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Research article

Synergy of hybridization of bauhinia vahlii and kenaf fiber on mechanical and sliding wear properties of epoxy composites: A Grey Taguchi Optimization Study

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ABSTRACT

The present research work aims to develop Bauhinia vahlii fibre epoxy composites with incorporation of different weight percentage (wt%) of kenaf fiber as secondary reinforcement to elevate the mechanical and wear properties of prepared composites (through hand layup method). Higher value of mechanical properties like tensile strength-114.85 MPa, flexural strength- 64.64 MPa, and hardness- 57.2 H_v are achieved for bauhina vahlii-epoxy composites. In case of hybrid composites, tensile strength-161.92 MPa; flexural strength- 93.28 MPa; and hardness- 76.0H_v for bauhinia vahlii/kenaf-epoxy composites at 10 wt% of fiber reinforcement. The design of experiment is developed by Taguchi L_9 orthogonal array to optimize the experimental run with three control factors; sliding velocity, fiber wt%, and normal load. In order to assess the multiple responses, the fabricated composite is analysed by Grey-Taguchi method with optimal factor setting to improve the output responses i.e. specific wear rate, tensile strength, flexural strength, and hardness. The optimal parameters which highly affect the properties of composites are sliding velocity (2.5 m/s), fiber wt% (10 wt %), and normal load (15 N). In wear mechanism analysis of composites by scanning electron microscopy (SEM), it is demonstrated that the synergy of hybridization of bauhinia vahlii and kenaf fiber improved the mechanical and wear properties of composites.

1. Introduction

Nowadays, the problem of environmental threats and global warming has encouraged the researchers to seek possible solutions and findings of eco-friendly materials from natural resources in many industrial fields. Fibre-polymer composites having high process capability and stiffness to weight ratio, make them useful materials for aerospace, defence, building/construction, and marine sectors [1]. Recently, natural fibres as a reinforcing agent in polymer composites has created more attention among the researchers because of their abundant availability in nature, ease in fabrication, less cost, good strength, low carbon emission and more important feature i.e. eco-friendly nature [2–5]. In particular, plant fibres like pineapple, jute, coir, banana, kenaf, and sisal have been extensively used in various industries (building [6–8], packaging [9,10], and aerospace/automotive [11]) due to their ravishing mechanical properties. Overall benefits of natural fiber composites (NFCs) are; high specific strength, biodegradability, renewable and sustainable, reduced energy consumption, cost saving potential, and carbon footprint reduction. Due to these benefits of NFCs, it is widely used in various

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industrial applications. These fibers are broadly used in automotive industry to replace man-made (traditional) fiber in different components of car like; seat back and door panel; sport equipment: bicycle, snowboards, and tennis rackets; construction materials: roofing materials, panels, and boards; and consumer goods: luggage and electronic device casing [12]. Based on their origin, plant fibres are classified as seed (collected from seed cases i.e oil palm, cotton, coir etc.), bast (prepared from inner bark i.e. jute, kenaf, hemp etc.), and leaf (sisal, banana, abaca etc.) fibre [13]. Among all the plant fibres, bast fibres act an important character in the composite industry because it contains 60–75% of cellulose which provides the structural stability and enhanced tensile strength to the fibre.

Bast fibres have some self-evident incompatibility with some thermosets/thermoplastic matrix like polyvinyl chloride and polypropylene because of their hydrophobic nature. These issues lead to improper interfacial bonding between reinforced fiber and the matrix which lead to debonding of bast fibers and resulted that failure in the end use production. Generally, the fiber/matrix interface acts a major character in determining the mechanical behaviour of NFCs [14]. Hence, it is very essential to diminish the water uptake capacity and hydrophobic nature of bast fibers by using a proper surface modification method for enhancing the compatibility of fiber with different resins. In previous reports hemicelluloses, lignin, pectin, and ash are the non-cellulosic constituents of bast fibre and removed by the chemical process for enhancing the mechanical properties of NFCs [15–17]. But the improper disposable of chemical waste after surface modification of fibres may put in danger the environment. Hence, the Fiore et al. [18] investigated the positive influence of sodium bicarbonate on tensile property of composites and proposed eco-friendly chemical treatments that incorporate of sodium bicarbonate instead of strong NaOH. Further, researchers are shifting from alkali treatment to eco-friendly sodium bicarbonate treatment of natural fibers and developed NFCs with affordable cost [19]. The agave fiber when successfully treated with (10%) $NaHCO_3$ enhanced the tensile strength (145 MPa), tensile modulus (1.71 GPa), flexural strength (214.50 MPa), and impact strength (3.65J) of agave-polyester composites [16]. Husana et al. [20] fabricated the palm kernel shell-high density polyethylene composites with $NaHCO_3$ treatment and observed that the $NaHCO_3$ has the capability to enhance the NFCs properties by cultivating the interfacial adhesion between filler-matrix constituents.

The two or more different fiber-fiber/filler-fiber reinforced together in a matrix is said to be a hybrid composite. Different combinations of natural fibers in common matrix are reported to drastically improve the mechanical properties earlier by many researchers. Some investigated hybrid composites by using natural fibers are oil palm/sisal, flax/carbon, jute/flax, grewia optiva/sisal/nettle, jute/hemp/flax, sisal/hemp, and nettle/cotton etc. which produce better performance [21–26]. Bauhinia vahlii fibers (family; *Caesalpiniacea*) are abundantly available in Himalayan zone of Uttarakhand, India and highly used for leaf dishes, fodder for cattle, and fancy baskets which offer earnings to local people. The properties of bauhinia vahlii based hybrid epoxy NFCs and the authors revealed that the superior mechanical and wear properties are achieved for 6 wt% of fiber content in epoxy composites [27]. In other investigation, bauhinia vahlii-grewia optiva based epoxy composites are fabricated and resulted that the superior mechanical properties like hardness; 43.60 H_v, tensile strength; 39.21 MPa, flexural strength; 40.13 MPa, and impact energy; 6.45J for 6 wt% of fiber content in developed composites [28]. Recently, Ray et al. [29] revealed the positive influence of bauhinia vahlii fiber on mechanical properties of bauhinia vahlii-propylene composites wit superior mechanical properties attained at 10 wt% of bauhinia vahlii reinforcement. Kenaf fiber is extracted from the bast of plant, and is broadly used as jute like reinforcing agents in different polymeric resins in past and have proven to show better mechanical properties [30]. There are so many combinations of kenaf fibers with different matrix materials are developed by the researchers for fabricating a composite such as; polyester [31–33], polypropylene [34], epoxy [35], high density polyethylene [36] etc. The various additions of natural fibers in polymeric resins are investigated by researchers where in the positive response on tribological behavior of fabricated composites is revealed. Most of the literature is based only on one influential parameter by maintaining all other factors fixed on wear rate of NFCs. These researches provide detailed information and are accurate, and valuable, but they fail in overall valuation of collective influence of all parameters and their interactions to be extrapolated from these parameters. Recognizing above fact, a statistical (Taguchi) method is used in wear studies. The approach of design of orthogonal arrays reduces number of experiments and enable to optimize critical factors. Taguchi method is used to study the sliding wear rate (SWR) of red-mud based polyester composites demonstrating the effect of selected factor increasing order as sliding velocity > normal load > red mud on sliding wear rate [37]. In other investigation, the consequence of various control factors like sliding velocity, walnut content, normal load and sliding distance on the SWR of ramie based hybrid epoxy composites are analysed where the order of prominence on wear rate are found as; sliding velocity > walnut content > normal load > sliding distance [38]. The Grey-Taguchi analysis is used for analyzing multi-response challenges in the manufacturing process. Previously, combined Grey relational and Taguchi approach were used to obtain the optimal parameter for mechanical properties of TiO_2-bamboo based hybrid polyester composites were the most significant to least significant factors were arrived as; bamboo length (42.18%), TiO_2 filler (39.65%), and diameter of bamboo (18.17%) on tensile, flexural and hardness properties of the NFCs [39].

