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RESEARCH ARTICLE

Mechanical Characterization and TOPSIS-Based Selection of Hybrid Natural Fiber-Cenosphere Reinforced Polymer Composites for Automotive Structures

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ABSTRACT – This study evaluates a novel composite material for automobile structural applications, consisting of a polymer-based matrix material reinforced with hybrid natural fibers (Jute, Kenaf, Coir) and cenospheres. Natural fibers provide sustainability and lightweight benefits, while cenospheres enhance mechanical properties and reduce density. We assess tensile, flexural, and impact strengths, examining the effects of 2 vol% and 4 vol% cenosphere concentrations. Scanning electron microscopy analyzes microstructural features and interfacial bonding. Results indicate that kenaf-reinforced laminates exhibit an 86.36% higher tensile strength than jute and are 2.73 times stronger than coir composites. While 2% cenosphere enhances tensile and flexural properties, 4% improves impact strength across all composites. Notably, 2% cenosphere boosts tensile strength by 28%, 23.4%, and 28.57% for jute, kenaf, and coir, respectively. Our findings highlight the synergistic effects of hybrid fibers and cenosphere reinforcements, with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach identifying the Kenaf/Epoxy composite with 4 vol% cenosphere as the superior option for practical applications. This research contributes innovative, sustainable solutions for enhancing automotive structural performance while minimizing weight.

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1. INTRODUCTION

The aerospace and auto industries currently strongly value lightweight construction and high durability. These industries have been increasingly focusing on the minimization of component weight, which has resulted in higher usage of fiber-reinforced polymer (FRP) composites[1], [2]. These composites have gained popularity because they use synthetic fibers, including carbon, glass, and aramid. However, there is now more interest in FRP composites made from natural fibers due to the growing impact of legislation and environmental concerns. Both a desire for responsible development and a dedication to preserving the welfare of future generations are driving this shift toward sustainability [3], [4]. Natural fibers with desirable qualities, such as jute, hemp, flax, coir, and kenaf, have emerged as viable alternatives to synthetic fibers due to their lower weight, less environmental effect, and cost. However, the performance characteristics of natural fibers hinder their full utilization in engineering domains [5], [6], [7].

Hybrid natural fiber composites are engineered materials that enhance mechanical, thermal, and environmental qualities by combining two or more natural fiber types in a single polymer matrix [8], [9]. Utilizing the distinct advantages of several fibers, these composites provide a well-rounded performance suited to certain uses. By increasing qualities like tensile strength, flexural modulus, and impact resistance, hybridization lessens the drawbacks of individual fibers, such as moisture absorption and poor thermal stability. The automotive, construction, and packaging industries see these materials becoming increasingly important because they offer sustainable solutions and biodegradable properties that can substitute traditional synthetic fiber composites. The use of renewable resources in production and the reduction of environmental impact through composite manufacturing enables hybrid natural fiber composites to advance circular economic models [10], [11]. Inorganic particle fillers such as nano/micro-SiO_2, Al_2O_3, $Mg(OH)_2$, $CaCO_3$, $MgCO_3$, TiO_2 and carbon nanotubes are frequently used to improve FRP composite properties. Fillers originally helped reduce raw material costs but now serve a critical function in enhancing composite mechanical properties [2], [12], [13].

Cenospheres represent intriguing and versatile materials that show great promise for application across various industries. Tiny hollow spheres emerge during combustion processes in industrial and power generation sectors [14], [15], [16]. The composition of cenospheres includes silica and alumina, among other oxide minerals, which grant them unique properties that make them ideal for multiple applications. The hollow structure of cenospheres results in an extraordinarily low density that makes them lightweight. Lightweight materials that maintain functional integrity for applications such as insulation, lightweight concrete and polymer composites benefit from this feature. The spherical shape and minuscule particle dimensions of these substances enhance fluid flow properties, which makes them suitable for drilling fluids, coatings, and paints. The introductory section sets the foundation for a detailed exploration of cenospheres by discussing their exceptional properties and production methods along with their diverse applications. Both researchers and

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companies can use microspheres to drive innovation and develop better materials, which will lead to a more sustainable future through comprehensive exploration of their properties [17], [18], [19].

One of the main advantages of incorporating cenospheres into polymer composites is the striking decrease in overall density with retention or improvement of mechanical strength. Unlike strengthening materials with a high weight ratio, these hollow microspheres can provide excellent reinforcement due to their intrinsic strength as well as their low density, which will not significantly increase the weight of composites. This is particularly attractive in domains like aerospace and automotive engineering that require lightweight components, as it enhances fuel efficiency, payload capacity, and performance [20]. Moreover, incorporating cenospheres could enhance the dimensional stability and impact resistance of the composite. The intrinsic stiffness of these microspheres provides additional support to the polymer matrix and facilitates better energy absorption and distribution during an impact. This property will be especially relevant for applications that are demanding materials in terms of dynamic loading and adverse environmental conditions.

Cenospheres significantly increase the stiffness-to-weight ratio of composites, making them ideal for lightweight applications in the automotive, marine, and aerospace industries. The hollow structure reduces the overall density of the material with no loss of compressive strength. Fabric structures play a vital role in absorbing energy and resisting impact, both essential in structural applications exposed to potential impact or dynamic loading [5], [21]. Composites are more heat resistant thanks to cenospheres' superior thermal stability and reduced thermal conductivity. Applications needing thermal insulation or exposure to high temperatures, such as those in industrial or aerospace settings, benefit greatly from this feature [22]. Sustainable engineering principles are adhered to, as lightweight composites containing cenospheres are not only stronger but use fewer raw materials, thus having less environmental impact. These benefits highlight their contemporary structural applications and growing use. Again, combining cenospheres with polymer matrices is a way to develop materials with improved mechanical properties. By strategically incorporating cenospheres, known for their lightweight, tough, and high-performance characteristics, industries can address the evolving requirements of modern engineering while aligning with sustainability and resource efficiency principles [23].

Multi-Attribute Decision-Making (MADM) is a well-liked and efficient analytical method for evaluating and ranking solutions based on multiple conflicting criteria [24]. This becomes important in decision-making across various fields, including material science, engineering, management, etc. MADM techniques have been developed to obtain objective and systematic evaluations, helping researchers to choose the preferred alternative among many competing alternatives incorporating both quantitative and qualitative characteristics. To solve complex decision-making problems, key MADM techniques such as the Weighted Sum Model (WSM), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Analytic Hierarchy Process (AHP) are used [25]. These methods often involve defining criteria, assigning a weight to each criterion based on its relative importance, normalizing data to ensure comparability, and assigning a score or ranking to each choice. In material science, MADM processes have been essential for enhancing composite design, material selection, and performance evaluation. By using MADM techniques, researchers may systematically assess and rank composite materials with a range of properties, such as mechanical strength, thermal stability, and environmental impact. By employing a MADM technique to evaluate and rank the produced composites based on their mechanical properties, this study offers a robust framework for material selection and application.

