Express Polymer Letters Vol.17, No.4 (2023) 353–372
Available online at www.expresspolymlett.com
https://doi.org/10.3144/expresspolymlett.2023.26

Research article

Experimental studies on the absorption, swelling and erosion performance of hybrid woven Kevlar/hemp reinforced epoxy composites

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Received 31 July 2022; accepted in revised form 10 October 2022

Abstract. Hybridization of natural and synthetic fibers in a single composite material can be made by several means, and one of the best methods is the intra-ply in which both fibers are woven within a single layer. Through hybridization, the advantages of one type of fiber can improve the limitations of the other. Further the blending of natural and synthetic fibers leads to the fabrication of composites with higher mechanical performance. Hence, this work focuses on the fabrication of intra-ply Kevlar and hemp fiber reinforced epoxy hybrid composites with different weaving patterns such as plain weave, basket weave, and twill weave type. Yarns were woven by handloom technique to make intra-ply Kevlar and hemp fiber mats, and the composites were fabricated by compression molding. The water absorption, thickness swelling, and solid particle erosion characteristics of the composites were examined. The results of the experiments showed that the hemp fiber composites exhibited the least resistance (8.45% change in absorption and 4.34% change in thickness) towards the absorption and swelling, whereas pure epoxy (0.67% change in absorption and 0.31% change in thickness) and Kevlar (2.67% change in absorption and 1.67% change in thickness) composites possessed higher resistance. The absorption and swelling performance of all other hybrids was found to be in between the hemp and Kevlar composites hence proving the effectiveness of the hybridization. Further, Taguchi's experimental design results indicated that the basket weave type hybrid composites had a minimal erosion rate for 2 minutes of exposure duration and an impact angle of 90°. The morphological analysis of the eroded surfaces of composites revealed the presence of micro cavities, broken fibers, crater formation, and microcracks.

Keywords: *polymer composites, hybridization, absorption and thickness swelling, solid particle erosion*

1. Introduction

Natural fibers are environmentally favorable due to their low density, renewable nature, low cost, and biodegradability. Natural fibers such as kenaf, banana, jute, pineapple leaf fiber (PALF), hemp, sisal *etc.* are reinforced with polymer matrices to form polymer composites [1–7]. Polymer composites have found enormous applications in the field of automobiles and are found to be more effective [8–15]. Natural fibers have many advantages, but they also have certain disadvantages, such as lower mechanical properties, high moisture absorption rate, uneven shapes with varied diameters, fiber and matrix incompatibility when compared to synthetic fibers [16–27].
A blend of natural/natural, natural/synthetic and synthetic/synthetic fibers in the same composite material

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is called hybridization. Inter-ply and intra-ply are the two distinct kinds of hybridization where two or more layers placed in a homogeneous reinforcement are called inter-ply and two fibers integrated into one layer are called intra-ply hybrid composites. Composites using intra-ply are also referred to as intra-yarn [28–34]. Synthetic fibers, including carbon, Kevlar, and glass are employed in high-strength applications [35–41]. The advantages of synthetic fibers over natural fibers include their higher mechanical qualities, reduced moisture absorption, and compatibility with the polymer matrices [42–48]. They are frequently utilized in automobile applications such as engine covers and sports car components [49–54]. However, the cost of these composites is extremely high. On the other hand, natural fibers are extremely cost-effective [55–60]. Hybridized synthetic and natural fiber composites are created to compensate for the inadequacies of natural fiber-based polymer composites and synthetic fiber-based polymer composites [61–66]. Although the natural/synthetic fiber reinforced combination has more economical and cost-effective, it reduces the moisture absorption properties and enhances the properties of the composites [67–71].

Recently, polymer matrix composites have replaced metallic components in several applications. However, because the epoxy matrix is fragile, they are vulnerable to eroding wear. Numerous studies have examined the erosion wear behavior of polymer matrix composites to solve the disadvantages and improve the erosion resistance of polymer matrix composites. It is critical to investigate the erosion wear resistance of polymer matrix composites before they may be employed in a range of applications, particularly in the aerospace and automotive industries [72–80]. Gupta *et al.* [75] explored the influence of erosion wear performance on bamboo fiber-reinforced epoxy composites. It was revealed that composites with 40% bamboo fiber reinforcement have higher erosion resistance than composites with the 10, 20, and 30% of fiber loadings. Researchers found that the bamboo fiber reinforced epoxy composites with red mud filler added possess stronger erosion resistance compared to glass fiber reinforced epoxy composites [76]. The influence of erosion characteristics of composites made from lantana camara fiber and epoxy matrix was investigated experimentally [77]. According to the findings, increasing fiber loading and impact velocity results in higher composite erosion rates. Mohanta and Acharya [78] examined the erosion behavior of luffa cylindrica fiber and glass fiber reinforced epoxy hybrid composites. The result showed that all laminate stacking sequences have an erosion rate that increases with impact velocity and peaks at an impact angle of 60°. This demonstrates the semiductile behavior of the luffa cylindrica fiber and glass fiber reinforced epoxy hybrid composites. Similarly, the investigation of hybrid Kevlar fiber and pineapple leaf fiber reinforced epoxy composites demonstrated a maximum erosion rate at 60° of impact angle, which implies a semi-ductile nature [79].

Statistical techniques are frequently employed to enhance the quality of a process. In an experiment with multiple variables, the user can select and assess the effect of each possible variable according to these statistical methodologies. In the instance of erosion rate, the experimental erosion technique is an illustration of a method where numerous control parameters interact to affect the performance output. The Taguchi's design involves using a robust design of tests to reduce the variability in a process. The method's predominant goal is to ensure high-quality of products at a cheap cost [80–83]. Vigneshwaran *et al*. [84] reported the Taguchi experimental design for erosion wear characteristics of sisal fiber and red mud filler reinforced epoxy hybrid composites. It was found that the erosion loss in the composites was mostly determined by the red mud particle, erodent velocity, and erodent feed rate. In another work, Johnson *et al*. [72] examined the erosion behavior of Sansevieria Cylindrica fiber-reinforced vinyl ester composites using Taguchi design. From the Taguchi experimental results, the optimal erosion process parameter was discovered from the data.

The effects of moisture absorption properties on a hybrid of flax-hemp-epoxy composites were studied by Saha *et al*. [85]. The results showed that hybrid composites absorbed the least amount of water when compared to pure hemp and pure flax composites. The effects of Kevlar fiber and *cocos nucifera* sheath hybridization reinforced with epoxy matrix composites were examined [86]. The results showed that composites with a higher percentage of (75 wt%) Kevlar had improved water absorption capabilities. Behera *et al*. [87] investigated the Luffa-coir-epoxy hybrid composites, and they concluded that the hybrid composites showed higher moisture resistance than pure composites. Yahaya *et al*. [88] examined the moisture absorption behavior of kenaf-kevlar-epoxy hybrid composites. In comparison to other hybrid compositions, hybrid composites with higher Kevlar fiber content exhibited lower water absorption and thickness swelling.

Many investigations have been performed on the swelling, absorption, and erosion properties of natural-synthetic fibre reinforced inter-ply hybrid composites, however, research on intra-ply hybrid composites is limited when compared with inter-ply hybrid composites [52, 79]. Hence, in this research, the moisture absorption, swelling, and erosion performance of intra-ply hybrid Kevlar and hemp fiber reinforced epoxy matrix composites with different weaving patterns such as plain (1×1), twill (2×2), and basket (3×3) were studied.

2. Materials and methods

2.1. Materials

The hemp and Kevlar fibers were procured from Go Green Products in Chennai, Tamil Nadu. The matrix materials, epoxy resin (LY556) and hardener (HY951) were supplied by Vasavibala Resins Pvt ltd., Chennai, Tamil Nadu. Table 1 lists the mechanical properties of fibers and matrix used in this study.

2.2. Methods

2.2.1. Fabrication of woven fabric mats

The Kevlar and hemp fibers were weaved using handloom technique. Pure kevlar (K) and hemp (H) woven fabric mats were prepared by weaving separate kevlar and hemp fibers. On the other hand, the kevlar and hemp fibers were inserted in warp and weft direction to obtain the intra-ply 1×1 plain (KH1), 2×2 twill (KH2) and 3×3 basket (KH3) type woven fabrics. The same quantity of Kevlar and hemp yarn were used for the weaving of different woven fabrics with the varied design of weaving patterns. Figure 1 and Figure 2 depicts the pure and intra-ply woven fabrics employed in this research.

Table 1. Mechanical properties of fibers and matrix.

Mechanical properties	Hemp fiber	Kevlar fiber	Epoxy	References
Density [g/cm^3]	1.50	1.76	1.16	[9], [10], [13], [88–90]
Tensile strength [MPa]	550–900	4500	31	
Young's modulus [GPa]	70	250	4	
Elongation at break [%]	1.6	3.3	5.0	

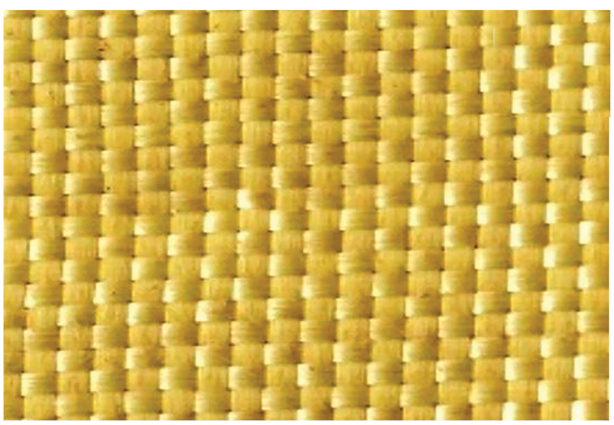
2.2.2. Preparation of composites

The pure composites and intra-ply hybrid composites were fabricated using a compression moulding machine. The woven fabrics with a thickness ranging from 0.9 and 1.1 mm were placed on a steel mould having a size of 300×300×3 mm. A 10:1 ratio of epoxy resin to hardener was used to fabricate the composites. The mould cavity was filled with 3 layers of woven fabrics, and then the matrix was poured and spread along the cavity. Air bubbles were carefully eliminated during the fabrication of composites using a roller. Finally, the mould was closed and compressed at a pressure of 200 bar for 12 hrs at room temperature. After removing the mould from the compression moulding machine, the laminates were subjected to post curing at 110 °C for about 15 minutes. The cured composites were then cut as per ASTM standards for of testing.

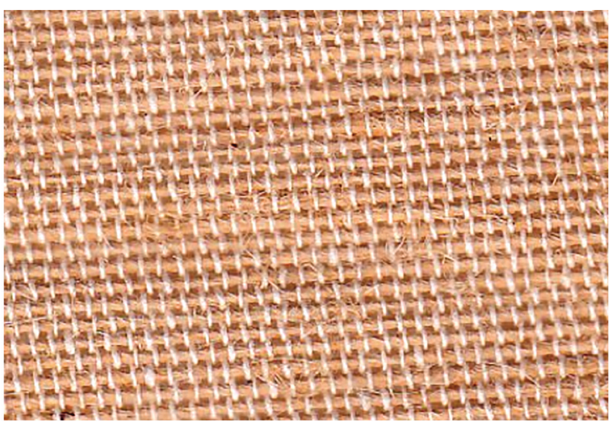
2.3. Characterization

2.3.1. Moisture absorption test

The developed Kevlar-hemp fiber-reinforced epoxy-based hybrid composites were tested for water absorption behaviour as per the ASTM D 570 standard. Three composite specimens in each composition



a)



b)

Figure 1. Pure woven mats a) Kevlar (K), b) Hemp (H).