At the best of our knowledge, the influence of combined bauhinia vahlii/kenaf fibers on mechanical and wear properties of NFCs have not been reported yet. The objective of research is to fabricate hybrid epoxy composites reinforced of $NaHCO_3$ treated bauhinia vahlii and hybrid bauhinia vahlii-kenaf fiber with variation of 6 to 10 wt%. After that, the authors have investigated the mechanical cum sliding wear properties of fabricated composites. Conversely, the polymer composites should deliver higher mechanical and wear resistance properties. Therefore, it may not be possible to determine the superior condition based on process parameters when two or more responses are observed simultaneously. Hence Grey-Taguchi approach is implemented to optimize the process parameters to accomplish the multiple performance criteria. Further, SEM images have been observed to fully understand the sliding wear mechanism of the NFCs.

Table 1
Physical property and chemical composition of bauhinia vahlii and kenaf fiber [30,41].

Bast fiber	Components			
	Density (gm/cm^3)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Bauhinia vahlii	1.45	54.0	18.20	1.35
Kenaf	1.44	56.4	26.2	13.4

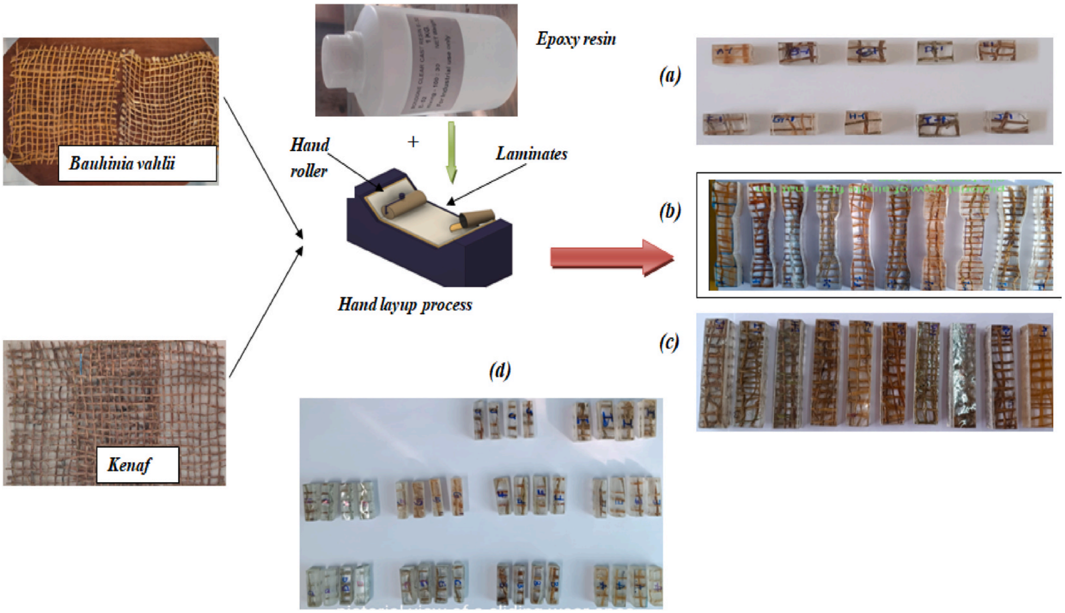

Fig. 1. Pictorial view of bi-directional fibre mat and testing specimens (a) hardness, (b) tensile strength, (c) flexural strength, and (d) sliding wear.

2. Experimental details

2.1. Materials and chemical modification of fibers

The raw bauhinia vahlii and kenaf fiber of density 1.45 g/cm^3 [30] and 1.44 g/cm^3 [32] respectively are used as reinforcing agents in present work. Bauhnia vahlii and kenaf fiber are recognized as stronger bast fibers among the other bast fibers owing to their high cellulosic content which lead to impart strong structural support. The physical property and chemical composition of raw kenaf [40,41] and bauhinia vahlii fibers are displayed in Table 1.

The epoxy resin E−51 (bisphenol A diglycidyl ether) having density of 1.11 g/cm^3 with curing agent Methyl tetrahydrophthalic anhydride (MTHPA) was procured from Novel chem., Vadodara, Gujrat, India. The raw bauhinia vahlii and kenaf fiber are first bathed with 10% $NaHCO_3$ at room temperature for 4 h s and further by washing with distilled water and later on sun dried for 48 h s. The chemical reaction between reinforcing fiber and concentration is depicted in Equation (1) and Equation (2) [42].

$$(BVFR/KFR)\ fiber + NaHCO_3 \rightarrow (BVFR/KFR)\ fiber + Na^+ + HCO_3^- \quad (1)$$

$$HCO_3^- + H_2O \rightarrow H_2CO_3 + OH^- \quad (2)$$

2.2. Fabrication of composites

The composite is successfully fabriacated by simplest and oldest method i.e. Hand-lay-up. The surface modified bi-direction fiber mats is prepared by hand and the open glass mould of dimesnion 200mm × 200mm × 6 mm is manually constructed. At first, epoxy and hardener at a ratio of 10:1 is mixed in beaker followed by dehydrating the mould. Then, mylar film is applied at the surface of glass and treated selected fiber mats are cut to required shapes and put on the surface of mould. Thus, epoxy-hardener mixture is permeated onto the surface of reinforcing constituent by brush and then hand roller are used continuously for getting uniform distribution of the resin. Finally, the prepared laminates are cured under normal room temperature under a load of 10 kg for 24 h and then required dimension of specimens is measured and cut on cured composite materials (Fig. 1). The designation of six samples which are fabricated

Table 2
Designation and weight percentage of fabricated composites.

