Sound Absorption and Mechanical Characterization of Neem Gum and Coconut Dust-Based Hybrid Epoxy Composites

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This study focuses on the development and characterization of lightweight hybrid epoxy composites reinforced with neem gum (NG) and coconut dust (CD), targeting sustainable structural applications. Composites were fabricated with a constant 70% epoxy resin and varying NG and CD contents (5NG25CD, 10NG20CD, 15NG15CD, 20NG10CD, and 25NG5CD). Among these, the 15NG15CD composition demonstrated optimal performance, achieving a tensile strength of 42.1 MPa, flexural strength of 83.2 MPa, impact strength of 6.12 J, and Shore D hardness of 82. Water absorption tests showed significantly reduced moisture uptake (25.6%), indicating enhanced dimensional stability. Sound absorption tests revealed a peak sound absorption coefficient of 0.35 for the 20NG10CD composite, followed by 0.33 for 15NG15CD, indicating effective acoustic damping characteristics across all variants (ranging from 0.24 to 0.35). Scanning electron microscopy (SEM) revealed strong interfacial adhesion and uniform particle dispersion within the epoxy matrix, contributing to superior mechanical properties. These eco-friendly, lightweight composites exhibited excellent strength, moisture resistance, and versatility, making them suitable for lightweight structural components, automotive interiors, and sustainable packaging solutions.

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INTRODUCTION

There has been growing interest in natural and eco-friendly materials. This has led to the exploration of neem gum (NG) powder and coir dust (CD) particles as components in composite materials. These materials are gaining attention for their potential to enhance the mechanical properties of composites while offering sustainable and biodegradable alternatives to traditional synthetic fillers and resins. The composite materials reinforced with natural fibers and fillers have become a significant area of interest for various industries due to their promising environmental and mechanical advantages (Sandeep *et al.* 2024). However, the combined influence of NG powder and CD particles in bio-composite formulations, especially in terms of their mechanical performance and environmental benefits, remains underexplored. This study is designed to fill that gap, focusing on the impact these natural materials have on the structural, thermal, and mechanical properties of bio-based composites (Palaniappan *et al*. 2024; Prabakaran *et al*. 2024).

NG, which can be extracted from the seeds of the neem tree, has long been used for its medicinal properties in the pharmaceutical and food industries (Inegbedion *et al.* 2024; Manickaraj *et al*. 2025). Its natural properties, such as antimicrobial, anti-inflammatory, and antioxidant activities, make it a highly valuable resource. In the realm of composite materials, neem gum powder, a ground form of the gum, retains these beneficial properties and brings unique characteristics to composite matrices. As a natural binder and filler, NG powder enhances the mechanical properties of composites by improving their strength and stability (Bhowmik *et al.* 2024). This powder also has high water retention and gel-forming abilities, which have led to its exploration as a reinforcing agent in bio-composites designed to perform under variable environmental conditions (Manickaraj *et al.* 2024b).

Incorporating neem gum powder into composite formulations can significantly improve the bonding between the matrix material and the filler particles. Due to its fine particle size, neem gum powder facilitates better dispersion within the composite, ensuring more uniform distribution and enhancing the overall mechanical properties (Palanisamy *et al.* 2021; El-Tayeb *et al*. 2023). The presence of neem gum powder also has the potential to enhance the biodegradability of the composite materials. This is an important aspect, especially for industries that are focused on reducing the environmental impact of plastic waste. The use of neem gum in composites, which is biodegradable and derived from a renewable source, provides a promising alternative to synthetic fillers (Rathnam *et al.* 2022). This study aims to investigate how neem gum powder influences the biodegradability of bio-composites, particularly in terms of its ability to decompose naturally without leaving harmful residues in the environment.

One of the key challenges in bio-composites is water absorption, which can negatively affect the mechanical properties, particularly in outdoor or high-humidity environments. Neem gum powder, with its natural water retention properties, may mitigate this issue (Karuppusamy *et al.* 2025). The powder's ability to form a cross-linked gel matrix within the composite acts as a tortuous barrier, effectively restricting the ingress and flow of free water into the bulk material. This preservation of the surrounding matrix helps maintain the composite's mechanical integrity and dimensional stability in humid or wet conditions. The study will explore the impact of neem gum powder on the water resistance and moisture absorption rates of bio-composites, offering insight into its potential to enhance the longevity of the materials in varying environmental conditions. NG, on account of the properties mentioned above, can play various roles in composites, including bonding agent, sealant, and filler.

Coir dust, also known as coco dust, is another promising natural material that can be used as a filler in composite materials. It is derived from the processing of coconut husks, which are rich in lignocellulosic fibers. Coir dust is composed primarily of cellulose, hemicellulose, and lignin, which make it lightweight, porous, and highly water-retentive (Karuppusamy *et al.* 2023; Dhal *et al*. 2023; Inegbedion *et al*. 2024). The natural properties of coir dust make it an attractive alternative to synthetic fillers such as glass fibers or plastic particles. Coir dust has already found applications in the automotive, construction, and packaging industries due to its ability to enhance the mechanical properties of composites (Gogoi 2015; Sathish *et al.* 2024). In bio-composites, coir dust can be used to improve the mechanical strength, rigidity, and thermal properties of the matrix. Coir dust's fibrous nature acts as a natural reinforcement, contributing to increased tensile, flexural, and impact strength in the final composite material (Cruz *et al*. 2024). Furthermore, coir dust's low thermal conductivity makes it an excellent choice for improving the insulation properties of composite materials (Satankar *et al.* 2024). This property is particularly beneficial in applications where insulation against heat or sound is required, such as in automotive panels and construction materials. This study investigated the extent to which coir dust improves the mechanical performance of bio-composites, focusing on its impact on strength, rigidity, and thermal properties (Jannat 2023).

