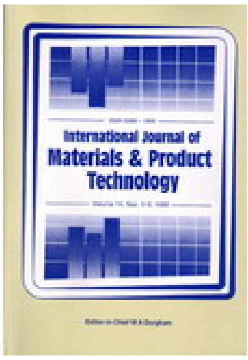

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S.P. Gairola, Y.K. Tyagi, Brijesh Gangil, Sandeep Kumar

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Synergy of wood ash on mechanical and sliding wear properties of banana/walnut-based epoxy composites and optimisation with grey relational analysis

S.P. Gairola and Y.K. Tyagi

Department of Mechanical Engineering,
D.I.T. University Dehradun,
Uttarakhand-248009, India
Email: suryapg07@gmail.com
Email: tyagi30@yahoo.com

Brijesh Gangil* and Sandeep Kumar

Department of Mechanical Engineering,
H.N.B. Garhwal University,
Srinagar-Garhwal, Uttarakhand-246174, India
Email: brijeshgangil@gmail.com
Email: sandeepagra06@gmail.com
*Corresponding author

Abstract: This study investigates the sliding wear characteristics of wood ash-based banana/walnut reinforced epoxy composites using the hand layup technique. This research investigates the impact of wood ash on composites to obtain excellent wear resistance and moderate mechanical properties, which can be utilised in various engineering applications. As the percentage of wood ash increases in the composites, the tensile strength and hardness of the composites increase, but the impact energy declines marginally. The sliding wear test is carried out on a dry sliding wear test machine (pin-on-disc). The Grey-Taguchi method and optimal factor settings are used to evaluate the multiple responses of composites. The results showed that the most critical factor influencing the properties of composites is wood ash content (41%), accompanied by sliding velocity (35%), and lastly, the normal load (24%). Scanning electron microscopy was used to analyse the composites' worn surfaces to investigate the potential wear mechanism.

Keywords: polymer composites; natural fibre; wood ash filler; Grey-Taguchi method.

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Biographical notes: S.P. Gairola is an Assistant Professor in Department of Mechanical Engineering, D.I.T. University Dehradun, Uttarakhand-248009, India. His research interests include Composite materials, tribology and computational fluid dynamics.

Y.K. Tyagi is a Professor in Department of Mechanical Engineering, D.I.T. University Dehradun, Uttarakhand-248009, India. His research interests include metal matrix composites, welding and tribology.

Brijesh Gangil is an Assistant Professor in Mechanical Engineering Department, Hemvati Nandan Bahuguna Garhwal University, Uttarakhand, India. His research interests include composites, functionally graded material and tribology.

Sandeep Kumar is working as a Guest Faculty in the Mechanical Engineering Department, Hemvati Nandan Bahuguna Garhwal University, Uttarakhand, India. His research interests include composites and tribology.

1 Introduction

Natural fibres have recently sparked a lot of interest as a substitute for artificial fibres in composites fabrication due to environmental concerns. Lightweight to strength ratio, cost-effectiveness, ample availability, low density, and relatively more robust physicomechanical properties are some of the practical advantages, making it a possible complete or partial replacement for artificial fibres (glass, carbon, and Kevlar). The fibre-reinforced composite structure's primary focus is growing significantly because it has a strong basic modulus and strength, is light in weight, and is cost-effective. Banana fibres are primarily manufactured in India and Brazil, and they are manually harvested from banana stems that are usually discarded in the land after banana cultivation. Several researchers have used banana fibre in fibre-reinforced composites, and advances in mechanical properties have been studied (Sivaranjana and Arumugaprabu, 2021; Komal et al., 2020; Al Rashid et al., 2020). Singh and Mukhopadhyay (2020) investigated the sound insulation properties of coir/banana polypropylene composites and discovered that adding fibres improved sound insulation up to a particular stage. Ramesh et al. (2014) focused on the mechanical properties of banana-epoxy composites. They found that the optimum values of the tensile strength (112.58 MPa) and flexural strength (76.53 MPa) are reached at 50% banana fibre reinforced in epoxy composites. Different fibre lengths, such as 4 cm, 6 cm, and 8 cm, and volume fractions 20%, 30%, and 40% of non-woven banana fibre-based composites have been manufactured, and mechanical properties have been evaluated (Murugan and Kumar, 2021). They discovered that banana fibre-based composites with a 6 cm length and 30% banana fibre content have the best mechanical properties of all fabricated composites.