One well-known multi-attribute decision-making (MADM) technique that makes it easier to rank and evaluate options based on several competing factors is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS offers an organized method for making decisions based on the idea of finding the alternative that is most similar to the ideal solution and most dissimilar from the negative perfect solution. Building a decision matrix, normalizing the data, and assigning weights to the criteria based on their importance are all steps in the process. After calculating each alternative's distance from the ideal and negative-ideal solutions, a proximity coefficient is derived that can be used for ranking. TOPSIS is widely used in material science to optimize material selection, performance evaluation, and composite design because of its ease of use, computational efficiency, and capacity to handle both benefit and cost factors. The mechanical properties of the created composites are thoroughly analyzed and ranked in this work using TOPSIS, providing insightful information for material optimization [13], [26], [27], [28].

As far as the authors are aware, there isn't much literature on using cenosphere to improve the mechanical properties of continuous natural fiber-reinforced composites, despite the fact that a large portion of the earlier literature describes its use in composites made out of FRP, primarily for fibers made from synthetic materials, small fibers, and cement-like substances. Therefore, an important strategy to change the properties of composites is tried.

2. METHODS AND MATERIAL

2.1 Materials

Jute, kenaf, and coir fibers, as well as cenosphere and epoxy resin, are used in this work to create the suggested composites. The suggested composite was reinforced with cenosphere, which was bought from local vendors. The recommended composites are laid up by hand. The fabric has been divided to have a measurement of 300 mm square. The L12 epoxy and K6 hardeners are mixed in a 100:10 weight ratio using an automated stirrer. A 3 mm thick laminate is made from three layers of jute, kenaf, or coir cloth. To ensure easy removal of the laminate, the entire mold surface is coated with wax. The jute, kenaf, or coir fabric is pre-soaked in a blend of L12 epoxy and K6 hardener before being placed in the mold. Excess resin is removed using a hand roller, and this process is repeated for all three fabric layers. Once the third layer is in place, the top mold plate is positioned over it. The assembly is then subjected to compression for 24 hours to facilitate curing. Before putting the epoxy on the fabric, the cenosphere is mixed into it to create hybrid composites. As a result, Table 1 lists the created composites and their identification, and Figure 1 depicts a schematic of the composites' creation process.

Table 1. Proposed composites and their designations

Prepared Composites	Designation
Jute+Epoxy	JE
Jute+ Epoxy +2% Cenosphere	JE-C2
Jute+ Epoxy +4% Cenosphere	JE-C4
Kenaf+Epoxy	KE
Kenaf+Epoxy+2% Cenosphere	KE-C2
Kenaf+Epoxy+4% Cenosphere	KE-C4
Coir+ Epoxy	CE
Coir+ Epoxy +2% Cenosphere	CE-C2
Coir+ Epoxy +4% Cenosphere	CE-C4

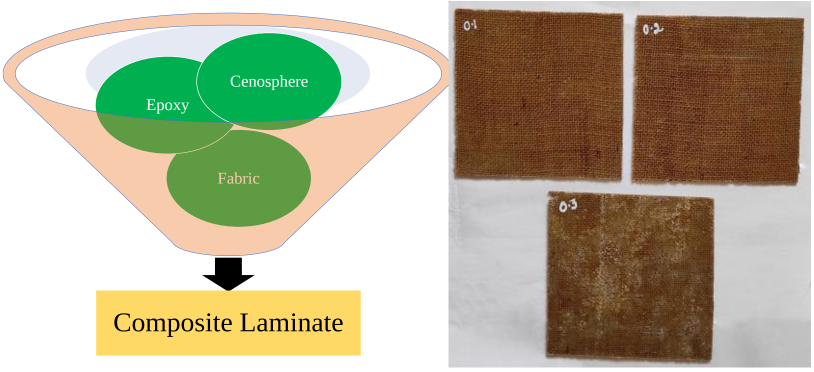


Figure 1. Schematic of composite laminate preparation and the prepared laminates

2.2 Mechanical Characterization

In line with ISO 13934-1 standards, the tensile characteristics of the fabrics were assessed. The suggested composites' tensile behavior was evaluated in accordance with ASTM D 3039 at a cross-head speed of 2 mm/min[29] using Instron 3382 USA at room temperature. Each mixture was tested on three samples, and the average outcome was displayed. The ASTM D 790 standard was used to test the bending strength of the suggested composites[30] using Instron 3382 USA at room temperature. Testing was executed on three samples from each composition, and the displayed value represents the average result. The impact strength of suggested composites was researched in accordance with ASTM D256 criteria[31] using Tinius Olsen, USA equipment at room temperature. In order to make contact with the specimen, the machine's connected pendulum is dropped, and the specimen's capacity to absorb energy is noted. The test is performed three times, and the results are presented as an average. The composite specimens used for mechanical characterization are presented in Figure 2.


Flexural Test Specimen

Impact Test Specimen

Tensile Test Specimen

Figure 2. Specimen used for mechanical characterization

2.2 Theoretical Principles of TOPSIS

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making method that identifies the best alternative by evaluating its proximity to an ideal solution (best-case scenario) and its distance from a negative-ideal solution (worst-case scenario). The process involves constructing a decision matrix, normalizing it to make criteria dimensionless, and weighting the normalized values based on criteria importance. The ideal solution is determined by maximizing benefit criteria and minimizing cost criteria, while the negative-ideal solution does the opposite. Euclidean distances from these solutions are computed for each alternative, and a closeness coefficient is calculated to rank the alternatives, with higher values indicating closer proximity to the ideal solution. TOPSIS is simple, computationally efficient, and accounts for both best and worst cases, but it can be sensitive to weight selection and normalization methods.

3. RESULTS AND DISCUSSIONS

3.1 Tensile Properties

An overview of results pertaining to the tensile strength of the fabrics used in the present study is presented in Table 2. The tensile properties of the fibers, as shown in Figure 3, provide insight into their mechanical behavior in both the warp and weft directions. The warp direction refers to the fibers aligned along the length of the fabric, while the weft direction refers to the fibers running across its width.

Table 2. Tensile behavior of fabrics used

Fiber	Tensile Load (N)		Rate of Elongation (%)	
	Warp	Weft	Warp	Weft
Jute	1215	1190	7	6.5
Kenaf	2378	2285	7.5	7.3
Coir	992	915	6.5	6.3

The results indicate that both the tensile strength (the maximum stress the fibers can withstand before breaking) and elongation (the extent to which the fibers stretch before failure) are marginally higher in the warp direction compared to the weft direction. This slight improvement in the warp direction could be attributed to the inherent characteristics of fiber placement during the weaving process, where warp fibers are often subjected to greater tension and stress, making them slightly stronger and more resistant to elongation.

