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Investigation of the Mechanical and Thermal Properties of Carbon Fiber Impregnated with Groundnut Shell Bio-composite

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ABSTRACT

The growing demand for sustainable materials for aerospace and transportation industries has prompted significant interest in bio-composites that blend natural and synthetic components. This study investigates the mechanical and thermal properties of hybrid composites made from carbon fiber and groundnut shell, an agricultural by-product. Five composite samples with varying ratios of carbon fiber (CBF) and groundnut shell (GNS) were prepared using epoxy resin as the matrix. Standard tests were conducted to measure tensile strength, impact resistance, hardness, thermal conductivity, and degradation temperature. Results showed that increasing the carbon fiber content significantly enhanced tensile strength between 120.63 to 300.31 MPa, impact resistance from 29.98 to 70.04 J/m², and hardness from 70.23 to 90.23 D. Therefore, higher carbon fiber concentrations also improved thermal conductivity (0.21–0.41 W/mK) and degradation temperature (263.52–339.65°C). In contrast, groundnut shell contributed to sustainability but demonstrated lower mechanical properties. The findings suggest that carbon fiber-groundnut shell composites can be tailored for applications requiring high strength and thermal stability, or for eco-friendly solutions where performance is less critical. This study provides a foundation for future development of high-performance sustainable composites.

Keywords: Carbon fiber, epoxy resin, groundnut shell, tensile strength, thermal conductivity, degradation temperature

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1 INTRODUCTION

The rising global need for sustainable materials, propelled by the imperative to mitigate environmental damage and decrease reliance on fossil fuels, has generated considerable interest in the advancement of eco-friendly composites. These materials are generally engineered to have favorable mechanical, thermal, and chemical characteristics while integrating renewable or recyclable components (Yongjun, 2023; IEA, 2023; Nature, 2023). In this situation, bio-composites consisting of natural fibers or particles and synthetic materials have emerged as a viable alternative. They offer an efficient equilibrium of strength, cost, and sustainability (Ngo, 2018; Shaker, et al., 2020). Among the bio-composites examined, agricultural by-products like groundnut shells have garnered interest as prospective fillers or reinforcements owing to their availability, biodegradability, and distinctive material characteristics (Lubwama, et al., 2022, Sadh, et al., 2018). Carbon fibre, recognized for its superior strength-to-weight ratio and exceptional thermal and electrical conductivity, has become an essential material in sectors such as aerospace, automotive, and energy (Lubwama, et al., 2022). The combination of carbon fibre and groundnut shell in composite form constitutes a compelling research domain, presenting opportunities for the creation of innovative materials that integrate high-performance attributes with sustainability (Potadar & Kadam 2018; Gupta et al., 2023).

Carbon fibre is widely employed in composite materials owing to its exceptional mechanical qualities, such as high tensile strength, low density, and improved thermal stability. These characteristics render it suitable for use in industries necessitating lightweight yet durable materials, including aerospace, automotive, sports equipment, and civil engineering (Lead, 2022). The exceptional thermal and electrical conductivity of carbon fibre increases its appeal in electronic and energy-related applications, such as electromagnetic shielding and fuel cell components (Mikinka & Siwak, 2021; Perumal, et al., 2020). Nonetheless, despite its exceptional characteristics, carbon fibre manufacturing is energy-consuming and costly, restricting its extensive use, particularly in price-sensitive sectors. Furthermore, carbon fibre is non-biodegradable, presenting environmental issues upon the conclusion of its lifecycle (Prenzel, et al., 2023; Groetsch, 2024). Researchers over the years have investigated hybridization ways to diminish the environmental impact of carbon fibre composites by using natural fibers or agricultural waste by products (Prenzel, et al., 2023; Zhang, 2022; Suriani, et al., 2021).

Groundnut shell, an agricultural by-product, has attracted interest in the materials science field for its potential as a bio-filler in composites (Potadar & Kadam, 2018; Patnaik, 2022). Annually, millions of tonnes of groundnut shells are produced worldwide, particularly in nations such as Nigeria, India, and China, where groundnut farming is prevalent (Sakha, et al., 2022; Nautiyal, 2002; Biswas, 2024). Groundnut shells, mostly consisting of cellulose, hemicellulose, and lignin, exhibit advantageous mechanical qualities such as moderate stiffness and impact resistance. Their accessibility and biodegradability render them a compelling substitute for synthetic fillers in composite applications (Ramu, 2024; Mandala, 2023).