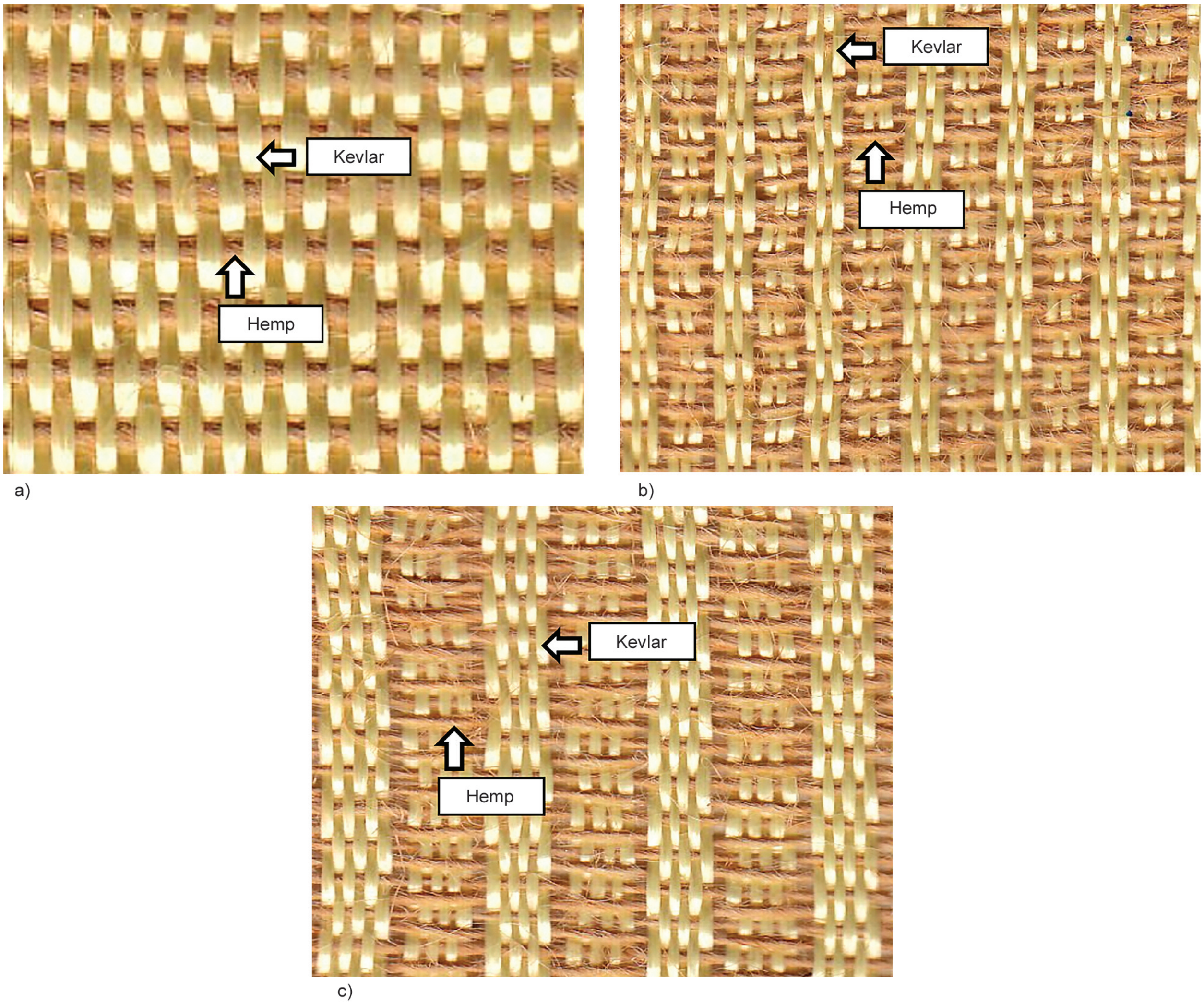


Figure 2. Intra-ply woven mats a) plain weave (KH1), b) twill weave (KH2), c) basket weave (KH3).

were soaked in distilled water at room temperature. Composite specimens were weighed initially prior to soaking in distilled water. After soaking in distilled water, the weight of each specimen was measured every 24 hours until a constant weight was reached. The percentage of moisture absorbed for each composite sample was determined using the Equation (1) [21, 25, 79, 104]:

Percentage of water absorbed [%] =

$$= \frac{W_f - W_i}{W_i} \cdot 100 \quad (1)$$

where W_f is the final weight and W_i is the initial weight of the composite specimen.

2.3.2. Thickness swelling test

The Kevlar-hemp fiber reinforced epoxy hybrid composites were measured for thickness swelling behaviour according to the ASTM D 570 standard. Three specimens were measured for each composition, and the average value was reported. The initial thickness of the specimens was weighed before immersion in pure water. After 24 hours, the specimens were taken out of pure water and were scrubbed gently using a soft tissue paper in order to remove the water particles on the surface of the specimen before being measured on a digital vernier scale. The specimen's secondary thickness was then measured every 24 hours for several days until a constant thickness value was reached. Based on Equation (2) [21, 25, 79, 104] the percentage of thickness swelling behaviour was estimated.

Percentage of thickness swelling [%] =

$$= \frac{T_f - T_i}{T_i} \cdot 100 \quad (2)$$

where T_f represents the final thickness of the composite specimen, T_i is the initial thickness of the composite specimen.

2.3.3. Erosion test

An air jet erosion machine (R-470 DUCOM) was utilized to perform the erosion wear test. Figure 3 depicts the machine used to carry out the erosion test. Figure 4 shows the composite specimens having dimensions of 25×25×3 mm used for the erosion wear test in accordance with ASTM G76 standards. The erosion test process variables and their levels are listed in Table 2. The erosion wear rate was estimated from the Equation (3) [74, 79, 84, 102]:

Table 2. Erosion process variables and working levels.

Erosion process variables		Symbols	Operating levels
Impingement angle	[°]	A	30, 60, 90
Erodent size	[µm]	ES	50
Exposure duration	[min]	B	2, 4, 6
Erodent	[–]	E	Alumina powder
Weaving	[–]	C	1, 2, 3
Erodent feed rate	[g/min]	EFR	3.3
Impact velocity	[m/s]	IV	100

$$\text{Erosion wear rate [g/g]} = \frac{\text{Specimen weight before wear} - \text{Specimen weight after wear}}{\text{Erodent feed rate} \cdot \text{time}} \quad (3)$$

2.3.4. Taguchi's design of experiment

The Taguchi technique was employed to examine the effects of erosion process factors on the Kevlar-hemp-epoxy hybrid composites with various weaving patterns. The Minitab 17 software was used for this Taguchi analysis. The significance of the control elements on output parameters was designed using Taguchi experimental design. The experiment was carried out using a conventional Taguchi L27 (3^3) design. The chosen control variables were weaving patterns, impact angle, exposure time and working levels (Table 2). To study the erosion process parameters at the working conditions in a typical full factorial test, $3^3 = 27$ runs were taken [78]. The experimental values are then used to estimate signal-to-noise (S/N) ratios. Regarding the S/N ratio for a low wear rate, 'smaller is better.' Equation (4) was used to compute the S/N ratio [91]:

$$S/N = -10\log\frac{1}{n}\sum y^2 \quad (4)$$

where n denotes the number of observations, y is the observed data.

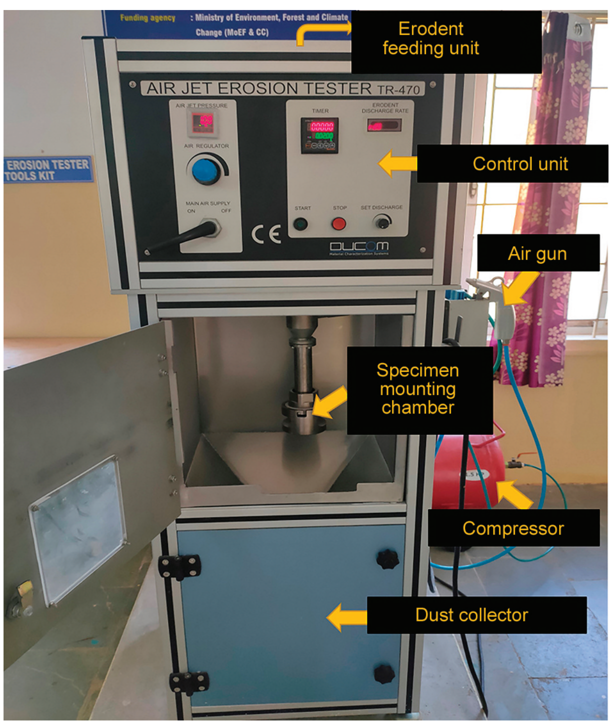


Figure 3. Air jet erosion tester used in the study.

3. Results and discussions

3.1. Moisture absorption properties

Figure 6 illustrates the moisture absorption properties of Kevlar-hemp-epoxy hybrid composites. It can be seen from Figure 6 that the absorption property of the intra-ply hybrid composites showed a linear increase during the first several days of soaking in water. This may be due to the quick penetration of water into the composites through the hydrophilic hemp fiber. As the soaking days increased, the intra-ply hybrid composites' ability to absorb water declined until they were saturated. The pure Kevlar composites had the lowest water absorption percentage of 2.6% after 30 days of soaking among all types of composites. On the other hand, pure epoxy resin composites possessed the lowest water absorption percentage (0.67%). In contrast to fiber-reinforced composites, epoxy resin restricts water absorption by creating a matrix that is water-resistant. Moreover, specimens of pure hemp fiber reinforced composites had the highest moisture absorption percentage of 8.4%, higher than all other composites. This could be attributed to the hydrophilic nature of the hemp fiber. The various weaving patterns affected the moisture absorption behaviour of hybrids. Results showed substantial differences in water absorption behaviour between kevlar-hemp-epoxy hybrid composites with various weaving patterns. Nevertheless, hybrid composites of the basket weave type (KH3) showed

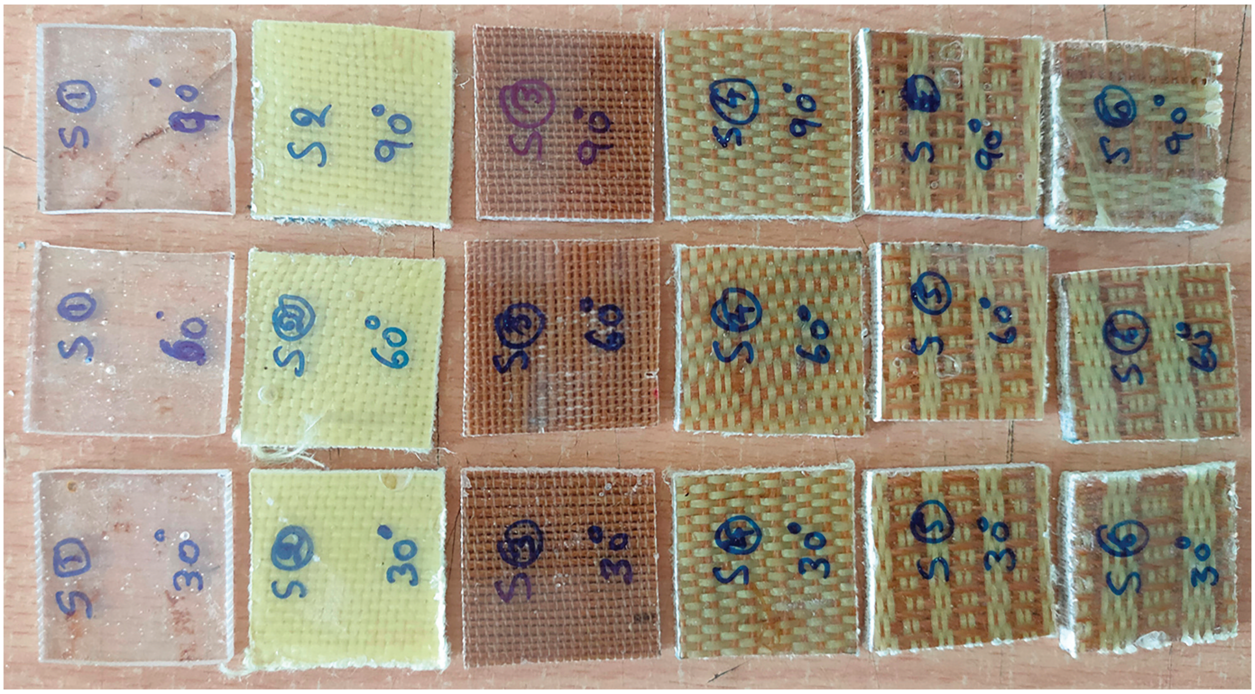


Figure 4. Erosion test specimens.

