Journal of Material Cycles and Waste Management (2022) 24:667–679
https://doi.org/10.1007/s10163-022-01357-1

ORIGINAL ARTICLE

The effect of various composite and operating parameters in wear properties of epoxy-based natural fiber composites

Sumesh Keerthiveettil Ramakrishnan[1] · Kavimani Vijayananth[2] · Gopal Pudhupalayam Muthukutti[2] · Petr Spatenka[1] · Ajithram Arivendan[3] · Suganya Priyadharshini Ganesan[4]

Received: 14 April 2021 / Accepted: 4 January 2022 / Published online: 10 February 2022

Abstract

In this experiment banana fly ash (BA) at 1, 3 and 4 wt% was mixed with the hybrid natural fiber combination of sisal/pineapple at 30, 40 and 50 wt%. Grey relational analysis (GRA) coupled with Taguchi method is followed to find the common optimal parameter combination that yields lesser specific wear rate (SWR) and coefficient of friction while testing the developed novel polymer matrix composites against steel ball. The multi-response optimization using GRA pointed out that minimal addition of BA filler (1 wt%), hybrid fibre content (30 wt%), higher sliding distance (1500 m) and lesser loading (5 N) results in good overall tribological properties. The addition of filler materials and hybrid fibres with the polymer matrix results in increased friction. The SEM results showed high adding up of fiber results in pull out of fibers in the epoxy resin resulting in high wear rate of natural composites. Good fiber/filler/epoxy bonding created a tribolayer surface in the combination and that reduces the surface contact between counter specimen and work piece with reduced SWR.

Keywords Fly ash filler · Hybrid natural fiber reinforcement · Wear properties · Epoxy-based composites · Multi-response optimization

Introduction

The current generation is finding a major problem in depositing plastic waste due to non-biodegradable nature and its harmful effects causing soil pollution, water pollution etc. The nature resource utilization using bio fibers and fillers are the only solution for this problem [1–4]. The research of natural fibers such as ramie, coir, kenaf, kapok, sisal, pineapple, banana, flax have been used for light weight applications of automobile industry. Hybridization and surface treatments are used for enhancing the mechanical and chemical resistance of the natural fiber composites [5–8]. Hybridization can be established using filler incorporation, natural fiber as well as synthetic fiber substitution with the resins. The natural fiber-based composites have been combined with polypropylene, epoxy, polyethylene, polylactic acid matrix-based composites based on the applications [8–10].

The addition of pineapple fiber reinforcement at 30% adds to the tensile properties of polymer composites. Coupling agents such as maleic anhydride polyethylene, maleic anhydride polypropylene and surface treatment with NaOH improved the bonding strength of fiber with tapioca resin phase [11]. Hybrid epoxy fiber combinations of pineapple and banana observed good tensile and flexural strength with a fiber length and reinforcement addition of 10 mm and 30 wt% [12].

The reinforcement addition of sisal fiber in waste glass and carbon fiber polypropylene composites showed better tribological properties. Sisal/glass composites showed better wetting interaction in the combination. Sisal fiber showed optimized properties at a weight percentage of 42 [13]. Least

✉ Sumesh Keerthiveettil Ramakrishnan
keerthiveettil.sumesh@fs.cvut.cz; sumesh2311@gmail.com

1 Department of Materials Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, Karlovo Namesti 13, 12135 Prague, Czech Republic

2 Centre for Material Science, Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu 641021, India

3 Department of Mechanical Engineering and Centre for Composite Materials, Kalasalingam Academy of Research and Education, Virudhunagar, Tamil Nadu, India

4 Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore, Tamil Nadu, India

specific wear rate (SWR) and frictional properties (CoF) was observed with 30 wt% sisal fiber incorporation. Increase in applied load from 10 to 30 N increases SWR and CoF due to high exerted pressure in sample specimen [14]. The increase in sliding distance observed decline in wear and friction behaviour of bamboo/epoxy composites, sliding speed add to the frictional properties of the combination [15].

Oil palm and kenaf epoxy based natural fiber composites showed high wear rate with good reinforcement addition up to 70 wt%. Addition of high reinforcement observed more cracks, debonding, broken fiber and more fractures in their composition due to high wear rate [16]. *Hibiscus sabdariffa* fiber substitution improved the wear resistance of urea–formaldehyde matrix composites [17]. Filler substitution with jute, multi wall carbon nano tube, solid glass microspheres, titanium oxide nano rods and *Jatropha* oil cake fillers improved the tribological properties of polymer matrix composites (PMC) [18–21]. Fillers such as alumina, titanium oxide and oil cake cellulose-based fillers add to the mechanical properties of natural fiber/epoxy-based composites [22–24].

Incorporation of jute and multi wall carbon nano tube fillers reduces the interface gap between polyvinyl alcohol and multi layered graphene, which enhanced the mechanical and wear resistant properties of the composites [18]. Addition of jute, flax, Musaceae, *Grewia optiva*, betelnut and short wood fiber reinforcements enhanced the wear resistance of polymer-based composites [25–30]. Addition of bagasse fly ash filler enhanced the mechanical and morphological properties of natural fiber epoxy matrix composites [31]. Fly ash filler hybrid epoxy composites showed lesser porosity in the composites with good tensile, flexural and impact strength nature [32].

The addition of short human hair fiber was optimized with response surface optimization technique. It showed reduction in the wear rate of epoxy-based composites by improved adhesion of filler/fiber/resin combination. ANOVA table proved the significance of fiber addition, sliding velocity, sliding distance and load applied in the experiment [19]. Taguchi-based L27 orthogonal array was followed for finding the influence of *Grewia optiva* with *Bauhinia vahlii* fiber and operating parameters in wear characteristics of epoxy-based composites. The results observed low wear rate at reinforcement addition of 4 wt%, operating parameters of sliding velocity, applied load and sliding distance with 2.5 m/s, 15 N and 2000 m [28].

In most of the research works, optimization related to tribological experimentation gave importance to operating parameters than composite specification. In this experiment biological waste materials such as banana fly ash (BA) filler % and sisal/pineapple (SP) hybrid fiber addition % were taken as composite specification, sliding distance and applied load were taken as operating parameters. Multi response optimization work is very much lesser in the field of tribological applications. Grey relational analysis (GRA) coupled with Taguchi method is followed to find the common optimal parameter combination that yields lesser SWR and coefficient of friction (CoF) while testing the developed novel PMC against steel ball. Overall, this research found best level of each factor in natural fiber hybrid combinations using epoxy for better wear and CoF application.

Materials and methods

Materials

The natural fibers of pineapple (P) and sisal (S) were purchased from 'Go Green' suppliers (southern part of India called as Tamil Nadu). Epoxy resin with hardener (10:1 ratio) was used as the base matrix, having a grade of LY566 and HY951. Banana fly ash (BA) at 1, 3 and 4 wt% was incorporated with natural fiber composites. The properties of reinforcements are mentioned in Table 1.

Natural fiber surface treatment

The hydrophilic nature of pineapple and sisal fibers reduced the adhesion with hydrophobic resin composites [12]. To improve the water-resistant property, the natural fibers were treated using 5% NaOH. This provides good compatibility with matrix phase and enhance the properties of polymer composites [33]. Initially sisal and pineapple fibers needs to be washed properly using distilled water and dipped in 5% NaOH solution for 180 min. Mechanical stirring was provided at regular intervals to ensure the proper treatment of fibers. Once the treatment process is over fiber needs to be cleaned with distilled water to remove the excess NaOH content. At last, fibers were placed in the sunlight for 2 days to remove the wet content and heated in hot oven for 240 min at 65 °C.

