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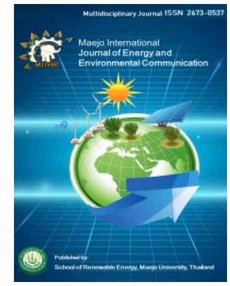

ARTICLE

Contribution of cashew nut shells as base material in the multi-response optimised automobile brake pad composites in the composition mix

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A B S T R A C T

The need to develop automobile brake pad materials from green and environmentally sustainable sources is an increasingly growing research direction. Many researchers have been working towards replacing carcinogenic asbestos with other agro-biomass reinforcements that are readily available, effective, and environmentally friendly. Therefore, Agro-waste such as Cashew Nut Shells has now emerged as a new and inexpensive material that could be used to form parts of brake pads composite matrix that are commercially viable and environmentally acceptable. This paper reports the contribution of Cashew Nut Shells (CNS) as a possible replacement of asbestos as base and reinforcement materials when utilized with other brake pads production ingredients. A total of twenty seven (27) trial composites of particle size 100 µm was generated via Taguchi Design of Experimental method and ANOVA from the optimized Grey Relational Analysis indicated that Cashew Nut Shells (CNS) has the highest significant contribution and effects on the multi-response performance of the developed brake pads composites with percentage contribution (p-value) of 27..558% while that of Granite and Plant Gum binder constituents were 25.892% and 15.479% respectfully.

1. Introduction

Brake assemblies form important parts of mechanisms activated and fitted to the wheels of vehicles, providing constant clamping or retarding forces that reduce or stop motion. The most important component of this system is the brake pad, which is a compound structure and, as such, contains fillers to enhance strength, abrasives to aid in braking, lubricants to facilitate smooth movement, and binders to hold the pad together (Abtew, 2024). In the past, the formulation of brake pads, which lasted over a century, about 117 years, relied on asbestos, metallic, and ceramic materials that were coated on one another using thermosetting synthetic resins, mostly phenol-formaldehyde or epoxy-based crimson (Bilvatej et al., 2024). But there has been increased concern over the carcinogenic risk and environmental pollution effects caused by asbestos, and there are environmental issues of the petrochemical-derived binders; therefore, there have recently been intensified attempts to find substitutes that are safer, renewable, and sustainable (Andrew & Dhakal, 2022; Sophanodorn et al., 2022).

To handle such environmental and health issues, modern research has explored the biomass and agricultural waste materials as alternatives to traditional materials (Reansuwan et al., 2024; Taechawatchananont et al., 2024; Nasution et al., 2024) for brake

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pads. These agro-based feedstocks are highly accessible and beneficial since some of their property characteristics include: biodegradability, low-cost, and use in mechanical properties (Behera et al., 2019; Chuanchai et al., 2019; Unpaprom et al., 2021). They comprise ligno-cellulosic biomass, including coconut shells, banana peels, and palm kernel shells, and calcified bio-wastes, including periwinkle shells and egg shells (Abdelgalil et al., 2024; Badamasi et al., 2024; Tikhe & Nadupuru, 2024). The fillers and reinforcement offered by these products are bio-fillers and have unique combinations of hardness, thermo resistance, and intrinsic integrity that make them potential replacements in brake pad applications.

Yawas et al. (2013) assessed the usage of periwinkle shells in the production of reinforced concrete with the binder including phenolic resin. They showed that their work exhibited mechanical and tribological characteristics close to conventional materials, and therefore, the viability of marine biomass in brake-pad applications is evident. Similar results were obtained by Bashar et al. (2012) who used ground coconut shell as a filler in an iron chip reinforced fillers and catalyzed cobalt naphthenate matrix to come up with composites having the desired frictional properties with no toxic effects whatsoever. Idris et al. (2015) were able to make brake pads using banana peels and phenol formaldehyde resin and achieved increases in hardness and compressive strength of 5-30 % at phenol-formaldehyde resin contents of 25-50 %. To reinforce the above study, Deepika et al. (2013) enhanced the brake-pad materials with palm kernel shell, cashew nut shell liquid, quartz, and carbon black since Bono and Dekyrger (2010) found that there is an improvement in brake-pad material when blended with agro-mineral fillers to form superior hybrid wear-resistant systems. This is a material innovation that has historical antecedents, which has moved away from using asbestos to molded thermoset resins, in which priority is given to a safer option instead of the toxic ones.