Prior research has investigated the incorporation of groundnut shells into diverse polymer matrices, encompassing both thermoset and thermoplastic types, to improve attributes like tensile strength, impact resistance, and thermal stability.

Mandala et al. (2023) present a thorough examination of peanut-shell-based polymer composites, focusing on how filler content, surface modification, and processing techniques influence mechanical performance. The study emphasizes the sustainability of these materials and explores their potential applications in industries such as packaging and construction, highlighting eco-friendly alternatives to conventional composites. Similarly, the research by Potadara and Kadama (2018) investigate the mechanical properties of natural fiber-based epoxy composites made from groundnut shells and coir fibers. Their findings show that while coir-based composites exhibit higher tensile and flexural strength compared to groundnut-based counterparts, both materials experience increased moisture absorption with larger grain sizes. The study notes limitations such as inconsistent mechanical properties and moisture resistance, indicating that further optimization is required for industrial applicability. Ngo (2018) also explores the use of natural fibers, including flax, hemp, and sisal, in bio-composite materials. These fibers are noted for their eco-friendliness, light weight, and industrial potential. However, the study identifies key challenges such as high moisture absorption, lower mechanical strength compared to synthetic fibers, and variability in fiber quality due to environmental factors. Additional research into surface treatments and fiber-matrix bonding is recommended to enhance performance.

Several researchers have also explored hybrid composites that combine carbon fibers with natural fibers to balance mechanical performance and sustainability (Patnaik, et al., 2023, Suriani et al., *2021,* Ramu et al., 2024; Atmakuri, et al., 2020). These hybrid composites demonstrate favorable mechanical properties while reducing reliance on synthetic fibers.

Notwithstanding these advancements, a limited number of investigations have concentrated on groundnut shell-carbon fibre composites. This disparity is significant due to the distinctive attributes that groundnut shell offers, like biodegradability and cost efficiency, with the superior performance of carbon fibre. Although numerous studies have explored the application of natural fibers in hybrid composites, research on the utilization of agricultural waste materials, such as groundnut shell, in conjunction with carbon fibre is scarce. Most prior researches have concentrated on utilizing groundnut shell as a filler in polymer matrices, neglecting its potential in conjunction with sophisticated materials like carbon fibre. Furthermore, although carbon fiber-natural fibre hybrid composites have been thoroughly investigated, the particular amalgamation of carbon fibre and groundnut shell is predominantly unexamined. This study's innovation is its emphasis on groundnut shell as a bio-filler in a carbon fiber-reinforced composite, offering a distinctive combination of sustainability and excellent performance.

This research aims to investigate the mechanical and thermal of carbon fiber-groundnut shell hybrid composites and assess their potential for use in various industrial applications. This will assist to create a composite material that combines the high tensile strength, low density, and thermal stability of carbon fibre with the economical, biodegradable characteristics of groundnut shell. The study seeks to develop a material that fulfils performance criteria for industrial uses while also advancing sustainability by diminishing dependence on non-renewable resources.

The objectives of this research are to synthesize carbon fiber-groundnut shell hybrid composites using a suitable epoxy resin and to evaluate their mechanical properties, including tensile strength, impact resistance, and hardness. Additionally, the study aims to assess the thermal properties of the composites, focusing on thermal conductivity, heat resistance, and degradation temperature Furthermore, the performance of the hybrid composite will be compared with that of conventional carbon fiber and natural fiber composites.

2 LITERATURE REVIEW

2.1 Materials and equipment selection

This study utilized commercially available polyacrylonitrile (PAN) based carbon fibers, chosen for their high strength-to-weight ratio and superior thermal properties. Groundnut shells were sourced from agricultural waste at the Federal University of Technology, Akure and purified, dried to a consistent moisture level, and also milled into fine particles.