Table 1 Properties of pineapple and sisal fibers

Properties	Units	Pineapple fiber [24]	Sisal fiber [33]
Cellulose	%	64.3	68
Hemicellulose	%	–	14
Lignin	%	25.7	9
Wax	%	0.184	0.23
Moisture content	%	8.09	8
Density	kg/m^3	1506	1448
Tensile strength	MPa	184	118
Youngs modulus	GPa	6.32	3.97

Fabrication

In this experiment BA at 1, 3 and 4 wt% was mixed with the hybrid natural fiber combination of SP at 30, 40 and 50 wt%. A total of nine samples were fabricated using compression moulding with 100 °C and 14 MPa of pressure and temperature inside the mould [32]. Fly ash filler was allowed to rotate in high energy ball milling machine with speed of 800 rpm and having ball to powder ratio of 3:1 for 6 h [32] (Fig. 1). After the fiber treatment process fibers were chopped with a length of 5 mm. The hybrid SP combinations in wt% were placed in the mould and combination of epoxy/BA filler is mixed with the mould and provide with temperature of 100 °C and pressure of 14 MPa to produce natural composite specimen.

Experimentation

Characterization of fly ash powder

Fly ash powder from the waste of banana (BA) were characterized using SEM, X-ray fluorescence spectroscopy (XRF), XRD, organic matter and ash content test.

X-ray fluorescence spectroscopy (XRF)

The XRF testing with X-ray tube of 4 kW Rh was used for this Bruker S4 pioneer model. Collimator (0.25°, 0.46°) is needed for beam narrowing and to spot the fly ash content.

Fig. 1 Ball milled banana fly ash (BA)

Organic matter and ash content

The ASTM D2974 standard was used to find the organic and fly ash content in the powder particles. Muffle furnace was used for finding this.

XRD test

The presence of quartz content in the fly ash filler was detected with BRUKER D8 XRD tester. Speed of scanning (10°/min), range varying from 5° to 60° was used for the testing.

Density and void testing

The density of hybrid composites (ρ_{ca}), theoretical density (ρ_{ct}) were determined for finding the void space in each combination. Archimedes rule was followed for finding the density of the combination, theoretical density was calculated by ASTM D 792 using the following equation (g/cm^3):

$$\rho_{ct} = \frac{1}{\left(\frac{W_r}{\rho_r}\right) + \left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_m}{\rho_m}\right)} \quad (1)$$

Here ρ_r, ρ_f is the reinforcement and filler density and ρ_m is the matrix density, then W_r is the weight fraction of reinforcement and W_f and W_m is the weight fraction of filler and matrix. The void percentage in the combination were determined using following equation (2) [34].

$$V_v = \frac{\rho_{ct} - \rho_{ca}}{\rho_{ct}} \quad (2)$$

Wear testing

The wear and frictional characteristics of hybrid natural composites were detected using linear reciprocating tribometer equipment. The Cr steel ball having 10 mm diameter were taken as the ball piece. This specimen slides in a linear reciprocating motion with the flat composite specimen (workpiece) of 4 × 4 × 0.3 cm^3. Wear testing specimens are showed in Fig. 2. The experiment has been repeated five times for the exactness of result and the average values are noted.

Wear and frictional characteristics during this reciprocating motions were calculated in the natural fiber composite specimen. ASTM G 133-05 (2016) standard was followed in this experimentation with stroke length 1 cm and oscillating frequency 10 Hz. Before the starting of the experiment steel alloy ball and composite specimen must be cleaned with mild liquid laboratory glassware cleaner. After placing

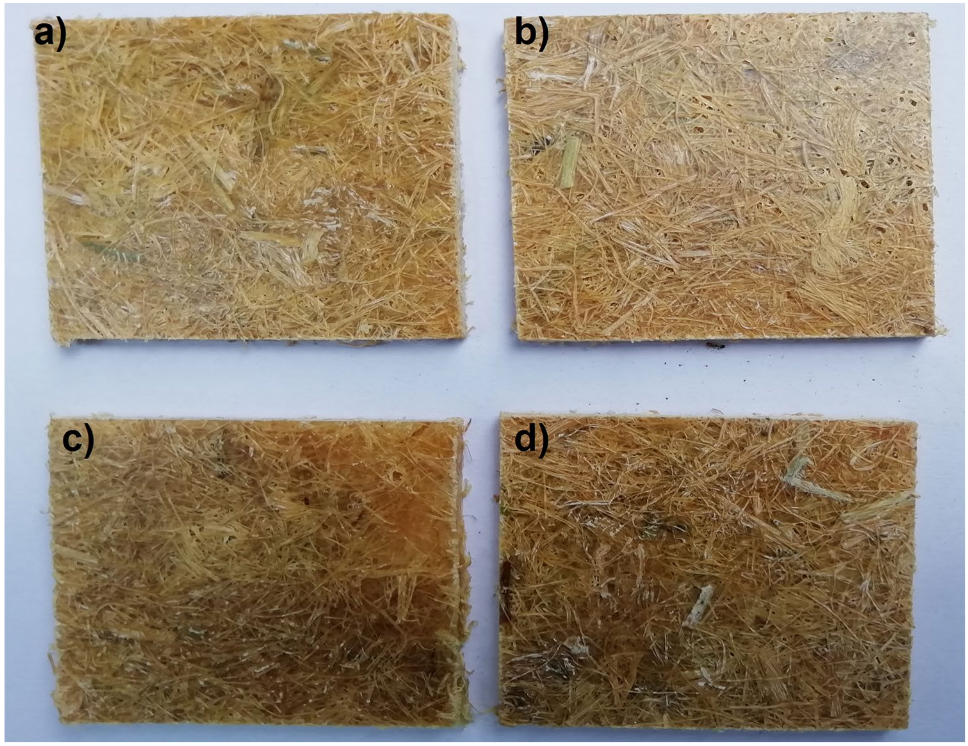

Fig. 2 Wear testing specimens. **a** 1% BA/30% SP, **b** 1% BA/40% SP, **c** 3% BA/50% SP and **d** 4% BA/50% SP combinations

it in atmospheric temperature, it needs to be cleaned using acetone for 120 s. After drying both the steel alloy ball and composite specimen, it needs to be cleaned using methanol for another 120 s. Specimens were cleaned using cotton swabs. In this experimentation operating parameters such as sliding distance was taken as 500, 1000 and 1500 m, load of 5, 10 and 15 N was applied in the natural fiber composite specimen. Sliding distance (X) (3), SWR (4) were calculated using the following equations.

$$X = 0.002 \times t \times f \times L, \tag{3}$$

X denotes sliding distance by the chromium alloy steel ball (m), t mentions time (s), f is frequency of oscillation (Hz), L denotes length of stroke (mm).

$$\mathrm{SWR} = \frac{\mathrm{WL}}{\rho \times L \times \mathrm{SD}}\ \mathrm{mm}^3/\mathrm{Nm}, \tag{4}$$

WL denotes weight loss of sample piece after wear experiment (g), ρ mentions density of hybrid fiber composite specimen (g/cm^3), L denotes acting load (N), SD mentions distance of sliding (m).

SEM analysis

SEM testing (Hitachi SU660) was used for detecting influence of various operating and fabrication parameters in wear and frictional properties of natural fiber composite specimen. In order for the smooth passage of electron beam, gold/palladium coating was provided with the natural fiber composites that will protect charging of samples.

Result and discussion

XRF results of BA filler

The XRF results in Table 2 observed major portion of silica with 60.64%, followed by alumina at 7.83%, potassium oxide with 6.35%, calcium oxide with 6.19% with the major portions. The data also showed high presence of inorganic materials with 95.45%. These high presence of SiO_2 and inorganic materials are also observed in various studies with fly ash [31, 32]. High percentage of inorganic content adds to the mechanical properties of polymer-based composites [31].

