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Optimizing Green Composites for Automotive Applications Using Taguchi-Based Grey Relational Analysis

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Abstract

The increasing demand for sustainable and lightweight materials in the automotive industry has driven the exploration of green composites as an alternative to conventional synthetic composites. This study focuses on optimizing the mechanical properties of green composites using Taguchi-based Grey Relational Analysis. Four natural fibers—pineapple, sisal, coir, and Nava—were reinforced with cashew resin and synthetic resin matrices, incorporating silica and granite fillers of varying sizes. Key properties, including hardness, impact strength, water absorption, and density were evaluated. The results revealed that Nava fiber with synthetic resin demonstrated superior hardness (HRA 74) and impact strength (137 KJ/m²), while sisal fiber with cashew resin exhibited the highest impact strength (152 KJ/m²). Water absorption was lowest in pineapple fiber with synthetic resin (1.76%), and Nava fiber composites exhibited lower moisture uptake compared to other fiber types. Density analysis indicated that cashew resin composites with smaller filler sizes showed higher densities, with coconut fiber with cashew resin achieving the maximum density. Taguchi-based Grey Relational Analysis was employed to identify optimal parameter combinations, balancing mechanical performance and sustainability. The findings underscore the potential of Nava and sisal fiber composites for specific automotive applications, such as dashboards and exterior body panels, while highlighting the need for improved moisture resistance in cashew resin composites. This study provides insights into the development of eco-friendly materials with competitive mechanical properties, aligning with the automotive industry's goals of weight reduction and environmental sustainability.

Keywords: Green composites, Natural fibers, Cashew resin, Sample fabrication, Taguchi based GRA

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INTRODUCTION

Green composites, composed of natural fibers and bio-based resins, are gaining traction as sustainable materials due to their renewability, biodegradability, and lightweight properties. These materials aim to reduce environmental impacts by replacing non-renewable resources in industries like automotive, construction, and consumer goods in the automotive sector, the use of natural fiber composites, such as those reinforced with hemp, sisal, or coir, has proven effective in reducing vehicle weight by 20–50%, thereby improving fuel efficiency and lowering CO_2 emissions. These composites are cost-effective and ideal for interior automotive parts such as dashboards, door panels, and seat backs, contributing to both performance and sustainability goals.

Natural fibers, including sisal, coir, pineapple leaf fiber (PALF), and Nava fiber, are widely utilized in green composites due to their abundance, low density, and favorable mechanical properties. Sisal offers high mechanical strength, coir provides impact resistance due to its lignin content, PALF is valued for its tensile strength and thermal stability, and Nava fiber exhibits unique interlocking properties with resins [1, 2, 3]. These fibers are often combined with matrix materials like cashew resin or synthetic resins, the latter improving water resistance and durability [3, 4]. Fabrication methods, ranging from hand layup to advanced techniques like resin transfer molding, influence the composites' properties and determine their suitability for specific applications [1].

Natural fiber composites (NFCs) have gained significant attention in recent years due to their environmental benefits, mechanical properties, and wide-ranging applications. These materials, composed of natural fibers embedded in a polymer matrix, serve as a sustainable alternative to conventional synthetic composites. The mechanical properties of NFCs, such as tensile strength, impact resistance, and thermal stability, largely depend on fiber type, orientation, and polymer matrix [5]. Chemical treatments, such as alkali treatment and silane coupling, are commonly employed to enhance fiber-matrix adhesion, leading to improved composite performance [6]. Furthermore, hybridization with synthetic fibers can improve impact resistance and overall mechanical properties [7]. Various processing techniques, including compression molding, injection molding, and resin transfer molding, influence fiber dispersion, matrix compatibility, and cost-effectiveness [8]. The characterization of NFCs involves assessing mechanical, thermal, and morphological properties using methods such as scanning electron microscopy (SEM) and dynamic mechanical analysis (DMA) [9].

