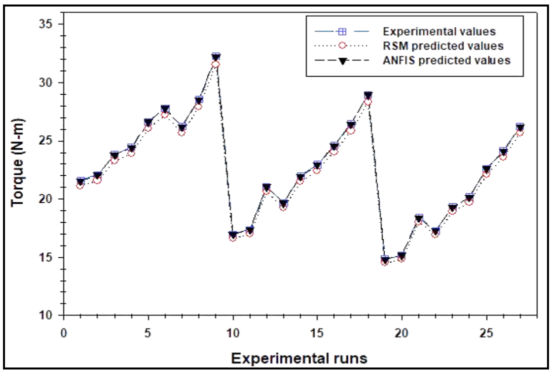

Figure 10: Experimental torque results compared with those generated by RSM and ANFIS models

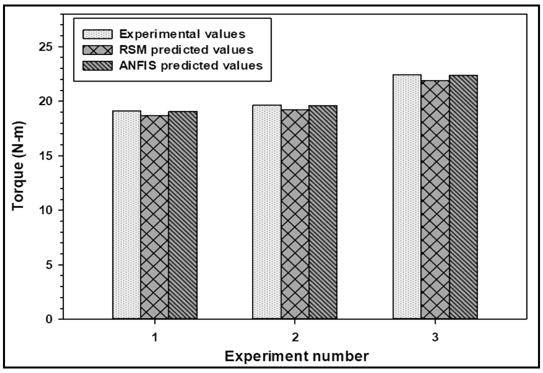

Figure 11: Confirmation test results for torque in drilling JREp composites

Table 11
Confirmation experiments for validating predicted values by RSM and ANFIS models

Expt. No	Model employed	Spindle speed (rpm)	Feed rate (mm/min)	Fiber content (wt%)	Torque (N-m)
	Experimental	1500	30	20	19.106
1	RSM	1500	30	20	18.676
	ANFIS	1500	30	20	19.071
	Experimental	1500	30	30	19.647
2	RSM	1500	30	30	19.210
	ANFIS	1500	30	30	19.611
	Experimental	1500	30	40	22.413
3	RSM	1500	30	40	21.908
	ANFIS	1500	30	40	22.372

CONCLUSION

In the present work, JREp composites with varying fiber loading were successfully fabricated and employed for investigating their behaviour to drilling. The study showed that the measured torque was in the range from 14.84 to 32.28 N-m. From the ANOVA, it was observed that feed rate is the most important factor influencing the output response, followed by spindle speed and fiber content of the composites.

Minimum torque is generated if the drilling setup is tuned to high spindle speed and low feed rate, provided drilling is performed on low fiber loaded JREp composites (20JREp). Thus, delamination can be reduced and good surface finish on drill holes can be anticipated. Fiber pull-out, fiber fracture, matrix debris and fiber projections are the major observations made based on the FESEM analysis.

The RSM regression model and the ANFIS model were used to predict the torque generated while drilling JREp composites. Both techniques have been found to be suitable in predicting the torque value, as their R^2 is found closer to 1, indicating that the models are very significant. Moreover, a confirmation test for the selected input range indicated the good predicting ability of the models, as the obtained experimental results were in close agreement with those generated by the ANFIS and RSM models.

To conclude, the developed JREp composites can be employed in construction and transportation applications for making supports and fences, and inner panels in automobiles, respectively. The scope of the current work can be extended to study the drilling performance of jute-epoxy composites as influenced by factors such as various chemical treatments of the fiber, stacking sequence of the fiber, architecture of the woven fabric and new drill types and geometries.

REFERENCES

[1] V. Raghunathan, V. Ayyappan, J. D. Dhilip, D. Sundarrajan, S. M. Rangappa *et al.*, *Biomass Convers. Biorefin.*, (2023), https://doi.org/10.1007/s13399-023-04240-7

[2] V. Raghunathan, V. Ayyappan, S. M. Rangappa and S. J. Siengchin, *J. Elastomer. Plast.*, (2024), https://doi.org/10.1177/009524432412291

[3] K. Debnath, I. Singh and A. Dvivedi, *Polym. Compos.*, **38**, 164 (2017), https://doi.org/10.1002/pc.23572

[4] V. K. Doomra, K. Debnath and I. Singh, *Proc. Inst. Mech. Eng. B: J. Eng. Manuf.*, **229**, 886 (2015), https://doi.org/10.1177/0954405414534227

[5] E. Sakthivelmurugan, G. Senthil Kumar, S. M. Vinu Kumar and H. Singh, *J. Braz. Soc. Mech. Sci.*, **45**, 400 (2023), https://doi.org/10.1007/s40430-023-04339-y

[6] P. K. Bajpai and I. Singh, *J. Reinf. Plast. Compos.*, **32**, 1569 (2013), https://doi.org/10.1177/0731684413492866