XRD and SEM results of BA filler

The XRD results (Fig. 3a) clearly showed quartz content as major element in BA powder. The peaks in the figure showed good similarities with PDF card 331161 [36, 37]. The silica content in the fly ash is mainly due to growth of plants in soil [31]. The morphological study using SEM is showed in Fig. 3b.

Table 2 XRF results of banana fly ash (BA) powder

Chemical composition	BA % [33]	[35]	[31]
SiO_2	60.64	75.46	50.40
CaO	6.19	4.42	18.90
Fe_2O_3	4.97	1.62	6.87
Al_2O_3	7.83	3.35	7.48
P_2O_5	3.97	2.18	2.47
K_2O	6.35	4.16	7.29
SO_3	2.74	2.99	1.94
MgO	2.20	3.04	1.61
TiO_2	–	0.19	1.28
Na_2O	0.15	0.30	0.33
Cl	0.21	–	0.59
MnO	–	0.06	0.23
Organic materials (%)	4.59	2.15	25.33
Inorganic materials (%)	95.45	97.85	74.67
Density (g/cm^3)	0.55	0.74	0.55
Loss on ignition (%)	1.86	2.15	–

Density and void testing

The density and void testing showed the following results (Table 3), it shows reduction in the void space of composites by the incorporation of BA filler and increase in void space with fiber incorporation. Fly ash filler reduces the gap between fiber and matrix phase that reduces the void space in the combinations [38]. Thus the filler incorporation improved the compatibility of natural fiber composites.

Influence of process parameter on SWR of developed composite

Figure 4 depicts the experimental values of SWR based on experimental plans. Error bars in figure represents that standard deviation is very low in most results. Influence of control factor over SWR was depicted in Fig. 4. It can be observed that increase in percentage of fly ash decreases the SWR of composite (Fig. 5). Addition of fillers in composite material helps in increasing the interfacial bonding between the matrix and reinforcement, resulting in property enhancement of developed composite [24]. Addition of fly ash helps in increasing the ability of reinforced fibers to distribute the applied stress over the composite material with incremental wear resistance up to 4 wt%. Another reason is the presence of silica or silica oxide particle in fly ash, these SiO_2 particles have dual properties viz. increases the hardness and ability to act as self-lubricant [35–37]. These extensive properties may also be the reason for incremental wear resistance of the developed composite. Addition of filler helps in reducing the formation of porosity over the composite material by increasing the bonding strength between the matrix and reinforcement with reduced surface deformation during wear condition [21].

It can also depict that increment in fibre percentage up to 50 wt% decrease the wear resistance of the composite. Increase in fibre percentage may be resulted in uneven dispersions of reinforcement over matrix this might results in formation of micro void that decreases the composite strength [39, 40]. Due to this fact, the hybrid fibre fails to transfer or distribute the applied load over the matrix that results in composite failures. Likewise increase in fibre

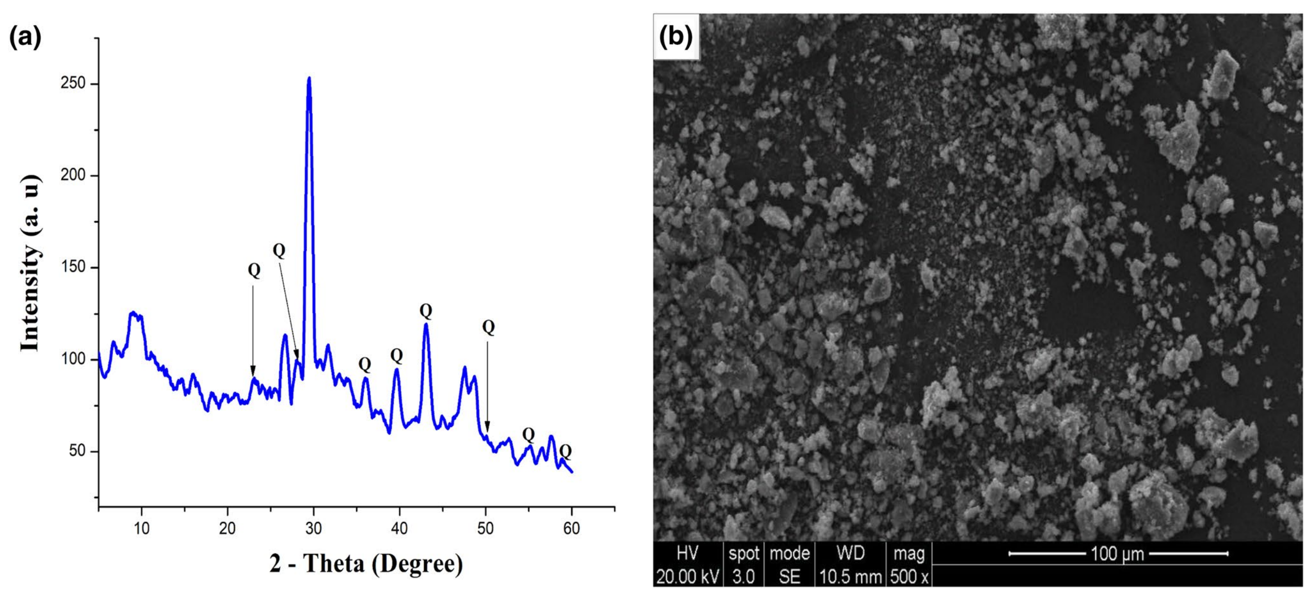

Fig. 3 XRD and SEM results of BA filler

Table 3 Density and voids in the combination [38]

Combinations	ρ_{ca} (g/cm^3)	ρ_{ct} (g/cm^3)	Void (%)
30 SP/1 BA	1.183	1.198	1.252
30 SP/3 BA	1.188	1.201	1.082
30 SP/4 BA	1.185	1.199	1.168
40 SP/1 BA	1.164	1.182	1.523
40 SP/3 BA	1.166	1.183	1.437
40 SP/4 BA	1.168	1.185	1.435
50 SP/1 BA	1.174	1.199	2.085
50 SP/3 BA	1.179	1.204	2.076
50 SP/4 BA	1.176	1.202	2.163

percentage decrease the mechanical bonding between them which might be another reason for decreased wear resistance [41]. During wear condition, increment in fibre percentage results in pull out mechanism that break up the mechanical bonding between matrix and reinforcement particles that decrease the wear resistance [42]. Similarly increase in fibre content changes the amount of matrix volume, due to this insufficient mixing of matrix material take place that decreases the composite strength. Based on attained results usage of hybrid fibre up to 30 wt% exhibits lower wear rate further addition decreases the wear resistance of the composite owing to the above-mentioned facts. Figure 5 displays that increment in sliding distance increases the SWR of composite. During wear condition, increase in sliding distance (up to 1500 m) increases the contact time between the steel ball and composite counterpart. This fact increases the surface temperature of the composite plate due to the friction effect, i.e., increases in contact timing increases the friction heat. Increment in surface temperature result in softening of matrix material that reduces the mechanical bonding between matrix and reinforcements thus higher SWR is evidenced [43]. Increment in applied load increases the SWR of composite. During wear condition, increment in load increases the pressure near the surface between steel ball and composite plate that results in incremental adhesion force [44]. This fact breakdown the interfacial bonding between the matrix and reinforcement that decrease the wear resistances of developed composite. The counter surface with mechanically mixed layer has positive impact on the wear properties of filler and reinforcement incorporated natural fiber composites [15, 18]. This layer will be formed between the interface of counter surface and composite sample by tribo-chemical action between them [44].