The composite's mechanical and thermal properties were assessed using a series of experiments. A Universal Testing Machine (UTM) with a 50 kN capacity evaluated tensile strength, while a Charpy impact tester with a 15 J capacity measured impact resistance. Hardness was assessed using a Rockwell hardness tester (Scale D, 100 kgf load), while thermal conductivity was measured using a thermal conductivity analyzer capable of a range from 0.005 to 500 W/m·K. Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) assessed degradation temperature and glass transition temperature (Tg), with temperature ranges extending to 1000°C and −150°C to 600°C, respectively.

Fourier-Transform Infrared Spectroscopy (FTIR), operating within a wavelength range of 4000 to 400 cm^{-1}, assessed the chemical composition, whereas Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS) yielded comprehensive microstructural pictures and elemental analysis. The integrated tests yielded a thorough comprehension of the composite's mechanical, thermal, and chemical characteristics, illustrating its applicability in industrial contexts. All the equipment stated were used according to the relevant ASTM standards.

2.1.1 Composite Production

This study developed composite formulations for five samples, consisting of carbon fiber (CBF), groundnut shell (GNS) particles, and epoxy resin (EPR), utilizing specific weight fractions for each component. The carbon fibers were cut into lengths of 10 to 20 mm and subsequently pulverized to ensure uniform distribution within the composite matrix. Both the carbon fibers and groundnut shells were ground into fine powder (<300 µm) using a ball mill to achieve homogeneous dispersion within the matrix. Epoxy resin was chosen as the polymer matrix due to its desirable mechanical and thermal properties, ensuring strong bonding between the fillers and the matrix. A curing agent or hardener was added to the epoxy resin in a 2:1 ratio (resin to hardener) to facilitate the thermosetting process and ensure the complete formation of the composite. Figures 1 and 2 present the PAN-based carbon fibers and groundnut shells, respectively, illustrating the primary materials used in the composite production.

Figure 1: PAN- Carbon Fiber

Figure 2: Groundnut Shell

The detailed formulation for the samples is presented in Table 1.

Table 1: Composition of the Composites

S/N	Sample Coded Name	Compositions (Weight)
1	$CMPS_1$	10% CBF, 40% GNS, and 50% EPR
2	$CMPS_2$	20% CBF, 30% GNS, and 50% EPR
3	$CMPS_3$	30% CBF, 20% GNS, and 50% EPR
4	$CMPS_4$	40% CBF, 10% GNS, and 50% EPR
5	$CMPS_5$	50% CBF, 0% GNS, and 50% EPR

Source: Authors Computation, 2024

The composite formulations for the five samples were designed with varying proportions of carbon fiber (CBF), groundnut shell (GNS) particles, and epoxy resin (EPR). These compositions were developed to explore the balance between the mechanical reinforcement provided by carbon fiber and the sustainability and cost-effectiveness offered by groundnut shell particles as a natural filler material. The prepared mixture of epoxy resin and hardener was first combined with groundnut shell particles to ensure homogeneous distribution. Pulverized carbon fibers were then gradually introduced to the mixture, promoting uniform dispersion and preventing agglomeration.

The resulting composite mixture was poured into a pre-designed mould (Figure 3) with cubic dimensions of 80 mm x 80 mm x 80 mm, which was used to create the composite specimens. After the molding process, the composite was carefully extracted from the mold, and any excess material was trimmed to create neat and uniform edges. The molded composite was then conditioned for a specified duration to ensure complete polymerization prior to testing. The mold and its contents were left to cool at room temperature for 30 minutes to achieve solidification, as shown in Figure 4. Once solidified and trimmed, the finished samples, free of rugged edges, are presented in Figure 5. This process ensured the production of high-quality composite specimens, ready for subsequent mechanical and thermal testing.