Another key benefit of coir dust is its sustainability. Coir dust is a byproduct of the coconut industry and is often considered a waste material. However, by incorporating coir dust into composite materials, this waste product can be given a new purpose, reducing the environmental impact of its disposal. The use of coir dust in composites not only provides a sustainable alternative to synthetic fillers, but it also helps in the efficient use of agricultural waste, contributing to a circular economy. This study will explore the environmental benefits of coir dust-based composites, particularly in terms of their potential to reduce the carbon footprint of manufacturing processes and the overall environmental impact.

While both neem gum powder and coir dust have been explored separately as natural components in composite materials, there has been limited research on the combined effects of these two materials in bio-composites (Hajare *et al*. 2023). The goal of this study was to investigate how neem gum powder and coir dust, when used together, influence the mechanical, thermal, and environmental properties of bio-composites. The hypothesis is that the combination of neem gum powder's gel-forming and water-retention properties with coir dust's mechanical reinforcement will result in a composite material with enhanced overall performance (Palanisamy *et al*. 2021).

The presence of neem gum powder is expected to improve the dispersion of coir dust within the composite matrix, leading to more uniform properties throughout the material. The interaction between NG powder and CD may also lead to a synergistic effect, where the strengths of both materials complement each other, resulting in bio-composites with improved mechanical strength, water resistance, and biodegradability (Gokul *et al*. 2024; Satankar *et al*. 2024). This research analyzed the potential for this synergistic effect by examining the interaction between NG and CD and their impact on the composite properties. In particular, the study assessed the tensile strength, flexural strength, impact resistance, and thermal conductivity of composites containing different ratios of neem gum powder and coir dust (Samanta *et al*. 2015; Aruchamy *et al*. 2025). The focus was on optimizing the combination of these components to create a composite material that is not only mechanically robust but also environmentally friendly and biodegradable. Furthermore, the study investigated the water absorption behavior of these composites, exploring how the combination of neem gum powder and coir dust affects the material’s moisture resistance and its ability to perform in humid environments (Katibi *et al*. 2024; Thangavel *et al*. 2024). The potential applications of neem gum powder and coir dust-based bio-composites are vast, spanning across several industries. In the automotive industry, the need for lightweight, durable, and sustainable materials is driving the search for alternative NG and CD. Neem gum powder and coir dust-based composites could be used in the production of non-structural automotive components, such as interior panels, dashboards, and door trims Gurusamy *et al*. 2024). The combination of NG and CD provides a cost-effective and environmentally friendly solution, while also contributing to improved thermal and sound insulation properties (Chandrika *et al.* 2024).

In the packaging industry, there is a growing demand for biodegradable and eco-friendly alternatives to conventional plastic materials. Bio-composites made from NG powder and CD offer a sustainable solution for packaging applications. These composites can be used to create biodegradable packaging materials that break down naturally over time, reducing the environmental impact of plastic waste (Manickaraj *et al.,* 2024c). This study also explored the use of NG powder and CD composites in food and beverage packaging, where biodegradability and non-toxicity are key considerations (Andezai *et al*. 2020; Katibi *et al.* 2024). In the construction sector, the use of natural materials such as neem gum powder and coir dust can contribute to the development of eco-friendly building materials. Bio-composites containing these materials could be used in the production of bricks, panels, and insulation materials, offering a sustainable alternative to conventional construction materials (Prashanth *et al*. 2024; Venkatesh 2024). The water retention and film-forming properties of neem gum powder, combined with the insulation properties of coir dust, could lead to the development of bio-composites that provide both strength and thermal insulation in construction applications (Chithra *et al.* 2024; Kabir *et al*. 2024). The agricultural industry also stands to benefit from these natural materials. Coir dust, with its excellent water retention properties, is widely used as a soil amendment, and when incorporated into composite materials, it can help in the creation of biodegradable plant pots and seedling trays. NG powder, with its antimicrobial properties, could also be used in agricultural applications where natural pest control and soil conditioning are required (Mohan *et al.* 2024; Lakshmaiya *et al*. 2024). The research will contribute to the growing body of knowledge on natural materials and help advance the development of sustainable, eco-friendly composites for use in a wide range of industries, including automotive, construction, packaging, and agriculture (Paul *et al*. 2021). Through this study, the potential for neem gum powder and coir dust to replace nonrenewable materials in bio-composites and contribute to a more sustainable future will be better understood.

EXPERIMENTAL

Materials

The materials used in this study included neem gum powder (NG), coconut coir dust (CD), and epoxy resin as the polymer matrix. Neem gum, a natural polysaccharide obtained from *Azadirachta indica*, was collected from the Pollachi region in Coimbatore, India. It was purified and ground into a fine powder, exhibiting gel-forming and bonding properties due to its composition of arabinose, galactose, and xylose (Bothiraj *et al.,* 2022). Coconut coir dust, a lignocellulosic byproduct primarily composed of cellulose, hemicellulose, and lignin, was sourced from Amman Impex, Pollachi, and sieved to eliminate coarse particles to ensure uniform filler distribution (Paul and Bhowmik 2024).