However, because the fabric used in the study has an even composition, meaning an equal number of warp and weft threads and a uniform material across the fabric, the difference in strength and elongation between the two directions is minimal. A desirable feature of composite materials, particularly when uniform load distribution is needed, is this uniformity, which guarantees that the mechanical properties are essentially the same in both orientations. Such mechanical property constancy can help provide more consistent and dependable performance in applications where the composite is subjected to complicated loading circumstances. Overall, the even structure reduces a great deal of variability between the two orientations, albeit the modest superiority in the warp direction may be the result of minute variations in how the fibers align or are tensioned during weaving.

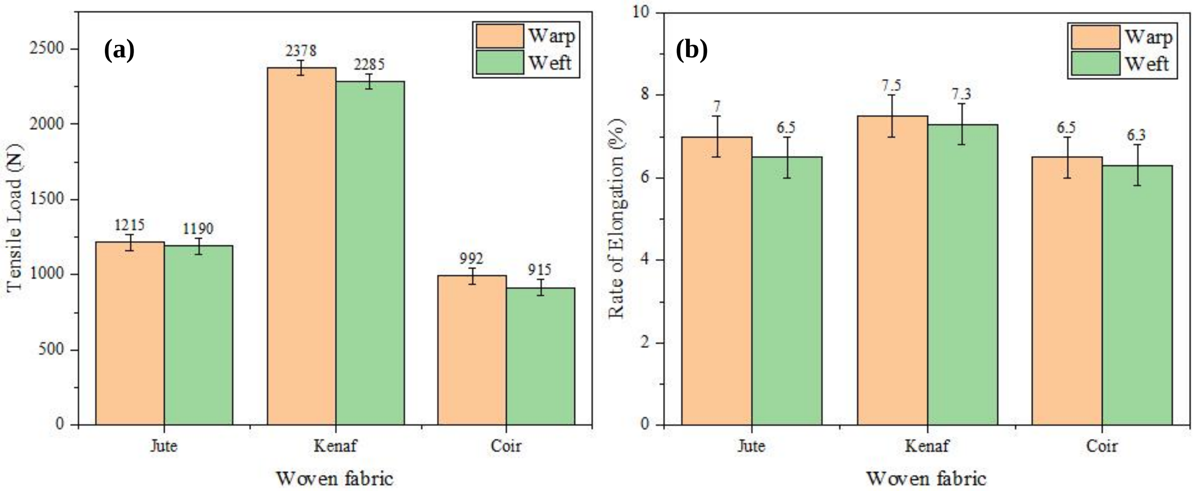


Figure 3. Characteristics of fabrics used in the present study under tensile load

When the tensile characteristics of kenaf, jute, and coir fibers are compared, it can be shown that kenaf has the highest tensile strength, followed by jute and coir fibers. This pattern holds true for both weft and warp directions. For instance, tanh kenaf has a tensile strength that is 2.39 times larger in the warp direction and 2.49 times bigger in the weft direction than coir fiber and is arguably a better option when you consider all of the above. Kenaf is better than jute as it has 1.95 times higher and 1.92 times greater tensile strength in the warp and weft directions, respectively. The meaning of this drastic impulse resistance strength is that kenaf is less liable to break than cotton, where strength is critical. Tufting into applications that require strength as the breakage-free rate between the two fibers means kenaf is a more resistant material.

Kenaf has even better elongation characteristics than either coir or jute, in addition to high tensile strength. The elongation of kenaf in the warp and weft directions is 15.38% and 15.87% higher than that of coir, respectively. Kenaf performs 7.14% and 12.3% better than jute with respect to elongation in the warp and weft orientations. Kenaf fibers display a higher ductility due to their appreciable tensile elongation (100 – 400%), aiding in the absorption of energy prior to fracture– critical for applications that require robustness and toughness. The higher cellulose content, better homogeneity, and lower microfibrillar angle of kenaf could be the primary reason for the superior mechanical properties [32]. Figure 4 displays the tensile testing experimental setup and pictures of the failed specimens. This gives insight into the failure processes at work for each type of fiber and enables a visual grasp of how the various fibers respond under stress.