Influence of process parameter on CoF of developed composite

The variation of COF values with respect to the process parameters was depicted in Fig. 6 and the error bar reveal the occurrence of acceptable deviations in the attained results. Figure 7 depicts the main effect plot for COF. It can be observed that increases in fly ash up to 4 wt% increases the

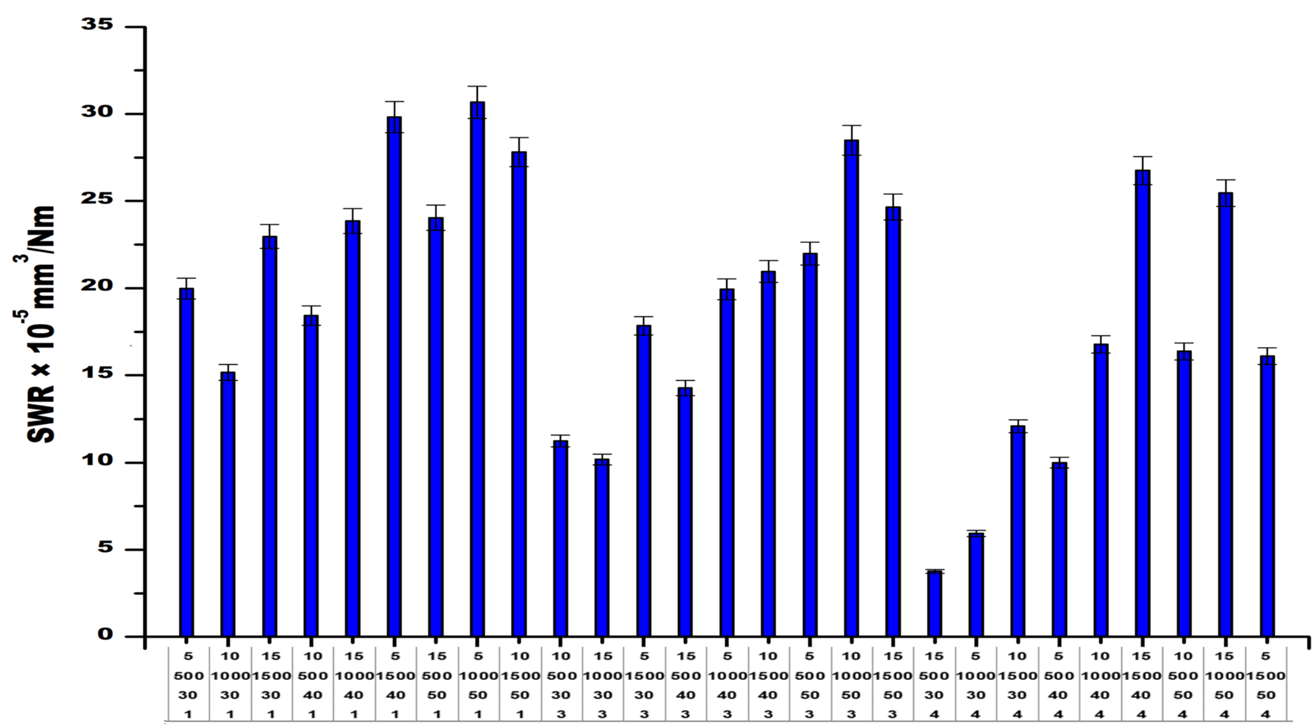

Fig. 4 Specific wear rate of developed composite with respect to control factors

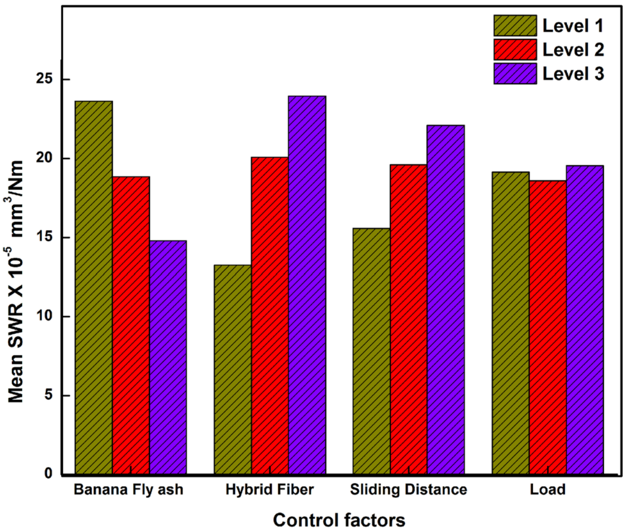

Fig. 5 Main effect plot for SWR

COF values of developed composite. Incremental addition of hard filler results in incremental hardness of developed composite thus results in increment in COF during wear [21]. Likewise increases in fibre percentage up to 50 wt% increases COF values, addition of fibre material increases the hardness of the matrix material. During wear condition addition of hybrid fibers results in increasing friction between the composite and steel ball thus COF increases. Increase in sliding distance results in thermal softening of matrix material, these polymer matrix materials forms a thin film over the counter surface that decreases the contact between the two surfaces which reduces the COF values of composite [28, 29].

Increase in applied load showcase increment and decremental trend in COF. Increases in applied load increases the surface pressure near the contour disk and thus COF value increases [16]. Further increment in applied load results in incremental friction temperature due to this fact softening of matrix material takes place and it form a thin film over pin surface thus COF value decrease. At higher applied load contact area between composite disk and ball increase that results in breaking of interfacial bonding or mechanical bonding among them (matrix and reinforcement) thus COF values increases.

Multi-objective optimization on process parameter

Optimizing the process parameters through Taguchi method for better quality characteristics yield different optimum combinations for different output variables. So it is better to find the common parameter combination that gives better output for multi responses [22]. This GRA technique is very prominent to solve the multi objective problems. Advantage of this technique is that it eliminates