Lawal et al. (2019a) then focused on attaching eggshells as bio-fillers to Gum Arabic (GA), which is a natural polymer produced by plants through a chemical bond. They showed successful results that composites that were prepared with 15 up to 18 % of GA content had a good resistance to water absorption, compressive strength, and wear. The paper thereby upheld the hypothesis that the use of agricultural wastes may not only be used as reinforcement, filler or filler material but also serve as bio-based binders, thus creating a fully sustainable material system. This line of enquiry is carried further in the current study by testing Cashew Nut Shells (CNS) as a multi-purpose component, as reinforcement and biomass provider of sustainable brake pad designs. CNS is a by-product of the global cashews processing industry and comprises both lignin and a naturally occurring phenolic resin (cashew nutshell liquid, CNSL) and is characterised by thermal and oxidative stability (Kyei et al., 2023). In powder form, CNS has a very high surface area and is very porous, leading to good interfacial bonding when used with plant gums as a binder. The qualities make the substance not only mechanically compatible but also ecologically beneficial, since it offers a renewable and biodegradable substitute to established mineral fillers and synthetic polymers.

One of such solutions is the valorization of crop fiber by the creation of composite materials to reduce the burning of agricultural waste and environmental pollution (Wannapokin et al., 2018). This makes the process result in biomass recovery (Unpaprom et al., 2019), and contributes to resource efficiency by the designation of CNS as an engineering material, with the view of establishing a link to the principles of circular economy (Piechota et al., 2023). Using plant gum to substitute petroleum-based binders avoids the use of formaldehyde and epoxy systems and hence lowers the carbon footprint and toxicity of conventional binder formulation. This technology can be matched with Sustainable Development Goals (SDGs) of the United Nations 7 (Affordable clean energy), 12 (Responsible Consumption), and 13 (Climate Action). The use of CNS and other agro components shows a sustainable way of brake pad production which keeps the functional behavior of the manufacturing but still resonates with the environmental engineering, materials science, and waste-management policies (Vu et al., 2017). The results show that bio-based innovation in the automotive industry provides significant prospects for industry improvement, especially since the eco-friendly materials represent an essential building block of sustainable development.

Lawal et al. (2019b) studied and compared eco-friendly formulations of brake pads made of egg shells (EGs). The samples had a concentration of Gum Arabic (GA) between 3 % and 18 % by weight. Thickness swelling in water, hardness, wear-rate, thermal resistance, specific-gravity, compressive-strength, and microstructure characterization were all included in the characterization program. The findings proved satisfactory bonding of EG compositions with 15 % to 18 % GA. The specimen containing 18 % GA was the most favorable one among these. The present research thus examines the potential of the usage of cashew nut shells in the form of good substitutes to carcinogenic asbestos in brake pads and friction-lining composites, which can be environmentally responsible.

2. Materials and methods

2.1 Material

As part of this study, all of the constituent compositions were locally purchased. The actual experimentation has been carried out in the Federal Institute of Industrial Research, Oshodi (FIIRO), located in Lagos State, Nigeria. The raw materials used in the formulation and production of the composites constituted Cashew Nut Shell (CNS), Steel Dust (SD), Graphite (G), Silicon Carbide (SC), and Plant Gum (PG).

2.2 Cashew nut shell as the base material and reinforcement

The cashew tree, which is named *Anacardium occidentale,* is native to the area of tropical South America and was spread through West Africa by the Portuguese colonization in the late sixteenth century during the occupation of Brazilian territories. The plant was later crossed over to India and most parts of Asia, and it quickly adjusted to the similar climatic conditions. Its common name, cashew, originated with the Brazilian Tupi acaju, and is now (apparently incorrectly) pronounced [k4USEU)). The range of the species has already expanded to a large number of temperate and tropical areas, including India, Vietnam, Tanzania, Côte d Ivoire, the Philippines, Indonesia, Guinea-Bissau, Nigeria, and many others (Duarte and Paul, 2015). Cashew nuts appearance illustrated in Figure 1.