Figure 3: Gang Mould for the Composite Production

Figure 4: Composite Production

Figure 5: Produced Composite

2.1.2 Mechanical Testing

Tensile strength analyses of both the raw and composite samples were performed using a Universal Testing Machine (UTM) according to ASTM D638 (ASTM, 2022). standards to determine the maximum load the composite could withstand before failure. The tensile strength, modulus of elasticity, and elongation at break were recorded to assess the mechanical performance of the material. For the impact resistance test, Charpy and Izod impact tests were conducted to evaluate the composite's ability to resist impact loading according to ASTM D8101 (ASTM, 2019). Standard-sized notched specimens were subjected to impact forces using a pendulum impact testing machine, and the energy absorbed during fracture was measured to determine the toughness of the composite. Hardness testing was conducted using a Rockwell or Shore D hardness tester following ASTM D92-16 ASTM (2017) standard. This test measured the material's surface resistance to indentation, providing critical information on the composite's resistance to wear and localized deformation.

2.1.3 Thermal Testing

The thermal conductivity of the composite was measured using a thermal conductivity analyzer under controlled environmental conditions. Heat flow through the material was recorded to evaluate its efficiency in conducting heat. The results from this test provide valuable data for assessing the composite's suitability for thermal management applications. The thermal stability of the composite was evaluated using thermogravimetric analysis (TGA). The samples were heated in a controlled atmosphere, and the weight loss as a function of temperature was measured. This test determined the degradation temperatures of the epoxy resin and bio-filler, offering insights into the material's thermal resilience. On the other hand, Differential scanning calorimetry (DSC) was employed to examine the heat resistance properties of the composite. The heat flow was analyzed as a function of temperature to determine the glass transition temperature (Tg), melting temperature (Tm), and crystallization behavior of the epoxy resin. These results contribute to the understanding of the composite's thermal behavior under varying conditions.

3 METHODOLOGY

3.1. Qualitative Analysis

Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed according to the ASTM (2021) to identify the chemical bonds and functional groups within the composite (Khan, 2018, Oyerinde, 2016) This provided insights into the chemical interactions between the carbon fiber, groundnut shell, and epoxy resin. The FTIR data also revealed any chemical changes, such as cross-linking or degradation that occurred during the composite formation process.

4 DATA ANALYSIS AND DISCUSSION OF FINDINGS

4.1 Results

Table 1 presents the results sample components. The Table presents a summary of the results from the various tests conducted on the carbon fiber groundnut shell hybrid composites. Each analysis was carried out both CBF and GNS and the five different compositions were prepared, with the carbon fiber and groundnut shell content expressed as percentages of the composite's total weight.

Table 1: Mechanical and Thermal Properties of the Produced Composites

Material	Tensile strength (MPa)	Impact resistance (J/m^2)	Hardness (D)	Degradation temperature (^oC)	Thermal conductivity (W/mK)
CBF	400.28 ± 2%	151.23 ± 2%	90.14 ± 1.5%	498.98 ± 1%	1.23 ±1%
GNS	14.96 ± 2%	5.12 ± 2%	44.97 ± 1%	219.90 ± 0.5%	0.05 ± 1%
$CMPS_1$	120.63 ± 2%	29.98 ± 2%	70.23 ± 2%	263.52 ± 1%	0.21 ± 1%
$CMPS_2$	159.73 ± 2%	40.14 ± 2%	75.33 ± 2%	274.65 ± 1%	0.24 ± 1%
$CMPS_3$	210.13 ± 2%	51.03 ± 2%	81.11 ± 2%	298.92 ± 1%	0.30 ± 1%
$CMPS_4$	259.98 ± 2%	60.32 ± 2%	84.95 ± 2%	320.14 ± 1%	0.37 ± 1%
$CMPS_5$	300.31 ± 2%	70.04 ± 2%	90.23 ± 1.5%	339.65 ± 1%	0.41 ± 1%

Source: Test Result 2024

Table 2: FTIR Analysis of the Samples

Material	FTIR		
	Peaks Identified	Bond	Nature
CBF	1581	C=C	Stretch
GNS	1730	C=C	Stretch
	3400	OH	
$CMPS_1$	1735	C=O	Stretch
	3400	OH	
$CMPS_2$	1731	C=O	Stretch
	3400	OH	
$CMPS_3$	1731	C=O	Stretch
	3400	OH	
$CMPS_4$	1738	C=O	Stretch
	3400	OH	
$CMPS_5$	1730	C=O	Stretch
	3400	OH	

Source: Test Result 2024

4.2 Discussion of Findings

The findings regarding the mechanical and thermal properties of the composite formulations demonstrate a distinct correlation between the carbon fibre (CBF) content and the overall performance of the composite materials. With the increasing proportion of carbon fibre in the samples (**$CMPS_1$** to **$CMPS_5$**), notable enhancements in tensile strength, impact resistance, hardness, thermal conductivity, and degradation temperature were recorded.