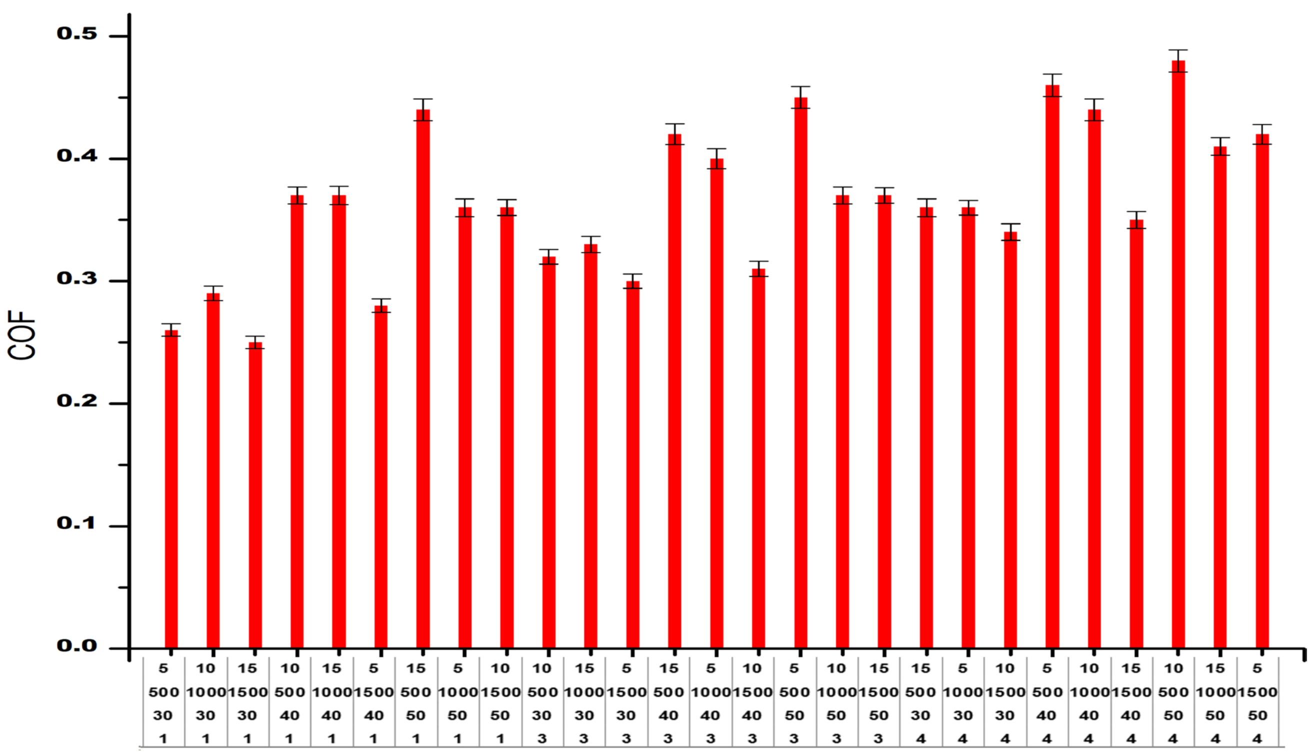

Fig. 6 COF rate of developed composite with respect to control factors

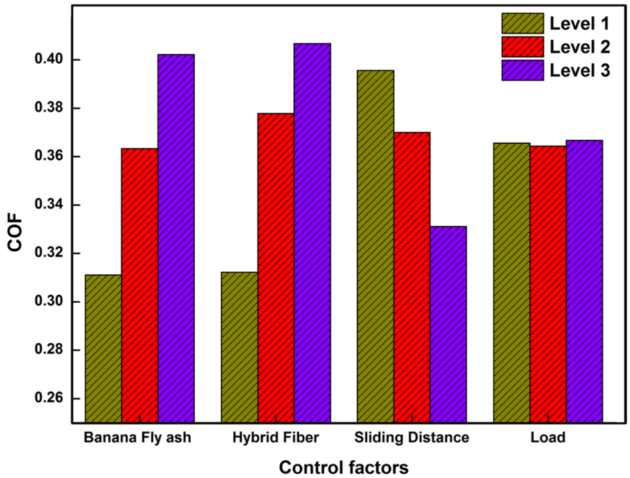

Fig. 7 Main effect plot for COF

the aforementioned setback in the Taguchi method by converting the multi objectives into the single criterion and by following few steps optimal combination is identified. This process of converting multi objective into single objective has three major steps that are normalization, calculation of grey relational coefficient (GRC) and grey relational grade (GRG) [22].

As an initial step of GRA, the obtained experimental results are normalized to the values of between 0 and 1 by following three criteria similar to Taguchi SN ratio method that are smaller the best, nominal is best and higher the best. Since the current study is focusing on decreasing the wear rate and CoF, smaller the better-quality characteristics is selected.

The equation for "smaller the better" criterion to normalize the SWR and CoF is as follows:

$$y_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)}, \tag{5}$$

where $x_i^0(k)$ is the experimental response, $\max x_i^0(k)$ is the largest number amongst $x_i^0(k)$ and $\min x_i^0(k)$ denotes the least number amongst $x_i^0(k)$, i denotes the trial no, and k stances for the output features.

The second step in GRA is to identify the GRC and the equation for calculating GRC is as follows:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{0i}(k) + \zeta\Delta_{\max}} \tag{6}$$

where $\Delta_{0i}(k)$ is the difference in absolute value in between $y_0{*}(k)$ and $y_i{*}(k)$, ζ signifies the unique coefficient and it is taken as 0.5 in this study, $\Delta_{\min}$ and $\Delta_{\max}$ are the smallest and largest value among $\Delta_{0i}(k)$, respectively.

The concluding and third step of GRA is to calculate the GRG values and it is done with the aid of following equation:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k), \tag{7}$$

where γ_i is in the array of 0–1, and n is the no of responses.

The calculated values such as normalized response, GRCs and GRGs are given in the Table 4. The rank is assigned to each trials based on the GRG values in which higher rank is assigned to the trial which possess higher GRG values, i.e., the trail which have larger GRG values is said to be optimum among the 27 trials conducted.

The effect of each control factors over GRG is analysed by calculating the mean values of the GRG for each parameter level and the same is plotted as chart in Fig. 8. It is clear from the figure that minimal addition of BA filler (1 wt%), hybrid fibre (HF) content (30 wt%), higher sliding distance (SD) (1500 m) and lesser loading (L) (5 N) results in better multi quality characteristics i.e. it gives good overall tribological properties. As the addition of filler materials and hybrid fibres with the polymer matrix results in increased friction, it is suggested to keep the percentage low for the filler and fibre. And it is a well understood fact that the increase in load always results in increased friction and wear due to increased interface pressure which results in increased adhesion between the sliding parts. So the lower loads is recommended to get the higher GRGs, i.e., lower SWR and CoF. The optimum condition recommended by the GRA for higher GRG can be clearly identified from the figure which is BA1, HF1, SD3 and L1.

The SEM results in Fig. 9a, b observed non-homogeneous distribution of fibers due to higher fiber incorporation. This will cause surface deformations in the epoxy-based combinations with fiber and matrix breakages reducing the properties. The high fiber incorporation up to 50 wt% declined the overall properties of natural fiber epoxy-based composites [12]. Higher filler incorporation of 3 and 4 wt% BA and low PS hybrid fiber combination at 30 wt% (Fig. 9c, d) improved the overall distribution of fibers with good bonding strength. Thus it is confirmed that the compatibility of fiber/resin improved with increase in filler incorporation and reduced with hybrid fiber incorporation of natural fibers [40].

The SEM results after the wear tests (Fig. 10) observed low resistance for combinations with low filler content of 1 wt% BA (Fig. 10a) and high fiber wt% of 50 (Fig. 10b). This is mainly due to the poor adhesion of fiber/matrix phase leading to the property reduction. Good fiber/filler/epoxy bonding created a tribolayer surface in the combination and that reduces the surface contact between counter specimen and work piece with reduced SWR [19, 21]. The high adding up of fiber results in pull out of fibers in the epoxy resin

Table 4 Grey relation analysis of developed composite

S. no.	Normalized SWR	Normalized CoF	GRC of SWR	GRC of CoF	GRG	Rank
1.	0.39725	0.956522	0.453412	0.92	0.686706	3
2.	0.575994	0.826087	0.541122	0.741935	0.641529	5
3.	0.286139	1	0.411909	1	0.705954	2
4.	0.455221	0.478261	0.47857	0.489362	0.483966	13
5.	0.253066	0.478261	0.400983	0.489362	0.445173	17
6.	0.031215	0.869565	0.340417	0.793103	0.56676	10
7.	0.246377	0.173913	0.398844	0.377049	0.387947	27
8.	0	0.521739	0.333333	0.511111	0.422222	23
9.	0.105909	0.521739	0.358657	0.511111	0.434884	21
10.	0.721665	0.695652	0.642397	0.621622	0.632009	7
11.	0.761427	0.652174	0.676981	0.589744	0.633362	6
12.	0.476774	0.782609	0.488651	0.69697	0.59281	8
13.	0.609067	0.26087	0.56121	0.403509	0.482359	14
14.	0.398737	0.347826	0.454024	0.433962	0.443993	18
15.	0.360832	0.73913	0.438917	0.657143	0.54803	11
16.	0.322557	0.130435	0.424649	0.365079	0.394864	26
17.	0.081011	0.478261	0.352363	0.489362	0.420863	24
18.	0.223337	0.478261	0.391646	0.489362	0.440504	20
19.	1	0.521739	1	0.511111	0.755556	1
20.	0.918989	0.521739	0.860569	0.511111	0.68584	4
21.	0.69045	0.608696	0.617627	0.560976	0.589301	9
22.	0.768116	0.086957	0.683168	0.353846	0.518507	12
23.	0.516537	0.173913	0.508407	0.377049	0.442728	19
24.	0.145671	0.565217	0.369186	0.534884	0.452035	16
25.	0.531401	0	0.516209	0.333333	0.424771	22
26.	0.193608	0.304348	0.382734	0.418182	0.400458	25
27.	0.541434	0.26087	0.521613	0.403509	0.462561	15