In the ripe cashew, not only the cashew apple, but also the cashew apple core or pseudocarp is part of the compound fruit, produced by the pedicel. Although the core of an apple is not a fruit, most people associate it with the fruit, leading to confusion. The apple core is an accessory structure that acts like a support to the actual fruit, the nut that is found below. Morphologically, the nut is reniform-shaped and is surrounded by a hard pericarp, which could be removed to expose the cashew kernel, the main commercial product. Cashew kernels are cooked either raw, fried or salted or sugar-treated, and they are extensively used in world cuisines, especially the Thai and Chinese dishes. Other edible products obtained through industrial processing include jam, juice, syrup, chutney, and other consumable beverages (Afzaal et al., 2022).

Figure 1. Cashew nuts

The harvesting of nuts is accompanied by the production of a by-product called cashew nutshell liquid (CNSL) by the pericarp. Being a mixture of anacardic acids and their derivatives, this oval substance is a commercial interest material due to its versatile use in everyday life in adhesives, pesticide formulations, cosmetics, and resins (Idah et al., 2014; Okele et al., 2016). There were estimates by Ohler (1979) that the total production and consumption of cashews in the whole world is expected to grow at a rate of about 1,260,000 tonnes per year within the next two decades with the major sources of this consumption being Nigeria, India, Mozambique, and Malawi, Thailand, Tanzania, Sri Lanka, Kenya, Madagascar, Malaysia, Indonesia, Senegal, and Angola. The country of Nigeria indeed produced 594,000 tonnes alone in 2010 of which certainly indicates the economic and industrial potential that raising yields would offer the region (Olife et al., 2013).

The physical and mechanical properties of cashew nut shells and kernels have unique characteristics that set them apart from other engineering materials, such as reinforcement material for the production of agro-based brake pads intended in this work. Research by Okele et al. (2016), Bart-Plange et al. (2012), and Teye & Abano (2012) has extensively determined these physical and mechanical properties with favorable results for the work intended in this study, as discussed earlier.

2.3 Materials for formulation and production of the brake pad composites

The base and additive materials used in the formulation were selected based on the criteria outlined by Bala et al. (2021). These include Cashew Nut Shell (CNS), which served as both the reinforcement/filler and the base material (2A), and plant gum, employed as the binder (2B, C). Silicon carbide (2D) was incorporated to enhance the thermal stability of the brake pad, while Graphite (E) was used as a friction modifier (2F). Additionally, Steel Dust (SD) was included in Figure 2, as the abrasive component to improve the material's braking efficiency.

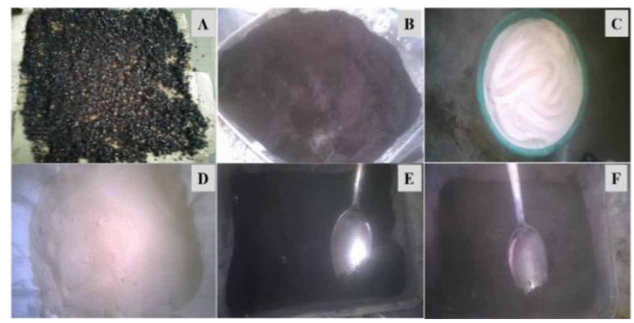

Figure 2. (A) Cashew nut shells, (B) Ground powder, (C) Gum-ground powder, (D) Silicon carbide, (E) Graphite, and (F) Steel dust (Source: Bala et al., 2021)

2.4 Experimental design and procedure

The study was experimentally designed and carried out, with the first step of the methods being the adoption of the L2735 orthogonal array Design of Experiment (DOE) via Taguchi with twenty-seven (27) different formulations of five constituent materials (Bala et al., 2020). The Cashew Nut Shells, Silicon Carbide, and Plant Gum (Nigerian Gum Arabic) compositions were varied while the other constituents, such as Graphite and Steel Dust were kept constant, and three (3) level L2735 orthogonal array Experimental Matrix for the Composition formulation that was originated and utilized is shown in Table 1.

2.5 Development of the composites

The second step is the preparation of the constituent materials into a 300μm sieve size and formulated into twenty-seven (27) different compositions as originated from Table 2, as carried out by Bala et al. (2021). The powder metallurgy method, also known as the Compression molding method, as successfully adopted and reported by Yawas et al. (2013), Fono–Tamo & Koya (2013), and Bashar et al. (2012), was used development of the brake pad composites. The powdered Cashew Nut Shells were sieved into grades of 100 μm, and the component materials of Cashew Nut Shells Powder, Plant Gum Powder, Steel Dust, Silicon Carbide, and Graphite were weighed in the Digital weighing Machine corresponding with formulations designed via Taguchi. The mixtures are thoroughly ensured with the help of a Homogenizer or Mixer of Model 89.2 Rid Scale & Co Ltd, Middleborough, England. The mixing of the composition was done for 20 to 30 minutes to achieve an almost homogeneous mixture inside the mixer before pouring into the mould kept on a hot plate press at a temperature of 150°C and 100,000N/cm^2 pressure for two (2) minutes.