Hybrid composites comprise more than one reinforcing agent (ceramic, metal, and polymer) in a single matrix (Rao et al., 2020). The hybridisation technique in composite industries has opened up a new avenue for expanding the spectrum of composite materials applications. Furthermore, in fibre-reinforced composites, a synergistic effect of fibre and filler has become a common research topic in the composite fabrication industry. The addition of fillers to composite materials will significantly affect their mechanical and wear properties. By incorporating different fillers (wood ash, walnut filler, pine, rice husk, etc.) as a hybrid element in polymer composites (Kumar et al., 2019, 2017, 2016; Gautam et al., 2019), rich results were obtained, primarily in mechanical and wear efficiency. Natural fillers are other substitutions into thermoplastic/thermoset matrix materials that allow for dramatically improved properties (mechanical, physical, and thermo-mechanical), thus lowering the cost of composites (Nunez et al., 2003; Andrzejewski et al., 2016). Natural fillers such as cashew (Sathishkumar et al., 2018), rice husk (Antunes et al., 2019), wheat (Memon et al., 2018), hazelnut (Balart et al., 2016), and sunflower have all been studied for their mechanical properties. The primary goal of embedding natural filler particles in hybrid composites is to reduce the % age of polymeric resin in the composite and create highly filled composite materials with superior mechanical properties. Incorporating walnut shell filler in polymer composites resulted in a booming increase in elastic modulus of composites with 15 with a 25-weight percentage (Barczewski et al., 2019). The mechanical properties of walnut-filled jute/basalt epoxy composites were investigated. It was discovered that walnut-filled jute/basalt epoxy composites have better tensile and flexural properties than jute/basalt epoxy composites (Dhiman and Sharma, 2020). In another study, Gupta et al. (2021) investigated the impact of walnut filler on ramie-glass fibre-based composites. They discovered that walnut-based composites with 9 wt% walnut content have higher tensile strength (62.59 MPa), flexural strength (55.52 MPa), and hardness (45.43 H_v) than all other fabricated composites. The combustion of wood-fired power plants, wood-burning facilities, and paper mills produces wood ash.

Food bundling and packaging advancements have frequently evolved to meet challenges in the globalised purchaser show. Due to the minimum cost and flexibility of the metal, paper, glass, plastic, and composites are extensively used for containerisation and packing (Mihindukulasuriya and Lim, 2014). Okafor et al. (2018) investigated the reliability of polyurethane wood ash composites for packing and containerisation application. They discovered that wood ash filler is a potential reinforcing agent in polymer composites. Increasing the filler loadings improves manufactured composites' mechanical properties (flexural and tensile strength). Sanusi et al. (2016) investigated the potential improvement in mechanical parameters such as impact energy: 112 J/mm^2, strength: 104 N/mm^2, and hardness: 25.4 HRF when wood ash-based high-density polyethylene composites are utilised as body armour. They identified the possibility of wood ash-based composites for different body armour applications of the investigated polymer composites, including anti-mine shoes, military helmets, bullet vests, and fire resistance jackets. Recognising the above literature, it is possible to use wood ash as a reinforcing agent in polymer composites for packing, containerisation, automobile industry, and body armour applications.

In concrete containing 10% wood ash (Ghorpade, 2020), the compressive and tensile strengths have been successfully increased. Sanusi et al. (2013) looked at the effect of wood ash on the mechanical properties of glass/epoxy composites in other studies. They discovered that adding 2.4% wood ash as a filler to glass/epoxy composites improved mechanical properties such as tensile strength (104 N/mm^2), impact strength (105 J/mm^2), and hardness (27.5 HRF) by more than 36%.

Fibre-reinforced polymeric materials are cost-effective for tribological applications due to their superior damping, low friction value, and self-lubricating ability. As a result, studying wear is essential, and numerous studies on the tribological properties of fibre-reinforced polymer composites have been performed. Several fillers (wood dust, walnut, periwinkle shell, pine needles, coconut shell, and so on) are used as reinforcing agents in thermoset/thermoplastic polymers and successfully replace synthetic fillers (Edoziuno et al., 2020). Previously, the main contribution to sliding wear research was focused on the effect of one factor while all other variables were kept constant. However, it is not a convincing study because interacting variables would have a reciprocal impact on wear in real-world conditions. As a result, the Taguchi approach is used in this study to examine the interacting effects of the control factor and the primary influence. Kumar et al. (2020) examined the impact of various control factors on the wear rate of polymer composites derived from jute. They discovered that the sliding velocity is the most important (fibre content, normal load, and sliding distance). No work has been conducted on wood ash fillers and their effect on the mechanical and sliding wear properties of banana/walnut-based epoxy composites. This research aims to develop and characterise wood ash epoxy composites with filler concentrations of 0 wt%, 2 wt%, 4 wt%, and 6 wt%. The banana fibres and walnut filler are set at 10% and 30%, respectively. Tensile effects and hardness properties are all measured and discussed. The impact of various control variables such as wood ash content, sliding velocity, and normal load on the sliding wear rate (dry sliding wear test) of banana/walnut epoxy composites is investigated using a low-cost and simple-to-use technique based on the design of experiments and a Taguchi L_{16} orthogonal array. The wear resistance and mechanical properties of polymer composites should be preserved at a high level. As a result, determining the optimal condition based on process parameters becomes challenging when several output responses are achieved concurrently. The present study uses the Grey-Taguchi multi-criteria optimisation technique to achieve multiple success criteria.

2 The raw material used for the preparation of composites

This study used a banana fibre (non-woven) mat with a fibre density of 1.25 gm/cm^3 acquired from C.P. and Company in Jaipur, India. The prepared mat is then washed under running water to remove dust and foreign particles and then dried in the sunlight for 24 hours to remove moisture. Walnut filler (1.16 gm/cm^3) and Wood ash (0.66 gm/cm^3) were obtained from the local villages (Pauri Garhwal) of Uttarakhand, India.