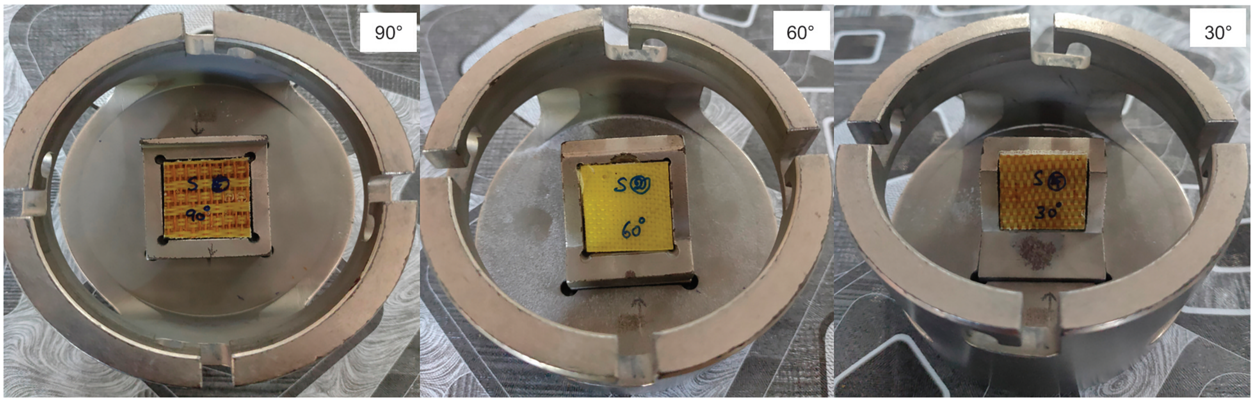


Figure 5. Specimen holders with various impact angles.

minimum water absorption of 4.4%. Alternatively, hybrid composites of plain weave (KH1) demonstrated a maximum water absorption of 5.3%. The twill weave type (KH2) hybrid composites were observed with an intermediate water absorption value of 4.8%. Following are the order of the examined composites increased water absorption percentages: Hemp > KH1 > KH2 > KH3 > Kevlar > Epoxy. The findings showed that, with the exception of hemp fiber composites, pure Kevlar, pure epoxy, and intra-ply Kevlar-hemp hybrid composites have better water absorption capabilities. Similar research was conducted on hybrid composites with jute and empty fruit bunch reinforced epoxy matrix, and they discovered that hybrid composites had better water absorption characteristics than pure composites [92, 93]. Another study that examined the hybrid of jute/Kevlar/epoxy composites concluded that all hybrid composites, with the exception of JKJK type hybrid composites, had better water absorption resistance [94].

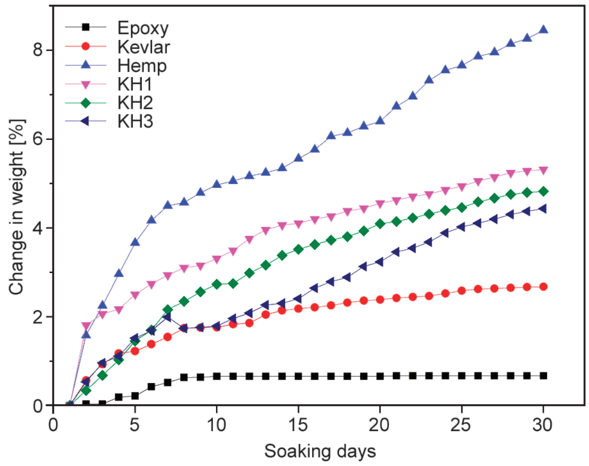


Figure 6. Water absorption behaviour of various composite specimens.

3.2. Thickness swelling properties

Figure 7 illustrates the findings from an investigation into the effect of thickness swelling behaviour of various Kevlar-hemp hybrid and pure composites. From the Figure 7 it can be observed that the thickness swelling of composites was increased with an increase in the soaking days. According to the results, the basket weave type KH3 hybrid composites (1.76%) and pure Kevlar composites (1.67%) possessed lower thickness swelling behaviour. This could be ascribed to the influence of the hybridization in which the hydrophobic Kevlar fiber restricted the moisture absorbance and hence resisted the swelling of the composites. A similar trend was also seen in the twill weave type KH2 (2%) and plain weave KH1 composites (2.3%), respectively. However, the pure hemp fiber reinforced epoxy composites exhibited higher thickness swelling behaviour (4.3%). It might be because of the existence of polar groups and hydrogen bonding, that natural fiber-based composites had lower water resistance. In this occurrence, moisture formed in the cell walls of composites made of natural fibers [95–97].

In contrast, pure epoxy matrix showed the least (0.3%) swelling behaviour. This is due to the hydrophobic nature of epoxy resin [93]. All composites exhibited a swelling behaviour in the following sequence: Hemp > KH1 > KH2 > KH3 > Kevlar > Epoxy. A study done earlier on Kevlar-PALF-Epoxy hybrid composites exhibited a similar trend [79]. The effect of moisture absorption and swelling characteristics of hybrid composites with lyocell and basalt fiber-reinforced with acrylated epoxidized soybean oil were examined [98]. The results found that hybrid composites with basket weave type showed lower moisture absorption and thickness swelling.

3.3. Erosion experiment

3.3.1. Effects of different impact angle

The angle between the particle's trajectory and the degraded surface right before impact is referred to as the angle of impact [99]. The erosion experiment was carried out for different impact angles 30, 60, 90° by varying the exposure time of 2, 4, and 6 min at a constant velocity and feed rate of 100 m/s and 3.3 g/min, respectively. Figure 5 shows a sample holder with various impact angles. The erosion rate of the composite specimens under varied impact angles is shown in Figure 8. Different process variables and operation levels had an impact on the erosion rate of the composite specimens. The findings demonstrated that the epoxy matrix exhibited a maximum erosion wear rate of $9.0909\cdot10^{-4}$ g/g than all other composites at an impact angle of 60°. Similarly, among the composites, pure hemp fiber composites showed a maximum erosion wear rate of $7.5757\cdot10^{-4}$ g/g at 60° impact angle. The lowest erosion rate of $1.0101\cdot10^{-4}$ g/g was observed for pure Kevlar fiber reinforced composites at 90° impact angle. This could be attributed due to the good bonding between the fiber and matrix. For basket weave type (KH3) and plain weave type (KH1) composites, the minimum and maximum values of erosion wear rate were found to be $1.0606\cdot10^{-4}$ and $4.5454\cdot10^{-4}$ g/g at impact angles of 90 and 60°. If the maximum erosion rate ranges from 15 to 30°, it is ductile in nature, while it goes above 90° it is brittle in nature [100–102]. In our research, the maximum erosion wear

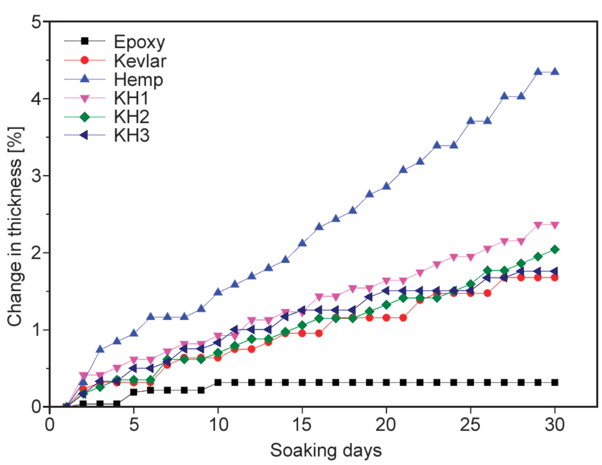


Figure 7. Thickness swelling characteristics of various hybrid composite specimens.

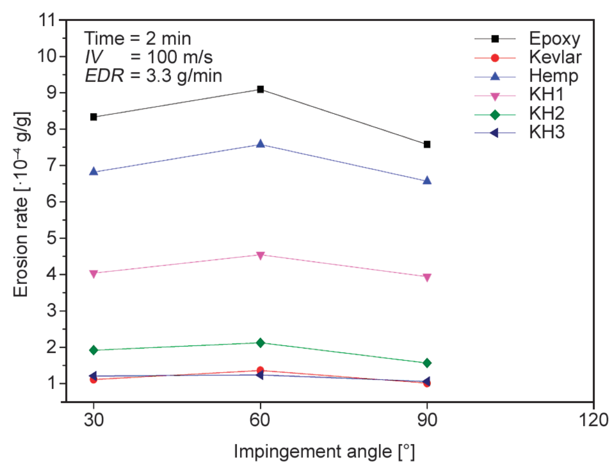


Figure 8. Impact angle versus erosion rate of various hybrid composite specimens

rate was 60° impact angle. Hence it is semi-ductile in nature. After 2 minutes of exposure, the erosion rate significantly expanded from 30 to 60° of impact angle while declining slightly to 90° impact angle for all composite specimen types. Similarly, numerous researchers have reported the erosion behaviour of Kevlar-PALF fiber reinforced epoxy hybrid composites and hence concluded that 60° of impact angle was found to have the maximum wear rate, suggesting the composites' semi-ductile nature [79]. Dalbehera *et al*. [103] investigated the erosion performance of hybrid with jute and glass fiber epoxy matrix composites and the results concluded that semi-ductile character of the composites is shown by the maximum erosion wear rate at 45 to 60° impact angles.

3.3.2. Effects of different exposure time

Exposure time is known as a measurement of cumulative exposure to an erosive or abrasive environment [99]. Erosion experiments for several impact angles (30, 60, and 90°), impact velocity 100 m/s, constant erosion feed rate of 3.3 g/min and the impacts of varied exposure intervals (2, 4, 6 minutes) were examined. Figure 9 illustrates the exposure duration and rate of erosion at different impact angles. The epoxy matrix and hemp composites showed the maximum rate of erosion between the different impact angle and exposure times. Moreover, the kevlar composites exhibited a minimum erosion rate of $1.0101 \cdot 10^{-4}$ g/g at an impact angle of 90° with an exposure time of 2 min. The highest rate of erosion $4.6666 \cdot 10^{-4}$ g/g in hybrid composites was attained for plain weave (KH1) composites at 90° impact angle and 2 minutes exposure duration. Furthermore, the basket weave type (KH3) hybrid composites showed the lowest rate of erosion ($1.0606 \cdot 10^{-4}$ g/g) at 90° impact angle with 2 minutes of exposure. The findings suggest that, aside from pure Kevlar composites, every hybrid composite had improved erosion properties than non-hybrid composites.

3.3.3. Effects of different weaving patterns

Results showed that basket weave type (KH3) had greater erosion resistance at all exposure times and impact angles than all other weaving types of intra-ply Kevlar-hemp-epoxy hybrid composites. This

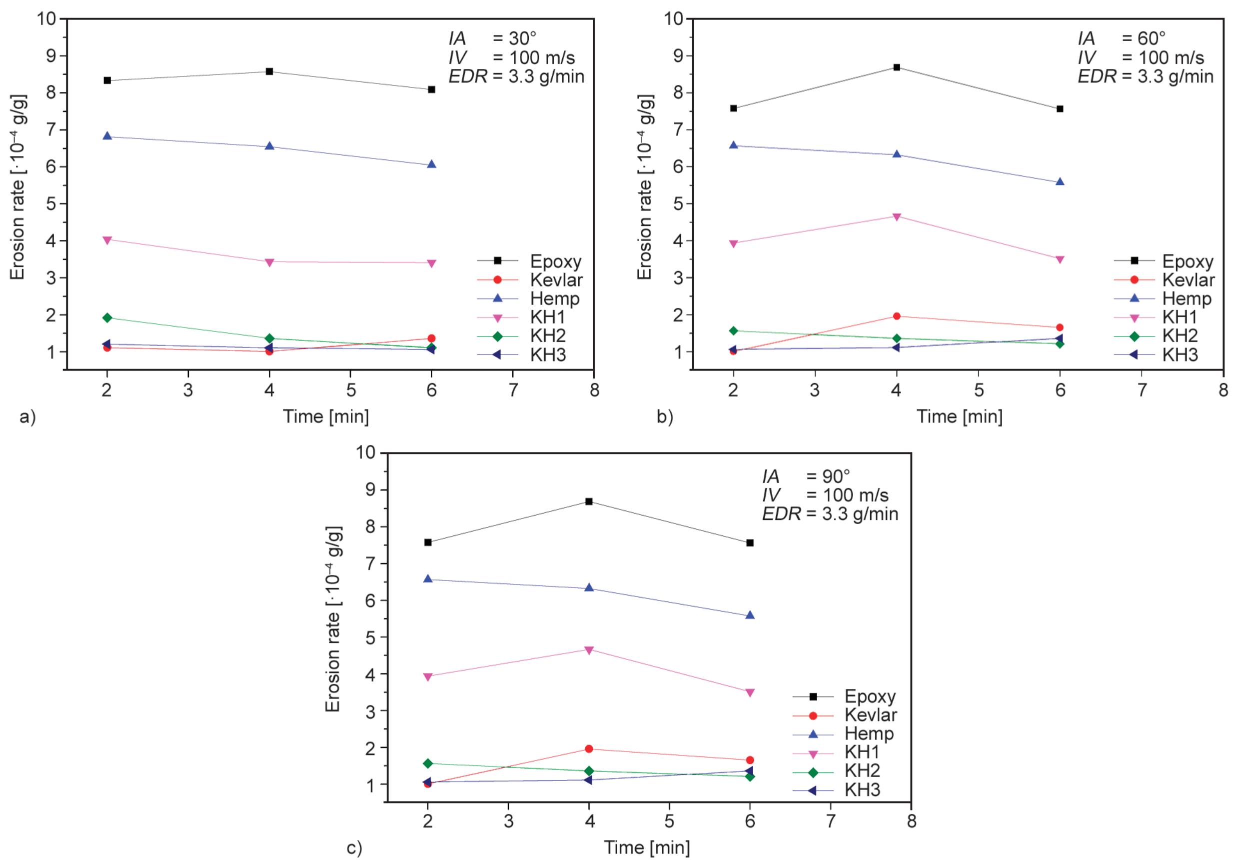


Figure 9. a) Erosion wear rate as a function of exposure duration at an impact angle of 30° of various hybrid composite specimens. b) Erosion wear rate as a function of exposure duration at an impact angle of 60° of various hybrid composite specimens. c) Erosion wear rate as a function of exposure duration at an impact angle of 90°.

could be attributed to the effect of the hybridizing where the hydrophobic Kevlar fiber dominated the hybrid composites. However, plain weave type (KH1) composites with various exposure times and impact angles demonstrated poor wear resistance behaviour. For plain weave type patterns, the highest wear rate was seen at an impact angle of 60° and various exposure time. This might be due to manufacturing flaws that result in the creation of micro voids in the composite specimens. Moreover, the twill weave type (KH2) displayed the middle of the wear resistance behaviour for all weaving designs. This is a result of the woven fabrics strong adhesion to the twill Kevlar and hemp fibers. The order of wear resistance to erosion at various composite weaving patterns was basket weave type (KH3) > Twill weave type (KH2) > plain weave type (KH1).