Figure 3. Produced brake pad composites

They were then subjected to cold pressing and hot pressing before being allowed to cool at room temperature. After being removed from the hot press, the composites were removed from the mould and properly cleaned. It was then heat-treated at a temperature of 120 °C for 8 hours in the hot air oven. These procedures were repeated for all twenty-seven (27) formulations to produce the respective composites. Grey Relational Analysis as outlined by Kuo & Huang, (2008) and successfully deployed by Abutu et al. (2018) and Bala et al. (2021) was use to optimize the multi-response performance of the Wear rate, Coefficient of Friction, Hardness and Compressive Strength of the brake bad samples produced while ANOVA was used to determine the Significant contribution of the Cashew Nut Shells reinforcement in the optimized performance of the brake pad samples.

2.6 Grey relational analysis for single response optimization

The procedures of Grey Relational Analysis (GRA) as outlined by Yiyo et al. (2008) and successfully deployed by Abutu et al. (2018) were conducted on the response values such as the compressive strength, coefficient of friction, wear rate, and hardness to compress the multi-response parameters into a single optimized response. The GRA equations for smaller-the better (wear rate) and larger-the better (compressive strength, hardness, and friction coefficient) quality characteristics are represented in equations 1 and 2, respectively.

S/N (Smaller-the better) = $$-10\log\frac{1}{n}\left(\sum_{i-1}^{n} x_i^2\right) \quad (1)$$

S/N (Larger-the better) $$-10\log\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{x^2}\right) \quad (2)$$

Where x = Responses of given factor level combination and n = number of experimental samples.

S/N ratio calculation was followed by calculation of Grey Relational Generating (GRG) using Equations 3 (smaller-the-better attributes) and 4 (larger-the-better attributes). GRG was conducted to normalize the S/N ratio values in the range between 0 and 1 (Abutu et al., 2018).

Smaller-the-better attributes = $$\frac{\overline{x_{ij}} - x_{ij}}{\overline{x_j} - \underline{x}_j} \quad (3)$$

Larger-the-better attributes = $$\frac{x_{ij} - \underline{x}_i}{\overline{x_i} - x_j} \quad (4)$$

Where, x_{ij} is the individual response value and $\overline{x}_j$ = max{x_{ij} , i = 1, 2, . . . , m} and $\underline{x}_j$ = min{x_{ij} , i = 1, 2, . . . , m}.

The GRG procedure is followed by the calculation of the Grey Relational Coefficient (GRC) using Equation 5.

GRC = $$\frac{\Delta_{\min} + \lambda\Delta_{\max}}{\Delta_{ij} + \lambda\Delta_{\max}} \quad (i = 1, 2, . . , m \text{ and } j = 1, 2, . . . , n) \quad (5)$$

Where $\Delta_{ij} = x_{0j} - x_{ij}$ while Δ_{min} = min (0)and Δ_{max} = max (1)
ƛ is the distinguishing coefficient, $\beta \in [0, 1]$.

Distinguishing coefficient (ƛ) is used to expand or compress the range of the GRC, and 0.5 is the accepted value (Abutu et al., 2018). The final stage of GRA is the calculation of Grey Relational Grades, which was obtained using Equation 6.

Grade = $$\frac{Indivisual\ GRC}{Number\ of\ responses} \quad (6)$$

The results of experimental response values along with its corresponding S/N ratio values are shown in Tables 2 and 3.