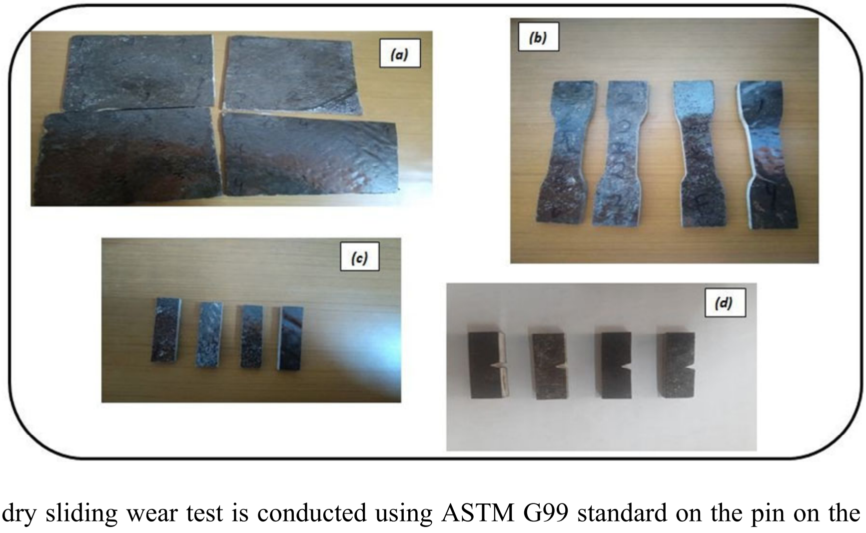
Figure 1 Pictorial view of non-woven (banana) fibre, walnut powder, and wood ash (see online version for colours)

In this analysis, an epoxy resin with the grade LY556 (density: 1.25 g/cm^3) and a compatible hardener with the grade HY951 were purchased from Amtech Pvt. Ltd. Delhi, India. The pictorial view of the non-woven banana fibre mat, walnut powder, and wood ash is depicted in Figure 1.

3 Fabrication and testing methods

Epoxy resin/hardener (400:40), wood ash content (0 to 6%), and fixed walnut content are combined thoroughly in a glass beaker using a hand stirrer. This mixture is slowly poured into a 300 mm × 300 mm × 8 mm open mould coated with mould releasing (silicon) spray. A hand roller is used to get rid of air bubbles. The powder and resin mixture is then covered with the desired weight percentage of banana fibre mats. After the mat has settled into the mould, a second layer of the mixture is added. Following that, the cast materials were allowed to cool for one day at room temperature under a pressure of 2043.75 N/m^2. There are four samples are prepared by using hand lay-up technique, i.e., composite-1 (wood ash (0 wt%) + banana fibre (30 wt%) + walnut (10 wt%) + epoxy (60 wt%)), composite-2 (wood ash (2 wt%) + banana fibre (30 wt%) + walnut (10 wt%) + epoxy (58 wt%)), composite-3(wood ash (4 wt%) + banana fibre (30wt%) + walnut (10 wt%) + epoxy (56 wt%)), and composite-4 (wood ash (6 wt%) + banana fibre (30 wt%) + walnut (10 wt%) + epoxy (54 wt%)). The desired dimensions of specimens are cut from fabricated composites, as depicted in Figure 1. Mechanical and wear tests as per the ASTM standards; tensile test (ASTM: D-638; dimension (mm) of 165 × 13 × 4 (thickness)), impact test (ASTM: E23; dimension of 55 mm × 10 mm × 10 mm), and Vicker hardness test (ASTM: E92; dimension of 25 ×25 mm^2).

Figure 2 Pictorial view of (a) fabricated composites, (b) tensile test specimen, (c) wear test specimen, and (d) impact test specimen (see online version for colours)

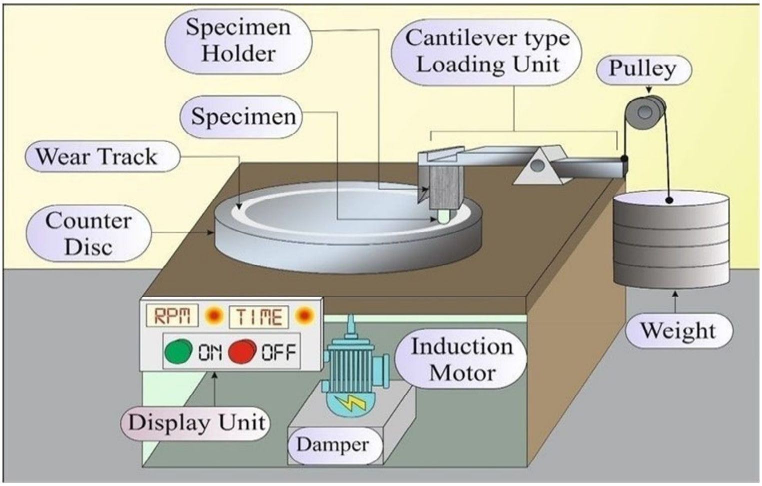


The dry sliding wear test is conducted using ASTM G99 standard on the pin on the disc machine with a specimen dimension of 35 × 8 mm^2. Figure 3 depicts a schematic view of the dry sliding wear test machine. The sample's surface is cleaned with acetone before applying it to the specimen holder. The precise wear rate is calculated using equation (1), and the mass loss is estimated using an electron weighing machine with a precision of 1/1,000 gram.

$$Specific\ wear\ rate\ (SWR) = \frac{m_{bt} - m_{at}}{\rho l f_n} \tag{1}$$

SWR (mm^3-(Nm)-1) specifies the specific wear rate. While m_{bt} and m_{at} indicate the mass of the specimens before and after the wear test (gm) and the density is represented by ρ, l is the sliding distance in (m), and f_n is the load applied to the specimen in (N).