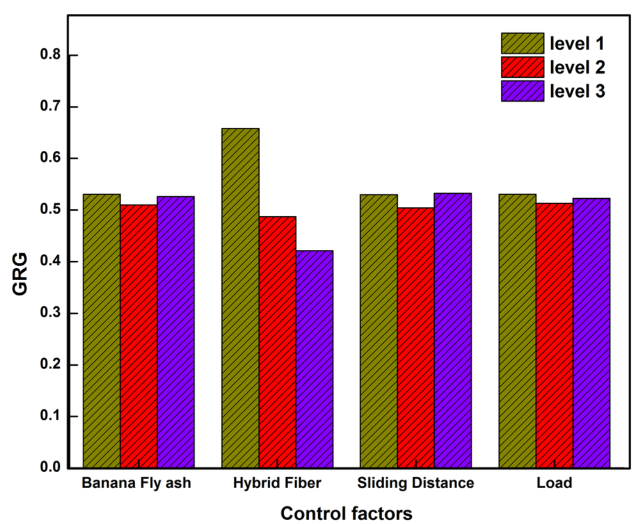

Fig. 8 Main effect plot for GRG

resulting in high wear rate of natural composites. Filler addition reduces the matrix/resin porosity, reduces the surfaces deformations and improve the wear resistance [20]. Low sliding distance of 500 m showed (Fig. 10c) reduction in the wear properties due to low contact of composite piece with counter specimen [41]. High load exerted using 15 N (Fig. 10d) created wear crack and wear debris in the natural fiber composites, high load creates high pressure zone in the composite specimen creating high wear rate [43].

Conclusions

The multi-response optimization using GRA with BA filler %, Sisal/Pineapple (SP) hybrid fiber addition %, sliding distance and applied load taken as main factors observed minimal addition of BA filler (1 wt%), hybrid fibre content (30 wt%), higher sliding distance (1500 m) and lesser loading (5 N) results in good overall tribological properties. The addition of filler materials and hybrid fibres with the polymer matrix results in increased friction. The increase in load always results in increased friction and wear due to increased interface pressure which results in increased adhesion between the sliding parts. So, the lower loads are recommended to get the higher GRGs, i.e.,

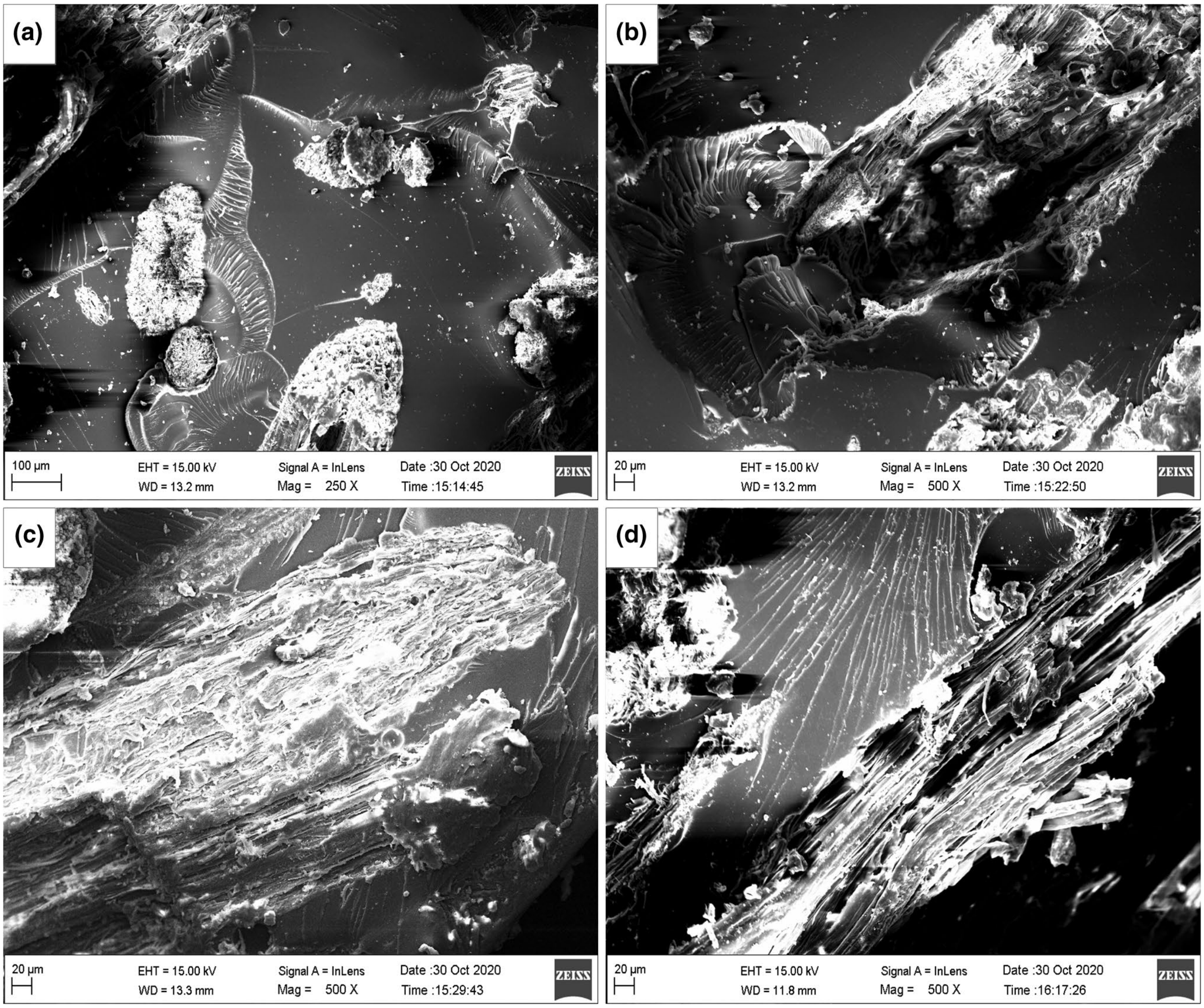

Fig. 9 The SEM results before wear for **a** 40 wt% PS/1 wt% BA, **b** 50 wt% PS/1 wt% BA, **c** 30 wt% PS/3 wt% BA and **d** 30 wt% PS/4 wt% BA

lower SWR and CoF. The SEM results after the wear tests observed low wear resistance for combinations with high fiber wt% of 50. This is mainly due to the poor adhesion of fiber/matrix phase leading to the property reduction. Good fiber/filler/epoxy bonding created a tribolayer surface in the combination and that reduces the surface contact between counter specimen and work piece with reduced SWR. These low-cost hybrid composites can be used for light weight application requiring some wear properties. As a future work, this BA can be tried for flammability application of polymer composites.