3. Results and discussion

3.1 Analysis of experimental responses and optimization using grey relational and Taguchi methods

The experimental responses for the wear rate, compressive strength, Coefficient of Friction, and Hardness were characterized as presented in Table 1. These values were used to obtain the respective Signal-to-Noise Ratio, Grey Relational Generating, Grey Relational Coefficient, and the Grades as presented in Table 2 (Bala et al., 2021). The table presents the results of 27 experimental runs, evaluating four key performance parameters of a composite material: wear rate, compressive strength, coefficient of friction (CoF), and hardness. corresponds to a specific trial, showing both the experimental response values and their corresponding Signal-to-Noise (S/N) ratios in decibels (dB). The experimental responses provide insight into how the material behaves under mechanical and tribological conditions. Lower wear rates indicate better durability under frictional forces, higher compressive strength reflects the material's ability to withstand compressive loads, lower CoF values suggest smoother surface interaction, and higher Brinell Hardness Numbers (BHN) indicate better resistance to indentation and surface degradation (Singh et al., 2020; Ahmad et al., 2022).

Each row corresponds to a specific trial, showing both the experimental response values and their corresponding Signal-to-Noise (S/N) ratios in decibels (dB). The experimental responses provide insight into how the material behaves under mechanical and tribological conditions. Lower wear rates indicate better durability under frictional forces, higher compressive strength reflects the material's ability to withstand compressive loads, lower CoF values suggest smoother surface interaction, and higher (Table 3 and 4).

Table 1. Three (3) level $L_{27}3^5$ orthogonal array experimental matrix for the compositions

W2	Cashew Nut Shells CNS (Grams)	Steel Dust SD (Grams)	Graphite G(Grams)	Silicon Carbide SC (Grams)	Plant Gum(PG) (Grams)
1	52.5	22.5	7.5	30	37.5
2	52.5	22.5	7.5	30	30
3	52.5	22.5	7.5	30	22.5
4	52.5	22.5	7.5	22.5	37.5
5	52.5	22.5	7.5	22.5	30
6	52.5	22.5	7.5	22.5	22.5
7	52.5	22.5	7.5	15	37.5
8	52.5	22.5	7.5	15	30
9	52.5	22.5	7.5	15	22.5
10	67.5	22.5	7.5	15	37.5
11	67.5	22.5	7.5	15	30
12	67.5	22.5	7.5	15	22.5
13	67.5	22.5	7.5	30	37.5
14	67.5	22.5	7.5	30	30
15	67.5	22.5	7.5	30	22.5
16	67.5	22.5	7.5	22.5	37.5
17	67.5	22.5	7.5	22.5	30
18	67.5	22.5	7.5	22.5	22.5
19	82.5	22.5	7.5	22.5	37.5
20	82.5	22.5	7.5	22.5	30
21	82.5	22.5	7.5	22.5	22.5
22	82.5	22.5	7.5	15	37.5
23	82.5	22.5	7.5	15	30
24	82.5	22.5	7.5	15	22.5
25	82.5	22.5	7.5	30	37.5
26	82.5	22.5	7.5	30	30
27	82.5	22.5	7.5	30	22.5

Table 2. Experimental Responses and S/N values

	Experimental Responses				Signal-to-Noise Ratios			
Runs	Wear Rate (gm/m)	Compressive Strength (N/mm^2)	Coefficient of Friction	Hardness (BHN)	Wear rate (dB)	Compressive strength (dB)	Coefficient of friction (dB)	Hardness (dB)
1	1.16	6.035	0.4456	22.27	-1.289	15.614	-7.021	26.954
2	3.08	11.58	0.4358	47.49	-9.771	21.274	-7.214	33.532
3	9.24	7.568	0.4554	31.83	-19.313	17.580	-6.832	30.057
4	11.56	9.519	0.4554	31.83	-21.259	19.572	-6.832	30.057
5	0.02	9.009	0.524	47.49	-20.017	19.094	-5.613	33.532
6	3.85	11.038	0.426	47.49	-11.709	20.858	-7.412	33.532
7	7.32	10.579	0.426	31.83	-17.290	20.489	-7.412	30.057
8	3.47	15.558	0.4162	31.83	-10.807	23.839	-7.614	30.057
9	5.39	17.197	0.4554	22.27	-14.632	24.709	-6.832	26.954
10	4.62	7.41	0.4652	31.83	-13.293	17.396	-6.647	30.057
11	10.02	13.869	0.3672	76.66	-20.017	22.841	-8.702	37.691
12	11.18	7.512	0.4162	47.49	-20.969	17.515	-7.614	33.532
13	8.09	10.867	0.475	76.66	-18.159	20.722	-6.466	37.691
14	5.78	11.012	0.5632	76.66	-15.239	20.837	-4.987	37.691
15	7.71	9.723	0.475	47.49	-17.741	19.756	-6.466	33.532
16	8.86	8.244	0.4456	22.26	-18.949	18.323	-7.021	26.951
17	1.16	6.298	0.5044	47.49	-1.289	15.984	-5.944	33.532
18	3.85	9.107	0.4946	31.83	-11.709	19.188	-6.115	30.057
19	3.85	5.736	0.4554	22.26	-11.709	15.172	-6.832	26.951
20	2.31	4.809	0.4358	47.49	-7.272	13.641	-7.214	33.532
21	5.39	6.712	0.4162	31.83	-14.632	16.537	-7.614	30.057
22	7.32	5.844	0.3966	47.49	-17.290	15.334	-8.033	33.532
23	1.93	3.654	0.3966	47.49	-5.711	11.255	-8.033	33.532
24	1.93	6.398	0.377	22.26	-5.711	16.121	-8.473	26.951
25	12.33	8.532	0.5142	31.83	-21.819	18.621	-5.777	30.057
26	17.73	8.219	0.377	31.83	-24.974	18.296	-8.473	30.057
27	4.24	4.552	0.5534	22.26	12.547	13.164	-5.139	26.951