Figure 3 Schematic view of the sliding wear test machine (see online version for colours)



4 Grey-Taguchi method

Minitab statistical program with 17 versions is used to create the design of the experiment (DOE). The first step in developing the goal of DOE is to select control factors (Table 1) and remove those that are not required. Wood ash (wt%), sliding velocity, and normal load, each at four operational stages, and the L_{16} (orthogonal array) configuration were chosen as control factors in this study (Table 2). Taguchi L_{16} significantly decreases the number of experiments from 256 to 16, resulting in cost-effective and time-saving experiments. The Taguchi method can only be used to optimise a single output at a time and not multiple responses simultaneously (Kuo et al., 2018). As a result, optimum parameter settings must be achieved that maximise all measured responses, such as higher tensile strength, hardness, impact energy, and lower sliding wear rate. The Grey-Taguchi method is used to achieve these goals (Mishra and Biswas, 2015).

Furthermore, the current research aims to improve tensile strength, hardness, impact energy, and wear rate (under sliding conditions). The following GRA measures are used to achieve our goal: normalising the responses, locating the deviation series, and calculating the relational degree between normalised and ideal experimental results using grey relational grade (*GRG*). According to the L_{16} orthogonal array, the response variables obtained from the experimental results are standardised using the larger is better (LB) and smaller is better (SB) characteristics, as shown in equations (2) and (3).

$$N_i(t) = [k_i(t) - minimum\ k_i(t)] / [maximum\ k_i(t) - minimum\ k_i(t)] \tag{2}$$

$$N_i(t) = [maximum\ k_i(t) - k_i(t)] / [maximum\ y_i(t) - minimum\ k_i(t)] \tag{3}$$

where $N_i(t)$ represented a normalised value and is the highest and lowest value for the response, indicates the control parameters; wood ash (wt%), sliding velocity, and normal load, represent the response variables (tensile strength, hardness, impact energy, and specific wear rate), and *t* indicates the Taguchi experiment number varying from *i* = 1 to 16.

Table 1 Selected control factors and their level

Level	*Sliding (m/s)*	*Velocity*	*Wood (wt%)*	*Ash*	*Content*	*Normal load (N)*
I	2		0			15
II	3		2			20
III	4		4			25
IV	5		6			30

Table 2 Taguchi L_{16} design for sliding wear

Tests	*Sliding (m/s)*	*Velocity*	*Wood ash content (wt.%)*	*Normal load (N)*
1	2		0	15
2	2		2	20
3	2		4	25
4	2		6	30
5	3		0	20
6	3		2	15
7	3		4	30
8	3		6	25
9	4		0	25
10	4		2	30
11	4		4	15
12	4		6	20
13	5		0	30
14	5		2	25
15	5		4	20
16	5		6	15

Here $N_i(t)$ is the value after the GRG, and the ideal sequence is $N_0(t)$. The GRG attained the relational degree between $N_i(t)$ and $N_0(t)$. Moreover, the grey relational coefficient can be evaluated by using equation (4).

$$GRC_i(t) = \left[\mu_{minimium+\beta\times}\mu_{maximum}\right] / \left[\mu_{0i}(r) + \alpha \times \mu_{maximum}\right] \tag{4}$$

where μ_{0i} represents the difference between absolute values of $N_0(t)$ and $N_i(t)$, they are evaluated by equation (5). *GRC* represents the grey relational coefficient. μ_{minimum} and μ_{maximum} indicate the minimum and maximum values of the absolute differences.

β – value ranges from 0 to 1, and to have better results, and several researchers used β to be 0.5.

$$\mu_{0i} = \left| N_0(t) - N_i(t) \right| \tag{5}$$

By averaging the values of the grey relational coefficient corresponding to each output characteristic after evaluating *GRC*, the *GRG* can be determined. The higher the grey relational rating, the better the output for given control factors, it can be expressed as equation (6).

$$GRG_i = 1 \Big/ \sum_{t=1}^{t} GRC_{i(t)} \tag{6}$$

GRG_i represents the grey relation grade for the i^{th} experiments, and n indicates the number of performance characteristics.

The Taguchi method is used to convert the value of *GRG* into signal-to-noise ratios. A higher *GRG* value characterises the optimum condition in Grey relational analysis. As a result, larger values are more important than smaller ones, and the LB characteristic is used to find the best condition [equation (7)].

$$(S/N)_{LB} = 10 \times \log\left(1/n \right)\left(\sum 1/y^2 \right) \tag{7}$$

S/N = signal to noise ratio, *n* = number of observations, and *y* = observed data (*GRG*).