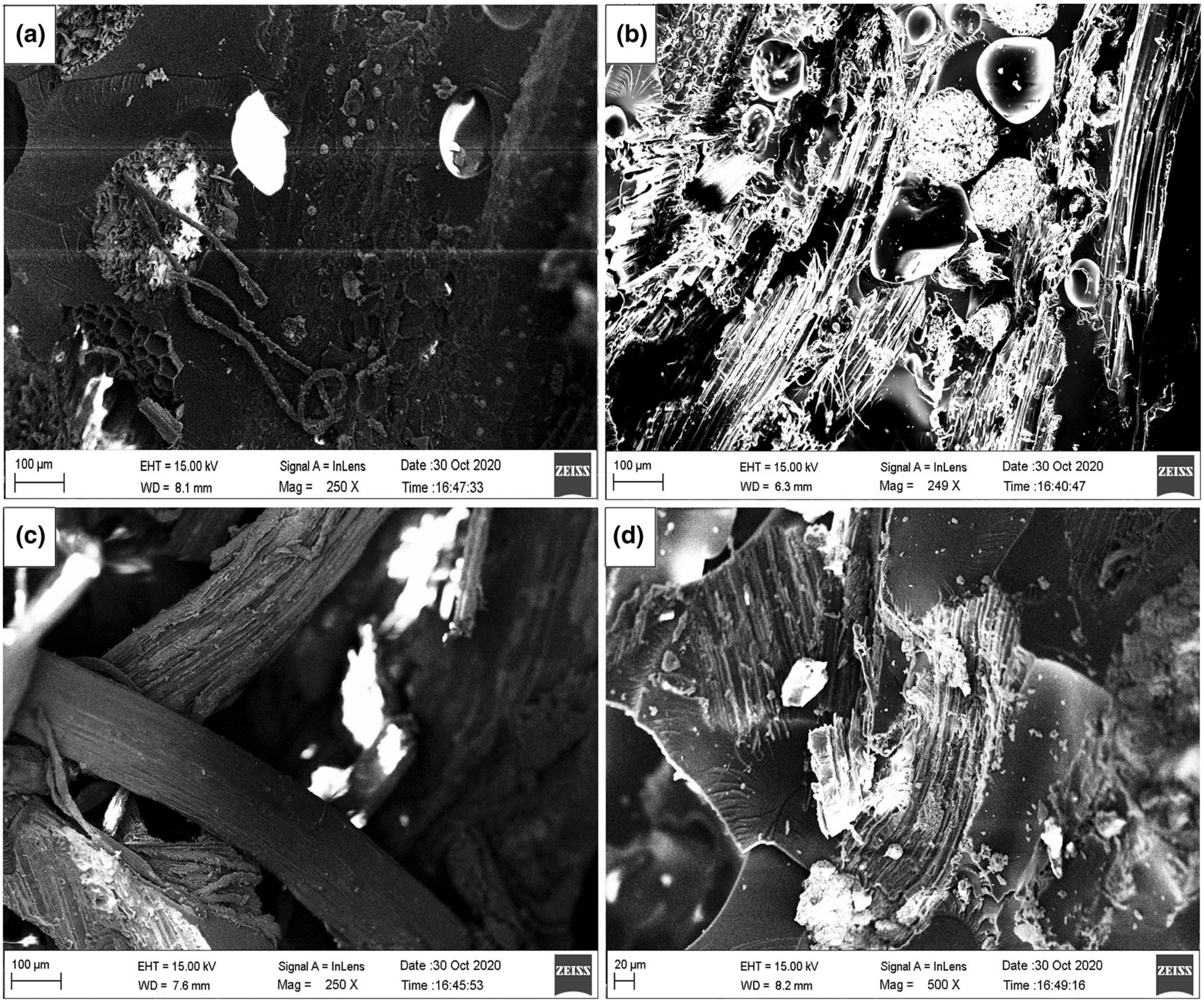

Fig. 10 The SEM results after wear test for **a** low filler content of 1 wt% BA, **b** high fiber wt% of 50, **c** low sliding distance of 500 m and **d** high load of 15 N

Funding The research work was funded by European Social Fund Project," International Mobility of Researchers in CTU" (CZ.02.2.69/0.0/0.0/16_027/0008465).

References

1. Sukudom N, Jariyasakoolroj P, Jarupan L, Tansin K (2019) Mechanical, thermal, and biodegradation behaviors of poly(vinyl alcohol) biocomposite with reinforcement of oil palm frond fiber. J Mater Cycles Waste Manag 21:125–133. https://doi.org/10.1007/s10163-018-0773-y
2. Bhogayata AC, Arora NK (2019) Utilization of metalized plastic waste of food packaging articles in geopolymer concrete. J Mater Cycles Waste Manag 21:1014–1026. https://doi.org/10.1007/s10163-019-00859-9
3. Balaji A, Karthikeyan B, Swaminathan J, Sundar RC (2017) Mechanical behavior of short bagasse fiber reinforced cardanol-formaldehyde composites. Fibers Polym 18:1193–1199. https://doi.org/10.1007/s12221-017-7009-y
4. Keskisaari A, Karki T (2017) Raw material potential of recyclable materials for fiber composites: a review study. J Mater Cycles Waste Manag 19:1136–1143. https://doi.org/10.1007/s10163-016-0511-2
5. De Paiva FFG, de Maria VPK, Torres GB et al (2019) Sugarcane bagasse fiber as semi-reinforcement filler in natural rubber composite sandals. J Mater Cycles Waste Manag 21:326–335. https://doi.org/10.1007/s10163-018-0801-y
6. Grause G, Mochizuki T, Kameda T, Yoshioka T (2013) Recovery of glass fibers from glass fiber reinforced plastics by pyrolysis. J Mater Cycles Waste Manag 15:122–128. https://doi.org/10.1007/s10163-012-0101-x
7. Chen W, Zhang S, He F et al (2019) Porosity and surface chemistry development and thermal degradation of textile waste jute during recycling as activated carbon. J Mater Cycles Waste Manag 21:315–325. https://doi.org/10.1007/s10163-018-0792-8