	Designation	Epoxy (wt%)	*BVFR* (wt%)	*KFR* (wt%)
	Epoxy	100	0	0
Bauhinia vahlii fiber based epoxy composites	*BVFR6*	94	6	0
	BVFR8	92	8	0
	BVFR10	90	10	0
Hybrid bauhinia vahlii/kenaf fiber based epoxy composites based composites	*BV3KFR3*	94	3	3
	BV4KFR4	92	4	4
	BV5KFR5	90	5	5

BVFR; bauhinia vahlii fiber reinforcement, *KFR*; Kenaf fiber reinforcement.

Table 3
Control parameters and levels.

Control parameters	Description	Level-I	Level-II	Level-III
A	Sliding velocity (m/s)	1.5	2.5	3.5
B	Fiber wt%	6	8	10
C	Normal load (N)	15	20	25

Table 4
The Taguchi L_9 design.

S.no	Sliding velocity (m/s)	Fiber wt%	Normal load (N)
1	1.5	6	15
2	1.5	8	20
3	1.5	10	25
4	2.5	6	20
5	2.5	8	25
6	2.5	10	15
7	3.5	6	25
8	3.5	8	15
9	3.5	10	20

with bi-directional bauhinia vahlii and kenaf fiber mats as illustrated in Table 2.

2.3. Mechanical and dry sliding wear characterization

Tensile and flexural properties are examined on specimen size-125mm × 12.7mm × 3 mm at cross-head speed of 5 mm/min by using respective standard ASTM:D3039 and ASTM: D790-07 respectively. For hardness; a load of 5 kg at an apical angle of 136° for a dwell time of 15 s is applied on specimen 25mm × 25 mm. The sliding wear properties of as-prepared NFCs are measured on pin-on-disc instrument; where steel disc-74HRC, specimen size of 35mm × 8 mm, and ASTM:G99 standard are practiced and the specific wear rate (SWR) is estimated by applying Equation (3).

$$SWR = (Mass)_i - (Mass)_f / \rho l f_n \tag{3}$$

SWR in (mm^3/N-m), mass in gram (*i*-initial and *f*-final) and ρ = density, and l = sliding distance (m), and fn = normal load (Newton).

2.4. Grey Taguchi analysis

The D.O.E (design of experiment) is plotted by MINITAB16 statistical software. Primarily, for creating D.O.E, the control parameters are first selected and the unnecessary parameters are pointed out. The control parameters is mentioned in Table 3 with their levels as; sliding velocity (1.5 m s^{-1}, 2.5 m s^{-1}, and 3.5 m s^{-1}); fiber wt% (6 wt%, 8 wt%, and 10 wt%); and normal load (15 N, 20 N, and 25 N).

The Taguchi L_9 (3^3) orthogonal array is a specific design matrix used in the Taguchi method, which is statistical method for optimization and robust design. The L_9 (orthogonal array) based on Taguchi method is used to evaluate the best combination of control parameters for minimal wear rate as depicted in Table 4. The arrangement of these 9 runs in the orthogonal array ensures that the effects of individual factors can be efficiently studied with a relatively small number of experiments. However, the optimization of a single output response is possible at a time via Taguchi method and it cannot be used for two or more out responses simultaneously [43]. Therefore, it is necessary to obtain superior parameter sets that optimize all evaluated responses i.e. high mechanical and wear properties at the same instant. This purpose is fulfilled by using the Grey–Taguchi method [44] and found to be an effective tool for

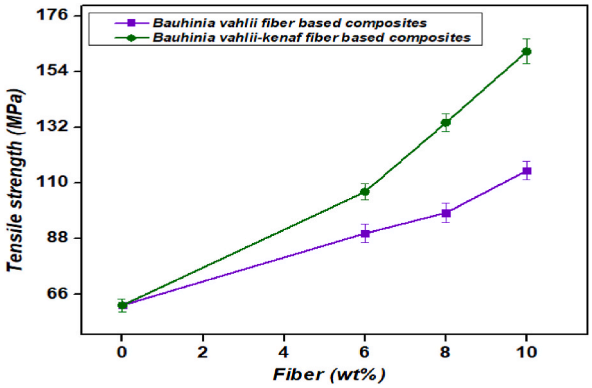

Fig. 2. Variations of tensile strength versus fiber weight percentage.

analyzing this kind of problem. Basically, Grey-Taguchi method is the extension of the conventional Taguchi method that incorporates Grey relational analysis (GRA) into the optimization process.

This work is focused to optimize the responses i.e. tensile strength, flexural strength, hardness, and SWR of prepared composites. Here are the six key steps involved in the Grey-Taguchi analysis; (a) factorial experiment, (b) Grey relational analysis, (c) Normalization, (d) calculation of Grey relational coefficient, (e) signal to noise ratio, (f) optimization. In short in Grey Relational Analysis; the collection of the responses and normalizing of the data, estimating deviation sequence and Grey relational grade (GRG) are obtained by setting up the relational degree between the ideal experimental and normalized output where the higher value of GRG reflects the evidence of strong correlation. The experimental values of output response are obtained from the L_9 array, and the normalizing is done by using the H.B. (Higher better) and L.B. (lower better) characteristic as per Equation (4) and Equation (5).

$$K_i(s) = [P_i(\mathrm{s}) - \text{minimum } P_i(\mathrm{s})] \,/\, [\textit{maximum } P_i(\mathrm{s}) - \text{minimum } P_i(\mathrm{s})] \tag{4}$$

$$K_i(s) = [\text{maximum } P_i(\mathrm{s}) - P_i(\mathrm{s})] \,/\, [\textit{maximum } P_i(\mathrm{s}) - \text{minimum } P_i(\mathrm{s})] \tag{5}$$

Where normalized data is presented as $K_i(s)$, maximum P_i(s) and minimum P_i(s) is higher and smaller value of P_i(s) for the sth response, K_i designates the chosen control parameters; sliding velocity, fiber wt%, and normal load, P_i shows the output response (tensile property, flexural property, hardness, SWR), and "*s*" indicates the Taguchi experimentations (for i = 1 to 9).