NFCs have found applications in multiple industries, notably in the automotive sector, where they offer a lightweight, durable, and cost-effective alternative to traditional composites [10]. Green composites are increasingly being integrated into vehicle interior panels, dashboards, and structural reinforcements due to their sustainability and enhanced performance [11]. Additionally, the use of biomass-derived materials in mid-size automotive industries has been explored for further sustainable advancements [12]. The demand for NFCs is expected to grow, driven by sustainability goals and advancements in fiber treatment and composite processing. Research continues to focus on improving durability, biodegradability, and multi-functionality to expand NFC applications in various sectors [5]. As the automotive and construction industries increasingly adopt eco-friendly materials, NFCs are poised to become a cornerstone of sustainable engineering. Ongoing research and innovation in fiber modification and composite manufacturing will further enhance their mechanical performance and applicability.

Norhidayah M.H [10] highlighted recent developments in the automobile industry but omitted details on natural resin applications. Koichi Goda [13] discussed advancements, challenges, and opportunities in bio-composites but overlooked required applications for material replacement. B.C. Mitra [14] detailed bio-composites' advantages and disadvantages but failed to address laying methods or natural resin types. Naguib H.M [15] utilized unsaturated polyester resin filled with bagasse agricultural waste but used synthetic resin and short fibers instead of long fibers. Satyanarayana K.G [16] developed sustainable green composites but did not fabricate samples. Elkington M et al [17] studied hand layup techniques but did not specify methods for natural fiber arrangement.

Dunne R. et al [18] investigated annual natural fiber production and identified some mechanical properties but did not test composites or provide detailed explanations. Torres J.P. et al [19] analyzed

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fiber samples and arrangements but lacked details on fiber filler and resin percentage verification. Nallusamy S. et al [20] identified natural fibers' stability and automotive applications but did not include comprehensive testing. Ramli N. et al [1] clarified mechanical properties for vehicle interior designs but omitted material specifics for natural fibers.

Siakeng R. et al [21] studied the thermal properties of coconut and pineapple fibers but did not include sisal or other fibers. M.O. Njoku et al [22] clarified mechanical testing for composite materials but did not specify natural fiber composites. Negara D.W [23] evaluated water absorption and mechanical properties of composite materials using synthetic resins but excluded natural resin matrices. Saba N. et al [24] performed mechanical and physical tests but did not focus on natural composite materials. Naveen J. et al [25] measured the density of pineapple, sisal, and coconut sheath fibers but did not include coconut fiber density.

Vijayakumar S. [2] introduced caryota fiber from fishtail palm but focused on chopped fibers, excluding continuous fibers. Arrohman S. [26] evaluated coconut fiber composites with varying fiber ratios but did not investigate the addition of fillers. Ibrahim M.M [27] discussed the mechanical, morphological, and chemical properties of gelatinized starch and Nile rose fiber composites but did not focus on the automobile sector. J. Joy Mathavan and Amar Patnaik [28] developed equations for mechanical testing and density calculations but did not evaluate natural fibers.

Preparation of Composites

The preparation of composites involved the systematic selection, extraction, and fabrication of natural fibers, including pineapple, coir, sisal, and Nava, reinforced with cashew resin and synthetic resin matrices. Fiber selection was based on strength, durability, and stress resistance, while water retting was chosen for extraction due to its eco-friendliness and ability to preserve fiber properties. Nava fibers were extracted from barks, coconut fibers from husks, and pineapple and sisal fibers from leaves. All fibers underwent manual processing to remove non-fibrous materials, followed by cleaning and drying to ensure quality. Granite and sand fillers were prepared by sieving into micro-sized particles (106–425 µm) to optimize their integration into the composites.

The composites were fabricated using the hand layup method, where fibers, resins, and fillers were layered sequentially with mold release wax to prevent adhesion to the mold. Rollers were used to ensure uniform resin distribution and eliminate air bubbles. The samples were cured under load for 24 hours and then exposed to sunlight for 3–4 days. Weight ratios of fibers, resins, and fillers were varied to study the effect of composition on mechanical properties. Additionally, cashew resin composites underwent surface modification with a synthetic resin coating to mitigate hydrophilic behavior and improve resistance to moisture and environmental degradation. This methodical approach ensured the production of high-quality composite samples as shown in Figure 1 and Figure 2 for further mechanical, physical, and chemical testing.