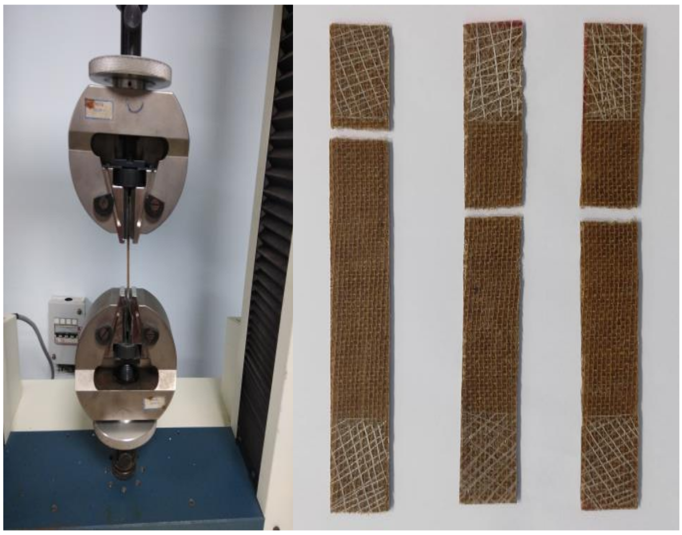


Figure 4. Tensile testing arrangement and failed specimen

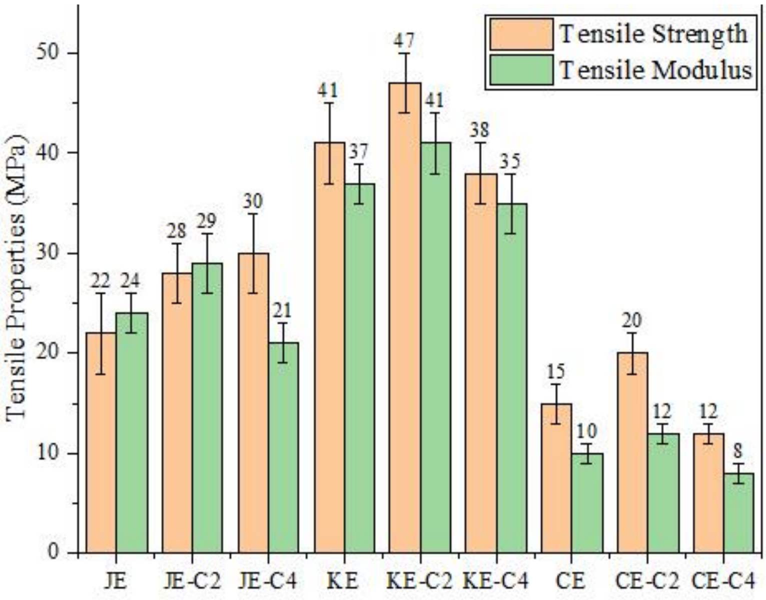
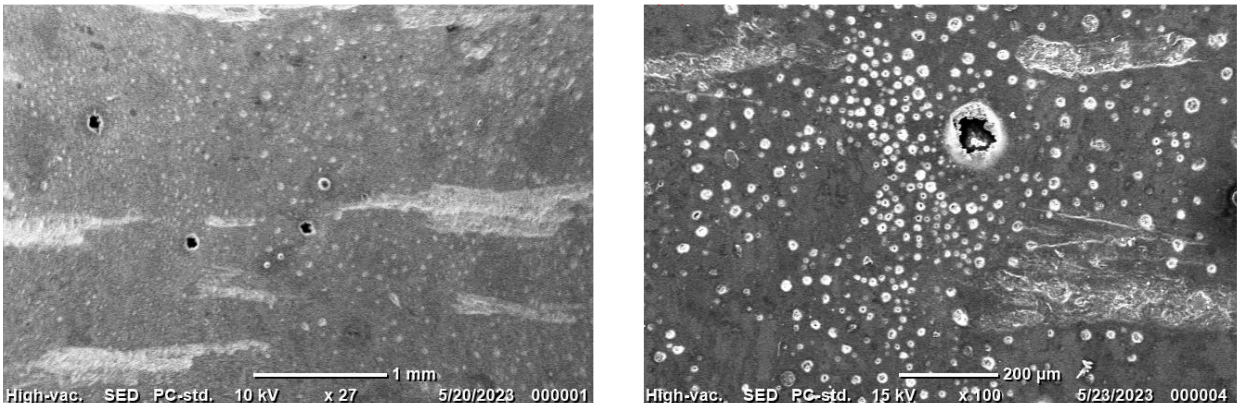


Figure 5. Variation in tensile characteristics of suggested composites

The inherent characteristics of the reinforcing fibers have a significant impact on the tensile performance of fiber-reinforced composites. Tensile characteristics of kenaf, jute, and coir fibers used as laminate reinforcements were investigated in this work. The laminates reinforced with kenaf had the highest tensile strength, with jute and coir laminates following closely behind. Kenaf laminates have a tensile strength of 41 MPa and a modulus of 37 MPa. Kenaf laminates outperformed jute-reinforced composites in terms of strength and modulus by 86.36% and 54.16%, respectively. Kenaf laminates have better tensile strength and modulus than coir-reinforced laminates by 2.73 and 3.7 times, respectively. These results are shown in Figure 5, demonstrating the better tensile characteristics of kenaf laminates. The study also explored the effect of incorporating cenosphere inclusions into the NFRP laminates at different volume fractions (2% and 4%) to assess their influence on tensile performance. The addition of 2% cenosphere resulted in a slight improvement in the tensile strength and modulus across all fiber-reinforced laminates. However, increasing the cenosphere content to 4% had a detrimental effect on the tensile properties, indicating that higher filler content may lead to performance degradation.

Among the three types of laminates, coir laminates demonstrated the most significant improvement in tensile strength (33.33%) with the addition of 2% cenosphere, followed by jute laminates (27.27%) and kenaf laminates (14.63%). This suggests that coir fibers, which inherently have the lowest tensile strength, benefit the most from the addition of cenosphere. Regarding tensile modulus, jute laminates exhibited the highest increase (20.84%) with the addition of 2% cenosphere, followed by coir laminates (20%) and kenaf laminates (10.81%). The improvement in tensile properties with 2% cenosphere can be attributed to better interfacial bonding between the matrix and the cenosphere particles. This enhanced bonding improves stress transfer efficiency within the laminate, resulting in better tensile performance. However, when the cenosphere content was increased to 4%, the tensile properties declined. This decline is likely due to the strong, cohesive forces between the cenosphere particles at higher loadings, which lead to particle agglomeration.

Scanning Electron Microscope (SEM) images, presented in Figure 6, confirm the morphological differences between the 2% and 4% cenosphere laminates. In the 2% cenosphere specimens, the cenosphere particles are uniformly distributed throughout the matrix, contributing to improved mechanical properties. However, in the 4% cenosphere specimens, significant aggregation is observed, which is responsible for the reduction in tensile strength and modulus. These findings suggest that while a small amount of cenosphere can enhance the tensile performance of NFRP laminates, excessive filler content may lead to poor dispersion and diminished mechanical properties.



(a) (b)

Figure 6. Scanning electron microscopic images (a) homogenous dispersion at 2% cenosphere and (b) aggregation of 4% cenosphere in the epoxy matrix

The tension stress-strain curves for the laminated materials, as depicted in Figure 7, exhibit typical patterns commonly observed in composites. These curves reveal that the laminates do not undergo a sudden, brittle failure; instead, they exhibit pseudo-plastic behavior before reaching their ultimate tensile strength (maximum stress). This pseudo-plastic behavior is characterized by a gradual yielding or deformation under stress, allowing the material to absorb and distribute the applied load more effectively before failure. In contrast to purely brittle materials, which fracture suddenly without significant prior deformation, laminated materials, particularly those reinforced with natural fibers, tend to display a degree of ductility. This is probably because of the laminates' multi-layered structure and the fiber reinforcement, which keeps the material from breaking suddenly and allows it to tolerate greater pressures. The presence of fibers helps spread the stress, enabling the laminate to continue bearing the load until it fails, even though microcracks or localized damage may start to appear inside the matrix or at the fiber-matrix interface as the load is applied. The early linear portion of the stress-strain curve is usually when the material behaves elastically or returns to its initial shape when unloaded. The curve starts to diverge from linearity as the stress rises, indicating the start of microcrack initiation or plastic deformation. This region is known as the pseudo-plastic region, which is the area where the material has to spread and change shape before it can tolerate pure stress across the full cross-section. Since the material is able to absorb energy in the plastic regime before breaking, the reduction of stress after the maximum may fall gradually and progressively down to breaking rather than giving way suddenly. This pseudo-plastic behavior is particularly beneficial for applications that require both strength and toughness in the material. It shows that the laminated composites can withstand a lot of strain, which makes them appropriate for application in structural or impact-resistant components where energy dissipation and gradual failure are preferred. The safety and durability of these materials under tensile stress conditions are improved by the lack of abrupt, catastrophic breakdown.