Fig. 1. (A) Neem gum; (B) neem gum powder

Fig. 2. (A) Coconut coir dust

The coir dust serves as a natural reinforcement that enhances mechanical strength and thermal insulation while offering environmental sustainability. The epoxy resin system, comprising resin and a polyamine-based curing agent, was procured from Covai Seenu Company, Coimbatore. This thermosetting polymer was selected on account of its excellent adhesion, mechanical integrity, and compatibility with bio-fillers, forming a rigid composite matrix upon curing (Paul *et al.* 2024). Figures 1 and 2 depict the neem gum and coir dust, respectively.

Preparation of Composite Samples

The composite samples were prepared by mixing neem gum powder and coir dust with epoxy resin, maintaining a constant resin content of 70% by weight. The materials were added in varying proportions in the range of 0 to 25%. (Sumesh *et al*. 2023; Manickaraj *et al*. 2024a). The mixture was then combined with a hardener in a specified ratio and stirred to ensure uniformity. Table 1 shows the composites designation for preparations.

Table 1. Composite Various Designations

S No	Fiber Content (%)		Epoxy Resin (%)	Composite Designation
	Neem Gum Particles (NG)	Coco Dust Particles (CD)		
1	5	25	70	5NG25CD
2	10	20	70	10NG20CD
3	15	15	70	15NG15CD
4	20	10	70	20NG10CD
5	25	5	70	25NG5CD
6	0	0	100	Without Filler

Manufacturing Methods

The manufacturing of hybrid epoxy composites involves the preparation and mixing of epoxy resin with reinforcing NG and CD. The process begins by accurately measuring and mixing the epoxy resin with a hardener in a fixed ratio to initiate curing. The NG and CD were added in varying proportions to ensure uniform dispersion within the resin matrix. The mixture is stirred mechanically for approximately 20 minutes to achieve homogeneous dispersion of the NG and CD. The mixture is then placed into a mold and subjected to compression molding, where heat and pressure are applied to shape and cure the composite material. The compression molding is carried out at a temperature of 120 °C and a pressure of 20 MPa, with a compression time of 30 min. This process ensured uniform distribution of the materials and helped to achieve a compact, durable structure. The compression molding technique also enhances the interfacial bonding between the NG and CD and the resin, improving the mechanical properties of the composite (Palanisamy *et al.* 2023b; Nithyanandhan *et al.* 2024). After curing, the composites are subjected to various tests, including tensile, flexural, impact, hardness, and water absorption tests, to assess their performance for applications in lightweight structural components, automotive interiors, and sustainable packaging solutions. Figure 3 shows the fabricated composite plate.

TESTINGS

Tensile Strength Test

Tensile strength was evaluated using a universal testing machine (UTM) following ASTM D638-14 (2022). Dog-bone-shaped specimens were prepared from each composite formulation (Mohit *et al*. 2021; Palanisamy *et al*. 2022a). The samples were subjected to a uniaxial tensile load until failure, and the maximum tensile strength was recorded in megapascals (MPa). The tensile strength helps assess the material's ability to withstand stretching forces and is critical for structural applications. The test was conducted using a Tinius Olsen H50KS UTM with a crosshead speed of 5 mm/min.

Flexural Strength Test

The flexural strength of the composites was determined using a three-point bending test (ASTM D790 2017). Specimens were placed on two supports, and a force was applied at the center to determine the maximum flexural strength (Iwuozor *et al*. 2024). This test provides insight into the bending performance of the composites, which is important for applications involving bending or deformation under load. The flexural tests were performed using the same Tinius Olsen UTM equipped with a standard 3-point bending fixture and a crosshead speed of 2 mm/min.

Impact Strength Test

The impact strength was measured using the Izod impact test (ASTM D256 2023). Notched specimens were subjected to a swinging pendulum, and the energy absorbed during fracture was recorded (Suja *et al*. 2024). The impact strength provides information about the material's ability to resist sudden, high-force impacts, which is crucial for applications exposed to dynamic forces. A Ceast Resil impact tester was used, fitted with a pendulum hammer.

Shore D Hardness Test

Shore D hardness was measured using a durometer (ASTM D2240 2021). The hardness test assesses the resistance of the composite surface to indentation, giving an indication of the material's stiffness and ability to withstand wear and tear. A higher Shore D hardness value indicates a harder, more rigid material (Palanivel *et al*. 2024). The measurements were taken using a Mitutoyo 811-336-10 Shore D durometer

Water Absorption Test

This test indicates the composite's ability to resist water absorption, which is important for applications exposed to moisture or outdoor environments. Water absorption (ASTM D570 2022) was measured by immersing the composite samples in distilled water at room temperature. The initial weight of the samples was recorded, and after 48 h of immersion, the samples were weighed again after removing excess water from the surface (Wadgave *et al*. 2024). The percentage water absorption was calculated by Eq. 1.

$$\text{Water Absorption (\%)} = \frac{\text{Final Weight} - \text{Initial Weight}}{\text{Initial Weight}} X100 \qquad (1)$$