Figure 1. Nava fiber with cashew resin samples.

Figure 2. Nava fiber with synthetic resin samples.

Testing Procedure of Samples

The test procedure of samples was conducted by preparing sample based on the kind of test to be conducted. In here base samples were cut standard sizes according to ASTM standard. The mechanical, physical and chemical tests conducted in this study. According to that impact test, hardness test, water absorption test, chemical test and density analysis was performed. There are some machines used to testing.

Rockwell Hardness Test (HRA)

Hardness of the material is ability of a material to resist deformation and its measured in standard test where the surface resistance to indentation and it determined by measuring the permeant depth of the indentation. In this experiment used to test Rockwell hardness testers for test hardness. The Rockwell hardness test method known as ASTM - E - 18. It's more simply put on the specimen holder and using a fixed load for the specimen. The principle of the Rockwell hardness test is loaded the standard load on the specimen with in standard time duration with standard indenter. Then can obtain the hardness number directly. The result can obtain in (Kgf). For this experiment ball indenter and size 1/16" was used. The applied load on the specimen was 60 Kgf. The specimen size was 55 mm × 20 mm and thickness around 3 mm and tested specimens were no any deformation.

Charpy Impact Test

One of the most important factors of the behavior of polymeric composites is their response to the impact load and the dimensions of the composites to resist it through their service life. The Charpy impact test is used to decide the toughness or impact strength of the material in the presence of a flaw. There are two types of impact tests are performed by most researchers. Impact tests were carried out according to ASTM D6110. The dimensions of the samples were 55 mm × 20 mm and thickness around 3mm and placed horizontally into the machine. These size samples were obtained after cutting from the base samples. Hence, each of coconut fiber base samples was used to cut another 3 samples. So overall, impact test was done for 18 of CF with SR samples. Impact tests were carried out on the Charpy impact test machine. Impact samples are shown in Figure 3 and Figure 4.

Water Absorption Test

This experiment tests to assess the water absorption behavior of composites. As shown in Figure 5, water absorption (WA) test was carried out according to water immersion technique by following ASTM D 570-98 standards where the size of 150 mm × 20 mm and thickness 3 mm were used for water absorption test. Samples were weighted and results were recorded for dry samples. Then these samples were placed in a container of distilled water, maintained at room temperature and then were removed from the water at the same time after 24 h. The surface water was wiped off with a dry cloth and the wet samples were weighted quickly.

Figure 3. NF+SR Samples

Figure 4. CF+SR samples.

Figure 5. Water Absorption Test.

Table 1. Control Process parameters.

Parameters	Designation	Levels of factors		
		1	2	3
Filler Percentage	A	5	10	15
Fiber Type	B	Nava	Coconut	Sisal
Filler Type	C	Granite	Sand	Silica Dust
Resin Type	D	Synthetic	Cashew	
Filler Size (μm)	E	100	200	400

Table 2. L_{18} Design matrix and Experimental results of Green Composites.

Exp. No.	A	B	C	D	E	Hardness (HRA)	Impact Strength (KJ/m²)	Water Absorption (%)	Density (Kg/m³)
1	1	1	1	1	1	74	137	1.5	1.3
2	1	1	2	2	2	68	91	3.1	1.35
3	1	1	3	3	3	72	110	1.76	1.32
4	1	2	1	1	2	67	88	3.5	1.4
5	1	2	2	2	3	60	105	2.5	1.25
6	1	2	3	3	1	58	84	3.7	1.3
7	1	3	1	2	1	62	102	2.8	1.28
8	1	3	2	3	2	59	80	3.9	1.35
9	1	3	3	1	3	66	152	1.9	1.15
10	2	1	1	3	3	64	100	3.4	1.3
11	2	1	2	1	1	65	140	2.2	1.2
12	2	1	3	2	2	62	85	3.6	1.33
13	2	2	1	2	3	66	120	1.8	1.1
14	2	2	2	3	1	60	98	3.3	1.25
15	2	2	3	1	2	65	125	2.1	1.3
16	2	3	1	3	2	61	87	3.7	1.34
17	2	3	2	1	3	74	140	1.6	1.3
18	2	3	3	2	1	60	95	3.4	1.25