[7] K. Debnath, I. Singh and A. Dvivedi, *Mater. Manuf. Process.*, **29**, 1401 (2014), https://doi.org/10.1080/10426914.2014.941870

[8] I. Singh and N. Bhatnagar, *Int. J. Adv. Manuf.*, **27**, 870 (2006), https://doi.org/10.1007/s00170-004-2280-7

[9] S. Jayabal and U. Natarajan, *Bull. Mater. Sci.*, **34**, 1563 (2011), https://doi.org/10.1007/s12034-011-0359-y

[10] B. Latha, V. Senthilkumar and K. Palanikumar, *J. Reinf. Plast. Compos.*, **30**, 463 (2011), https://doi.org/10.1177/07316844103976

[11] A. Yardimeden, E. Kilickap and Y. H. Celik, *Mater. Test.*, **56**, 1042 (2014), https://doi.org/10.3139/120.110666

[12] N. Venkateshwaran and A. ElayaPerumal, *J. Reinf. Plast. Compos.*, **32**, 1188 (2013), https://doi.org/10.1177/073168441348684

[13] A. Lotfi, H. Li and D. V. Dao, *J. Nat. Fibers*, **17**, 1264 (2018), https://doi.org/10.1080/15440478.2018.1558158

[14] P. Krishnasamy, G. Rajamurugan, S. Aravindraj and P. E. Sudhagar, *J. Nat. Fibers*, **19**, 2885 (2022), https://doi.org/10.1080/15440478.2020.1835782

[15] V. K. Mahakur, S. Bhowmik and P. K. Patowari, *Proc. Inst. Mech. Eng. C: J. Mech. Eng. Sci.*, **236**, 6232 (2022), https://doi.org/10.1177/09544062211063752

[16] G. C. Onwubolu and S. Kumar, *J. Mater. Process.*, **171**, 41 (2006), https://doi.org/10.1016/j.jmatprotec.2005.06.064

[17] T. Valarmathi, K. Palanikumar, S. Sekar and B. Latha, *Mater. Manuf. Process.*, **35**, 469 (2020), https://doi.org/10.1080/10426914.2020.1711931.

[18] A. Karthik and P. Sampath, *Indian J. Fibre Text. Res.*, **45**, 267 (2020), https://nopr.niscpr.res.in/bitstream/123456789/55280/3/IJFTR%2045%283%29%20267-273.pdf

[19] C. Anjinappa, O. S. Ahmed, M. Abbas, A. A. Alahmadi, M. Alwetaishi *et al.*, *Processes*, **10**, 2735 (2022), https://doi.org/10.3390/pr10122735

[20] A. Kumar, H. Singh and V. Kumar, *Mater. Manuf. Process.*, **33**, 1483 (2018), https://doi.org/10.1080/10426914.2017.1401727

[21] D. S. Tran, V. Songmene and A. D. Ngo, *Neural. Comput. Appl.*, **33**, 11721 (2021), https://doi.org/10.1007/s00521-021-05869-z

[22] D. Karaboga and E. Kaya, *Artif. Intel. Rev.* **52**, 2263 (2019), https://doi.org/10.1007/s10462-017-9610-2

[23] S. T. Kumaran, T. J. Ko, R. Kurniawan, C. Li and M. Uthayakumar, *J. Mech. Sci. Technol.*, **31**, 3949 (2017), https://doi.org/10.1007/s12206-017-0741-9

[24] G. Özden, M. Ö. Öteyaka and F. M. Cabrera, *J. Thermoplast. Compos. Mater.*, **36**, 493 (2023), https://doi.org/10.1177/08927057211013070

[25] A. Azmi, *Adv. Eng. Softw.*, **82**, 53 (2015), https://doi.org/10.1016/j.advengsoft.2014.12.010

[26] N. Manikandan, K. Balasubramanian, D. Palanisamy, P. Gopal, D. Arulkirubakaran *et al.*, *Mater. Manuf. Process.*, **34**, 1866 (2019), https://doi.org/10.1080/10426914.2019.1689264

[27] M. Marani, V. Songmene, M. Zeinali, J. Kouam and Y. Zedan, *Neural. Comput. Appl.*, **32**, 8115 (2020), https://doi.org/10.1007/s00521-019-04314-6

[28] E. Sakthivelmurugan, G. Senthilkumar, S. M. Kumar and H. Singh, *Cellulose Chem. Technol.*, **57**, 399 (2023), https://doi.org/10.35812/CelluloseChemTechnol.2023.57.35

[29] E. O. Ogunsona, A. Codou, M. Misra and A. K. Mohanty, *Mater. Today Sustain.*, **5**, 100014 (2019), https://doi.org/10.1016/j.mtsust.2019.100014