3.4. Taguchi method

The influence of different control variables on the rate of erosion wear of the Kevlar-hemp-epoxy hybrid composites was investigated through the analysis of experiments using Taguchi method. Using 27 different combinations of the control parameters, experiments were run in accordance with the Taguchi analysis design. There were three levels, three factors, and 27 experimental runs in the Taguchi L27 (3^3) orthogonal array. Table 3 lists the erosion rate and accompanying *S*/*N* ratios. The MINITAB 17 software was used to analyse the rate of erosion wear for Kevlar-hemp hybrid epoxy composites. The erosion wear rates mean signal-to-noise ratio was found to be –5.6854 dB.

The effects of different variables on the Signal to Noise ratio and mean of erosion wear rate are graphically depicted in Figures 10 and 11. The interaction plot of exposure time, impact angle, and various weaving patterns on the Kevlar-hemp fiber reinforced epoxy intra-ply hybrid composites are also shown in Figures 12 and 13. Both figures make it simple to comprehend how various control elements affect erosion wear rate. Additionally, Table 4 shows

Table 3. L27 Experimental design.

Experimental run	Impact angle [°]	Exposure duration [min]	Weaving patterns	Erosion wear rate [$\cdot 10^{-4}$ g/g]	*S*/*N* ratio [dB]
1	30	2	1	4.0404	–12.1285
2	30	4	1	3.4393	–10.7294
3	30	6	1	3.4141	–10.6655
4	60	2	1	4.5454	–13.1514
5	60	4	1	4.4949	–13.0544
6	60	6	1	4.4454	–12.9582
7	90	2	1	3.9393	–11.9084
8	90	4	1	4.6666	–13.3800
9	90	6	1	3.5151	–10.9188
10	30	2	2	1.9191	–5.6620
11	30	4	2	1.3636	–2.6937
12	30	6	2	1.1111	–0.9151
13	60	2	2	2.1212	–6.5316
14	60	4	2	1.9595	–5.8429
15	60	6	2	1.5656	–3.8936
16	90	2	2	1.5656	–3.8936
17	90	4	2	1.3636	–2.6937
18	90	6	2	1.2121	–1.6708
19	30	2	3	1.2121	–1.6708
20	30	4	3	1.1110	–0.9143
21	30	6	3	1.0606	–0.5110
22	60	2	3	1.2360	–1.8404
23	60	4	3	1.2121	–1.6708
24	60	6	3	1.0101	–0.0873
25	90	2	3	1.0606	–0.5110
26	90	4	3	1.1111	–0.9151
27	90	6	3	1.3636	–2.6937

the *S*/*N* ratio values. According to these results, the weaving pattern characteristic has the greatest impact on the erosion wear rate for Kevlar-hemp-epoxy intra-ply hybrid composites. The remaining control variables, such as exposure time and impact angle, only slightly affect the erosion wear rate.

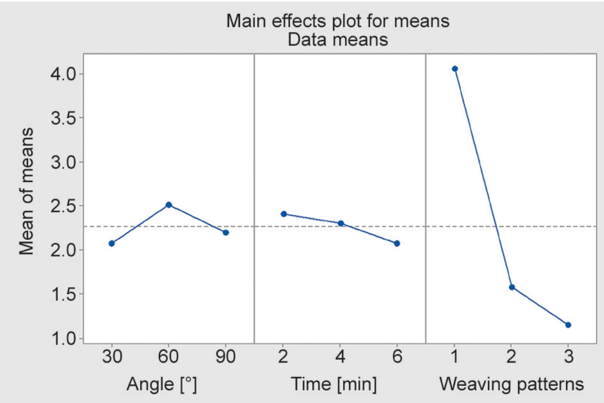


Figure 10. Mean erosion rate and erosion parameter main effect chart.

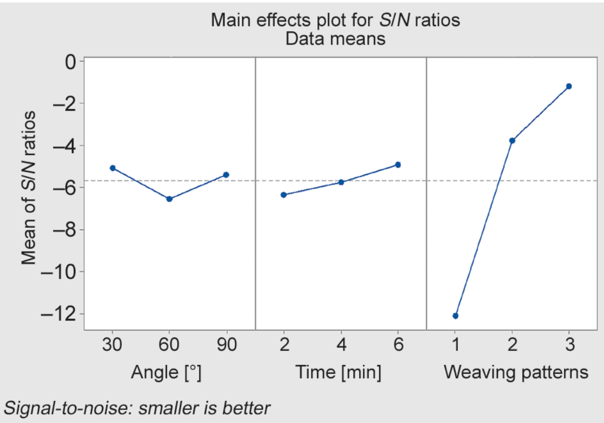


Figure 11. *S*/*N* ratio and erosion parameter main effect chart.

The highest and lowest erosion rates for each experimental factor are shown in Figure 11. This investigation led to the conclusion that the control factor combination A3B1C3 resulted in the prepared sample's erosion rate to be the lowest. The basket type weave pattern, 90° impact angle, and 2 posure time were found to have the lowest erosion wear rates of hybrid composites.

3.4.1. ANOVA regression analysis

In this work, an effort has been made to identify the ideal control factor values for the lowest erosion wear rate. For single-objective optimization, the connection between the rate of erosion wear and control variables must be quantified. The analysis of variance (ANOVA) findings for the erosion rate at a 5% level

Table 4. Signal-to-noise (*S*/*N*) ratio response table.

Level	Impact angle [°]	Exposure time [min]	Weaving patterns
1	–5.009	–6.366	–12.099
2	–6.559	–5.766	–3.755
3	–5.398	–4.924	–1.202
Delta	1.460	1.443	10.898
Rank	2	3	1

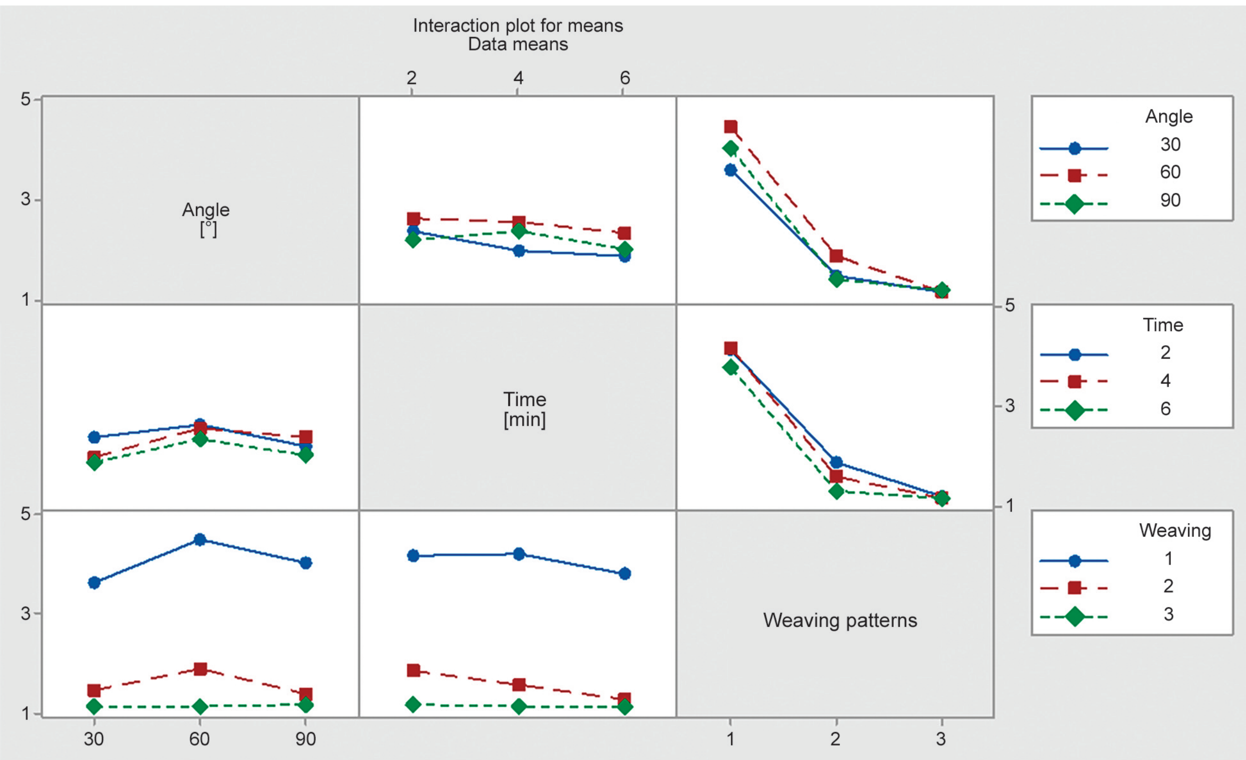


Figure 12. Erosion rate and process parameter interaction chart.

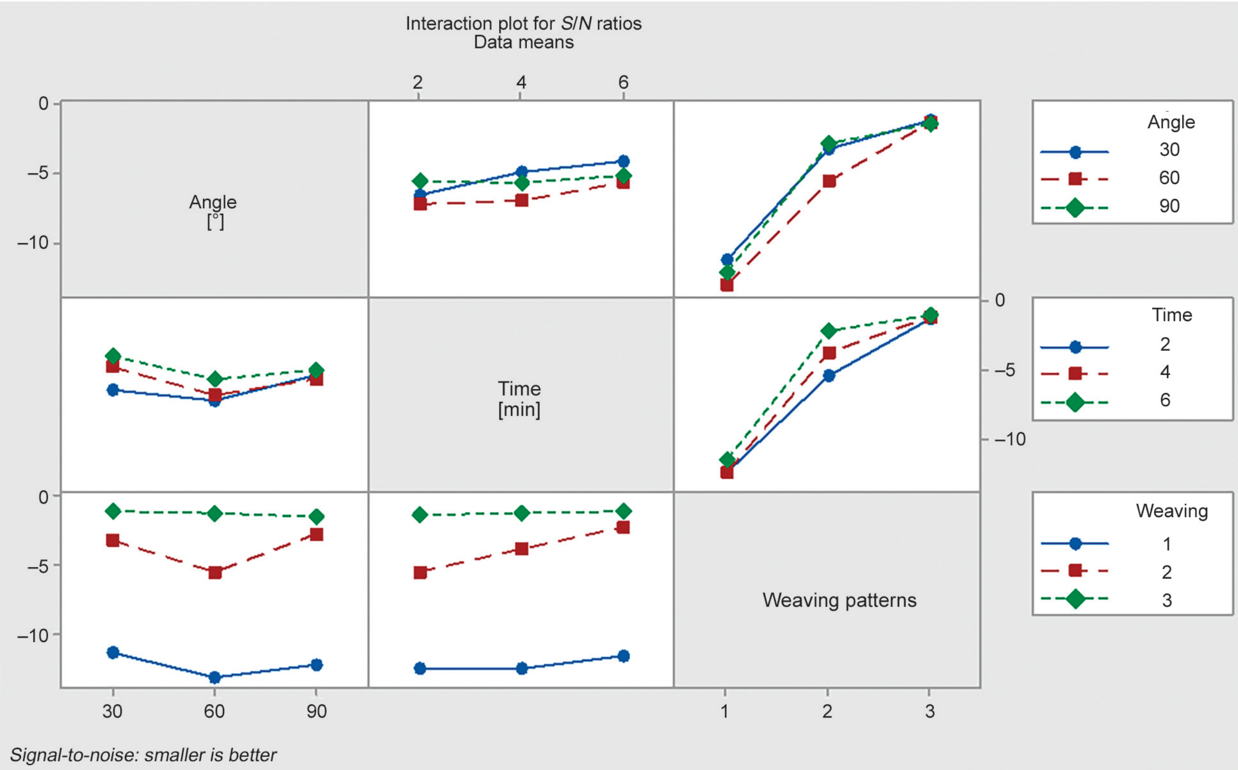


Figure 13. *S*/*N* ratio and process parameter interaction chart.

of significance are shown in Table 5. According to the findings, exposure time (p = 0.278) impingement angle (p = 0.674) had a less significant impact on the erosion rate. They also contribute less percentage significantly to the rate of erosion 1.01 and 0.15%, respectively. The weaving patterns exhibit a higher level of significance (p = 0.000) and a greater impact (79.96%) to the erosion wear rate. Regression analysis had utilized to calculate the theoretical erosion rate for using MINITAB software, yielding the following regression Equation (5):

$$\text{Erosion wear rate} = 5.366 + 0.00209\cdot\text{Angle} - 0.0817\cdot\text{Time} - 1.451\cdot\text{Weaving} \quad (5)$$

The erosion wear rate for Kevlar-hemp-epoxy hybrid composites is compared in Table 6 with theoretical and experimental results, with the percentage error being within an acceptable range of 0 to 20%.