Brinell Hardness Numbers (BHN) indicate better resistance to indentation and surface degradation (Singh et al., 2022; Quian et al., 2024). The S/N ratios, widely used in Taguchi methods for robust design, help quantify the desirability of each response by combining performance magnitude with variability. For wear rate, the "smaller-the-better" criterion is applied, meaning lower wear values result in higher (less negative) S/N ratios. In contrast, the "larger-the-better" approach is suitable for properties like compressive strength, CoF, and hardness, where higher values are desirable to enhance material performance (Taguchi & Konishi, 1987). These ratios are effective in identifying optimal parameter levels by minimizing variability and enhancing consistency in performance.

Notably, Run 5 demonstrates the best wear resistance with an exceptionally low wear rate of 0.02 gm/m, while Run 9 exhibits the highest compressive strength at 17.197 N/mm^2. The lowest coefficient of friction appears in Run 11 (0.3672), which, along with Runs 13 and 14, also shows the highest hardness value of 76.66 BHN. These superior performance values align with the corresponding S/N ratios, indicating that these specific runs represent the most favorable material compositions or processing conditions within the experimental range. From the Main Effect Plot in Figure 4, the optimal composition in grams of the formulation of cashew nut shells (CNS), steel dust (SD), graphite (G), silicon carbide (SC), and Plant gum binder (PG) is 82.25,22.5,7.5,15 and 30 grams, respectively.

3.4 ANOVA of grey relational grades for factor significance

Analysis of Variance (ANOVA) was performed based on the Grey Relational Grades (GRG) obtained from the multi-response optimization using Grey Relational Analysis (GRA). The objective was to determine the statistically significant effects of the formulation constituents—namely Cashew Nut Shells (CNS), Steel Dust (SD), Graphite (G), Silicon Carbide (SC), and Natural Gum Additive (NGA)—on the overall quality and performance characteristics of the fabricated brake pad composites. This analysis was conducted at a 5% significance level ($\alpha = 0.05$), corresponding to a 95% confidence interval (Montgomery, 2017). The ANOVA results, presented in Table 4, reveal that Cashew Nut Shells (CNS) exert the most significant influence on the

Table 3. Results of Grey Relational Generating (GRG) and Grey Relational Coefficient (GRC)