5 Result and discussion

5.1 Mechanical properties of wood ash-based banana/walnut epoxy composites

The figure depicts the effect of wood ash on banana/walnut epoxy composites. The tensile strength of fabricated composites depends on the filler content and increases linearly with an increase in the weight percentage of wood ash (Figure 4). As wood ash content is added to composites, the average tensile strength rises from 72.62 MPa to 81.42 MPa for 0 wt% to 6 wt%. The tensile strength of wood ash-based banana/walnut composites is approximately 10% higher than the tensile strength of banana/walnut epoxy composites at 6 wt%. This improvement may be attributed to the excellent adhesion between the reinforcement (banana/walnut/wood ash) and matrix, which allows for more excellent load-bearing and stress transfer (Kumar et al., 2020).

Similarly, gradual increases in hardness behaviour have been observed with increasing wood ash content, as shown in Figure 4. The findings showed that banana/walnut epoxy composites containing 6 wt% wood ash had superior hardness (51.7 H_v), which was 13% higher than unfilled banana/walnut composites. The increase in hardness can be due to the addition of reinforcement contents, which can resist indenter penetration into the composite surface 29. Secondly, wood ash has constituents of C_aO and S_iO_2, which is attaining an affinity of improving composites' abrasive and hardness behaviour. The reason is responsible for raising the hardness performance by adding wood ash in fabricated composites (Sanusi et al., 2013).

Figure 4 Variation of tensile strength and hardness with wood ash content (wt%) (see online version for colours)

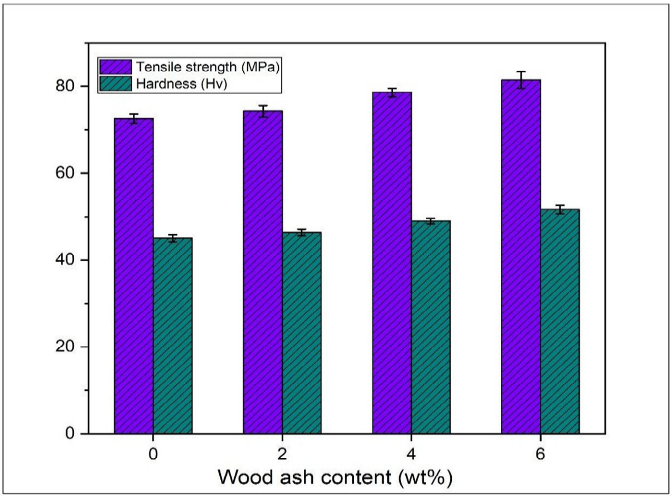


Figure 5 Variation of impact energy with wood ash content (wt%) (see online version for colours)

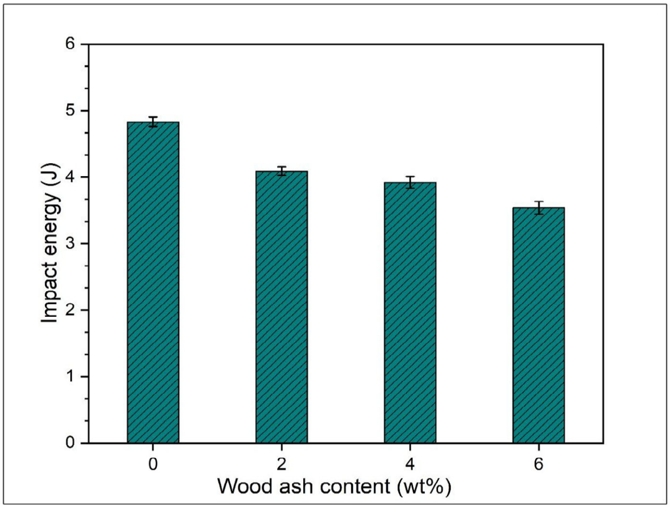


Figure 5 depicts the Charpy V notch test, which calculates the impact energy absorbed by fabricated composites. The impact energy of composites has marginally deteriorated, and this deterioration may be due to the presence of wood ash fillers, which limited the deformability behaviour of the matrix constituent; Bledzki and Jaszkiewicz (2010) offer a similar explanation for this deterioration. The random inclination of the filler contents is also responsible for reducing the toughness ability of the fabricated composites. Figure 4 shows the experimental results of composites versus impact energy, revealing that the impact energy obtained varies from 4.83 J to 3.54 J for banana/walnut composites containing 0 wt% to 6 wt% wood ash. However, when comparing unfilled banana/walnut epoxy composites to wood ash (6 wt%), filled composites impact energy degradation is approximately 18%. This performance can be attained to the influence of wood ash on the molecular flexibility of the thermosets and a vital role played by molecular flexibility in determining the comparative toughness of the material. This means that the impact produced brittle failure due to unable to respond to the sudden application of mechanical stress. Further, the lesser epoxy quantity increases the wood ash content to the detected brittle fracture with lesser impact energy (Sanusi et al., 2013).