3.4.2. Confirmation test

The confirmation test is the last step in the process of designing an experiment. The goal of the confirmation test is to confirm the outcomes of the analytical phase. In the confirmation experiment, a fresh set of factor settings A3B1C3 is utilised to accurately predict the erosion rate. Taguchi analysis can be used to calculate a predicted value and the erosion wear rate's *S*/*N* ratio. The wear rate is predicted using the Taguchi approach employing a new predicted parameter of A3B1C3, and the *S*/*N* ratio is discovered to be –0.5177 dB. As stated in Table 7, an experiment was conducted utilising the combination factor A3B1C3, along the outcomes which had been compared to the results predicted. This created model seems to be able to predict erosion rate with accuracy. There is a 1.31% error in the *S*/*N* ratio of erosion rate. Nevertheless, the error can be decreased if the number of measurements has risen. As a result, the

Table 5. Results of an ANOVA on the erosion wear rate.

Source	Degree of freedom	Sequential sum of square	Percentage of contribution [%]	Adjacent sum of square	Adjacent mean square	*F* value	*p* value
Regression	3	38.4639	81.12	38.4639	12.8213	32.94	0.000
Angle	1	0.0705	0.15	0.0705	0.0705	0.18	0.674
Time	1	0.4809	1.01	0.4809	0.4809	1.24	0.278
Weaving	1	37.9126	79.96	37.9126	37.9126	97.40	0.000
Residual error	23	8.9525	18.88	8.9525	0.3892	–	–
Total	26	47.4164	100.00	–	–	–	–

Table 6. The outcome of experimental and theoretical comparison.

Ex No.	Erosion wear rate for theoretical values, E_{th} [$\cdot 10^{-4}$ g/g]	Erosion wear rate for experimental values, E_{ex} [$\cdot 10^{-4}$ g/g]	Error [%]
1	3.923670	4.0404	–2.88906
2	3.631670	3.4393	5.59330
3	3.338459	3.4141	–2.21554
4	4.595870	4.5454	1.11036
5	4.644404	4.4949	3.32607
6	4.245426	4.4454	–4.49845
7	4.005559	3.9393	1.68201
8	4.324726	4.6666	–7.32598
9	3.790715	3.5151	7.84088
10	1.930504	1.9191	0.59422
11	1.306870	1.3636	–4.16028
12	1.156426	1.1111	4.07937
13	2.156237	2.1212	1.65176
14	1.873137	1.9595	–4.40740
15	1.616926	1.5656	3.27836
16	1.519159	1.5656	–2.96632
17	1.506693	1.3636	10.49374
18	1.115448	1.2121	–7.97392
19	1.317426	1.2121	8.68954
20	0.975359	1.1110	–12.20890
21	1.090915	1.0606	2.85827
22	1.150493	1.2360	–6.91808
23	1.148959	1.2121	–5.20920
24	1.158748	1.0101	14.71618
25	1.040781	1.0606	–1.86861
26	1.309881	1.1111	17.89051
27	1.184637	1.3636	–13.12430

Table 7. Confirmation tests for erosion wear rate.

	Optimal control variables		Percentage error
	Prediction	Experiment	
Operating levels	A3B1C3	A3B1C3	1.31%
Erosion rate [$\cdot 10^{-4}$ g/g]	1.0909	1.0606	
S/N ratio [dB]	–0.5177	–0.5110	

Taguchi method of estimating the outcome measures were based on input variables.

3.5. Morphological analysis of eroded surfaces

In this investigation of eroded composite, the eroded surface failure mechanism of intra-ply hybrid composite samples was observed by using the SEM (scanning electron microscope, performed with a Tescan Vega3 SEM) analysis. Figure 14 illustrate the eroded surfaces of plain and twill weave type intra-ply hybrid composites at 30 and 60° impact angle of 2 min exposure time. It clearly demonstrates the local loss of matrix material from the surface caused by eroded particles. Fiber breakages can also be seen on the damaged surfaces. Further on the surfaces of composite, micro cavities are also formed. This could have occurred as a result of compressive stresses developing on the composite's surface due to alumina particle indentation. Fibers were also broken as a result of the impact. After the breaking of the fibers, they become detached from the surface, resulting in the creation of cavities.

Figure 15 shows the same microscopy image at a higher magnification, revealing the grooves and broken

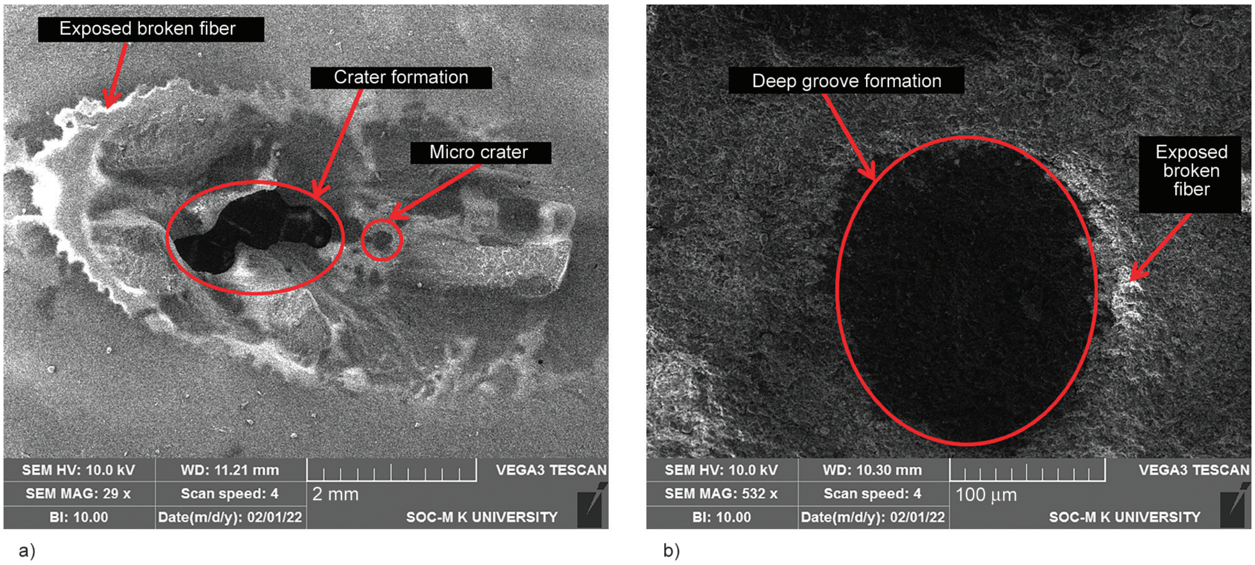


Figure 14. Eroded surfaces of a) plain (KH1) and b) twill (KH2) type woven fabric composites.

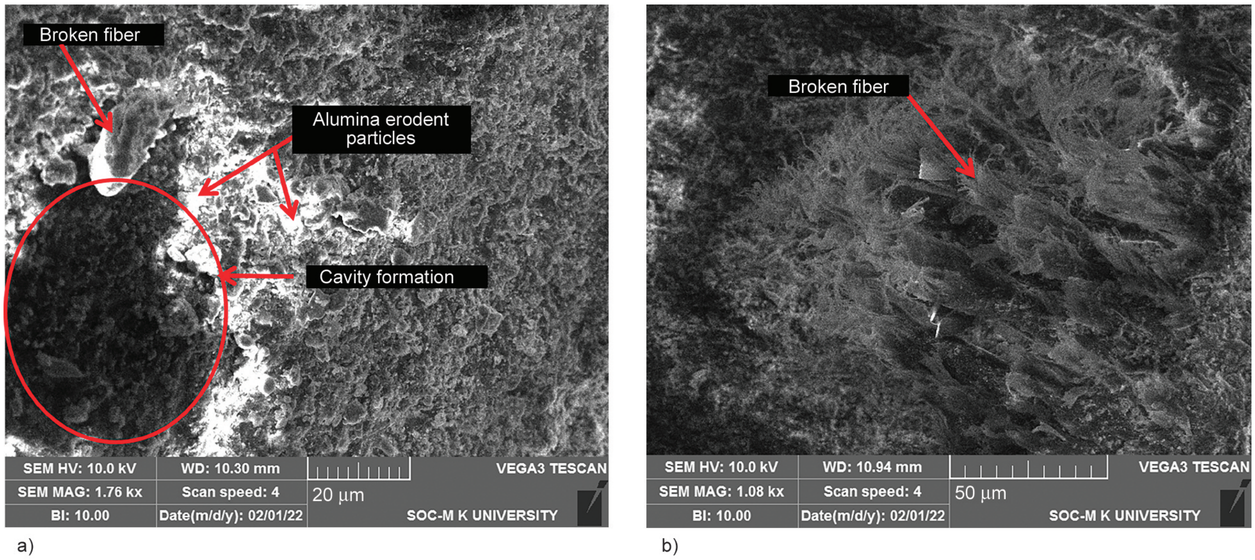


Figure 15. Eroded surfaces of a) plain (KH1) and b) twill (KH2) type woven fabric composites at higher magnification.

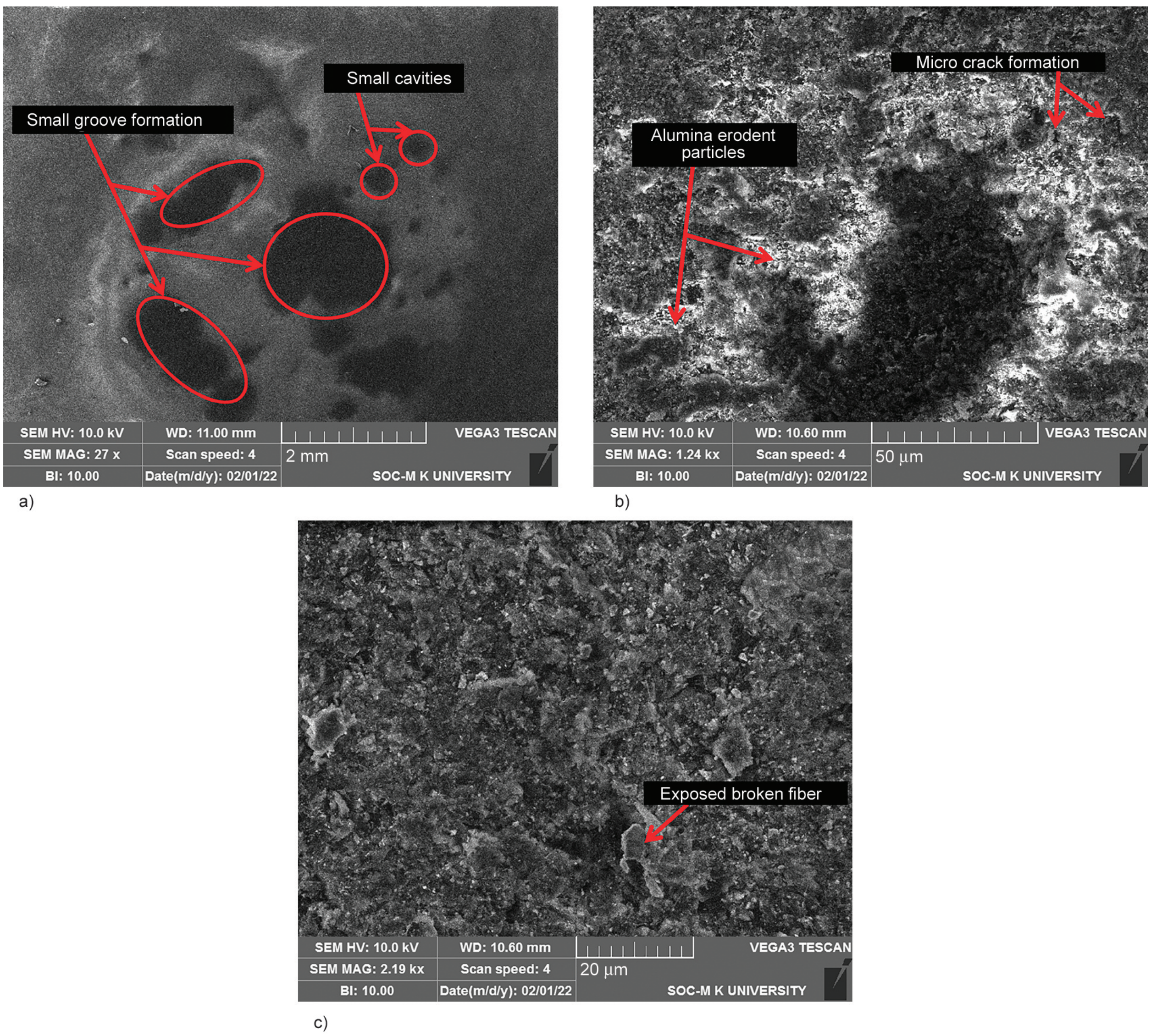


Figure 16. Eroded surfaces of basket (KH3) weave composites at higher magnification. a) 27×, b) 1240×, c) 2190×.

fibers clearly. Figures 16a and 16b displays a microscopy image of intra-ply hybrid Kevlar/hemp epoxy composite with a basket type weaving pattern at 90° of impact angle and 2 min exposure time. Local matrix removal occurred here as well, but the creation of cavities was smaller. Fiber breakage and matrix removal are also reduced, as shown in Figure 16c. This could have happened because the addition of Kevlar fiber good bonding between the woven fabrics of the composites, limiting the impact of eroding the surface. As a result, the resistance of the composites improves.