Here, $K_i(s)$ and $K_0(s)$ *are* the values after grey relational generation, and the ideal sequencing respectively. The GRG sets up the relational degree between $K_i(s)$ and $K_0(s)$ and the grey relational coefficient (*GRC*) can be estimated with the help of Equation (6).

$$GRC = (\Delta_{minimum} + \beta \times \Delta_{maximum}) / (\Delta_{0i}(s) + \beta \times \Delta_{maximum}) \tag{6}$$

Where Δ_{0i} denotes the difference between absolute values of $K_i(s)$ and $K_0(s)$ acquired by Equation (7). $\Delta_{minimum}$ and $\Delta_{maximum}$ are the symbols of minimum and maximum value respectively of the absolute differences. β ranges from 0 to 1 with better performance at β to be 0.5 as reported by most of the researchers.

$$\Delta_{0i} = |K_0(s) - K_i(s)| \tag{7}$$

Further, GRG is estimated by taking the average of the GRC values taken for each concert characteristic. The best performance for chosen parameters is attained by using highest magnitude of assessed *GRG* and calculated by Equation (8).

$$GRG_i = \frac{1}{n}\sum_{s=1}^{n} GRC_i\,(s) \tag{8}$$

The GRG for ith experiments is denoted by GRG_i with n representing number of performance characteristics. Ahead, the *GRG* is transformed into the signal to noise ratios (S/N) through Taguchi method. For GRA, the higher magnitude of GRG gives more noteworthy parameter than the lower value, so higher is better characteristic is utilized for evaluating optimum condition and depicted in Equation (9).

$$(S/N)_{H.B} = -10 \times \log_e (n^{-1}) \left[\sum 1/t^2\right] \tag{9}$$

Where, S/N is taken at higher is better characteristic, n = number of experiment, t = GRG data.

3. Results and discussion

3.1. Influence of BVFR and BVKFR loading on mechanical properties of composites

The change in tensile strength of composites with bauhinia vahlii/bauhinia vahlii-kenaf fiber content as reinforcement in the epoxy

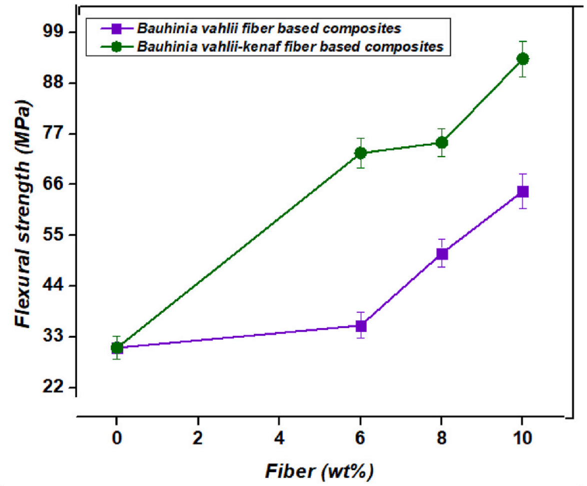

Fig. 3. Variations of flexural strength versus fiber weight percentage.

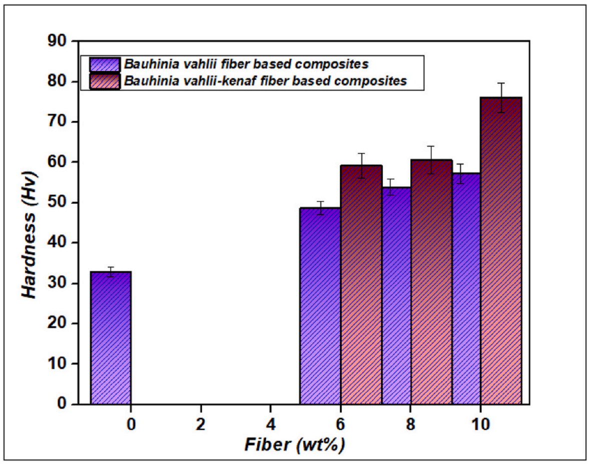

Fig. 4. Variations of hardness versus fiber weight percentage.

composites is depicted in Fig. 2. Basically, the overall tensile properties of the NFCs can be enhanced by reinforcing of such natural fibers which have higher inherent strength properties. In this research, tensile strength of prepared composites progressively enhanced with an increment in fiber wt% and superior value is achieved for 10 wt% of bauhinia vahlii (114.85 MPa) and bauhinia vahlli-kenaf fiber (161.92 MPa) in epoxy composites. This may be due to proper flow of matrix around the fiber mats and the fiber's surface is modified by $NaHCO_3$ which reduces the interfacial tension resulted that improved stress transfer between constituents of composites. Because of better adhesive bonding at the interfacial zone between chemically treated natural fibers and matrix it leads less debonding, detachment, and fibre pullout which are responsible for tensile property enhancement [45]. The attractive tensile property is obtained with *BV5KFR5* because at particular combination (wt%), bauhinia vahlii fiber is able to efficiently share the load with kenaf which facilitate the simplified load transfer from matrix to fibers. At equal fiber weight percentages, however positive synergistic influence of fibers was optimized. Thus, the tensile strength is evident about 46.32% and 61.92% improvement for *BVFR10* and *BV5KFR5* composites as compared to neat epoxy composites (61.65 MPa). This may be due to fact that the tensile property of composites depends on the cellulose content and it is envisaged that the kenaf fibers contain more cellulose content as compared to bauhinia vahlii fibers (Table 1). Also, it may be envisioned that the kenaf fibers have the ability to develop a proper interfacial bonding between selected reinforcement and epoxy matrix at this ratio. The improvement in tensile strength by the hybridization of kenaf fiber with other natural fiber is detected and observed that positive response of kenaf fiber in tensile property of sisal-epoxy NFCs. They revealed that 9 wt% incorporation of kenaf fiber gives 42.34 MPa which is 50% more than sisal-epoxy composites with same fiber loading [46]. Moreover, the compatibility of bauhinia vahlii-kenaf fibers provides the benefits of hybridization behaviour in the resulting composites.