5.2 Grey relational analysis

Three input variables, namely sliding velocity, wood ash content, and normal load, are used in this study, and four output responses are obtained. As a result, 16 ($i = 16$) experiments on composite specimens are carried out, as shown in Table 2. The outcomes of the Grey relational approach are standardised in the varying range of 0 to 1. However, it is noted that the smaller the values for individual wear rate in column 1 of Table 3 are, the better, so the SB characteristic is used. Other performance responses such as tensile strength, stiffness, and impact energy are also based on LB characteristics (columns 2–4, Table 3). Equations (2) and (3) are used to measure targeted values while normalising output response results. Table 4 shows the normalised values of the answers. After that, equation (4) calculates the grey relational coefficient for very output responses. The average value of *GRC* determines the overall GRG [equation (6)] for each answer, and finally, ranking is determined by a higher value of *GRG*. The *GRG* is then converted into *S/N* ratios using equation (7), as shown in Table 5, and the effects of control factors are depicted in Figure 6. The optimal parameter settings and maximum overall *GRG* was found to be the factor combination of control variables, sliding velocity-II, wood ash content-I, and standard load-III.

Table 3 Evaluated results for specific wear rate and mechanical properties

Tests	*SWR × 1 – 08 (mm^3/Nm)*	*Tensile strength (MPa)*	*Hardness (H_v)*	*Impact energy (Joule)*
1	5.49	72.62	45.12	4.83
2	4.99	74.31	47.02	4.10
3	3.35	78.64	49.31	3.92
4	4.45	81.42	51.70	3.54
5	4.93	72.62	45.12	4.83
6	3.09	74.31	47.02	4.10
7	2.76	78.64	49.31	3.92
8	4.53	81.42	51.70	3.54
9	5.62	72.62	45.12	4.83
10	3.84	74.31	47.02	4.10
11	4.06	78.64	49.31	3.92
12	2.92	81.42	51.70	3.54
13	4.74	72.62	45.12	4.83
14	2.86	74.31	47.02	4.10
15	3.12	78.64	49.31	3.92
16	3.44	81.42	51.7	3.54

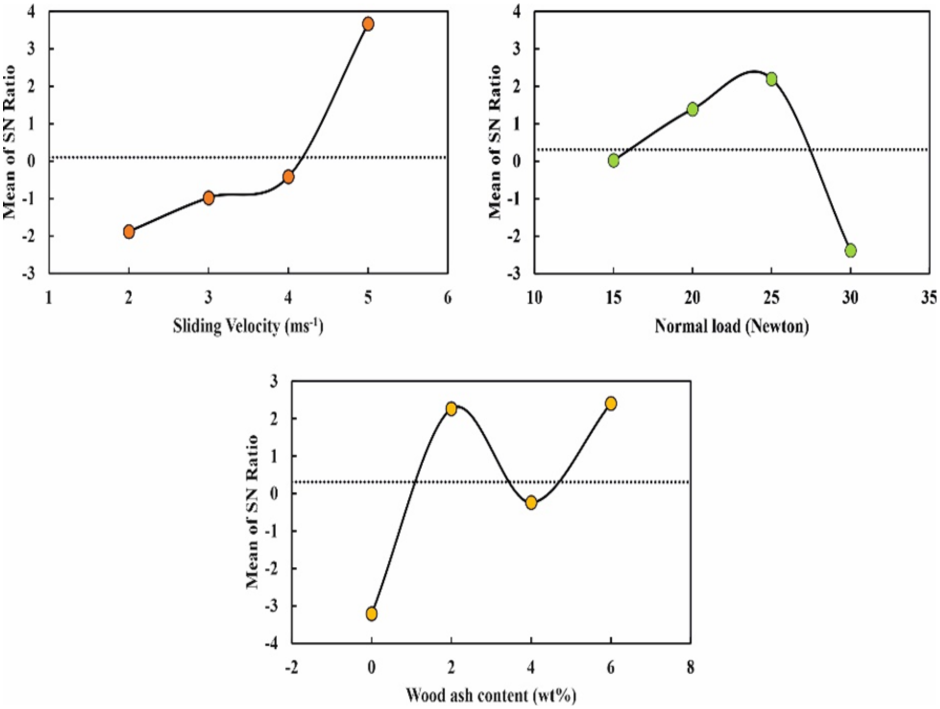
Table 4 Normalised data for output responses

	Tests normalised data			
	SWR	*Tensile strength*	*Hardness*	*Impact energy*
1	0.045455	0	0	1
2	0.22028	0.192045	0.288754	0.434109
3	0.793706	0.684091	0.636778	0.294574
4	0.409091	1	1	0
5	0.241259	0	0	1
6	0.884615	0.192045	0.288754	0.434109
7	1	0.684091	0.636778	0.294574
8	0.381119	1	1	0
9	0	0	0	1
10	0.622378	0.192045	0.288754	0.434109
11	0.545455	0.684091	0.636778	0.294574
12	0.944056	1	1	0
13	0.307692	0	0	1
14	0.965035	0.192045	0.288754	0.434109
15	0.874126	0.684091	0.636778	0.294574
16	0.762238	1	1	0