The tensile strength of the composites exhibited a proportionate increase with carbon fibre content, varying from 120.63 MPa for **$CMPS_1$** (10% CBF) to 300.31 MPa for **$CMPS_5$** (50% CBF) as shown in Figure 6. This tendency emphasizes the reinforcing function of carbon fibre in enhancing the load-bearing capacity of the composite. The minimal tensile strength of groundnut shell (GNS) alone (14.96 MPa) highlights its restricted mechanical reinforcing potential relative to CBF. The incremental rise in tensile strength from **$CMPS_1$** to **$CMPS_5$** indicates that elevated carbon fibre content results in improved material rigidity and resilience, consistent with the characteristics of a robust fibrous substance possessing exceptional mechanical capabilities.

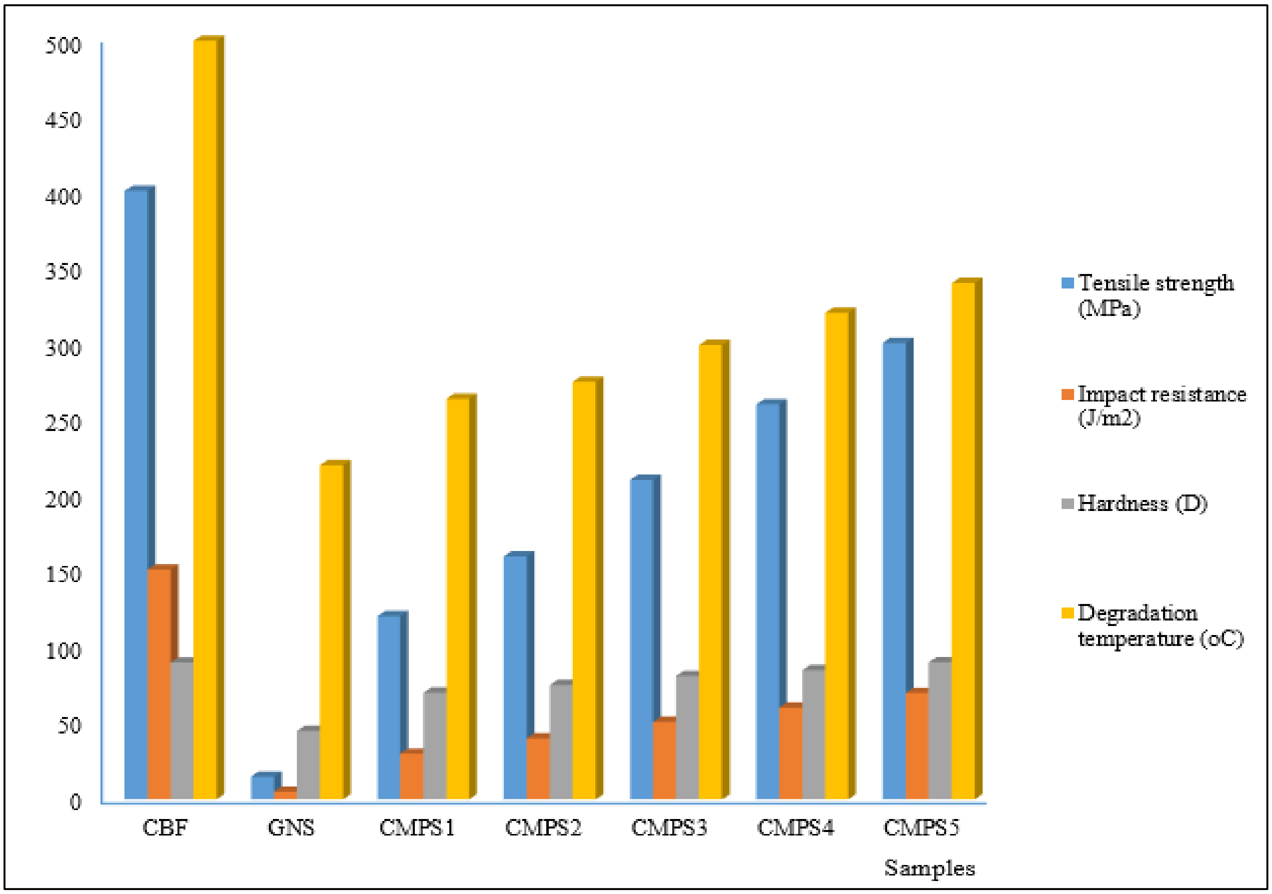

Figure 6: Tensile Strength Composite

The impact resistance exhibited a comparable trend, demonstrating a substantial rise from **$CMPS_1$** (29.98 J/m²) to **$CMPS_5$** (70.04 J/m²), so reinforcing the contribution of carbon fibre to the composite's toughness. GNS, exhibiting an impact resistance of merely 5.12 J/m², has a negligible contribution to this attribute. With an increase in carbon fibre content, the composite's capacity to absorb energy during impact loads enhances, which is essential for applications requiring resistance to abrupt forces.