The evaluated results of flexural strength showed a more comprehensive hybridization influence between bauhinia vahlii-kenaf fibers. The flexural strength improved with an increase in kenaf wt% inside the composite even bauhinia vahlii-kenaf exhibited much more flexural strength as compared to bauhinia vahlii based NFCs as illustrated in Fig. 3. The higher magnitude of flexural

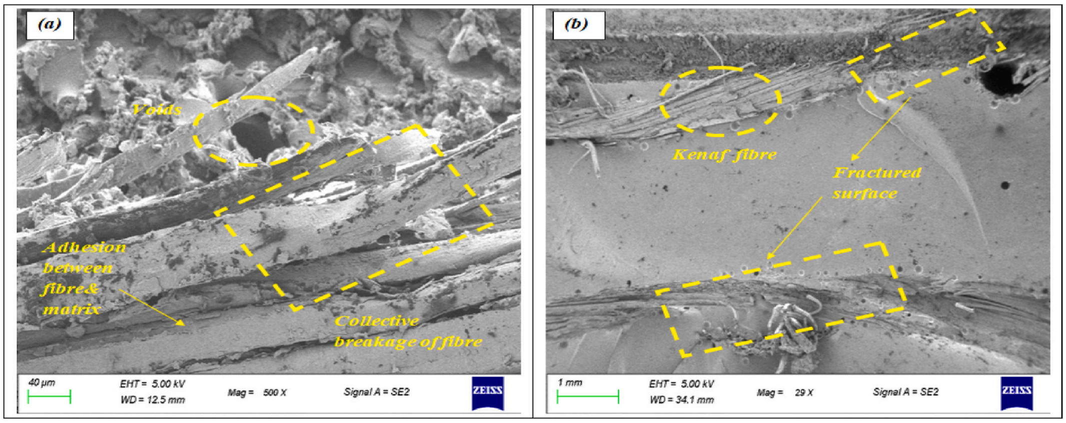

Fig. 5. (a) SEM micrograph of bauhinia valii-epoxy composite (*BVFR10*) and (b) bauhinia vahlii-kenaf based epoxy composites (*BV5KFR5*).

Table 5
Response for mechanical and SWR characteristics of bauhinia vahlii and bauhinia vahlii-kenaf fibre based NFCs.

Exp. No.	Bauhinia vahlii fibre based epoxy composites				Bauhinia vahlii-kenaf fibre based epoxy composites			
	SWR × 10^{-8}	Hardness (H_v)	Tensile strength (MPa)	Flexural strength (MPa)	SWR × 10^{-8}	Hardness (H_v)	Tensile strength (MPa)	Flexural strength (MPa)
1	4.01	48.7	90.07	35.50	3.77	57.1	133.78	72.85
2	4.13	53.8	98.22	51.14	4.11	59.2	106.50	75.13
3	3.41	57.2	114.85	64.64	2.61	76.0	161.92	93.28
4	3.89	48.7	90.07	35.50	3.43	57.1	133.78	72.85
5	4.15	53.8	98.22	51.14	4.22	59.2	106.50	75.13
6	2.77	57.2	114.85	64.64	2.02	76.0	161.92	93.28
7	3.22	48.7	90.07	35.50	3.31	57.1	133.78	72.85
8	3.82	53.8	98.22	51.14	4.85	59.2	106.50	75.13
9	3.29	57.2	114.85	64.64	3.61	76.0	161.92	93.28

Table 6
Normalized data for bauhinia vahlii and bauhinia vahlii-kenaf fibre based NFCs.

Exp. No.	Normalized data							
	Bauhinia vahlii fibre based epoxy composites				Bauhinia vahlii-kenaf fibre based epoxy composites			
	SWR × 10^{-8}	Hardness (H_v)	Tensile strength (MPa)	Flexural strength (MPa)	SWR × 10^{-8}	Hardness (H_v)	Tensile strength (MPa)	Flexural strength (MPa)
1	0.101	0	0	0	0.381	0	0.492	0
2	0.014	0.6	0.328	0.536	0.261	0.111	0	0.111
3	0.536	1	1	1	0.791	1	1	1
4	0.188	0	0	0	0.501	0	0.492	0
5	0	0.6	0.328	0.536	0.222	0.111	0	0.111
6	1	1	1	1	1	1	1	1
7	0.673	0	0	0	0.544	0	0.492	0
8	0.239	0.6	0.328	0.536	0	0.111	0	0.111
9	0.623	1	1	1	0.438	1	1	1

strength is accomplished at 10 wt% of fiber reinforcement which is 64.64 MPa (52.52%) and 93.28 MPa (67%) for *BVFR10* and *BV5KFR5* composites as compared to neat epoxy (30.69 MPa). The reason for that enhancement is kenaf fiber at the outer surface for hybrid bauhinia vahlii-kenaf-epoxy composites and envisioned to give enhancement the resistance of compressive force when normal load is applied to composites [47]. Superior tensile and flexural properties of the prepared composites are achieved at weight fraction of fiber of 1:1 because at this combination of the bauhinia vahlii-kenaf fibers, the higher compatibility and better fiber-matrix adhesion leads better synergy.

Similarly hardness is a function of reinforcing fiber wt% as reflected by Fig. 4, the *BVFR10* and *BV5KFR5* composites carry 42.65% and 56.84% superior hardness in comparison to pure epoxy composites (32.8 H_v). This improvement is attributed to sharing of the applied load by enhancing the fiber weight percentage of the bauhinia vahlii-kenaf fibres, which offers resistance to the indenter penetration of the composite surface and obtaining higher hardness for *BVFR10/BV5KFR5* composites [48].

Moreover, the SEM images (Fig. 5 (a) and (b)) for *BVFR10* and *BV5KFR5* composites are used to support the tensile results and

Table 7
GRC for bauhinia vahlii and bauhinia vahlii-kenaf fibre based NFCs.

Exp. No.	GRC							
	Bauhinia vahlii fibre based epoxy composites				Bauhinia vahlii-kenaf fibre based epoxy composites			
	SWR × 10^{-8}	Hardness (H_v)	Tensile strength (MPa)	Flexural strength (MPa)	SWR × 10^{-8}	Hardness (H_v)	Tensile strength (MPa)	Flexural strength (MPa)
1	1.072	0.333	0.333	0.333	1.341	0.333	0.496	0.333
2	1.009	0.555	0.426	0.519	1.211	0.36	0.333	0.360
3	1.556	1	1	1	2.117	1	1	1
4	1.1436	0.333	0.333	0.333	1.502	0.333	0.496	0.333
5	1	0.555	0.426	0.519	1.174	0.360	0.333	0.360
6	3	1	1	1	3	1	1	1
7	1.815	0.333	0.333	0.333	1.569	0.333	0.496	0.333
8	1.1896	0.555	0.426	0.519	1	0.360	0.333	0.360
9	1.710	1	1	1	1.412	1	1	1

Table 8
GRG and S/N ratios for bauhinia vahlii and bauhinia vahlii-kenaf fibre based NFCs.