DESIGN OF EXPERIMENTS

To obtain a good performance from the composite, it is necessary to have a good fiber distribution within the resin. A good distribution means that the fibers are completely separated from each other, and each fiber is fully surrounded by the resin as shown in Table 1. Insufficient fiber dispersion can lead to mixture of resin-rich and fiber rich areas. This area, as the resin rich areas are weak, while the fiber rich areas have tendency to micro cracking. Therefore, it is essential to ensure a homogeneous fiber distribution in order to achieve maximum strength and performance of the composite material. According to this research, to get correct idea and identify properties of newly fabricated green composites, another factor which needs to be considered is weight ratio of the fiber, resin and filler materials. This can obtain good properties as shown in Table 2 by using suitable quantity of materials. Mainly fiber resin ratio affects and change the properties of samples. So, weight of each material is measured which are used for fabrication. Figure 6 shows the cause and effect diagram.

RESULTS AND DISCUSSIONS

Data Pre-processing or Normalization of Experimental Results

In GRA, Data pre-processing is very much essential required especially when there is too much scattering in sequence range. It is a process by which shifting the original sequence to an equivalent sequence. The significant objective of the current investigation was to enhance the performance characteristics of the Green composites. Therefore, the "larger-the-better" characteristic has been chosen for experimental data pre-processing, which can be done as follows:

$$X_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (1)$$

Where, $X_i^*(k)$ and $x_i(k)$ are the data after normalization and the experimental data respectively for i^{th} number of experiment and $k^{th}$the response. The normalization of experimental results are as represented in Table 3.

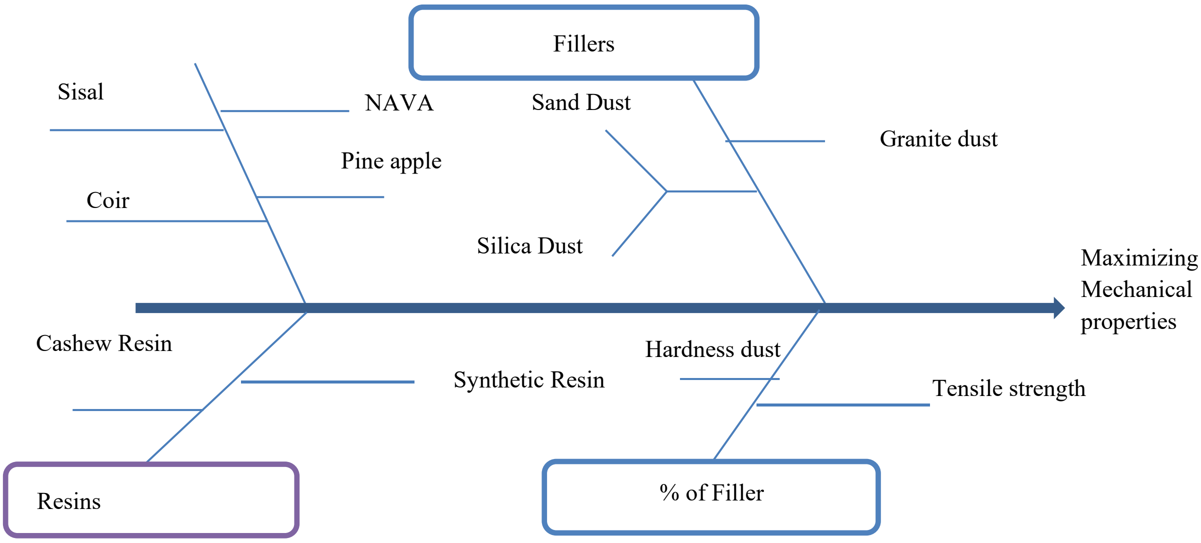

Figure 6. Cause and Effect Diagram.

Table 3. Normalization of the experimental results.