Sound Absorption Test

The sound absorption coefficient of the composites was measured using an impedance tube following ASTM E1050 (2012). The test involved placing circular composite specimens inside the tube, where sound waves were directed at the sample, and the proportion of absorbed sound energy was recorded. The sound absorption coefficient was calculated as the ratio of absorbed sound energy to incident sound energy, with values ranging between 0 (total reflection) and 1 (total absorption). The test was conducted over a frequency range of 100 to 3200 Hz**.** A Brüel & Kjær Type 4206 two-microphone impedance tube setup with a Type 3560-B-120 front-end analyser was used. The results demonstrated that the composition and distribution of NG and CD significantly influenced the acoustic properties of the composites (Berardi and Iannace 2015; Tiuc *et al.* 2016). Increased porosity and internal friction contributed to enhanced sound absorption, facilitating better dissipation of sound energy. However, excessive NG and CD content led to irregular porosity, slightly reducing absorption efficiency. The sound absorption coefficient was generally found to increase with frequency, with peak values typically observed between 2000 and 2500 Hz depending on the composition. The optimal balance between the NG and CD resulted in improved acoustic damping characteristics, making these composites suitable for noise-reducing applications in automotive interiors, construction materials, and acoustic panels.

Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy (Carl Zeiss model EVO MA 15, Carl Zeiss GmBH, Jena, Germany) was used to analyze the microstructure of the fractured composite surfaces. SEM imaging provided detailed insights into the NG and CD dispersion, interfacial bonding between the epoxy resin and NG and CD, and the failure mechanisms within the composites (Manickaraj *et al*. 2022; Palanisamy *et al*. 2023a). SEM analysis helped evaluate the morphology and identify any voids, cracks, or poor NG and CD-matrix interaction that could affect the material's mechanical performance.

RESULTS AND DISCUSSION

Tensile Test

The tensile strength test (Fig. 3) measures how much force a material can endure before breaking under tension. In this study, the tensile strength of composites made from epoxy resin mixed with varying amounts of NG and CD was evaluated. The composite without any fillers exhibited a tensile strength of 32.2 MPa, serving as the baseline for comparison. When NG and CD were added, the tensile strength of the composites increased, with the highest value recorded for the composite containing 15% neem gum and 15% CD (42.1 MPa). This indicates that the combination of both NG and CD significantly enhanced the composite's ability to resist tensile forces. However, as the NG and CD content increased beyond this balanced mix, such as in the 20% NG and 10% CD formulation (40.4 MPa) and the 25% NG and 5% CD formulation (38.2 MPa), the tensile strength slightly decreased. This suggests that there is an optimal balance of components, and exceeding this balance may lead to issues such as poor dispersion or weak bonding between the NG and CD and the resin matrix (Andezai *et al*. 2020). The results demonstrate that adding NG and CD improves the mechanical properties of epoxy composites, with the best performance achieved when the NG and CD are proportioned evenly (Muthalagu *et al*. 2021; Fragassa *et al*. 2024).

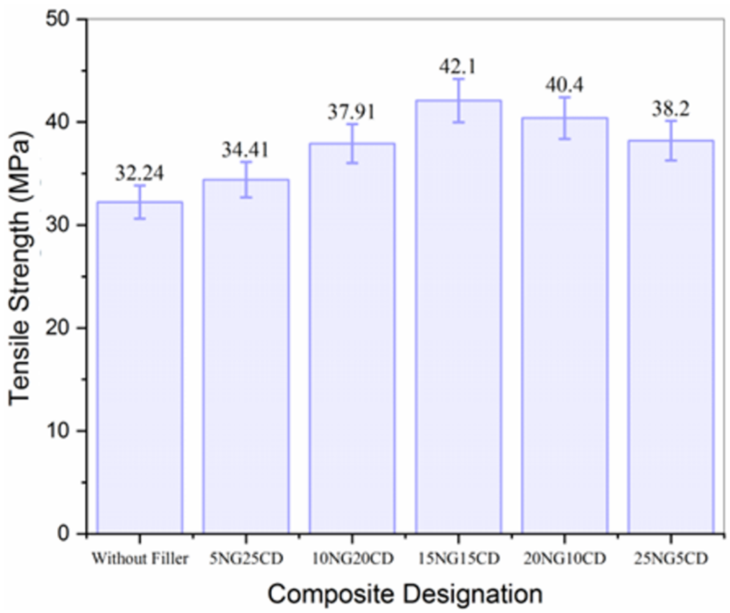

Fig. 3. Tensile strength of the composites

Flexural Strength

The flexural strength of epoxy composites with varying amounts of NG and CD was tested, as shown in Fig. 4. The unfilled epoxy resin had a flexural strength of 52.3 MPa, serving as the baseline. The composite without fillers had a flexural strength of 52.3 MPa, serving as the baseline. As NG and CD were added, the flexural strength of the composites increased, with the highest flexural strength (83.2 MPa) achieved by the composite containing 15% NG and 15% coir dust. This suggests that a balanced combination of NG and CD enhances the composite's ability to resist bending and deformation, providing greater structural integrity under bending forces. Composites with NG and CD ratios, such as 10% NG and 20% CD (76.55 MPa) and 20% NG and 10% CD (81.2 MPa), also exhibited improved flexural strength compared to the unfilled epoxy resin. However, as the NG and CD content increased further (25% NG and 5% CD), the flexural strength (79.8 MPa) slightly decreased, indicating that beyond a certain level of NG and CD content, the performance began to plateau or decline. This decrease could be attributed to factors such as poor NG and CD distribution or an imbalance in the bonding between the resin and NG and CD. The addition of NG generally improves the flexural strength of the epoxy composite, with the best performance observed in composites containing equal proportions of both NG and CD (Sundram *et al*. 2024). The results indicate that an optimal

NG content is crucial for achieving the best mechanical properties, especially for applications involving bending or flexural forces.