Exp. No.	Bauhinia vahlii fibre based epoxy composites		Bauhinia vahlii-kenaf fibre based epoxy composites	
	GRG	S/N ratios	GRG	S/N ratios
1	0.518	−5.71340	0.626	−4.06851
2	0.627	−4.05465	0.566	−4.94367
3	1.139	1.13047	1.279	2.13741
4	0.535	−5.43292	0.666	−3.53052
5	0.625	−4.08240	0.556	−5.09850
6	1.500	3.52183	1.500	3.52183
7	0.703	−3.06089	0.683	−3.31159
8	0.672	−3.45261	0.513	−5.79765
9	1.177	1.41553	1.103	0.85151

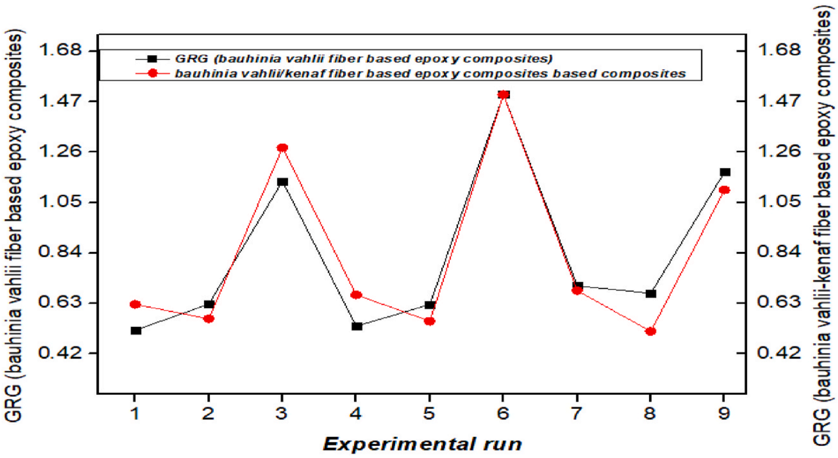

Fig. 6. Variation of GRG of fabricated composites with experimental run.

observed their surface characteristics; fracture surface, internal cracks, and interfacial properties. The fractured surface of *BVFR10* composites after tensile measurement is depicted in Fig. 5 (a) which reflects the presence of extreme fibre matrix debonding, prolonged and collective breakage of bauhinia vahlii fibers] being responsible for less mechanical strength. Since, *BV5KFR5* composites have better performance in tensile property and supportive image is presented in Fig. 5 (b) and shows that less debonding of fiber and fracture occurred locally of the fibres. Also, detected that higher interfacial bonding which resisting the pullout and fracture of combined fibers. However, bauhinia vahlii fibers are broken down collectively at higher extent than the kenaf fibers. There, it is clearly evident a better bonding of kenaf to epoxy than that of bauhinia vahlii. Therefore, greater tendency of fiber pull out in bauhinia vahlii fiber-epoxy composite is observed than in bauhinia vahlii-kenaf based composite.

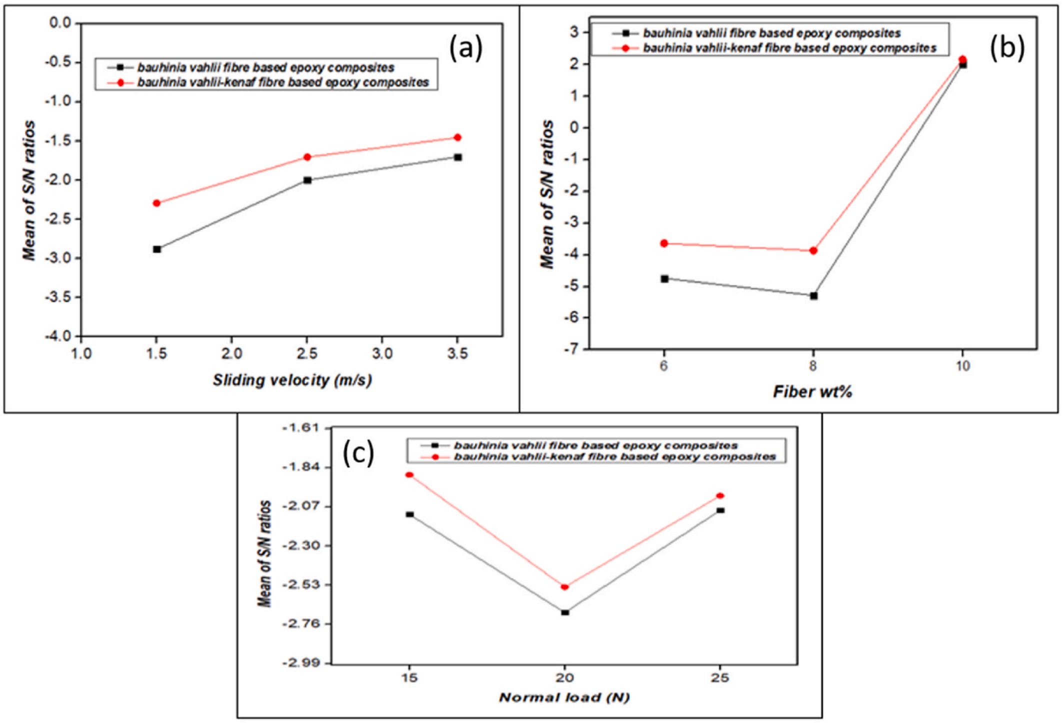

Fig. 7. Plot of S/N ratio of GRG vs (a) sliding velocity (b) fiber wt% (c) normal load.

Table 9
ANOVA results for bauhinia vahlii and bauhinia vahlii-kenaf fiber based epoxy composites.