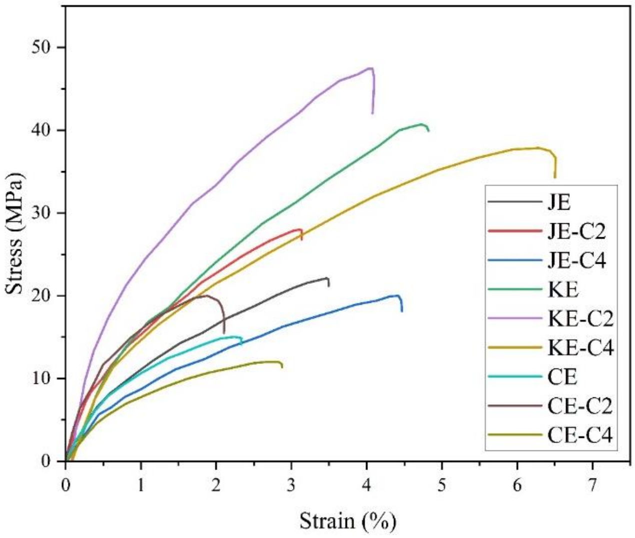


Figure 7. Stress-strain behavior of proposed composites under tensile loading

Significant variations in tensile strength and elongation were found between the control (cenosphere-free) and cenosphere-embedded laminates in the study of the effects of cenosphere loading on natural fiber-reinforced polymer (NFRP) laminates. In order to determine how cenosphere, a lightweight, hollow filler, affects mechanical, performance-specifically tensile strength and elongation—it was added to jute, kenaf, and coir laminates at two volume fractions (2% and 4%). According to the study, laminates with 4% cenosphere had a higher average strain capacity-the amount of strain or elongation a material can withstand before failing—than laminates with 2% cenosphere and control laminates without cenosphere. According to this finding, laminates that include more cenosphere are more ductile, meaning they may stretch farther before breaking. The cenosphere's capacity to improve the composite's energy absorption qualities, giving it greater flexibility and durability under tensile loads, could be the cause of this improved strain capacity.

The incorporation of 4% cenosphere notably enhanced the elongation capacity when compared to the typical behavior observed in particulate-reinforced composites, where excessive filler content often leads to embrittlement. This peculiar performance can likely be attributed to the unique structure of cenospheres, which facilitates localized stress relief within the matrix. Being both lightweight and hollow, cenospheres contribute to minor matrix deformations under tensile loading, thereby reducing the risk of sudden fracture initiation and subsequent failure. Consequently, laminates containing 4% cenosphere demonstrated improved strain performance, indicating an increased capacity for tensile stress tolerance.

Nevertheless, with greater cenosphere loadings, particularly above 4%, the tensile strength usually decreased despite the increased strain capacity. This trade-off implies that although a larger cenosphere content improves the laminates' ductility and strain tolerance, it may also result in the introduction of stress concentration sites or a decrease in the overall effectiveness of the link between the fibers and the matrix. Lower tensile strength could result from the increased elongation at 4% cenosphere content because the bigger volume of filler may obstruct stress transfer between the fibers and matrix. Each fiber type interacts differently with the matrix and the cenosphere particles, leading to variations in how the laminate responds to tensile loading. Nonetheless, the study underscores the role of cenospheres as a modifier of mechanical properties, specifically enhancing ductility and strain capacity at higher loading levels, which may be desirable in applications requiring flexible, impact-resistant materials.

The observed increase in elongation in cenosphere-embedded laminates is likely due to weak adhesion between the cenosphere particles and the matrix material. In composites, effective load transfer between the matrix and reinforcing particles is critical for maximizing mechanical properties like tensile strength. However, in this case, the relatively weak bonding between the hollow cenosphere particles and the matrix likely results in debonding under tensile stress, meaning that instead of contributing to the load-bearing capacity, the cenospheres detach from the matrix when subjected to stress. This debonding process leads to increased elongation as the matrix continues to deform without efficiently transferring the stress through the cenospheres.

The agglomeration of cenosphere particles-where they cluster together instead of dispersing uniformly-exacerbates this debonding phenomenon. When particles agglomerate, they form weak points within the composite. These areas of particle clustering create stress concentrations, further reducing the efficiency of load transfer between the matrix and the reinforcing particles. As a result, rather than distributing the applied load evenly, these clusters can act as failure initiation sites, which contributes to the limited functionality of the cenospheres as effective reinforcing elements. While this weak interaction and particle agglomeration lead to increased elongation, it is typically at the expense of tensile strength. The increased elongation is associated with more ductile behavior, but it also signals a reduction in the stiffness and load-bearing capacity of the material. This behavior is consistent with the hypothesis that inorganic fillers, such as cenospheres, may interfere with the mobility of polymer chains in the matrix. The rigid, inorganic nature of the cenosphere particles can hinder the movement of the macromolecules in the polymer matrix, restricting their flexibility and increasing the overall stiffness of the laminate. However, when the adhesion between the filler and matrix is poor, as seen here, the stiffness may not increase significantly, and the composite may exhibit more ductile behavior with higher elongation. The outcomes obtained align with existing literature on the subject[33], [34].

3.2 Flexural Properties

The flexural testing arrangement and the failed specimen are presented in Figure 8. The bending characteristics of the laminated materials (Figure 9) show a similar pattern to the tensile values. The laminates' strength at bending and elasticity was increased by the addition of 2% Cenosphere; however, increasing the cenosphere concentration decreased the flexural strength and modulus values. When compared to the control laminates, the addition of Cenosphere by 2% resulted in an enhancement of 28%, 23.4% and 28.57% in tensile strength of jute, kenaf and coir-reinforced composites. Similarly, the addition of Cenosphere by 2% results in an improvement of flexural modulus by 10%, 10.37% and 11.50%, respectively, for jute, kenaf and coir-reinforced composites. The reinforcing action of the cenosphere can be used to explain these improved flexural qualities. The composite matrix and connected interfaces effectively absorbed energy, which increased the flexural strength. However, the insertion of 4% cenosphere resulted in an 8.69%, 4.44%, and 16.6% decrease in flexural strength and a 0.5%, 2.25%, and 12.89% decrease in modulus of jute, kenaf, and coir laminates, respectively, when compared to corresponding reference laminates.