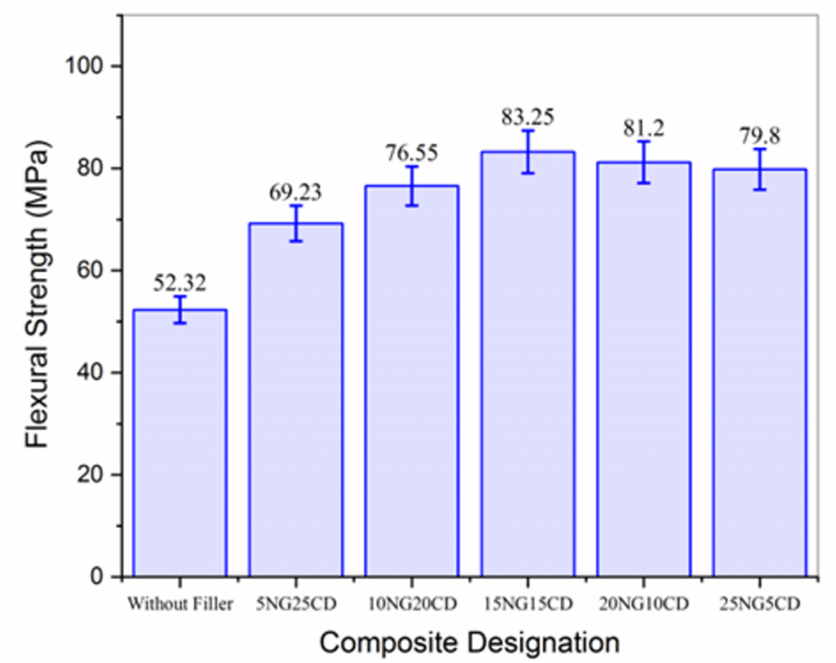

Fig. 4. Flexural strength

Impact Strength

The impact strength of composite materials containing varying amounts of NG and CD was evaluated, alongside a baseline composite made of epoxy resin without NG and CD, as shown in Fig. 5. The composite without NG and CD had an impact strength of 4.03 J, serving as the baseline. The addition of NG and CD generally increased the impact strength, with the highest value (6.12 J) observed in the composite containing 15% NG and 15% CD. This improvement can be attributed to the better distribution and reinforcement provided by the NG and CD, which help absorb and dissipate impact energy more efficiently. The presence of NG, with its high viscosity and gel-forming properties, likely enhanced the bonding between the resin and NC and CD, while CD, being a lignocellulosic material, contributes to increased toughness and crack resistance. Other NG and CD combinations also showed an increase in impact strength compared to the unfilled resin, such as 10% NG and 20% CD (5.48 J) and 20% NG and 10% CD (5.98 J), indicating that both NG and CD contribute positively to the composite's impact resistance. However, composites with 25% NG and 5% CD showed a slight decrease in impact strength (5.56 J). This decrease could be due to an imbalance in the NG and CD content, where excessive NG may result in poor NG and CD dispersion or weaker bonding with the matrix, reducing the composite's ability to withstand sudden impacts. These results suggest that the addition of NG and CD improves the material's ability to withstand impact forces, with balanced NG and CD content yielding the best performance (Firdaus *et al*. 2024; Palanisamy *et al*. 2024).