Source	DF	Adj SS	Adj MS	F-Value	*P*-Value	Rank
Panel 1: GRG of bauhinia vahlii fiber based epoxy composites						
Sliding velocity (m/s)	2	2.258	1.129	0.50	0.667	2
Fiber wt%	2	81.080	40.540	17.96	0.053	1
Normal load (N)	2	1.141	0.571	0.25	0.798	3
Error	2	4.513	2.257			
Total	8	88.992				
S = 1.50220; R-Sq = 94.93%; R-Sq (adj) = 79.71%						
Panel 2: GRG of bauhinia vahlii-kenaf fiber based epoxy composites						
Sliding velocity (m/s)	2	1.663	0.831	0.74	0.574	2
Fiber wt%	2	91.928	45.964	41.09	0.024	1
Normal load (N)	2	0.385	0.192	0.17	0.853	3
Error	2	2.237	1.119			
Total	8	96.212				
S = 1.05764; R-Sq = 97.67%; R-Sq (adj) = 90.70%						

3.2. Grey-Taguchi analysis of mechanical and wear properties of NFCs

For the present work, there are three input variables are considered, namely sliding velocity, fibre wt%, and normal load. Therefore, total number of experiments is nine which are performed on fabricated composites as illustrated in Table 5. According to Grey-relational analysis, the normalizing of experimental results is conducted in the range from 0 to 1 (Table 5) by using Equations (4) and (5). The higher value of mechanical properties of composites is desired, so higher is better characteristic is used but in case of wear, the lower is better characteristic is adapted. The normalized data is evaluated from selected output responses are illustrated in Table 6. Further, *GRC* is computed for every normalized output response through Equation (6) as presented in Table 7. After that, overall *GRG* is calculated by mean value of *GRC* which is obtained from every response (Equation (8)) and higher value of *GRG* means higher ranking. Hence, the superior level of the selected parameters is the level containing the highest magnitude of *GRG* as depicted in Table 8 (Fig. 6).

The experiment number 6 has highest grey relational grade (1.500) for fabricated composites to establish the multiple response of low SWR and greater mechanical properties. The higher value of GRG (S/N ratio) is achieved for dry sliding control factors setting at sliding velocity (2.5 m/s), fiber wt% (10 wt%), and normal load (15 N) as shown in main effect plot (Fig. 7). The objective of analysis of variance (ANOVA) is to determine the ranking of selected control parameters and its contribution on output response (SWR and

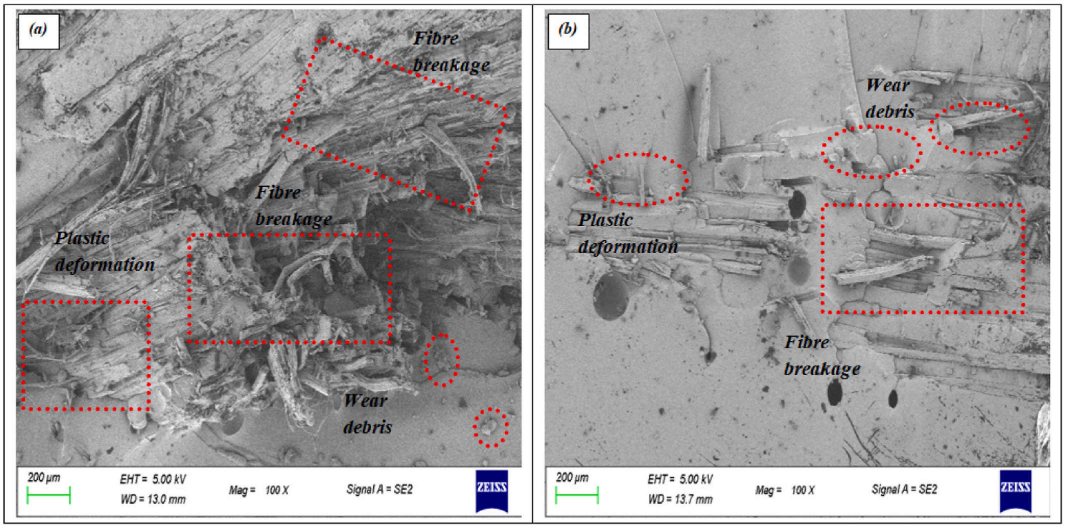

Fig. 8. SEM micrograph of *BVFR6* (a) and *BV3KFR3* (b) composites (at sliding velocity = 3.5 m/s, and normal load = 25 N).

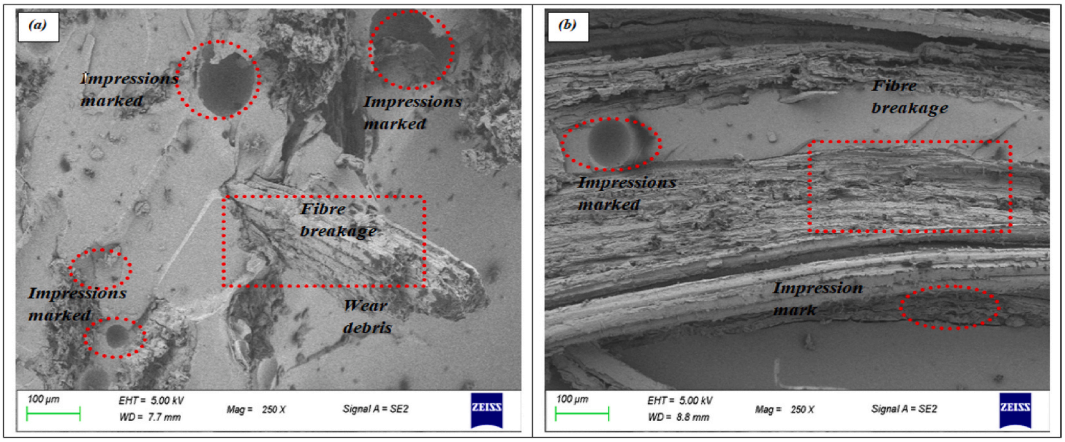

Fig. 9. SEM micrograph of *BVFR8* (a) and *BV4KFR4* (b) composites (at sliding velocity = 3.5 m/s, and normal load = 15 N).

mechanical properties).

The ANOVA results for both types of NFCs is illustrated in Table 9 (panel 1 for mono fiber composites) and panel 2 (hybrid fiebr composites) and ranking is decided according to their significance of composites. From Table 8, it is evident that fiber wt% has lowest p-value (0.053) for bauhinia vahlii-composites and p-value (0.024) for bauhinia-kenaf fiber based epoxy composites. Hence the fiber wt% is found to be the most significant control parameter affecting the output responses whereas sliding velocity is revealed the second influential parameter followed by normal load. The influence of reinforced fiber (wt%) on mechanical and wear properties of composites are examined by Grey-Taguchi method and it is evaluated that the type of fiber and its percentage is the most prominent factor affecting the mechanical and wear responses of composites [49].