S. No	Hardness	Impact Strength	Water Absorption	Density
1	1.000	0.792	0.000	0.667
2	0.625	0.153	0.667	0.833
3	0.875	0.417	0.108	0.733
4	0.563	0.111	0.833	1.000
5	0.125	0.347	0.417	0.500
6	0.000	0.056	0.917	0.667
7	0.250	0.306	0.542	0.600
8	0.063	0.000	1.000	0.833
9	0.500	1.000	0.167	0.167
10	0.375	0.278	0.792	0.667
11	0.438	0.833	0.292	0.333
12	0.250	0.069	0.875	0.767
13	0.500	0.556	0.125	0.000
14	0.125	0.250	0.750	0.500
15	0.438	0.625	0.250	0.667
16	0.188	0.097	0.917	0.800
17	1.000	0.833	0.042	0.667
18	0.125	0.208	0.792	0.500

Effect of GRG on Multi-performance Characteristics of the Green Composites Alloy
Now, $\Delta_{0i}(k)$ is the deviation sequence value of $X_0^*(k)$ and $X_i^*(k)$, that is

$$\Delta_{oi}(k) = |X_0^*(k) - X_i^*(k)| \tag{2}$$

Grey relational coefficient can be measured with the deviation sequence and expresses the relationship between the ideal and actual normalized experimental results, which can be determined by the following formula:

$$\xi_i(k) = \frac{\Delta_{\min}+\zeta\,\Delta_{\max}}{\Delta_{oi}(k)+\zeta\,\Delta_{\max}} \tag{3}$$

$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k)$Where, ζ is distinguishing coefficient, is considered as 0.5 for all the parameters of equal preference. Next, the Grey relational grade(γ) is calculated by the mean value of the grey relational coefficient of each response.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{4}$$

Where, $\gamma_i$is the GRG for thei^{th} experiment number and n is the response characteristic number
The grey relational coefficients and GRG values are depicted in Table 4.

Where, ζ is distinguishing coefficient, is considered as 0.5 for all the parameters of equal preference. Next, the Grey relational grade(γ) is calculated by the mean value of the grey relational coefficient of each response.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{5}$$

Where, $\gamma_i$is the GRG for thei^{th} experiment number and n is the response characteristic number.
The grey relational coefficients and GRG values are depicted in Table 5.

Table 4. Grey relational and Grey relational grade of the experimental results.

Expt. No.	Grey relational coefficients				GRG	Rank
	Hardness	Impact Strength	Water Absorption	Density		
1	1.0000	0.7059	0.3333	0.6000	0.6598	3
2	0.5714	0.3711	0.6000	0.7500	0.5731	6
3	0.8000	0.4615	0.3593	0.6522	0.5682	7
4	0.5333	0.3600	0.7500	1.0000	0.6608	2
5	0.3636	0.4337	0.4615	0.5000	0.4397	17
6	0.3333	0.3462	0.8571	0.6000	0.5342	11
7	0.4000	0.4186	0.5217	0.5556	0.4740	16
8	0.3478	0.3333	1.0000	0.7500	0.6078	4
9	0.5000	1.0000	0.3750	0.3750	0.5625	8
10	0.4444	0.4091	0.7059	0.6000	0.5399	10
11	0.4706	0.7500	0.4138	0.4286	0.5157	12
12	0.4000	0.3495	0.8000	0.6818	0.5578	9
13	0.5000	0.5294	0.3636	0.3333	0.4316	**18**
14	0.3636	0.4000	0.6667	0.5000	0.4826	15
15	0.4706	0.5714	0.4000	0.6000	0.5105	13
16	0.3810	0.3564	0.8571	0.7143	0.5772	5
17	1.0000	0.7500	0.3429	0.6000	0.6732	**1**
18	0.3636	0.3871	0.7059	0.5000	0.4892	14

In essence, the larger the GRG represents the product quality nearer to the ideal value and it is desired for optimum quality of composites. The complete assessment of mechanical properties is based on the GRG. It was observed that the seventeenth number experiment i.e. Synthetic- 5 (wt.%) and Cashew- 10 (Wt.%) has the best multi-performance characteristics among eighteen experiments because it has the highest GRG value 0.6732. The process parameter optimum level was the level at which highest GRG is obtained. The main effect i.e. difference between the maximum and the minimum values, which describe the significance of process parameters on the multi-performance characteristics as shown in Table 5. The maximum main effect value from the results indicated that the pouring temperature is the most influential parameter among the other process parameters.