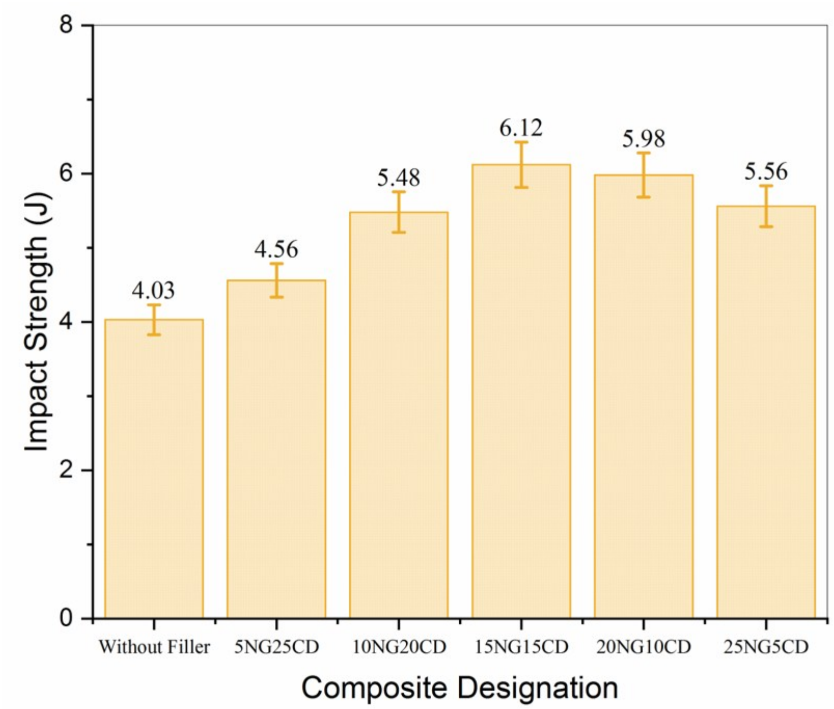

Fig. 5. The impact strength of the composites

Shore D hardness

The Shore D hardness of composite materials with varying amounts of NG and CD was evaluated, along with a baseline composite made of epoxy resin without NG and CD (Fig. 6). The unfilled composite exhibited a Shore D hardness of 60.6, which serves as the baseline. The addition of NG and CD generally resulted in an increase in hardness, with the highest value (82) observed in the composite containing 15% NG and 15% CD. This enhancement in hardness can be explained by the reinforcing effect of the NG and CD. NG, which is rich in polysaccharides, has gel-forming properties that likely improve the bonding between the resin and the NG and CD, thereby increasing the overall rigidity of the composite. CD, being a lignocellulosic material, provides structural strength due to its cellulose and lignin content, contributing to the composite's resistance to indentation. Combinations of NG and CD, such as 10% NG and 20% CD (77.2) and 20% NG and 10% CD (80), also showed improvements in hardness compared to the unfilled resin, demonstrating that both NG and CD enhance the material's rigidity and durability. However, the composite with 25% NG and 5% CD exhibited a slight reduction in hardness (79), indicating that a high proportion of NG may lead to poor NG and CD dispersion or weaker interfacial bonding, reducing the composite's overall stiffness (Govindarajan *et al*. 2024; Kumar *et al*. 2024). This suggests that while NG and CD enhance the hardness of epoxy-based composites, an optimal balance between NG and CD is crucial for achieving the best mechanical properties.

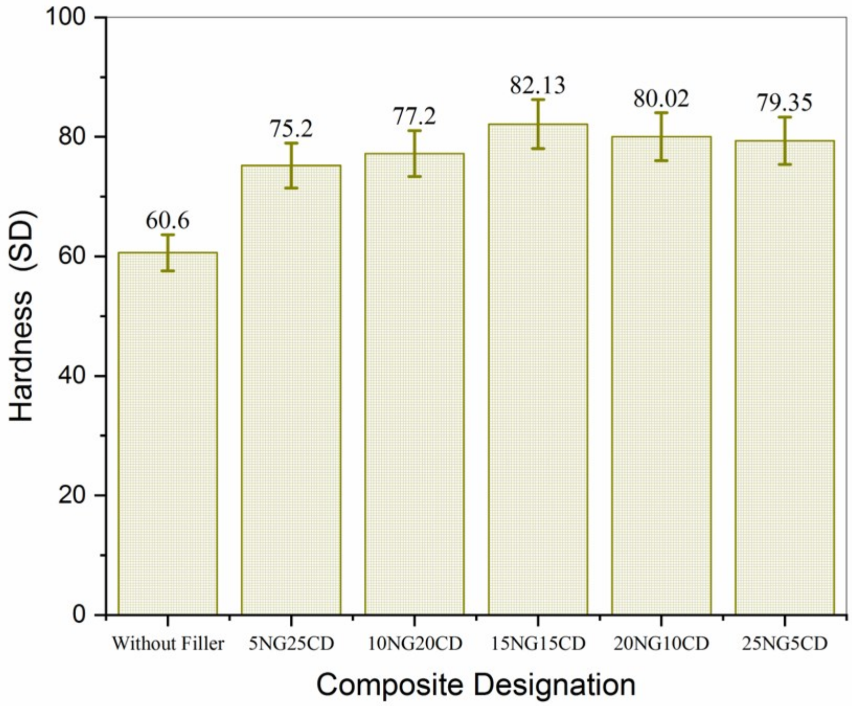

Fig. 6. Hardness of the composites

Water Absorption Test

This study compared the water absorption (Fig. 7) of composites with varying NG and CD to an unfilled epoxy resin baseline. The water absorption percentage for the unfilled composite was 42.17%, serving as the baseline for comparison. When NG and CD were added, the water absorption generally decreased, with the lowest value (25.6%) observed in the composite containing 15% NG and 15% CD. This decrease can be attributed to the role of the NG and CD in reducing the overall porosity of the composite, limiting the material's ability to absorb water. NG, with its polysaccharide content, has hydrophilic properties but can help form a stronger bond between the resin and NG and CD, potentially reducing the number of free spaces for water absorption. As a lignocellulosic material, CD contributes to the reduction in water uptake due to its fibrous structure, which may create a denser network within the composite. Other NG and CD combinations also showed reduced water absorption compared to the unfilled resin, such as 10% NG and 20% CD (38.8%) and 20% NG and 10% CD (34.0%). However, composites with 25% NG and 5% CD exhibited a slight increase in water absorption (34.8%) compared to other NG and CD combinations, possibly due to an imbalance in the NG and CD distribution or excessive hydrophilic content from the NG, which may have increased the moisture uptake. In conclusion, the incorporation of NG and CD helped to reduce the water absorption of epoxy-based composites, with balanced NG and CD content yielding the best performance (Jabeen *et al*. 2024; Karuppiah *et al*. 2020; Subash Chandrabose *et al*. 2024). The reduction in water absorption is critical for improving the durability and long-term stability of the composite materials in humid or wet conditions.