In comparison to Figure 14, Figures 16a and 16b depicts the same microscopy image at a higher magnification, revealing the creation of smaller and fewer grooves. Table 8 represents the eroded surface failure mechanism of hybrid composites using SEM analysis.

4. Conclusions

The effect of swell thickness, water absorption, and erosion property in intra-ply composites with Kevlar-hemp fiber reinforced epoxy matrix has been investigated experimentally. The following observations are:

- The moisture absorption and thickness swelling of hybrid composites showed greater resistance than hemp composites and epoxy matrix composites.
- The basket weave composites exhibited minimum absorption of moisture of 4.8% and thickness of swelling of 1.7%. Although, Kevlar composites had minimum water absorption of 2.6% and swelling thickness of 1.6% percentages.
- The basket weave composites and kevlar composites were discovered to have increased erosion resistance behaviour among all types of composites with a variety of control parameters.
- In comparison with our previous study of Kevlar-PALF-epoxy hybrid composites, the Kevlar-hemp-epoxy hybrid composites have better erosion resistance properties. Moreover, the minimum erosion wear rate of Kevlar-hemp-epoxy hybrid composites is $1.0606 \cdot 10^{-4}$ g/g.
- The Taguchi design analyses revealed that the hybrid composites' optimal control parameters were 90° impact angle and 2 minute exposure time for a basket type weaving pattern.
- ANOVA results showed that weaving types contributed more significantly while impact angle contributed less significantly.
- According to the results of the confirmation test, the improved parameter can offer superior resistance to erosion on the hybrids of Kevlar-hemp-epoxy composites.
- From the SEM study of eroded surfaces, it was evident that the fiber breakages, micro cavities, crater formation, small grooves were the failure mechanisms of material removal for the intra-ply hybrid composites.

Based on the literature and the investigations carried out so far by the researchers, there is a necessity to detect the defects in the intra layers in the hybridized composite materials for the performance improvement, and this could be seen as a future perspective.

Table 8. Eroded surfaces failure mechanism of hybrid composites using SEM analysis.

Hybrid composites	Erosion failures
Plain weave type hybrid composites	Micro cavities, broken fibers, crater formation
Twill weave type hybrid composites	Small cavities, smaller and fewer grooves
Basket weave type hybrid composites	Small cavities, disposed fibers, crater formation, micro crack

Acknowledgements

The authors thank the management of KARE, India and KMUTNB for providing fabrication and testing facilities for this research work.
This research was funded by National Science, Research and Innovation Fund (NSRF), and King Mongkut's University of Technology North Bangkok with Contract no. KMUTNB-FF-66-14.

References

[1] Rangappa S. M., Siengchin S.: Moving towards biofiber-based composites: Knowledge gaps and insights. Express Polymer Letters, **16**, 451–452 (2022). https://doi.org/10.3144/expresspolymlett.2022.33
[2] Senthil Kumar K., Siva I., Rajini N., Jappes J. T. W., Amico S. C.: Layering pattern effects on vibrational behavior of coconut sheath/banana fiber hybrid composites. Materials and Design, **90**, 795–803 (2016). https://doi.org/10.1016/j.matdes.2015.11.051
[3] Singh T., Patnaik A., Ranakoti L., Dogossy G., Lendvai L.: Thermal and sliding wear properties of wood waste-filled poly(lactic acid) biocomposites. Polymers, **14**, 2230 (2022). https://doi.org/10.3390/polym14112230
[4] Sanjay M. R., Siengchin S.: Exploring the applicability of natural fibers for the development of biocomposites. Express Polymer Letters, **15**, 193 (2021). https://doi.org/10.3144/expresspolymlett.2021.17

[5] Singh T., Pattnaik P., Kumar S. R., Fekete G., Dogossy G., Lendvai L.: Optimization on physicomechanical and wear properties of wood waste filled poly(lactic acid) biocomposites using integrated entropy-simple additive weighting approach. South African Journal of Chemical Engineering, **41**, 193–202 (2022). https://doi.org/10.1016/j.sajce.2022.06.008

[6] Puttegowda M., Pulikkalparambil H., Rangappa S. M.: Trends and developments in natural fiber composites. Applied Science and Engineering Progress, **14**, 543–552 (2021). https://doi.org/10.14416/j.asep.2021.06.006

[7] Singh T.: Optimum design based on fabricated natural fiber reinforced automotive brake friction composites using hybrid CRITIC-MEW approach. Journal of Materials Research and Technology, **14**, 81–92 (2021). https://doi.org/10.1016/j.jmrt.2021.06.051

[8] Jeyaguru S., Thiagamani S. M. K., Pulikkalparambil H., Siengchin S., Subramaniam J., Rangappa S. M., Muthukumar C., Krishnasamy S.: Mechanical, acoustic and vibration performance of intra-ply kevlar/PALF epoxy hybrid composites: Effects of different weaving patterns. Polymer Composites, **43**, 3902–3914 (2022). https://doi.org/10.1002/pc.26665

[9] Rangappa S. M., Siengchin S., Parameswaranpillai J., Jawaid M., Ozbakkaloglu T.: Lignocellulosic fiber reinforced composites: Progress, performance, properties, applications, and future perspectives. Polymer Composites, **43**, 645–691 (2022). https://doi.org/10.1002/pc.26413

[10] Sanjay M. R., Madhu P., Jawaid M., Senthamaraikannan P., Senthil S., Pradeep S.: Characterization and properties of natural fiber polymer composites: A comprehensive review. Journal of Cleaner Production, **172**, 566–581 (2018). https://doi.org/10.1016/j.jclepro.2017.10.101

[11] Puttegowda M., Rangappa S. M., Jawaid M., Shivanna P., Basavegowda Y., Saba N.: Potential of natural/synthetic hybrid composites for aerospace applications. in 'Sustainable composites for aerospace applications' (eds.: Jawaid M., Thariq M.) Elsevier, Amsterdam, 315–351 (2018). https://doi.org/10.1016/B978-0-08-102131-6.00021-9

[12] Atiqah A., Chandrasekar M., Kumar T. S. M., Senthilkumar K., Ansari M. N.: Characterization and interface of natural and synthetic hybrid composites. in 'Encyclopedia of renewable and sustainable materials' (eds.: Hashmi S., Choudhury I. A.) Elsevier, Amsterdam, Vol. 4, 389–400 (2020). https://doi.org/10.1016/B978-0-12-803581-8.10805-7

[13] Sanjay M. R., Siengchin S., Parameswaranpillai J., Jawaid M., Pruncu C. I., Khan A.: A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization. Carbohydrate Polymers, **207**, 108–121 (2019). https://doi.org/10.1016/j.carbpol.2018.11.083

[14] Chandrasekar M., Shahroze R. M., Ishak M. R., Saba N., Jawaid M., Senthilkumar K., Kumar T. S. M., Siengchin S.: Flax and sugar palm reinforced epoxy composites: Effect of hybridization on physical, mechanical, morphological and dynamic mechanical properties. Materials Research Express, **6**, 105331 (2019). https://doi.org/10.1088/2053-1591/ab382c

[15] Nagarajan K. J., Ramanujam N. R., Sanjay M. R., Siengchin S., Surya Rajan B., Sathick Basha K., Madhu P., Raghav G. R.: A comprehensive review on cellulose nanocrystals and cellulose nanofibers: Pretreatment, preparation, and characterization. Polymer Composites, **42**, 1588–1630 (2021). https://doi.org/10.1002/pc.25929

[16] Shahroze R. M., Muthukumar C., Krishnasamy S., Senthilmuthukumar T., Ishak M. R., Asyraf M. R. M.: A review on the various fibre treatment techniques used for the fibre surface modification of the sugar palm fibres. in 'Proceedings of the Seminar Enau Kebangsaan 2019. Bahau, Malaysia', 48–52 (2019).

[17] Mohit H., Rangappa S. M., Siengchin S., Gorbatyuk S., Manimaran P., Alka Kumari C., Khan A., Doddamani M.: A comprehensive review on performance and machinability of plant fiber polymer composites. Polymer Composites, **43**, 608–623 (2022). https://doi.org/10.1002/pc.26403

[18] Krishnasamy S., Muthukumar C., Nagarajan R., Thiagamani S. M. K., Saba N., Jawaid M., Siengchin S., Ayrilmis N.: Effect of fibre loading and $Ca(OH)_2$ treatment on thermal, mechanical, and physical properties of pineapple leaf fibre/polyester reinforced composites. Materials Research Express, **6**, 085545 (2019). https://doi.org/10.1088/2053-1591/ab2702

[19] Vinod A., Sanjay M. R., Suchart S., Jyotishkumar P.: Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites. Journal of Cleaner Production, **258**, 120978 (2020). https://doi.org/10.1016/j.jclepro.2020.120978

[20] Jagadeesh P., Puttegowda M., Rangappa S. M., Siengchin S.: Influence of nanofillers on biodegradable composites: A comprehensive review. Polymer Composites, **42**, 5691–5711 (2021). https://doi.org/10.1002/pc.26291

[21] Thiagamani S. M. K., Krishnasamy S., Muthukumar C., Tengsuthiwat J., Nagarajan R., Siengchin S., Ismail S. O.: Investigation into mechanical, absorption and swelling behaviour of hemp/sisal fibre reinforced bioepoxy hybrid composites: Effects of stacking sequences. International Journal of Biological Macromolecules, **140**, 637–646 (2019). https://doi.org/10.1016/j.ijbiomac.2019.08.166

[22] Radoor S., Karayil J., Rangappa S. M., Siengchin S., Parameswaranpillai J.: A review on the extraction of pineapple, sisal and abaca fibers and their use as reinforcement in polymer matrix. Express Polymer Letters, **14**, 309–335 (2020). https://doi.org/10.3144/expresspolymlett.2020.27

[23] Parameswaranpillai J., Jacob J., Dominic C. D. M., Muthukumar C., Thiagamani S. M. K., Jayakumar A., Siengchin S., Radoor S.: Effect of water absorption on the tensile, flexural, fracture toughness and impact properties of biocomposites. in 'Aging effects on natural fiber-reinforced polymer composites' (eds.: Muthukumar C., Krishnasamy S., Thiagamani S. M. K., Siengchin S.) Springer, Singapore, 35–50 (2022). https://doi.org/10.1007/978-981-16-8360-2_3

[24] Ramesh M., Deepa C., Kumar L. R., Sanjay M. R., Siengchin S.: Life-cycle and environmental impact assessments on processing of plant fibres and its biocomposites: A critical review. Journal of Industrial Textiles, **51**, 5518S–5542S (2020). https://doi.org/10.1177/1528083720924730

[25] Thiagamani S. M. K., Pulikkalparambil H., Siengchin S., Ilyas R. A., Krishnasamy S., Muthukumar C., Radzi A. M., Rangappa S. M.: Mechanical, absorption, and swelling properties of jute/kenaf/banana reinforced epoxy hybrid composites: Influence of various stacking sequences. Polymer Composites, in press (2022). https://doi.org/10.1002/pc.26999