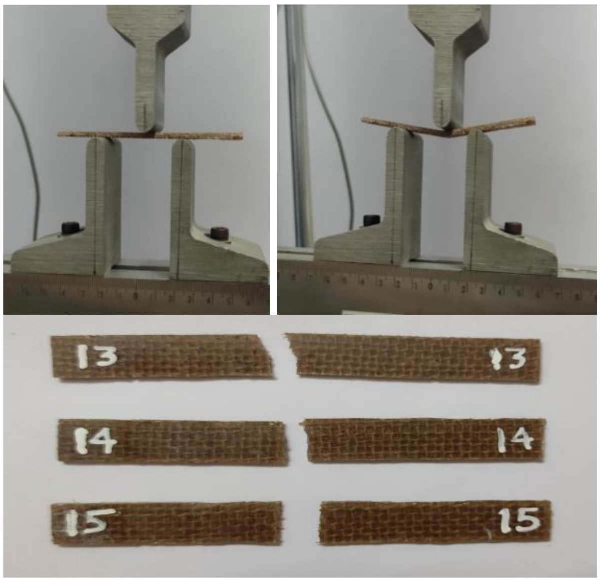


Figure 8. Flexural testing arrangement and failed specimen

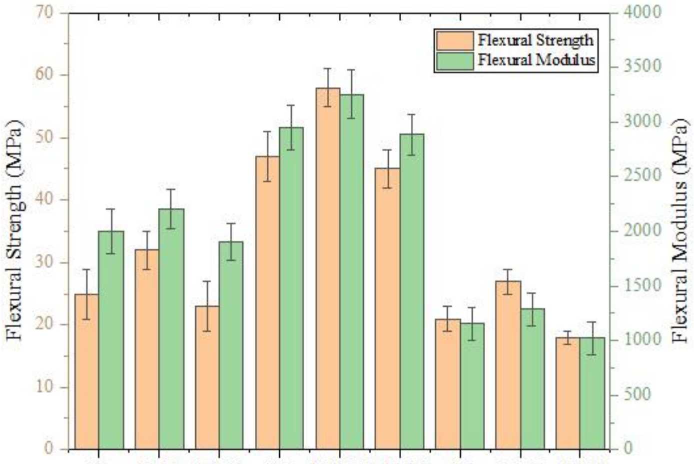


Figure 9. Flexural properties of proposed composites

This decline in properties could potentially be linked to the inclusion of 4% cenospheres, which caused a reduction in the matrix's volume fraction. As a result, the laminates faced challenges in efficiently transmitting applied stress from the matrix to the cenospheres. The closer spacing between cenosphere particles likely led to the aggregation of fillers and their entrapment within the matrix, contributing to the diminished flexural characteristics at the 4% cenosphere inclusion level. Another plausible explanation for the decrease in flexural properties could be the increasing presence of voids within the laminates as the filler content rose. These observations are consistent with prior research, where the introduction of filler initially improved mechanical properties up to a certain point, followed by a subsequent decrease as the filler content continued to rise[35]. Figure 10 illustrates the influence of cenosphere loading on flexural stress plotted against strain (%).

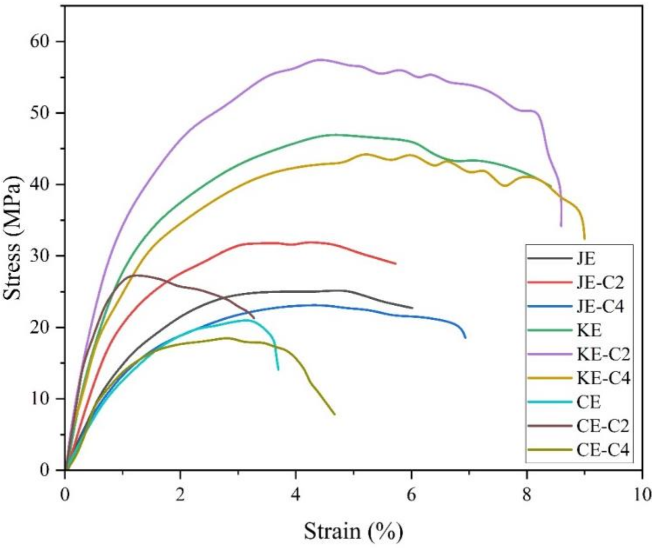


Figure 10. Stress-strain plot of proposed composites subjected to flexural loading

The bending response of laminates varied significantly with cenosphere loading. Non-linear curves in the laminates indicate the viscoelastic behavior of composites. The curves demonstrate a 2% improvement in stiffness and ultimate stress. Cenosphere loading and further cenosphere addition reduce stiffness and ultimate stress. The results reveal that low cenosphere concentration (2%) imparts stiffness to composite laminates, but greater loading (4%) increases laminate ductility. The results are explained in the same way as the tensile characteristics. The existence of cenospheres retards or halts the propagation of fractures through mechanisms like deflection or crack bridging. The development of a characteristic zigzag crack route (seen in Figure 10) on the flexural stress-strain curves of laminates loaded with 2% and 4% cenospheres is indicative of this phenomenon.

3.3 Impact Properties

The impact testing arrangement and the failed specimen are presented in Figure 11. Impact performance evaluation of the manufactured laminates involved the utilization of the Charpy impact test with unnotched specimens. Among the tested materials, kenaf laminates exhibited the most remarkable energy absorption capacity, outperforming jute and coir laminates. Analysis of impact strength data pertaining to control specimens revealed that kenaf woven laminates demonstrated an impact strength surpassing that of jute and coir woven laminates by 50% and 225%, respectively (as depicted in Figure 12). This greater strength can be due to the significant strain-to-failure qualities of kenaf's fabric, as illustrated in Table 2. The inclusion of cenospheres in the composition directly and positively influences the impact characteristics of the laminates. For specimens containing 2% cenosphere loading, the un-notched impact strength surpassed that of control laminates made from jute, kenaf, and coir by 108.3%, 61.11%, and 37.5%, respectively. Moreover, when loaded with 4% cenospheres, the laminate's impact strength increased by 3.66, 2.88, and 2.5 times correspondingly. This phenomenon can be attributed to the enhanced plastic deformation occurring around the cenospheres within the matrix under impact stress. This mechanism potentially absorbs the shock energy and impedes the formation of new fractures.