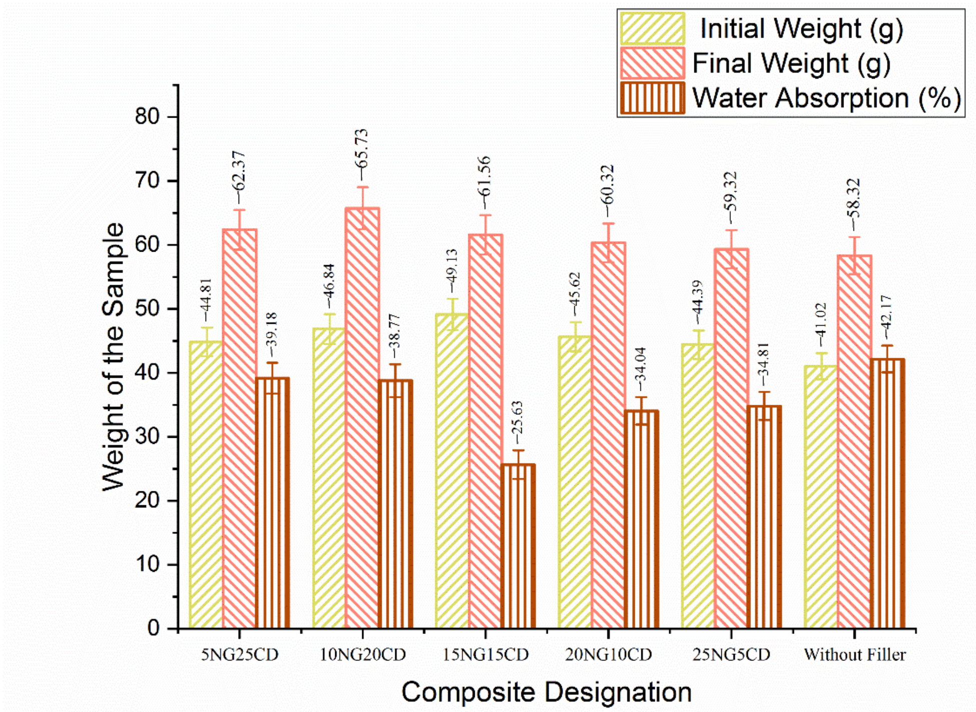

Fig. 7. The water absorption analysis of the composites

Acoustic Characterization

The sound absorption coefficient (SAC) (Fig. 8) of NG and CD reinforced hybrid epoxy composites varies with NG and CD composition, ranging from 0.24 (5NG25CD) to 0.35 (20NG10CD), with the highest absorption observed in the 20NG10CD composition. This variation is influenced by the interplay of porosity, NG and CD dispersion, and matrix- NG and CD interactions (Tiuc *et al*. 2016; Cai *et al*. 2021). NG, being an amorphous biopolymer, contributes to internal friction and microvoid formation, which enhances energy dissipation and sound absorption. In contrast, CD, a particulate filler, increases composite density and stiffness, reducing the formation of interconnected pores, which are essential for effective sound damping. At lower NG content (5NG25CD), the dominance of CD resulted in a denser structure with reduced sound absorption (0.24). As NG content increased, the porosity of the composite increased, facilitating better acoustic energy dissipation, as seen in 10NG20CD (0.28) and 15NG15CD (0.33). The maximum SAC (0.35) at 20NG10CD suggests an optimal balance where sufficient porosity was achieved without compromising mechanical integrity (Koizumi *et al*. 2002; Wang *et al*. 2022). However, further increasing NG content to 25NG5CD slightly reduced SAC (0.32), which was likely due to irregular porosity leading to inefficient sound wave attenuation. These findings highlight the critical role of NG and CD ratio optimization in designing composites with superior acoustic damping properties, making them suitable for noise reduction applications in automotive, construction, and packaging industries.