The hardness values, quantified in Shore D, escalated with the carbon fibre content as shown in Figure 3, beginning at 70.23 for **CMPS**$_1$ and culminating at 90.23 for **CMPS**$_2$. This aligns with the observation that carbon fibre improves the stiffness and surface durability of the composite (Lee, et al., 2022). GNS, possessing a hardness of 44.97, functions as a softer filler in comparison to CBF. The rising hardness values suggest that higher carbon fibre content enhances the material's resistance to surface indentation, rendering it more appropriate for applications demanding wear resistance and longevity (Mandala, 2023).

Enhanced thermal conductivity and elevated degradation temperature were observed with increased carbon fibre content. As shown in Figure 4, **CMPS**$_1$, containing 10% CBF, exhibited a thermal conductivity of 0.21 W/mK, whereas **CMPS**$_5$, comprising 50% CBF, attained a thermal conductivity of 0.41 W/mK. This clearly indicates that carbon fibre improves heat conduction in the composite, rendering it appropriate for thermal management applications (Shaker, et al., 2020; Discovery Engineering, 2024). The degradation temperature exhibited a comparable trend, rising from 263.52°C for **CMPS**$_1$ to 339.65°C for **CMPS**$_5$, in contrast to the significantly lower 219.90°C for GNS alone (Perumal, et al., 2020). This indicates that increased carbon fibre content markedly enhances the thermal stability of the composite, which is crucial for use in high-temperature settings (Suriani et al., 2021).