4. SEM analysis of bauhinia vahlii and bauhinia vahlii-kenaf fiber based NFCs (dry sliding condition)

The SEM micrograph of worn out surface of wear specimen of mono and hybrid composites are presented in Fig. 8(a) and (b). The worn surface of the wear samples of *BVFR6* and *BV3KFR3* composites show the different mechanisms; plastic deformation occur in matrix, cracking is detected in reinforcing fibers, and fewer wear debris is observed attached to surface of specimen. It is also detected that, more breakage of fiber in *BVFR6* composites is observed as compared to hybrid *BV3KFR3* composites as clearly indicated in Fig. 8 (a) and (b).

There is only few breakages of fiber and impressions marked are indicated in SEM micrographs of *BVFR8* and *BV4KFR4* composites as perceived in Fig. 9(a) and (b). The less fiber breakage and impressions marked in *BV4KFR4* as compared to *BVFR8* composites revealed that positive effect of bauhinia vahlii-kenaf fiber on sliding wear of NFCs.

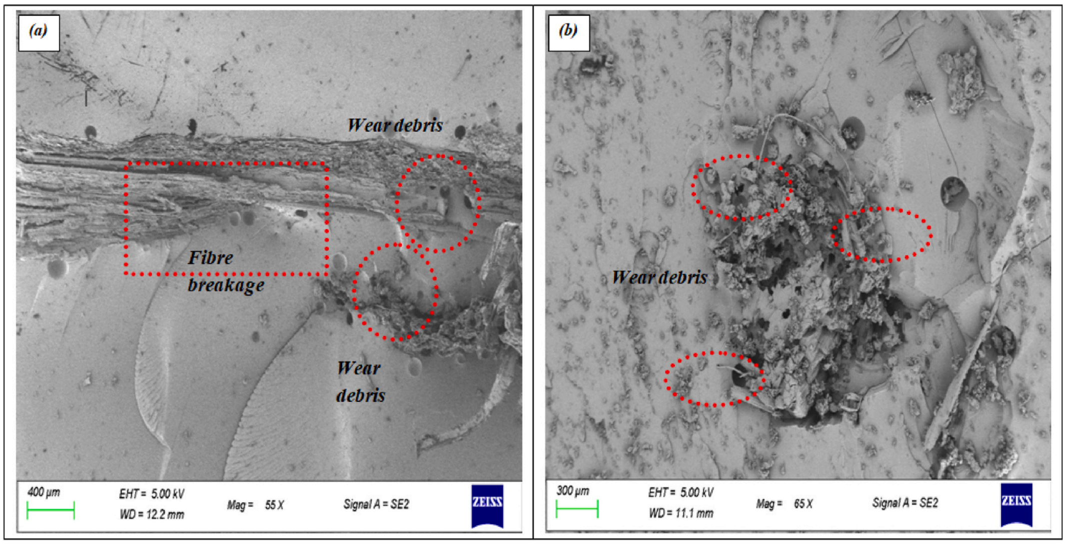

Fig. 10. SEM micrograph of *BVFR10* (a) and *BV5KFR5* (b) composites (at sliding velocity = 3.5 m/s, and normal load = 20 N).

The wear behavior of *BVFR10* and *BV5KFR5* composites (Fig. 10 (a) and (b)) indicated the relatively smooth planner surface, whereas there is no evidence of fiber elimination and destruction. Also, less visible fibers are shown in worn surface of *BVFR10* and *BV5KFR5* composites as compared to *BVFR6* and *BV3KFR3* composites. From the discussion, it can be argued that the bauhinia vahlii and bauhinia vahlii-kenaf fiber based NFCs at 10 wt% have the capacity to handle the applied load. From the SEM analysis, the fatigue abrasion is detected as the dominant wear mechanism for *BVFR6* and *BV3KFR3* samples which may be transformed to adhesive abrasion in *BVFR10* and *BV5KFR5* samples. Sliding velocity (2.5 m/s), higher fiber 10 wt%, and lower normal load (15 N) are the superior condition for both mono and hybrid composites. The optimum value of SWR is 2.77×10^{-8} mm^3/Nm for *BVFR10* and 2.02×10^{-8} mm^3/Nm for *BV5KFR5* NFCs. From Table 5, it is clearly perceived that wear rate is reduced by 14.96% and 30.76% with the increment in the loading of reinforcing fiber is from 6 wt% to 10 wt% in the epoxy resin. This deterioration in SWR may occur due to betterment in fiber-matrix interfacial adhesion resulting in higher resistance offered by the composites against sliding scratch. Furthermore, there is strong relation between wear and hardness properties of polymer composites and enhancement in hardness has seen in this investigation which may be responsible for reducing the SWR of composites.

5. Conclusion

Bauhinia vahlii and bauhinia vahlii-keanf fiber based epoxy NFCs are produced by Hand layup process and the influence of fiber weight percentage on mechanical and SWR behaviour are observed. The following conclusions are visualized:

- The fiber reinforcement of bauhinia vahlii/bauhinia vahlii-kenaf from 6 wt% to 10 wt% in the epoxy composites improved the mechanical properties. The optimum value is achieved at 10 wt% of fiber reinforcement i.e. tensile strength (114.85 MPa), flexural strength (64.64 MPa), and hardness (57.2 H_v) for *BVFR10* composites and tensile strength (161.92 MPa), flexural strength (93.28 MPa), and hardness (76.0 H_v) for *BV5KFR5* composites.
- The L_9 orthogonal array with enactment of GRA is applied to optimize the multiple performance of mechanical and SWR characteristics of fabricated composites. From the outcomes, it is demonstrated that the SWR is dominated by fiber weight percentages, sliding velocity, and normal load.
- Grey-Taguchi optimization transformed the multi-responses of tensile strength, flexural strength, hardness, and SWR into single response, The combination of 03 control parameters i.e. sliding velocity (2.5 m/s), fiber weight percentage (10 wt%), and normal load (15 N) are arrived as superior combination where in lowest SWR and greater mechanical strength of composites is reflected.
- According to ANOVA analysis of grey relation grade, it is observed that most significant control parameter is fiber wt% followed by sliding velocity and normal load which significantly influence the SWR of composites. An increase in fiber wt% of bauhinia vahlii and kenaf fiber showed better wear resistance under different sliding velocity and normal load, this may be attributed to better interfacial adhesion between fiber and matrix.
- The worn surface of specimen shows wear debris, fiber debonding, and fibre breakage for NFCs and it is detected that switching of mechanism from fatigue abrasion to adhesive abrasion for bauhinia vahlii-kenaf fiber based composites leads to good accord with the SWR results.

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Bhanu Pratap: Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vinay Kumar Patel:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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