[26] Girijappa Y. G. T., Rangappa S. M., Parameswaranpillai J., Siengchin S.: Natural fibers as sustainable and renewable resource for development of eco-friendly composites: A comprehensive review. Frontiers in Materials, **6**, 226 (2019). https://doi.org/10.3389/fmats.2019.00226

[27] Senthilkumar K., Saba N., Rajini N., Chandrasekar M., Jawaid M., Siengchin S., Othman Y., Alotman Y.: Mechanical properties evaluation of sisal fibre reinforced polymer composites: A review. Construction and Building Materials, **174**, 713–729 (2018). https://doi.org/10.1016/j.conbuildmat.2018.04.143

[28] Chandrasekar M., Siva I., Kumar T. S. M., Senthilkumar K., Siengchin S., Rajini N.: Influence of fibre inter-ply orientation on the mechanical and free vibration properties of banana fibre reinforced polyester composite laminates. Journal of Polymers and the Environment, **28**, 2789–2800 (2020). https://doi.org/10.1007/s10924-020-01814-8

[29] Rangappa S. M., Parameswaranpillai J., Siengchin S., Jawaid M., Ozbakkaloglu T.: Bioepoxy based hybrid composites from nano-fillers of chicken feather and lignocellulose ceiba pentandra. Scientific Reports, **12**, 397 (2022). https://doi.org/10.1038/s41598-021-04386-2

[30] Senthilkumar K., Subramaniam S., Ungtrakul T., Kumar T. S. M., Chandrasekar M., Rajini N., Siengchin S., Parameswaranpillai J.: Dual cantilever creep and recovery behavior of sisal/hemp fibre reinforced hybrid biocomposites: Effects of layering sequence, accelerated weathering and temperature. Journal of Industrial Textiles, **51**, 2372S–2390S (2022). https://doi.org/10.1177/1528083720961416

[31] Athith D., Sanjay M. R., Yashas Gowda T. G., Madhu P., Arpitha G. R., Yogesha B., Omri M. A.: Effect of tungsten carbide on mechanical and tribological properties of jute/sisal/E-glass fabrics reinforced natural rubber/epoxy composites. Journal of Industrial Textiles, **48**, 713–737 (2018). https://doi.org/10.1177/1528083717740765

[32] Shaik S., Reddy D. R. R., Kornipalli A., Kasam A., Aravind D., Krishnasamy S., Muthukumar C., Thiagamani S. M. K.: Influencing effects of hybridization and addition of fillers on the viscoelastic properties of reinforced polymer-based composites. in 'Vibration and damping behavior of biocomposites' (eds.: Thiagamani S. M. K., Hoque E., Krishnasamy S., Muthukumar C., Siengchin S.) CRC Press, Boca Raton, 189–200 (2022).

[33] Arpitha G. R., Sanjay M. R., Senthamaraikannan P., Barile C., Yogesha B.: Hybridization effect of sisal/glass/epoxy/filler based woven fabric reinforced composites. Experimental Techniques, **41**, 577–584 (2017). https://doi.org/10.1007/s40799-017-0203-4

[34] Sanjay M. R., Yogesha B.: Studies on hybridization effect of jute/kenaf/E-glass woven fabric epoxy composites for potential applications: Effect of laminate stacking sequences. Journal of Industrial Textiles, **47**, 1830–1848 (2018). https://doi.org/10.1177/1528083717710713

[35] Joshi S. V., Drzal L. T., Mohanty A. K., Arora S.: Are natural fiber composites environmentally superior to glass fiber reinforced composites? Composites Part A: Applied Science and Manufacturing, **35**, 371–376 (2004). https://doi.org/10.1016/j.compositesa.2003.09.016

[36] Jothibasu S., Mohanamurugan S., Vijay R., Lenin Singaravelu D., Vinod A., Sanjay M. R.: Investigation on the mechanical behavior of areca sheath fibers/jute fibers/glass fabrics reinforced hybrid composite for light weight applications. Journal of Industrial Textiles, **49**, 1036–1060 (2020). https://doi.org/10.1177/1528083718804207

[37] Begum K., Islam M.: Natural fiber as a substitute to synthetic fiber in polymer composites: A review. Research Journal of Engineering Sciences, **2**, 46–53 (2013).

[38] Ganesan K., Kailasanathan C., Sanjay M. R., Senthamaraikannan P., Saravanakumar S. S.: A new assessment on mechanical properties of jute fiber mat with egg shell powder/nanoclay-reinforced polyester matrix composites. Journal of Natural Fibers, **17**, 482–490 (2020). https://doi.org/10.1080/15440478.2018.1500340

[39] John K. M., Kumaran S. T., Kumar K S., Kumar S. S., Aslan M. U., Alver Ü. M.: Mechanical and vibrational behavior of twill woven carbon fiber reinforced composites. International Polymer Processing, **35**, 203–210 (2020). https://doi.org/10.3139/217.3918

[40] Bharath K. N., Sanjay M. R., Jawaid M., Harisha, Basavarajappa S., Siengchin S.: Effect of stacking sequence on properties of coconut leaf sheath/jute/E-glass reinforced phenol formaldehyde hybrid composites. Journal of Industrial Textiles, **49**, 3–32 (2019). https://doi.org/10.1177/1528083718769926

[41] Sangilimuthukumar J., Jappes J. T. W., Siva I., Brintha N. C.: The low-cost, high-performance material for automotive application. International Journal of Innovative Technology and Exploring Engineering, **9**, 1084–1087 (2019). https://doi.org/10.35940/ijitee.B1428.1292S219

[42] Madhu P., Sanjay M. R., Senthamaraikannan P., Pradeep S., Saravanakumar S. S., Yogesha B.: A review on synthesis and characterization of commercially available natural fibers: Part-I. Journal of Natural Fibers, **16**, 1132–1144 (2018). https://doi.org/10.1080/15440478.2018.1453433

[43] Shahzad A., Nasir S. U.: Mechanical properties of natural fiber/synthetic fiber reinforced polymer hybrid composites. in 'Green biocomposites' (eds.: Jawaid M., Sapuan S., Alothman O.) Springer, 355–396 (2017). https://doi.org/10.1007/978-3-319-46610-1_15

[44] Gowda T. G. Y., Sanjay M. R., Bhat K. S., Madhu P., Senthamaraikannan P., Yogesha B., Pham D.: Polymer matrix-natural fiber composites: An overview. Cogent Engineering, **5**, 1446667 (2018). https://doi.org/10.1080/23311916.2018.1446667

[45] Vinod A., Gowda T. Y., Vijay R., Sanjay M. R., Gupta M. K., Jamil M., Kushvaha V., Siengchin S.: Novel *Muntingia Calabura bark* fiber reinforced green-epoxy composite: A sustainable and green material for cleaner production. Journal of Cleaner Production, **294**, 126337 (2021). https://doi.org/10.1016/j.jclepro.2021.126337

[46] Vignesh V., Balaji A. N., Nagaprasad N., Sanjay M. R., Khan A., Asiri A. M., Ashraf G. M., Siengchin S.: Indian mallow fiber reinforced polyester composites: Mechanical and thermal properties. Journal of Materials Research and Technology, **11**, 274–284 (2021). https://doi.org/10.1016/j.jmrt.2021.01.023

[47] Kavya H. M., Bavan S., Sanjay M. R., Siengchin S., Gorbatyuk S.: Effect of coir fiber and inorganic filler on physical and mechanical properties of epoxy based hybrid composites. Polymer Composites, **42**, 3911–3921 (2021). https://doi.org/10.1002/pc.26103

[48] Yorseng K., Rangappa S. M., Pulikkalparambil H., Siengchin S., Parameswaranpillai J.: Accelerated weathering studies of kenaf/sisal fiber fabric reinforced fully biobased hybrid bioepoxy composites for semi-structural applications: Morphology, thermo-mechanical, water absorption behavior and surface hydrophobicity. Construction and Building Materials, **235**, 117464 (2020). https://doi.org/10.1016/j.conbuildmat.2019.117464

[49] Dér A., Kaluza A., Kurle D., Herrmann C., Kara S., Varley R.: Life cycle engineering of carbon fibres for lightweight structures. Procedia CIRP, **69**, 43–48 (2018). https://doi.org/10.1016/j.procir.2017.11.007

[50] Prabhu L., Krishnaraj V., Gokulkumar S., Sathish S., Sanjay M. R., Siengchin S.: Mechanical, chemical and sound absorption properties of glass/kenaf/waste tea leaf fiber-reinforced hybrid epoxy composites. Journal of Industrial Textiles, **51**, 1674–1700 (2022). https://doi.org/10.1177/1528083720957392

[51] Zhang J., Chaisombat K., He S., Wang C. H.: Hybrid composite laminates reinforced with glass/carbon woven fabrics for lightweight load bearing structures. Materials and Design (1980–2015), **36**, 75–80 (2012). https://doi.org/10.1016/j.matdes.2011.11.006

[52] Jeyaguru S., Thiagamani S. M. K., Pulikkalparambil H., Siengchin S., Krishnasamy S., Rajkumar A. G., Muthukumar C., Rangappa S. M.: Effects of different weaving patterns on thermomechanical and dynamic mechanical properties of kevlar/pineapple leaf fiber hybrid composites. Polymer Composites, **43**, 4979–4997 (2022). https://doi.org/10.1002/pc.26764

[53] Muthukumar C., Krishnasamy S., Thiagamani S. M. K., Jeyaguru S., Siengchin S., Nagarajan R.: Polymers in aerospace applications. in 'Encyclopedia of materials: Plastics and polymers' (eds.: Hashmi J.) Elsevier, Vol. 4, 382–389 (2022). https://doi.org/10.1016/B978-0-12-820352-1.00077-8

[54] Sanjay M. R., Arpitha G. R., Senthamaraikannan P., Kathiresan M., Saibalaji M. A., Yogesha B.: The hybrid effect of jute/kenaf/E-glass woven fabric epoxy composites for medium load applications: Impact, inter-laminar strength, and failure surface characterization. Journal of Natural Fibers, **16**, 600–612 (2018). https://doi.org/10.1080/15440478.2018.1431828

[55] Sharma P., Bhanot V. K., Singh D., Undal H. S., Sharma M.: Research work on fiber glass wool reinforced and epoxy matrix composite material. International Journal of Mechanical Engineering and Robotics Research, **2**, 106–124 (2013).

[56] Stalin A., Mothilal S., Vignesh V., Sanjay M. R., Siengchin S.: Mechanical properties of hybrid vetiver/banana fiber mat reinforced vinyl ester composites. Journal of Industrial Textiles, **51**, 5869S–5886S (2022). https://doi.org/10.1177/1528083720938161

[57] Krishnasamy S., Thiagamani S. M. K., Muthukumar C., Tengsuthiwat J., Nagarajan R., Siengchin S., Ismail S. O., Brintha N. C.: Effects of stacking sequences on static, dynamic mechanical and thermal properties of completely biodegradable green epoxy hybrid composites. Materials Research Express, **6**, 105351 (2019). https://doi.org/10.1088/2053-1591/ab3ec7

[58] Kavya H. M., Bavan S., Yogesha B., Sanjay M. R., Suchart S., Sergey G.: Effect of coir fiber and inorganic filler hybridization on Innegra fiber-reinforced epoxy polymer composites: Physical and mechanical properties. Cellulose, **28**, 9803–9820 (2021). https://doi.org/10.1007/s10570-021-04140-x

[59] Senthilkumar K., Ungtrakul T., Chandrasekar M., Kumar T. S. M., Rajini N., Siengchin S., Pulikkalparambil H., Parameswaranpillai J., Parameswaranpillai J., Ayrilmis N.: Performance of sisal/hemp bio-based epoxy composites under accelerated weathering. Journal of Polymers and the Environment, **29**, 624–636 (2021). https://doi.org/10.1007/s10924-020-01904-7

[60] Ramachandran A., Rangappa S. M., Khan A., Seingchin S., Dhakal H. N.: Modification of fibers and matrices in natural fiber reinforced polymer composites: A comprehensive review. Macromolecular Rapid Communications, **43**, e2100862 (2022). https://doi.org/10.1002/marc.202100862

[61] Yashas Gowda T. G., Madhu P., Kushvaha V., Rangappa S. M., Siengchin S.: Comparative evaluation of areca/carbon/basalt fiber reinforced epoxy/bio epoxy based hybrid composites. Polymer Composites, **43**, 4179–4190 (2022). https://doi.org/10.1002/pc.26680

[62] Suriani M. J., Radzi F. S. M., Ilyas R. A., Petrů M., Sapuan S. M., Ruzaidi C. M.: Flammability, tensile, and morphological properties of oil palm empty fruit bunches fiber/PET yarn-reinforced epoxy fire retardant hybrid polymer composites. Polymers, **13**, 1282 (2021). https://doi.org/10.3390/polym13081282