3.3 Analysis of Variance (ANOVA) of Experimental Results

Analysis of Variance (ANOVA) was performed using statistical software MINITAB 17 on grey relational grade values to evaluate the influence of process parameters on multi-performance characteristics as shown in Table 6. ANOVA results indicate that five parameters such as Filler Percentage (A), Fiber Type (B), Filler Type (C), Resin Type (D) and Filler Size (E) are the most significant that affect the multi-performance characteristics of the Green composites (p-value< 0.95) under 95% confidence levels. The multi-performance characteristics of the Green composites are mostly influenced by resins contributing 36.28% followed by Fiber type- 14.69%, Filler size- 11.87%, and Filler Percentage- 5.78% as depicted in Figure 6, whereas, the percentage of filler addition to resins have a less significant contribution to the performance characteristics.

3.4 Effect of Process Parameters on Performance Characteristics

The hardness range in Nava fiber with synthetic and cashew resin is obtained from Rockwell Hardness - A Test value (HRA) 65 to HRA 75 and Nava fiber with cashew resin range is from HRA 56 to HRA 68. In the case of Nava fiber with cashew resin, most of the specimens with the addition of filler particle show the good hardness properties than the non-filler added specimen. It can be observed that along with the increase of the size of the filler, the hardness values are decreasing. Then it can be said that, Nava fiber with cashew resin can accommodate filler for improving hardness.

Table 5. Mean Responses for Overall Grey Relational Grade.

Designation	Process parameters	GRG			Main effect (Max-Min)	Rank
		Level 1	*Level 2*	*Level 3*		
A	Filler Percentage	*0.5691	0.5099	0.564	0.0336	4
B	Fiber Type	*0.5572	0.5487	0.5371	0.0592	2
C	Filler Type	*0.5971	0.4942	0.5516	0.0201	5
D	Resin Type	*0.5645	0.5309		0.1029	1
E	Filler Size (µm)	0.5259	*0.5812	0.5359	0.0553	3
Total mean value of the GRG = 0.5476						
* Optimum levels for GRG						

Table 6. ANOVA of experimental results.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage contribution
Filler Percentage	1	0.005084	0.005084	1.54	0.249	5.78%
Fiber Type	2	0.012911	0.006455	1.96	0.203	14.69%
Filler Type	2	0.001227	0.000614	0.19	0.834	1.40%
Resin Type	2	0.031884	0.015942	4.84	0.042	36.28%
Filler Size (µm)	2	0.010433	0.005217	1.58	0.263	11.87%
Error	8	0.026346	0.003293			
Total	17	0.087885				