Table 5 Grey relational coefficient and GRG with *S/N* ratios

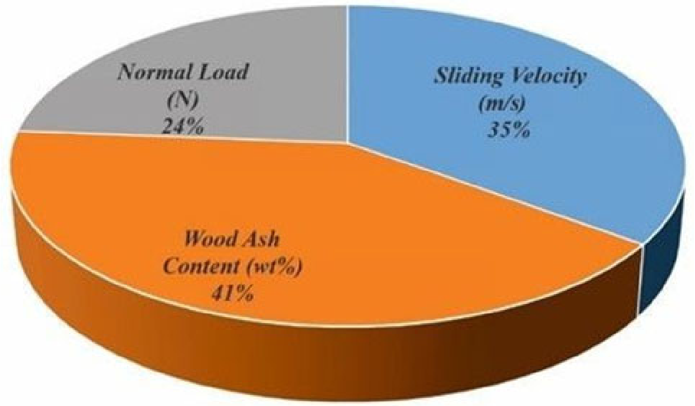
	Tests		*GRC*		*GRG*	*S/N ratios*
	SWR	*Tensile strength*	*Hardness*	*Impact energy*		
1	1.023	0.333	0.333	1	0.672	–3.4526
2	1.141	0.382	0.412	0.469	0.601	–4.4225
3	2.923	0.612	0.579	0.414	1.132	1.0769
4	1.346	1	1	0.333	0.919	–0.7337
5	1.158	0.333	0.333	1	0.706	–3.0239
6	4.833	0.382	0.412	0.469	1.524	3.6597
7	1	0.612	0.579	0.414	0.651	–3.7284
8	1.307	1	1	0.333	0.910	–0.8192
9	1	0.333	0.333	1	0.666	–3.5305
10	1.824	0.382	0.412	0.469	0.772	–2.2477
11	1.6	0.612	0.579	0.414	0.801	–1.9273
12	9.437	1	1	0.333	4.016	9.3729
13	1.222	0.333	0.333	1	0.722	–2.8293
14	14.8	0.382	0.412	0.469	2.942	12.0759
15	4.472	0.612	0.579	0.414	1.519	3.6312
16	2.602	1	1	0.333	1.234	1.8263

Figure 6 Main effect plot (*GRG*) for wood ash-based banana/walnut epoxy composites (see online version for colours)



Moreover, ANOVA is conducted on *GRG* to identify the significance of each control factor on *GRG*. The percentage of contribution of each selected parameter on output response is indicated in Figure 7. It is evident from the result; the contribution of wood ash content (41%) having 1st rank, sliding velocity (35%) having 2nd rank, and normal load (24%) attaining 3rd rank.

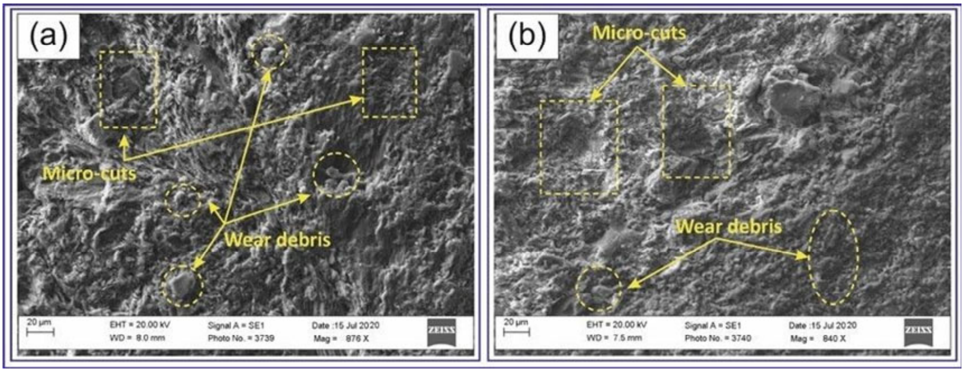
Figure 7 Contribution of control factors on the specific wear rate of wood ash-based banana/walnut epoxy composites (see online version for colours)



6 Surface morphology of wood ash-based banana/walnut epoxy composites

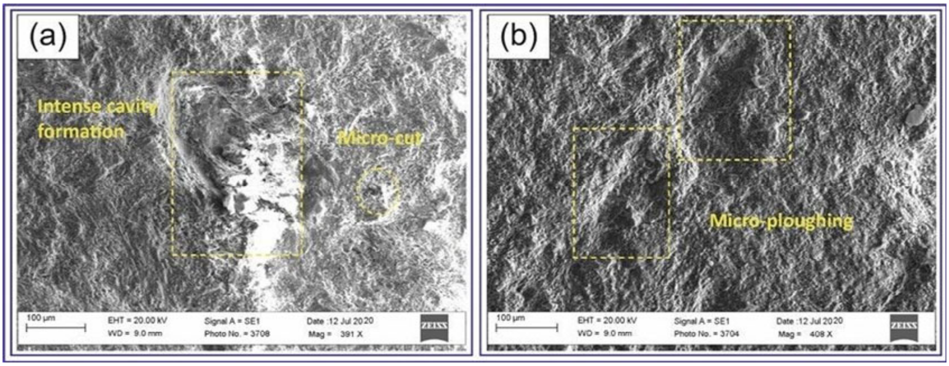
The evaluated results are obtained from the dry sliding wear test are shown in Table 3, column1. These results are supported by scanning electron microscopic (SEM) images of worn surfaces of specimens at different sliding velocity conditions for observing the predominant wear mechanism. Three primary mechanisms occur during material removal in the sliding wear test, i.e., micro-cutting, ploughing, and cracking. SEM images of banana/walnut composites with varying weight percent of wood ash content (0 wt%–6wt%) at 2 m/s to 5 m/s (sliding velocity) is discussed in this observation. Wood ash content with 0 wt%, sliding velocity 2 m/s, and normal load 20 N (see Table 3, expt. no. 1), micro-cracks, wear debris, and micro ploughing are noticeably seen on micrograph [Figure 8(a)]. Further, increased the weight percentage of wood ash content from 0 wt% to 6 wt% with the same (2 m/s) sliding velocity (see Table 3, exp. no. 4), the less wear debris and micro-cuts are detected over the worn surface of wood ash content filled banana/walnut epoxy composite [Figure 8(b)]. Moreover, compared to the specific wear rate of composites with lower (0 wt%) and higher (6 wt%) wood ash content, the specimen with 6 wt% wood ash content is occurring lower wear rate 18.90% lesser than 0 wt% wood ash content.