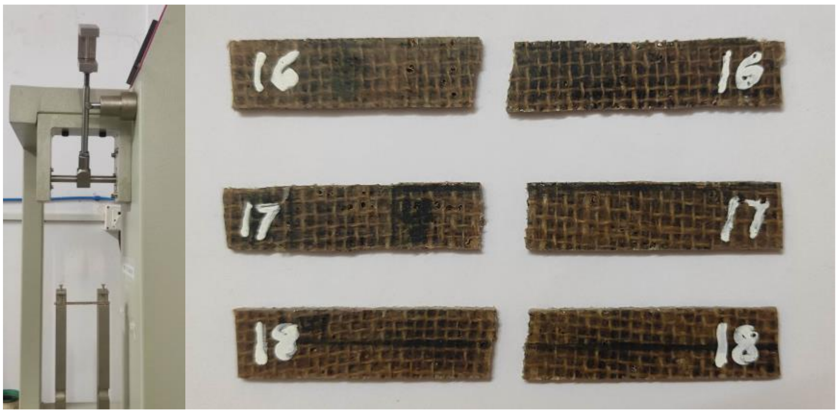


Figure 11. Impact testing arrangement and failed specimen

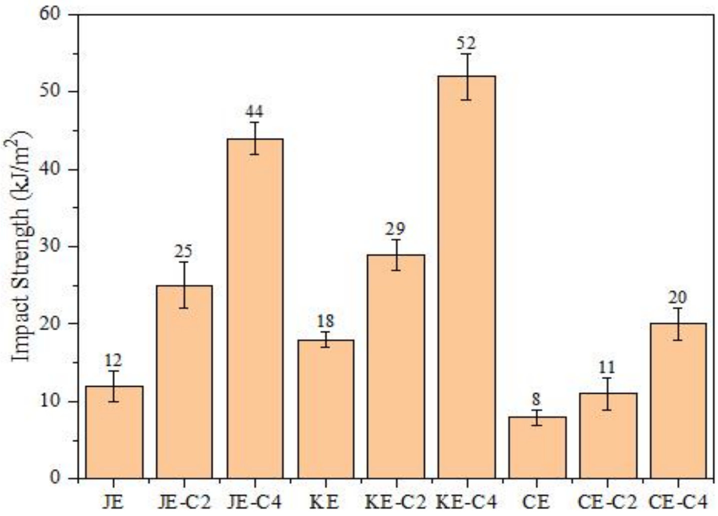


Figure 12. Composites with varied impact strength

Similar patterns were seen in prior investigations[36], where the inclusion of fillers improved the impact characteristics. Another factor might be the impact strength's reliance on a full stress transfer channel[37], which plays an important role in transmitting stress and, therefore, improving impact strength. Because of the presence of an epoxy matrix, hinge fracture was found in all cases. The results align with established composite reinforcement theories, particularly the role of filler distribution and fiber orientation in enhancing mechanical properties. The findings confirm that moderate cenosphere inclusion (2 vol%) strengthens the composite structure by improving stress transfer and load distribution. However, an excessive cenosphere content (4 vol%) leads to a decline in tensile and flexural properties, likely due to stress concentration effects and potential weakening of the fiber-matrix interface. This behavior underscores the need for optimized filler content to maximize mechanical efficiency in composite design.

Furthermore, the impact strength trends observed in the study highlight the role of energy absorption mechanisms in hybrid composites. Unlike tensile and flexural properties, impact resistance either remained stable or improved with increasing cenosphere content. The highest impact strength was achieved with kenaf-based laminates, which exhibited 50% and 225% greater energy absorption than jute and coir-based composites, respectively. This supports the premise that cenosphere-filled NFRCs can effectively dissipate impact energy, making them suitable for automotive applications where crashworthiness is a key consideration.

3.4 Fractography

The mechanisms involved in the failure of the developed composites are discussed with the help of Figure 13. The fractography images reveal key failure mechanisms in fiber-reinforced composites, including fiber breakage, matrix cracking, delamination, and fiber pull-out. Fiber breakage occurs when the applied load exceeds the tensile strength of the fibers, indicating their critical role in load-bearing. Matrix cracking and delamination are prominent failure modes, with matrix cracking resulting from stress concentrations and delamination caused by weak interlayer bonding or out-of-plane stresses, leading to reduced structural integrity. Fiber pull-out, observed in the third image, suggests inadequate fiber-matrix adhesion, where fibers partially detach, dissipating energy but compromising strength. These combined brittle (matrix cracking and delamination) and ductile (fiber pull-out) failure modes highlight the importance of optimizing fiber-matrix adhesion, fiber distribution, and matrix toughness to enhance the composite's mechanical performance and mitigate these failure mechanisms.

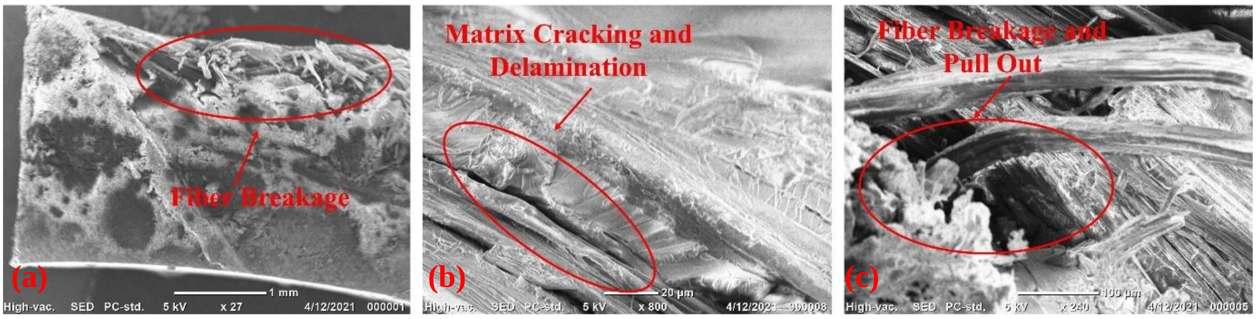


Figure 13. Fractographic images of composites showing (a) fiber breakage; (b) matrix cracking along with delamination and (c) fiber breakage and pullout

3.5 TOPSIS

Table 3 provides the consolidated mechanical properties of the developed composites. The findings show that while KE-C2 lacks impact strength, it has superior tensile and flexural qualities. In terms of impact strength, KE-C4 outperforms the other composites. Because of this, the designer finds it challenging to choose the best composite. Therefore, the MADM approach is used to choose the best composites out of all of them. Table 4 lists the characteristics that define performance together with their implications. Tables 5 and 6 display the decision matrix and the normalized matrix that was created based on the experiments that were conducted, respectively. Using the outcomes of every test for every composite configuration, the decision matrix is created.

Table 3. Mechanical properties of hybrid natural fiber composites

Composite	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m^2)
JE	22	25	12
JE-C2	28	32	25
JE-C4	20	23	44
KE	41	47	18
KE-C2	47	58	29
KE-C4	38	45	52
CE	15	21	8
CE-C2	20	27	11
CE-C4	12	18	20

Table 4. Performance defining attributes description used in MADM

Performance defining attributes (PDA's)	PDA's Implication
Tensile strength (Mpa)	Higher the better
Flexural strength (MPa)	Higher the better
Impact strength (kJ/m^2)	Higher the better

Table 5. Decision matrix formulated for the TOPSIS method

Composite Configuration	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m^2)
JE	22	25	12
JE-C2	28	32	25
JE-C4	20	23	44
KE	41	47	18
KE-C2	47	58	29
KE-C4	38	45	52
CE	15	21	8
CE-C2	20	27	11
CE-C4	12	18	20

Table 6. Normalized matrix used in TOPSIS approach

Composite Configuration	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m^2)
JE	0.250	0.235	0.142
JE-C2	0.318	0.301	0.295
JE-C4	0.227	0.217	0.520
KE	0.465	0.443	0.213
KE-C2	0.533	0.546	0.343
KE-C4	0.431	0.424	0.615
CE	0.170	0.198	0.095
CE-C2	0.227	0.254	0.130
CE-C4	0.136	0.170	0.236

The weights for the qualities are determined by the entropy approach and are reported in Table 7. The weighted normalized matrix is then formed using these weights, as indicated in Table 8. The positive and negative ideal solutions are calculated and tabulated in Table 9. The composite configurations are ranked according to their relative closeness, separation from the positive ideal solution, and separation from the negative ideal solution, as indicated in Table 10. The configuration with the highest relative closeness is ranked number one, and the configuration with the lowest relative closeness is ranked number nine.