8. Mittal V, Saini R, Sinha S (2016) Natural fiber-mediated epoxy composites—a review. Compos B 99:425–435. https://doi.org/10.1016/j.compositesb.2016.06.051
9. Nguyen H, Jamali Moghadam M, Moayedi H (2019) Agricultural wastes preparation, management, and applications in civil engineering: a review. J Mater Cycles Waste Manag 21:1039–1051. https://doi.org/10.1007/s10163-019-00872-y
10. Oushabi A (2019) The pull-out behavior of chemically treated lignocellulosic fibers/polymeric matrix interface (LF/PM): a review. Compos B. https://doi.org/10.1016/j.compositesb.2019.107059
11. Jaafar J, Parlaungan J, Mohd S et al (2018) Influence of selected treatment on tensile properties of short pineapple leaf fiber reinforced tapioca resin biopolymer composites. J Polym Environ 26:4271–4281. https://doi.org/10.1007/s10924-018-1296-2
12. Todkar SS, Patil SA (2019) Review on mechanical properties evaluation of pineapple leaf fibre (PALF) reinforced polymer composites. Compos B. https://doi.org/10.1016/j.compositesb.2019.106927
13. Aslan M, Tufan M, Küçükömeroğlu T (2018) Tribological and mechanical performance of sisal-filled waste carbon and glass fibre hybrid composites. Compos B 140:241–249. https://doi.org/10.1016/j.compositesb.2017.12.039
14. Maurya HO, Jha K, Tyagi YK (2017) Tribological behavior of short sisal fiber reinforced epoxy composite. Polym Polym Compos 25:215–220. https://doi.org/10.1177/096739111702500306
15. Nirmal U, Hashim J, Low KO (2012) Adhesive wear and frictional performance of bamboo fibres reinforced epoxy composite. Tribol Int 47:122–133. https://doi.org/10.1016/j.triboint.2011.10.012
16. Shuhimi FF, Bin AMF, Kalam MA et al (2016) Tribological characteristics comparison for oil palm fibre/epoxy and kenaf fibre/epoxy composites under dry sliding conditions. Tribol Int 101:247–254. https://doi.org/10.1016/j.triboint.2016.04.020
17. Singha AS, Thakur VK (2008) Mechanical properties of natural fibre reinforced polymer composites. Bull Mater Sci 31:791–799. https://doi.org/10.1007/s12034-008-0126-x
18. Joseph J, Munda PR, Kumar M et al (2020) Sustainable conducting polymer composites: study of mechanical and tribological properties of natural fiber reinforced PVA composites with carbon nanofillers. Polym Plast Technol Mater. https://doi.org/10.1080/25740881.2020.1719144
19. Nanda BP, Satapathy A (2020) An analysis of the sliding wear characteristics of epoxy-based hybrid composites using response surface method and neural computation. J Nat Fibers. https://doi.org/10.1080/15440478.2020.1722781
20. Fei J, Zhang C, Luo D et al (2018) Vertically aligned TiO_2 nanorods-woven carbon fiber for reinforcement of both mechanical and anti-wear properties in resin composite. Appl Surf Sci 435:156–162. https://doi.org/10.1016/j.apsusc.2017.10.182
21. Kumar MNS, Yaakob Z, Mohan N, Babu SPK (2010) Mechanical and abrasive wear studies on biobased jatropha oil cake incorporated glass–epoxy composites. J Am Oil Chem Soc 87:929–936. https://doi.org/10.1007/s11746-010-1575-0
22. Sumesh KR, Kanthavel K (2019) Synergy of fiber content, Al2O3 nanopowder, NaOH treatment and compression pressure on free vibration and damping behavior of natural hybrid-based epoxy composites. Polym Bull. https://doi.org/10.1007/s00289-019-02823-x
23. Sumesh KR, Kanthavel K (2020) Effect of TiO2 nano - filler in mechanical and free vibration damping behavior of hybrid natural fiber composites. J Braz Soc Mech Sci Eng. https://doi.org/10.1007/s40430-020-02308-3
24. Sumesh KR, Kavimani V, Rajeshkumar G, Ravikumar P (2020) An investigation into the mechanical and wear characteristics of hybrid composites: influence of different types and content of biodegradable reinforcements. J Nat Fibers. https://doi.org/10.1080/15440478.2020.1821297
25. Mahesh V, Joladarashi S, Kulkarni SM (2019) Physio-mechanical and wear properties of novel jute reinforced natural rubber based flexible composite. Mater Res Express. https://doi.org/10.1088/2053-1591/ab0164
26. Chegdani F, El Mansori M, Bukkapatnam STS, El Amri I (2019) Thermal effect on the tribo-mechanical behavior of natural fiber composites at micro-scale. Tribol Int. https://doi.org/10.1016/j.triboint.2019.06.024
27. Correa CE, Betancourt S, Vázquez A, Gañan P (2017) Wear performance of vinyl ester reinforced with Musaceae fiber bundles sliding against different metallic surfaces. Tribol Int 109:447–459. https://doi.org/10.1016/j.triboint.2017.01.009
28. Kumar S, Patel VK, Mer KKS et al (2019) Himalayan natural fiber-reinforced epoxy composites: effect of *Grewia optiva*/*Bauhinia vahlii* fibers on physico-mechanical and dry sliding wear behavior. J Nat Fibers. https://doi.org/10.1080/15440478.2019.1612814
29. Yousif BF, Lau STW, McWilliam S (2010) Polyester composite based on betelnut fibre for tribological applications. Tribol Int 43:503–511. https://doi.org/10.1016/j.triboint.2009.08.006
30. Akpan EI, Wetzel B, Friedrich K (2018) A fully biobased tribology material based on acrylic resin and short wood fibres. Tribol Int 120:381–390. https://doi.org/10.1016/j.triboint.2018.01.010
31. Vivek S, Kanthavel K (2019) Effect of bagasse ash filled epoxy composites reinforced with hybrid plant fibres for mechanical and thermal properties. Compos B Eng 160:170–176. https://doi.org/10.1016/j.compositesb.2018.10.038
32. Sumesh KR, Kanthavel K (2020) Abrasive water jet machining of sisal/pineapple epoxy hybrid composites with the addition of various fly ash filler. Mater Res Express. https://doi.org/10.1088/2053-1591/ab7865
33. Sumesh KR, Saikrishnan G, Pandiyan P, Prabhu L, Gokulkumar S, Priya AK et al (2021) The influence of different parameters in tribological characteristics of pineapple/sisal/TiO_2 filler incorporation. J Ind Text. https://doi.org/10.1177/15280837211022614
34. Rajeshkumar G (2020) An experimental study on the interdependence of mercerization, moisture absorption and mechanical properties of sustainable *Phoenix* sp. fibre-reinforced epoxy composites. J Ind Text 49:1233–1251. https://doi.org/10.1177/1528083718811085
35. Rodríguez-díaz JM, Omar J, García P, Ramón L, Sánchez B, Gurgel M et al (2015) Comprehensive characterization of sugarcane bagasse ash for its use as an adsorbent. Bioenergy Res 8:1885–1895. https://doi.org/10.1007/s12155-015-9646-6
36. Castaldelli VN, Akasaki JL, Melges JLP et al (2013) Use of slag/sugar cane bagasse ash (SCBA) blends in the production of alkali-activated materials. Materials 6:3108–3127. https://doi.org/10.3390/ma6083108
37. Pereira AM, Moraes JCB, Moraes MJB et al (2018) Valorisation of sugarcane bagasse ash (SCBA) with high quartz content as pozzolanic material in Portland cement mixtures. Mater Constr 68:1–10. https://doi.org/10.3989/mc.2018.00617
38. Sumesh KR, Kavimani V, Rajeshkumar G, Indran S, Saikrishnan G (2021) Effect of banana, pineapple and coir fly ash filled with hybrid fiber epoxy based composites for mechanical and morphological study. J Mater Cycles Waste Manag 23:1277–1288. https://doi.org/10.1007/s10163-021-01196-6
39. Balaji A, Purushothaman R, Udhayasankar R, Vijayaraj S, Karthikeyan B (2020) Study on mechanical, thermal and morphological properties of banana fiber-reinforced epoxy composites. J Bio Tribo Corros. https://doi.org/10.1007/s40735-020-00357-8
40. Udhayasankar R, Karthikeyan B, Balaji A (2020) Comparative mechanical, thermal properties and morphological study of untreated and NaOH-treated coconut shell-reinforced cardanol

environmental friendly green composites. J Adhes Sci Technol 34:1720–1740. https://doi.org/10.1080/01694243.2020.1727643
41. Rajeshkumar G (2020) A new study on tribological performance of *Phoenix* sp. fiber-reinforced epoxy composites. J Nat Fibers. https://doi.org/10.1080/15440478.2020.1724235
42. Nirmal U, Hashim J, Megat Ahmad MMH (2015) A review on tribological performance of natural fibre polymeric composites. Tribol Int 83:77–104. https://doi.org/10.1016/j.triboint.2014.11.003
43. Liu Y, Xie J, Wu N et al (2019) Influence of silane treatment on the mechanical, tribological and morphological properties of corn stalk fiber reinforced polymer composites. Tribol Int 131:398–405. https://doi.org/10.1016/j.triboint.2018.11.004
44. Chang BP, Chan WH, Zamri MH et al (2019) Investigating the effects of operational factors on wear properties of heat-treated pultruded kenaf fiber-reinforced polyester composites using Taguchi method. J Nat Fibers 16:702–717. https://doi.org/10.1080/15440478.2018.1432001