[63] Mukesh S. K., Bettagowda N., Praveenkumara J., Girijappa Y. G. T., Puttegowda M., Rangappa S. M., Gorbatyuk S.: Influence of stacking sequence on flax/kevlar hybrid epoxy composites: Mechanical and morphological studies. Polymer Composites, **43**, 3782–3793 (2022). https://doi.org/10.1002/pc.26655

[64] Yorseng K., Rangappa S. M., Parameswaranpillai J., Siengchin S.: Towards green composites: Bioepoxy composites reinforced with bamboo/basalt/carbon fabrics. Journal of Cleaner Production, **363**, 132314 (2022). https://doi.org/10.1016/j.jclepro.2022.132314

[65] Puttegowda M., Rangappa S. M., Khan A., Al-Zahrani S. A., Otaibi A. A., Shivanna P., Liu Y., Siengchin S.: Effect of layering sequence on impact properties of alkali treated phoenix pusilla fibers-glass-carbon fabrics reinforced hybrid composite laminates. Journal of Natural Fibers, in press (2022). https://doi.org/10.1080/15440478.2021.1932683

[66] Praveenkumara J., Vidya Sagar H. N., Madhu P., Gowda Y., Rangappa S. M., Khan M. R., Khan I., Siengchin S.: Pongamia pinnata (PP) shell powder filled sisal/kevlar hybrid composites: Physico-mechanical and morphological characteristics. Research Square, in press (2021). https://doi.org/10.21203/rs.3.rs-273651/v1

[67] Jagadeesh P., Puttegowda M., Girijappa Y. G. T., Rangappa S. M., Siengchin S.: Carbon fiber reinforced areca/sisal hybrid composites for railway interior applications: Mechanical and morphological properties. Polymer Composites, **43**, 160–172 (2022). https://doi.org/10.1002/pc.26364

[68] Arpitha G. R., Verma A., Sanjay M. R., Siengchin S.: Preparation and experimental investigation on mechanical and tribological performance of hemp-glass fiber reinforced laminated composites for lightweight applications. Advances in Civil Engineering Materials, **10**, 427–439 (2021). https://doi.org/10.1520/ACEM20200187

[69] Madhu P., Sanjay M. R., Khan A., Otaibi A. A., Al-Zahrani S. A., Pradeep S., Boonyasopone P., Siengchin S.: Hybrid effect of PJFs/e-glass/carbon fabric reinforced hybrid epoxy composites for structural applications. Journal of Natural Fibers, **19**, 3742–3752 (2020). https://doi.org/10.1080/15440478.2020.1848724

[70] Puttegowda M., Rangappa S. M., Khan A., Al-Zahrani S. A., Al Otaibi A., Shivanna P., Moure M. M., Siengchin S.: Preparation and characterization of new hybrid polymer composites from *Phoenix pusilla* fibers/e-glass/carbon fabrics on potential engineering applications: Effect of stacking sequence. Polymer Composites, **41**, 4572–4582 (2020). https://doi.org/10.1002/pc.25734

[71] Omri M. A., Sanjay M. R., Triki A., Yogesha B., Kallel A.: Dielectric properties and interfacial adhesion of jute, kenaf and E-glass fabrics reinforcing epoxy composites. Polymer Composites, **40**, 2142–2153 (2019). https://doi.org/10.1002/pc.25001

[72] Johnson R. D. J., Arumugaprabu V., Uthayakumar M., Vigneshwaran S., Manikandan V., Bennet C.: Erosion performance studies on sansevieria cylindrica reinforced vinylester composite. Materials Research Express, **5**, 035309 (2018). https://doi.org/10.1088/2053-1591/aab412

[73] Das G., Biswas S.: Erosion wear behavior of coir fiber-reinforced epoxy composites filled with Al_2O_3 filler. Journal of Industrial Textiles, **47**, 472–488 (2017). https://doi.org/10.1177/1528083716652832

[74] Muthusamy A. R., Thiagamani S. M. K., Krishnaswamy S., Muthukumar C., Pulikkalparambil H., Subramanian J., Madasamy N.: Erosion performance of natural fiber reinforced vinyl ester hybrid composites: Effect of layering sequences. Materials Today: Proceedings, **64**, 200–206 (2022). https://doi.org/10.1016/j.matpr.2022.04.365

[75] Gupta A., Kumar A., Patnaik A., Biswas S.: Effect of different parameters on mechanical and erosion wear behavior of bamboo fiber reinforced epoxy composites. International Journal of Polymer Science, **2011**, 592906 (2011). https://doi.org/10.1155/2011/592906

[76] Biswas S., Satapathy A.: A comparative study on erosion characteristics of red mud filled bamboo–epoxy and glass–epoxy composites. Materials and Design, **31**, 1752–1767 (2010). https://doi.org/10.1016/j.matdes.2009.11.021

[77] Deo C., Acharya S. K.: Solid particle erosion of lantana camara fiber-reinforced polymer matrix composite. Polymer-Plastics Technology and Engineering, **48**, 1084–1087 (2009). https://doi.org/10.1080/03602550903094340

[78] Mohanta N., Acharya S. K.: Implementations of the Taguchi design for the erosive wear of *Luffa cylindrica* fiber-reinforced epoxy hybrid composite. Journal of Polymer Engineering, **35**, 391–399 (2015). https://doi.org/10.1515/polyeng-2014-0235

[79] Jeyaguru S., Thiagamani S. M. K., Rajkumar A. G., Rangappa S. M., Siengchin S.: Solid particle erosion, water absorption and thickness swelling behavior of intra-ply kevlar/PALF fiber epoxy hybrid composites. Polymer Composites, **43**, 3929–3943 (2022). https://doi.org/10.1002/pc.26667

[80] Patnaik A., Tejyan S., Rawal A.: Solid particle erosion behavior of needlepunched nonwoven reinforced composites. Research Journal of Textile and Apparel, **14**, 12–22 (2010). https://doi.org/10.1108/RJTA-14-03-2010-B002

[81] Mishra S. C., Praharaj S., Satapathy A.: Evaluation of erosion wear of a ceramic coating with Taguchi approach. Journal of Manufacturing Engineering, **4**, 241–246 (2009).

[82] Sathishkumar T. P., Satheeshkumar S., Bhuvaneshkumar K., Sanjay M. R., Siengchin S.: Crashworthiness characterization of jute fiber woven mat reinforced epoxy composite tube for structural application using Taguchi's method. International Journal of Crashworthiness, **27**, 1351–1367 (2021). https://doi.org/10.1080/13588265.2021.1926861

[83] Rajan B. M. C., Kumar S. A., Sornakumar T., Senthamaraikannan P., Sanjay M. R.: Multi response optimization of fabrication parameters of carbon fiber-reinforced aluminium laminates (CARAL): By taguchi method and gray relational analysis. Polymer Composites, **40**, E1041–E1048 (2019). https://doi.org/10.1002/pc.24815

[84] Vigneshwaran S., Uthayakumar M., Arumugaprabu V.: Solid particle erosion study on redmud – An industrial waste reinforced sisal/polyester hybrid composite. Materials Research Express, **6**, 065307 (2019). https://doi.org/10.1088/2053-1591/ab0a44

[85] Saha A., Kumar S., Zindani D.: Investigation of the effect of water absorption on thermomechanical and viscoelastic properties of flax-hemp-reinforced hybrid composite. Polymer Composites, **42**, 4497–4516 (2021). https://doi.org/10.1002/pc.26164

[86] Naveen J., Jawaid M., Zainudin E. S., Sultan M. T. H., Yahaya R.: Mechanical and moisture diffusion behaviour of hybrid kevlar/*Cocos nucifera* sheath reinforced epoxy composites. Journal of Materials Research and Technology, **8**, 1308–1318 (2019). https://doi.org/10.1016/j.jmrt.2018.07.023

[87] Behera A., Dehury J., Thaware M. M.: A comparative study on laminated and randomly oriented luffa-kevlar reinforced hybrid composites. Journal of Natural Fibers, **16**, 237–244 (2019). https://doi.org/10.1080/15440478.2017.1414653

[88] Yahaya R., Sapuan S. M., Jawaid M., Leman Z., Zainudin E. S.: Water absorption behaviour and impact strength of kenaf-kevlar reinforced epoxy hybrid composites. Advanced Composites Letters, **25**, 99–102 (2016). https://doi.org/10.1177/096369351602500403

[89] Karimzadeh A., Yahya M. Y., Abdullah M. N., Wong K. J.: Effect of stacking sequence on mechanical properties and moisture absorption characteristic of hybrid PALF/glass fiber composites. Fibers and Polymers, **21**, 1583–1593 (2020). https://doi.org/10.1007/s12221-020-9640-2

[90] Suresha K. V., Shivanand H. K., Amith A., Vidyasagar H. N.: Evaluation of mechanical properties of hybrid fiber (hemp, jute, kevlar) reinforced composites. AIP Conference Proceedings, **1943**, 020109 (2018). https://doi.org/10.1063/1.5029685

[91] Colomer-Romero V., Rogiest D., García-Manrique J. A., Crespo J. E.: Comparison of mechanical properties of hemp-fibre biocomposites fabricated with biobased and regular epoxy resins. Materials, **13**, 5720 (2020). https://doi.org/10.3390/ma13245720

[92] Patnaik A., Satapathy A., Mahapatra S. S., Dash R. R.: Implementation of Taguchi design for erosion of fiber-reinforced polyester composite systems with SiC filler. Journal of Reinforced Plastics and Composites, **27**, 1093–1111 (2008). https://doi.org/10.1177/0731684407087688

[93] Khalil H. A., Jawaid M., Bakar A. A.: Woven hybrid composites: Water absorption and thickness swelling behaviours. BioResources, **6**, 1043–1052 (2011).

[94] Rahman M. A., Mia S., Rana M. S., Ferdous M. S.: Experimental investigation on mechanical characterization of jute-kevlar hybrid composites. in 'International Conference on Mechanical, Industrial and Energy Engineering, Khulna, Bangladesh', Vol. 93, 1–6 (2020).

[95] Ashori A., Sheshmani S.: Hybrid composites made from recycled materials: Moisture absorption and thickness swelling behavior. Bioresource Technology, **101**, 4717–4720 (2010). https://doi.org/10.1016/j.biortech.2010.01.060

[96] Khalil H. A., Hanida S., Kang C. W., Fuaad N. N.: Agro-hybrid composite: The effects on mechanical and physical properties of oil palm fiber (EFB)/glass hybrid reinforced polyester composites. Journal of Reinforced Plastics and Composites, **26**, 203–218 (2007). https://doi.org/10.1177/0731684407070027

[97] Nourbakhsh A., Ashori A.: Particleboard made from waste paper treated with maleic anhydride. Waste Management and Research, **28**, 51–55 (2010). https://doi.org/10.1177/0734242X09336463

[98] Adekunle K., Cho S-W., Patzelt C., Blomfeldt T., Skrifvars M.: Impact and flexural properties of flax fabrics and lyocell fiber-reinforced bio-based thermoset. Journal of Reinforced Plastics and Composites, **30**, 685–697 (2011). https://doi.org/10.1177/0731684411405874

[99] Tewari U. S., Harsha A. P., Häger A. M., Friedrich K.: Solid particle erosion of carbon fibre– and glass fibre–epoxy composites. Composites Science and Technology, **63**, 549–557 (2003). https://doi.org/10.1016/S0266-3538(02)00210-5

[100] Barkoula N-M., Karger-Kocsis J.: Effects of fibre content and relative fibre-orientation on the solid particle erosion of GF/PP composites. Wear, **252**, 80–87 (2002). https://doi.org/10.1016/S0043-1648(01)00855-9

[101] Rattan R., Bijwe J.: Influence of impingement angle on solid particle erosion of carbon fabric reinforced polyetherimide composite. Wear, **262**, 568–574 (2007). https://doi.org/10.1016/j.wear.2006.07.001

[102] Sangilimuthukumar J., Thiagamani S. M. K., Kumar C. M., Krishnasamy S., Arpitha G. R., Mayakannan S.: Erosion characteristics of epoxy-based jute, kenaf and banana fibre reinforced hybrid composites. Materials Today: Proceedings, **64**, 6–10 (2022). https://doi.org/10.1016/j.matpr.2022.03.469

[103] Dalbehera S., Acharya S. K.: Impact of cenosphere on the erosion wear response of woven hybrid jute–glass epoxy composites. Advances in Polymer Technology, **37**, 240–246 (2018). https://doi.org/10.1002/adv.21662

[104] Nasimudeen N. A., Karounamourthy S., Selvarathinam J., Thiagamani S. M. K., Pulikkalparambil H., Krishnasamy S., Muthukumar C.: Mechanical, absorption and swelling properties of natural fibre-based vinyl ester hybrid composites. Applied Science and Engineering Progress, **14**, 680–688 (2021). https://doi.org/10.14416/j.asep.2021.08.006