Table 7. Computed weights using the entropy method

Criteria	Weightage
Tensile strength (Mpa)	0.276
Flexural strength (MPa)	0.228
Impact strength (kJ/m^2)	0.496

Table 8. Weighted normalized matrix used is TOPSIS approach

Composite Configuration	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m^2)
JE	0.069	0.054	0.070
JE-C2	0.088	0.069	0.147
JE-C4	0.063	0.049	0.258
KE	0.128	0.101	0.106
KE-C2	0.147	0.124	0.170
KE-C4	0.119	0.097	0.305
CE	0.047	0.045	0.047
CE-C2	0.063	0.058	0.065
CE-C4	0.038	0.039	0.117

Table 9. Positive and negative ideal solution used in TOPSIS approach

Criteria	Positive Ideal Solution	Negative Ideal Solution
Tensile strength (Mpa)	0.147	0.038
Flexural strength (MPa)	0.124	0.039
Impact strength (kJ/m^2)	0.305	0.047

Table 10. Ranking of composites developed according to TOPSIS

Composite configuration	Separation from positive ideal solution	Separation from negative ideal solution	Relative closeness	Rank
JE	0.257	0.042	0.140	7
JE-C2	0.178	0.116	0.393	4
JE-C4	0.122	0.213	0.635	2
KE	0.202	0.125	0.382	5
KE-C2	0.135	0.186	0.579	3
KE-C4	0.040	0.277	0.875	1
CE	0.288	0.011	0.038	9
CE-C2	0.263	0.036	0.121	8
CE-C4	0.234	0.070	0.231	6

3.6 A Comparative Analysis

The acquired findings pertaining to mechanical properties are compared with those of the composites available in the literature [38] with an intention for usage in automobile applications. The same is presented in Table 11.

Table 11. Comparative study of mechanical properties

Properties	Value obtained through developed composites	Literature[38] *(neem wood waste-15%+coir-5%,+ sugarcane bagasse-5 %)*
Tensile Strength (MPa)	47 (KEC2)	9.178
Flexural Strength (MPa)	58 (KEC2)	9.6
Impact Strength	52 kJ/m^2 (KEC4)	2J

The comparison analysis reveals that the suggested composites have superior mechanical qualities to the hybrid composites identified in the literature. The hybrid natural fiber and cenosphere-reinforced polymer composites studied here offer a sustainable and lightweight alternative for automotive applications, balancing cost-effectiveness with mechanical performance. These composites provide sufficient tensile, flexural, and impact strength for non-load-bearing components like door panels, dashboards, and bumpers, though their strength may be lower than conventional glass or carbon fiber-reinforced composites. Cenospheres contribute to significant weight reduction and improved impact resistance, enhancing fuel efficiency and crashworthiness. Natural fibers are instrumental in facilitating the automotive sector's shift towards more eco-friendly materials, as they contribute to cost reduction while simultaneously improving sustainability. When taking all factors into account, these hybrid composites prove to be highly effective for crafting environmentally conscious and lightweight components in vehicles. Furthermore, with further material optimization, these composites have the potential to be employed in a broader range of applications.

The significant enhancements in tensile, flexural, and impact strength are underscored through a comparative analysis of the mechanical properties of the newly developed hybrid natural fiber and cenosphere-reinforced polymer composites alongside previously reported data in the literature. The findings reveal that these composites offer a lightweight, sustainable, and practical alternative for non-load-bearing automobile components, such as bumpers, dashboards, and door panels. Although they do not possess the mechanical strength of traditional glass or carbon fiber-reinforced materials, the advantageous balance between cost-effectiveness and weight reduction presents a compelling benefit.

4. CONCLUSIONS

This study illustrates the potential advantages of incorporating cenospheres into high-performance, lightweight, non-fiber-reinforced composites (NFRC). The results highlight the significant impact of cenosphere concentration on the mechanical properties of the laminates, providing valuable insights for their practical use across various sectors, including the automotive industry. Notably, the mechanical characteristics of these composites reveal superior performance along the warp direction in contrast to the weft direction. Among the natural fibers tested, kenaf exhibited the highest tensile strength, outperforming jute and coir fibers. Specifically, kenaf-reinforced laminates achieved a tensile strength and modulus of 41 MPa and 37 MPa, respectively, which are 86.36% and 54.16% higher than jute and significantly higher (2.73 and 3.7 times, respectively) than coir-reinforced composites. Incorporating 2 vol% cenospheres enhanced the tensile characteristics (strength and modulus) of the laminates, whereas increasing the cenosphere content to 4% led to a decline in these properties. This suggests that higher cenosphere concentrations may induce stress concentrations or weaken the fiber-matrix interface, which could limit tensile performance. A 2% cenosphere addition resulted in improved bending strength and stiffness across the composites. For instance, tensile strength improvements of 28%, 23.4%, and 28.57% were observed in jute-, kenaf-, and coir-reinforced composites, respectively. However, further increases in cenosphere content led to reductions in flexural strength and modulus, emphasizing the need for optimized cenosphere concentrations for structural applications. Unlike tensile and flexural properties, the impact strength of the NFRCs remained stable or even improved with increased cenosphere content. Kenaf-reinforced laminates exhibited the highest energy absorption capacity, with impact strength surpassing jute and coir laminates by 50% and 225%, respectively. This highlights the suitability of kenaf-based laminates for applications requiring superior impact resistance. Based on the TOPSIS analysis, the KE-C4 composite emerges as a favorable choice, balancing mechanical properties for practical applications. These findings suggest potential use cases in automotive interior components, panels, and other lightweight structures where energy absorption, impact resistance, and moderate strength are critical. While the study demonstrates the benefits of cenosphere incorporation, further research is needed to understand long-term performance under cyclic loading, environmental exposure, and thermal variations.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

Vishwas Mahesh: Research idea, analysis of results, collection of results, experimentation, writing original draft

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