Runs	GRG				GRC				Grade
	Wear Rate	Compressive Strength	Coefficient of Friction	Hardness	Wear rate	Compressive strength	Coeff. of friction	Hardness	
X_o	1.000	1.000	1.000	1.000					
1	0.000	0.324	0.452	0.000	0.333	0.425	0.477	0.333	0.530
2	0.358	0.745	0.400	0.613	0.438	0.662	0.455	0.564	0.519
3	0.761	0.470	0.503	0.289	0.677	0.485	0.502	0.413	0.561
4	0.843	0.618	0.503	0.289	0.761	0.567	0.502	0.413	0.640
5	0.791	0.583	0.831	0.613	0.705	0.545	0.748	0.564	0.526
6	0.440	0.714	0.347	0.613	0.472	0.636	0.434	0.564	0.517
7	0.676	0.686	0.347	0.289	0.607	0.614	0.434	0.413	0.542
8	0.402	0.935	0.293	0.289	0.455	0.885	0.414	0.413	0.592
9	0.563	1.000	0.503	0.000	0.534	1.000	0.502	0.333	0.481
10	0.507	0.456	0.553	0.289	0.503	0.479	0.528	0.413	0.705
11	0.791	0.861	0.000	1.000	0.705	0.783	0.333	1.000	0.552
12	0.831	0.465	0.293	0.613	0.747	0.483	0.414	0.564	0.705
13	0.712	0.704	0.602	1.000	0.635	0.628	0.557	1.000	0.796
14	0.589	0.712	1.000	1.000	0.549	0.635	1.000	1.000	0.579
15	0.695	0.632	0.602	0.613	0.621	0.576	0.557	0.564	0.497
16	0.746	0.525	0.452	0.000	0.663	0.513	0.477	0.333	0.498
17	0.000	0.351	0.742	0.613	0.333	0.435	0.660	0.564	0.514
18	0.440	0.590	0.696	0.289	0.472	0.549	0.622	0.413	0.430
19	0.440	0.291	0.503	0.000	0.472	0.414	0.502	0.333	0.449
20	0.253	0.177	0.400	0.613	0.401	0.378	0.455	0.564	0.453
21	0.563	0.393	0.293	0.289	0.534	0.452	0.414	0.413	0.492
22	0.676	0.303	0.180	0.613	0.607	0.418	0.379	0.564	0.414
23	0.187	0.000	0.180	0.613	0.381	0.333	0.379	0.564	0.375
24	0.187	0.362	0.062	0.000	0.381	0.439	0.348	0.333	0.607
25	0.867	0.547	0.787	0.289	0.790	0.525	0.701	0.413	0.568
26	1.000	0.523	0.062	0.289	1.000	0.512	0.348	0.413	0.528
27	0.475	0.142	0.959	0.000	0.488	0.368	0.924	0.333	0.530

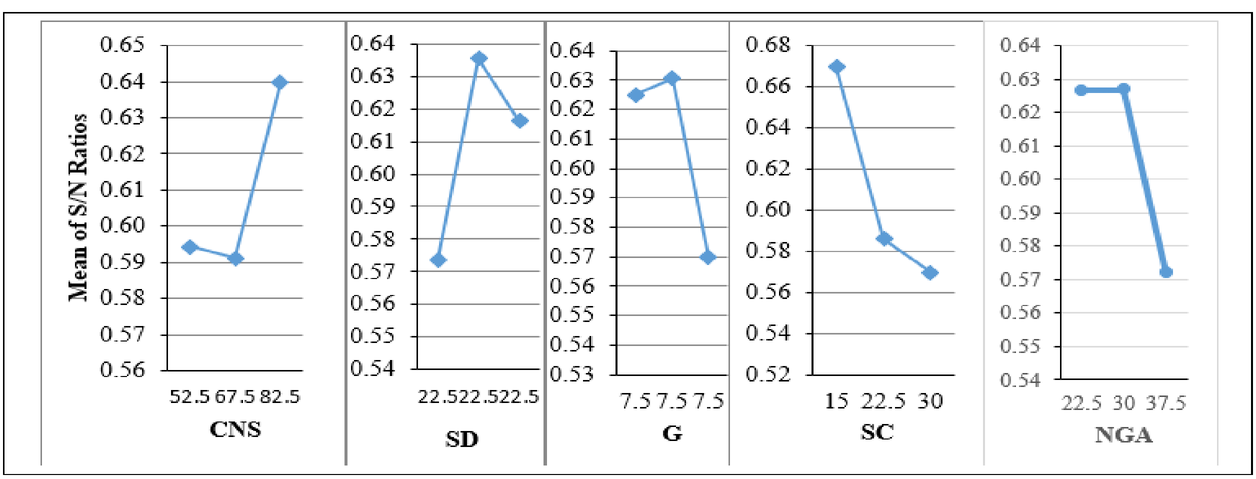

Figure 4. Main effect plot for grey relational analysis

composite's performance, with the highest F-value of 43.074 and a contribution of 27.558% to the total variation. This is followed by Graphite (G) and Silicon Carbide (SC), with F-values of 40.470 and 28.889, and contribution percentages of 25.892% and 18.483%, respectively. Natural Gum Additive (NGA) and Steel Dust (SD) also show notable but relatively lower significance, contributing 15.479% and 7.470%, respectively. The error term accounts for just 5.118%, indicating a good model fit and low unexplained variation.