Figure 8 SEM micrograph of wood ash-based banana/walnut epoxy composites for (a) 0 wt% and (b) 6 wt% wood ash at 2 m/s sliding velocity (see online version for colours)



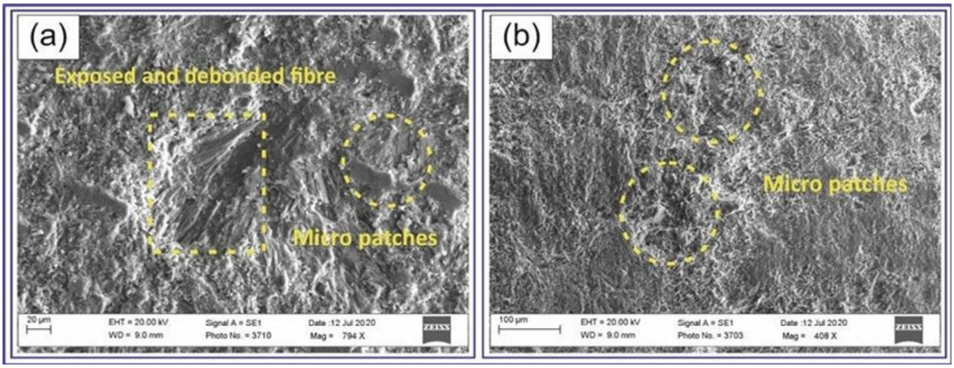
It can also be understood that the optimum wear result is obtained at 4wt% wood ash content for 2 m/s sliding velocity (3.35×10^{-8} mm^3/N-m). This deterioration in wear rate is due to better wood ash/banana-epoxy interfacial bonding strength, enhancing the resistance offered by fabricated composite against sliding harm. Further, increase the sliding velocity to 4 m/s. The reinforcement and matrix interfacial bonding occur in composites, leading to widespread filler pulverisation, resulting in higher heat accumulated along the interfacial contact surface (see Table 3, exp. no. 9). This leads to micro-cracks, micro-cuttings, and micro-ploughing detected on the composites' worn surface. The removal of the matrix is more in 0 wt% wood ash banana/walnut composites [Figure 9(a)] as compared to 6 wt% wood ash-based composites [Figure 9(b)] at 4 m/s of sliding velocity, for a maximum sliding velocity (5 m/s) for 0 wt% and 6 wt% composites (see Table 3, exp. nos. 13, 16), the number of cracks and patches are detected overworn surfaces.

Figure 9 SEM micrograph of wood ash-based banana/walnut epoxy composites for (a) 0 wt% and (b) 6 wt% wood ash at 4 m/s sliding velocity (see online version for colours)



A composite reinforcing with wood ash (6 wt%) is attaining fewer cracks and patches, and this leads to a lower specific wear rate as compared to unfilled wood ash composites [Figures 10(a) and 10(b)]. Kumar et al. (2019) presented a similar finding, where the specific wear rate of composites is evaluated using rice husk as filler content, and bauhinia vahlli is used as reinforcing fibre. They observed that the specific wear rate of composites is decreased with increases in the filler content in epoxy composites.

Figure 10 SEM micrograph of wood ash-based banana/walnut epoxy composites for (a) 0 wt% and (b) 6 wt% wood ash at 5 m/s sliding velocity (see online version for colours)



7 Conclusions

This paper attempts to use the Grey-Taguchi method to study the multi-response behaviour of wood ash-based banana/walnut composites. From the analysis following conclusion can be drawn:

- Wood ash has emerged as possible filler reinforcement in natural fibre epoxy composites. This study demonstrates that hand lay-up can successfully fabricate natural fibre-reinforced composites (using wood ash, banana, and walnut as reinforcing constituents and epoxy as the matrix material).

- The tensile strength and hardness of wood ash-based banana/walnut composites are approximately 10% and 13% higher than unfilled banana/walnut composites. Wood ash has constituents of C_aO and S_iO_2, which is attaining an affinity of improving composites' abrasive and hardness behaviour.
- The Grey-Taguchi method successfully converts the multiple response output into a single response GRG, and it is observed that at a higher *GRG* (4.016), the optimum parameter settings are sliding velocity (4 m/s), wood ash content (6 wt%), and normal load (2 N). The following order of effect of selected parameters on composite wear properties is observed: wood ash content (41%) > sliding velocity (35%) > normal load (24%).
- Wear debris, micro-cracks, micro-ploughing, and patches on the worn surfaces of wood ash-based banana/walnut reinforced epoxy composites were also revealed using SEM analysis.

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