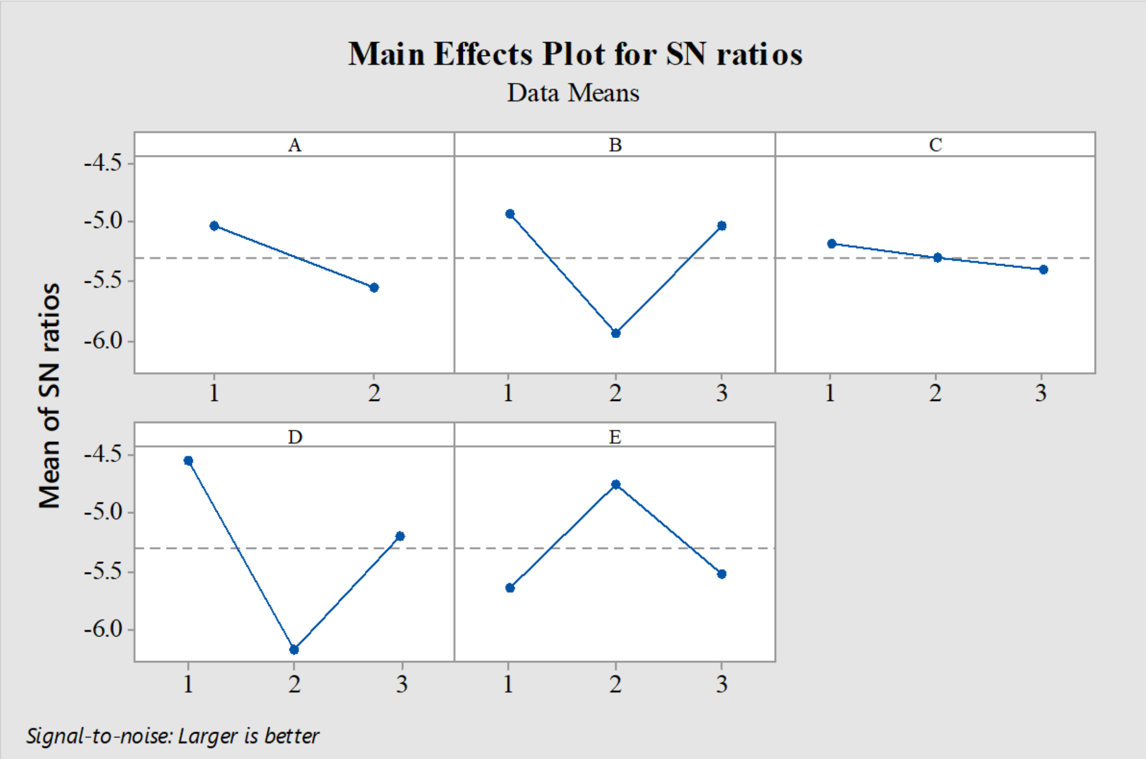

Figure 7. S/N ratio of the GRG for process parameters.

Hardness was fluctuated for Nava fibers with cashew resin samples on filler percentage of both sand and granite particles in the sample. But there is a general pattern of reduction in hardness value along with increase in filler percentage. Hardness of Nava fiber with synthetic resin showed a kind of uniform pattern with filler addition percentage. The maximum hardness of synthetic resin and cashew resin was obtained as HRA 74 and HRA 67 respectively.

The hardness and impact strength of the green composites performance characteristics come under the criteria of "larger the better" type characteristic. The S/N ratios of the GRG for all 18 experiments were determined by the following equation.

$$\text{S/N ratio(Larger the better)} = -10 \log \left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right] \tag{6}$$

The S/N ratio of the GRG for process parameters are shown in Figure 7.

CONCLUSIONS

Based on the analysis and experimental work following conclusions have been made:

1. Nava fiber with synthetic resin (HRA 74) and Nava fiber with cashew resin (HRA 72) demonstrated the highest hardness values, attributed to their layered fiber arrangement, which improved adhesion and strength compared to individually laid fibers. Granite filler composites exhibited better hardness than sand filler composites, while coconut fiber with cashew resin outperformed coconut fiber with synthetic resin in hardness tests. Overall, green composites showed slightly lower hardness values (HRA 72-74) compared to glass fiber-reinforced composites (HRA 82-83).
2. For impact strength, the highest values were observed in sisal fiber with cashew resin (152 KJ/m²) and Nava fiber with synthetic resin (137 KJ/m²). Synthetic resin composites generally had higher impact strength than cashew resin composites, with minimal differences between the two in sisal and pineapple fiber samples. Sand filler composites outperformed granite filler composites, and

green composites' impact strengths (80–100 KJ/m²) were nearly double those of glass fiber composites (48–55 KJ/m²).
3. Water absorption was highest in sisal fiber with 300 µm granite filler (6.2%) and lowest in pineapple fiber with synthetic resin (1.76%). Nava fiber composites absorbed less water than coconut fiber composites, and synthetic resin composites had lower water absorption than cashew resin composites. High water-absorbing materials were deemed unsuitable for exterior vehicle parts but were recommended for interior components like dashboards.
4. In terms of density, cashew resin composites with smaller filler sizes showed higher densities, with Nava fiber and cashew resin exhibiting the highest density among the fiber composites. Coconut fiber with cashew resin had the overall highest density. Despite some limitations, green composites showed comparable performance to glass fiber-reinforced polyester composites.

Declaration of Interest

We declare that there is no conflict of interest regarding the publication of this manuscript.

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