These findings confirm that CNS, G, and SC are the primary factors influencing the multi-performance optimization of the composite materials, validating their critical roles in tailoring brake pad characteristics such as wear resistance, mechanical strength, frictional behavior, and hardness for automotive applications (Lawal, 2021; Singh et al., 2020; Ahmad et al., 2022).ANOVA was conducted using the multi-response GRA and Grade values to identify the significant effects of the Cashew nut shells, which affect the quality, characteristics, and Performance of the resulting composites for brake pads in Automobiles. This analysis was conducted using α = 0.05 significance level, at 95 % confidence level. These results are shown in Table 4.

Table 4. ANOVA for grey relational analysis

Factor	DOF	SS	MS	F	P
CNS	2	0.061	0.031	43.074	27.558
SD	2	0.017	0.008	11.676	7.470
G	2	0.058	0.029	40.470	25.892
SC	2	0.041	0.021	28.889	18.483
NGA	2	0.034	0.017	24.194	15.479
Error	16	0.011	0.001		**5.118**
Total	26	0.223	0.009		100.000

3.4 Environmental, biomass, and sustainable development perspective

The incorporation of cashew nut shells (CNS) as a base and reinforcement material in automobile brake pad composites presents a compelling case for sustainable engineering innovation. This approach aligns strongly with the United Nations sustainable development goals (SDGs), particularly SDG 7: affordable and clean energy, SDG 12: responsible consumption and production, and SDG 13: climate action. By transforming an underutilized agro-waste biomass into a high-performance engineering material, the study contributes to the valorization of renewable biological resources, reducing dependence on virgin raw materials and minimizing the environmental burden associated with hazardous substances such as asbestos (Dang et al., 2023; Pandi et al., 2024).

Cashew Nut Shells, an abundant agro-industrial residue in countries like Nigeria, are biodegradable and non-toxic, making them an ideal candidate for eco-composite development. Their conversion into value-added products through powder metallurgy not only addresses biomass waste management challenges but also supports low-energy, low-emission production pathways. Furthermore, the substitution of petroleum-based synthetic binders with natural plant gum, a biodegradable polymer, enhances the eco-efficiency of the overall composite. This substitution supports green chemistry principles and drastically lowers the carbon intensity of brake pad manufacturing.

From an energy and biomass utilization standpoint, this research contributes to the bio-economy by converting renewable organic feedstocks into functional, safety-critical components (Ramaraj et al., 2023a,b). The energy embedded in the biomass is indirectly harnessed through its conversion into mechanical performance, thereby promoting energy recovery from waste streams. Such innovations pave the way for decentralized, biomass-based material industries that are energy-conscious and environmentally compliant.

Technically, the study integrates multi-response optimization techniques, such as Grey Relational Analysis and ANOVA, to ensure that the adoption of green materials does not compromise product performance. The optimized composites demonstrated excellent wear resistance, mechanical strength, and thermal stability—validating that sustainable materials can compete with conventional counterparts in demanding automotive applications. Therefore, this research offers a scalable, sustainable, and energy-efficient alternative to conventional brake pad materials, contributing to industrial decarbonization, circular material flows, and rural bio-resource valorization. It sets a significant precedent for future material development efforts focused on integrating biomass, energy sustainability, and environmental stewardship within the core of product engineering strategies.

4. Conclusion

The current study focuses on the potential of the cashew nut shell in the manufacture of brake pad composites with environmental responsibility as the binder component. To this effect, a Taguchi L2735 orthogonal design of experiment is employed, giving rise to 27 formulations which consist of cashew nut shells, steel dust, graphite, silicon carbide, and plant gum. Powder metal technology and compression moulding are then used in fabricating the composite samples. The resulting optimisation of the multiple responses of wear rate, coefficient of friction, hardness, and compressive strength is then achieved using Grey Relational Analysis. ANOVA indicates that the effect of cashew nutshell contributes to 27.558 % of the total variance in the performance of the composite and consequently confirms its significant role in the composite performance. Overall, cashew nut shells can be taken as a potential alternative to asbestos when it comes to the mass production of brake pads, and, consequently, the attainment of the goals of the sustainable engineering practice and the United Nations Sustainable Development Goals.

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