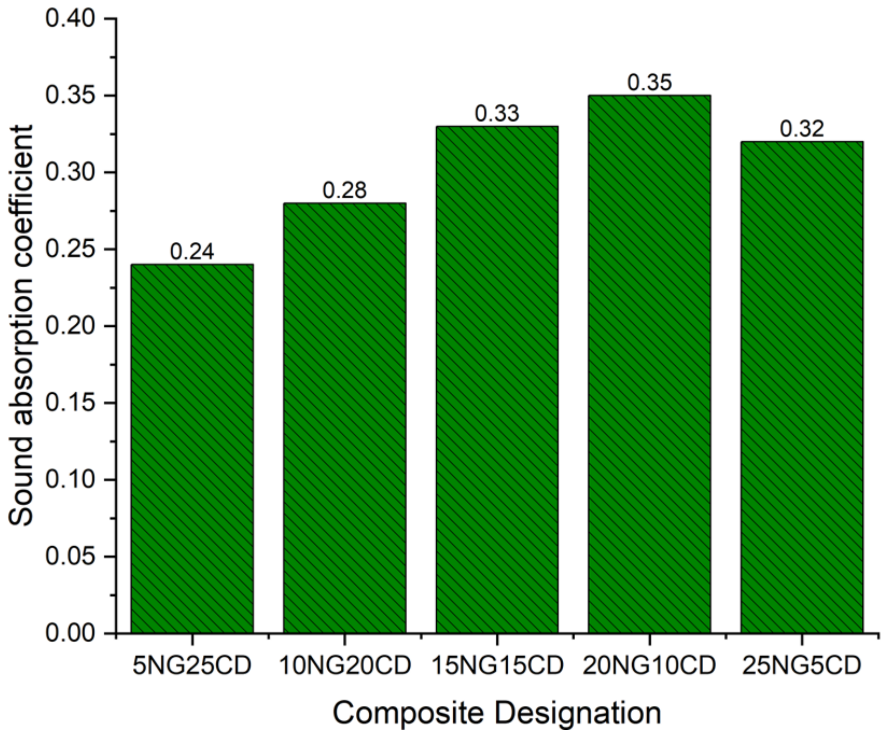

Fig. 8. The sound absorption coefficent behavior of the composites

SEM Analysis

Scanning electron microscopy is used to examine the surface morphology and structure of materials at a high resolution (Viswanathan and Krishnan 2024). Figure 9 shows SEM analysis of the composite samples and the dispersion and bonding of NG and CD within the epoxy resin matrix. The SEM images of the composites with NG and CD showed a more consistent and well-dispersed structure compared to the unfilled epoxy resin (Palanisamy *et al*. 2022b; Ramesh *et al*. 2024). The presence of NG and CD particles in the composites helped enhance the interfacial bonding between the resin and the NC and CD, leading to improved mechanical properties. The NG and CD also appeared to reduce the presence of voids, which are typically areas of weakness in the material. In composites with higher NG and CD content, such as the 15% NG and 15% CD formulation, the SEM analysis revealed a smoother and more compact surface, indicating better interaction between the NG and CD and the matrix. The SEM analysis provided valuable information on the microstructural characteristics of the composites, helping to explain the observed mechanical and physical property variations.

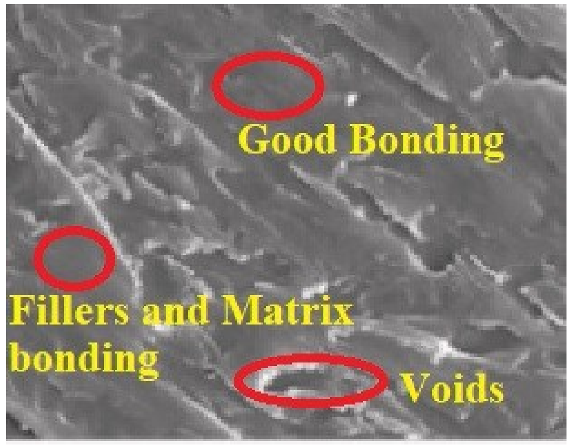

Fig. 9. SEM of 15NG15CD

Overall, these lightweight hybrid composites exhibited excellent mechanical strength, moisture resistance, and sound absorption capabilities, making them ideal candidates for applications in lightweight structural components, automotive interiors, and sustainable packaging solutions. This research highlights the potential of neem gum and coconut dust as sustainable, cost-effective reinforcements for the development of advanced composite materials with multifunctional properties.

CONCLUSIONS

This study successfully developed and characterized lightweight hybrid epoxy composites reinforced with neem gum (NG) and coconut dust (CD) for sustainable structural applications. The comprehensive analysis revealed that the incorporation of these eco-friendly NG and CD significantly enhanced the mechanical, physical, and acoustic properties of the composites.

1. Mechanical Properties

- The tensile strength of the composites increased with the incorporation of NG and CD, with the highest value observed in the 15% NG and 15% CD formulation, indicating better load-bearing capacity.
- Similarly, flexural strength showed significant enhancement across all NG and CD formulations, with the 15% NG and 15% CD composite again exhibiting the highest value, suggesting improved resistance to bending and deformation.
- Impact strength also improved with the addition of NG and CD, particularly in the balanced 15% NG and 15% CD formulation, which exhibited the highest impact resistance, highlighting the composites' ability to absorb sudden forces.
- Hardness values were enhanced in all NG and CD composites, with the greatest increase observed in the 15% NG and 15% CD formulation, indicating greater rigidity and wear resistance.
- Water absorption tests revealed a decrease in moisture uptake in composites with NG and CD, with the 15% NG and 15% CD composite demonstrating the lowest absorption, enhancing the material's durability in humid environments.

- Scanning electron microscope (SEM) analysis provided further insights, confirming that the NG and CD were well-dispersed and contributed to stronger bonding with the resin, which led to improved overall structural integrity. However, composites with excessive NG and CD content (such as 25% NG) showed slight decreases in performance due to poor dispersion and agglomeration of NG and CD.

2. **Acoustic Properties**
   - Sound absorption tests showed that the composites exhibited varying acoustic performance depending on the NG-to-CD ratio. The sound absorption coefficient ranged from 0.24 (5NG25CD) to 0.35 (20NG10CD), with the highest absorption observed for the 20NG10CD composition, indicating optimal porosity and internal damping characteristics. The 15NG15CD composite, which exhibited the best mechanical properties, also demonstrated a relatively high sound absorption coefficient (0.33), making it an excellent candidate for applications requiring both strength and acoustic performance.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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