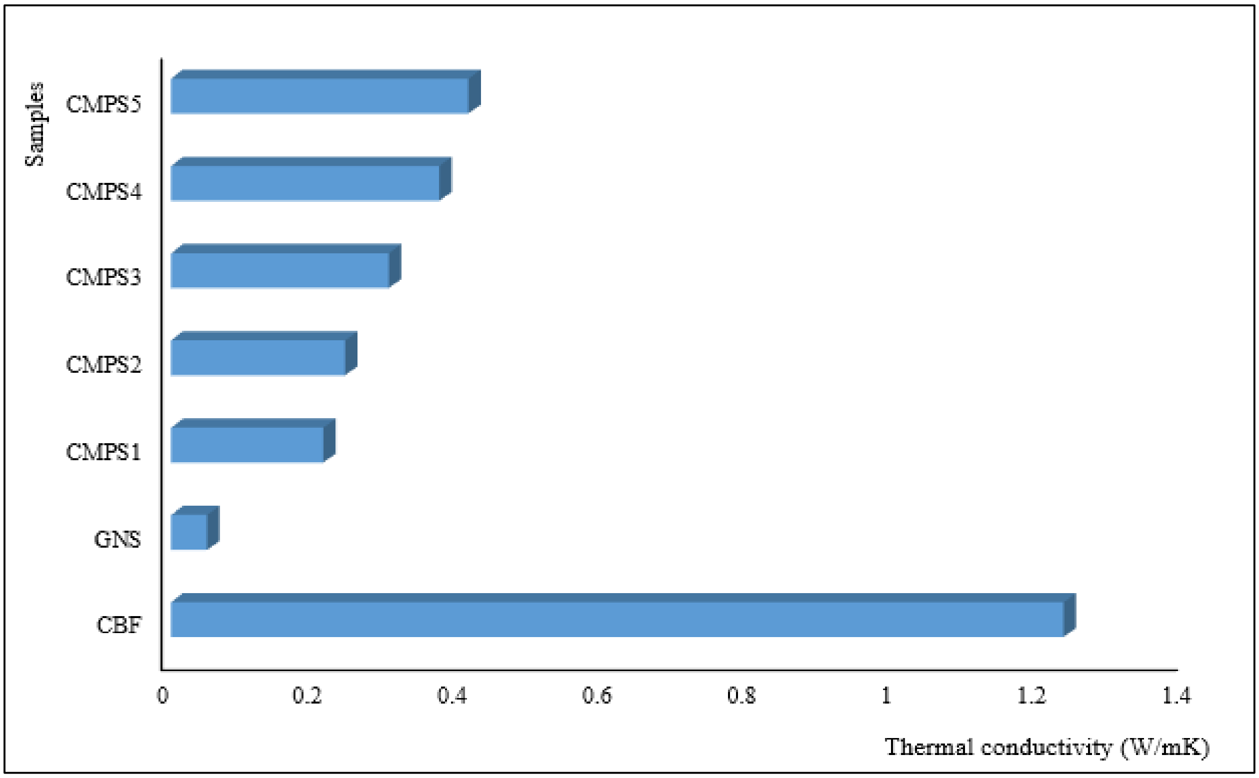

Figure 7: Thermal conductivity and Temperature

The FTIR data in Table 2 indicate the presence of significant functional groups, including C=O and OH, in all composite samples. The persistent peaks seen at 1730–1738 cm^{-1} (C=O) and 3400 cm^{-1} (OH) suggest that the chemical interactions between the epoxy resin and fillers (GNS and CBF) are stable across several formulations (Oyerinde & Bello, 2016). The peaks signify the presence of ester and hydroxyl functional groups, so affirming the existence of the polymer and the interaction of the natural fillers inside the matrix. The uniformity of the peaks among the samples indicates that the chemical structure of the composite stays preserved despite differing filler ratios, but increased carbon fibre concentration does not seem to cause substantial chemical alterations (Oyerinde & Bello, 2016).

The findings indicate a clear relationship between the augmentation of carbon fibre content and the improved mechanical and thermal properties of the composite. The formulation **CMPS**$_5$, including the maximum carbon fibre content (50% CBF), demonstrates superior performance in strength, impact resistance, hardness, and thermal stability. The trade-off between performance and sustainability is apparent, as diminished GNS content results in decreased environmental friendliness. Composites with elevated peanut shell content (e.g., **CMPS**$_1$ and **CMPS**$_2$) demonstrate enhanced sustainability and cost-effectiveness, although possess inferior mechanical qualities.

The results highlight the adaptability of hybrid composites in achieving a balance between performance and sustainability (Zhang, et al., 2022). The amalgamation of natural fillers such as groundnut shell with high-performance reinforcements like carbon fibre can provide composites customized for particular applications, ranging from lightweight and sustainable materials to high-strength and thermally stable components (Perumal, et al., 2020; Todd, 2018). Future research may investigate the optimization of filler interactions and the enhancement of mechanical properties by surface treatments or hybridization with alternative materials.

4.3 Potential Industrial Application Assessment

The results of this study provide a foundation for assessing the industrial applications of the carbon fiber (CBF) and groundnut shell (GNS) hybrid composites. The varying proportions of carbon fiber and groundnut shell significantly influence the mechanical and thermal properties of the composites, making them suitable for a range of industrial uses based on specific performance requirements.

The superior tensile strength observed in composites with higher carbon fiber content (**CMPS**$_3$, **CMPS**$_4$, and **CMPS**$_5$) suggests that these formulations are well-suited for structural applications where high mechanical performance is crucial (Gumel, et al., 2014). For example, **CMPS**$_5$, with a tensile strength of 300.31 MPa, is comparable to conventional carbon fiber-reinforced polymers used in aerospace, automotive, and construction industries for load-bearing components such as beams, panels, and frames (Oxana, et al., 2021). The high strength-to-weight ratio of these composites can help reduce overall structural weight while maintaining durability and safety, especially in transportation and high-performance engineering (Gumel, et al., 2014; Oxana, et al., 2021).

The increasing impact resistance, particularly in **CMPS**$_4$ and **CMPS**$_5$, indicates that these composites could be used in industries requiring materials that can withstand sudden or dynamic loads. Applications such as automotive parts (bumpers, side panels), protective gear, and packaging materials that must resist mechanical shocks can benefit from these properties (Prenzel, et al., 2023; Todd , 2020). For instance, **CMPS**$_5$'s impact resistance of 70.04 J/m^2 makes it an attractive option for high-impact zones in vehicle manufacturing, contributing to enhanced safety and durability in automotive design.

The hardness results, showing increasing surface resistance with higher carbon fiber content (up to 90.23 Shore D in **CMPS**$_5$), indicate potential applications in industries where materials are subjected to frequent wear and surface degradation (Perumal, et al., 2020). Components such as machine parts, conveyor belts, and tools used in heavy machinery or production lines could benefit from the enhanced hardness and wear resistance of **CMPS**$_4$ and **CMPS**$_5$. These composites would likely provide greater longevity and lower maintenance costs, especially in harsh industrial environments where materials are prone to abrasion and surface wear (Perumal, et al., 2020).

The thermal conductivity and degradation temperature results indicate that composites with higher carbon fiber content (such as CMPS5 with a thermal conductivity of 0.41 W/mK and degradation temperature of 339.65°C) are suitable for applications requiring thermal management and stability under high temperatures (Macias, et al., 2019). These characteristics are particularly relevant in electronics, automotive, and aerospace industries where materials are exposed to heat. For instance, heat-dissipating components such as engine covers, heat shields, and electronic enclosures could utilize these composites to improve heat management, prolonging the life of components and improving performance under high-temperature conditions (Zhang, et al., 2024).

Composites with higher groundnut shell content, such as **CMPS**$_1$ and **CMPS**$_2$, though lower in mechanical strength, offer the advantage of being more eco-friendly and cost-effective due to the use of agricultural waste as filler. These formulations could be valuable in industries looking to reduce environmental impact while still achieving acceptable performance levels (Sankaran, et al. 2024). Lightweight applications such as non-structural automotive parts, consumer goods, and packaging materials could benefit from these formulations. Their sustainability appeal could align with industry goals for greener production processes and materials that support circular economy principles (Mandala, et al., 2023; Sankaran, et al., 2024).

The lower thermal conductivity and reduced mechanical strength of GNS-rich composites (**CMPS**$_1$ and **CMPS**$_2$) suggest they could be suitable for insulation applications where high mechanical performance is not required. Industries such as construction, HVAC (heating, ventilation, and air conditioning), and refrigeration may use these composites for thermal insulation panels, duct linings, or other applications where the primary requirement is to minimize heat transfer rather than bear heavy loads (Macias, et al., 2019; Zhang, et al., 2024).

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study explored the mechanical and thermal properties of hybrid composites made from carbon fiber and groundnut shell. Key findings revealed that increasing the carbon fiber content consistently enhanced the tensile strength, impact resistance, hardness, thermal conductivity, and thermal stability of the composites. The highest-performing composite (CMPS$_5$) achieved a tensile strength of 300.31 MPa, impact resistance of 70.04 J/m², and thermal conductivity of 0.41 W/mK, demonstrating its suitability for industrial applications requiring high mechanical and thermal performance. In contrast, composites with higher groundnut shell content exhibited lower mechanical properties but offered advantages in sustainability and cost-effectiveness.

5.2 Recommendations

It is recommended that the tensile strength trade-off highlights the potential to tailor composites for specific industrial applications, balancing performance and environmental impact. Future work could focus on optimizing the filler interactions and further enhancing the mechanical properties through hybridization techniques or surface treatments.

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