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Fabrication and Mechanical Evaluation of Epoxy Composites Reinforced with Banana Pseudostem Fibers

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Abstract. *Amid increasing environmental concerns and the urgent need to reduce dependence on non-renewable, non-biodegradable resources, natural fiber-reinforced composites have emerged as promising sustainable alternatives. Banana pseudostem fibers, an agricultural byproduct, offer notable advantages such as low density, biodegradability, renewability, and favorable mechanical characteristics. In this study, an epoxy-based composite reinforced with chopped banana pseudostem fibers was developed using the compression molding technique, incorporating varying fiber volume fractions. To enhance fiber–matrix adhesion, the banana fibers were alkali-treated prior to fabrication. The mechanical performance of the composites was assessed through a series of tests including tensile, flexural, impact, and hardness evaluations. Results revealed that the incorporation of treated banana fibers significantly improved the mechanical properties of the epoxy matrix. The optimal performance was observed at a 20% fiber volume fraction, showing a near-linear increase in mechanical strength up to this point. Beyond 20%, a gradual decline in properties was noted, indicating saturation and possible fiber agglomeration. Thus, 20% was identified as the optimal reinforcement level for maximizing the structural performance of the composite.*

Keywords: *Agglomeration, Mechanical, Pseudostem Fiber, Resin, Structural*

INTRODUCTION

With escalating global concerns surrounding the depletion of petroleum-based resources and the urgency to mitigate environmental pollution, there has been a significant shift in research focus toward the development of sustainable, biodegradable, and renewable materials. In this context, natural fibers have emerged as viable alternatives to synthetic reinforcements due to their low density, cost-effectiveness, biodegradability, and renewability.Various natural fibers—including bamboo, flax, jute, coconut, sisal, abaca, and hemp—have been extensively investigated for their potential as reinforcements in polymer matrix composites [1]. Alkali treatment, commonly applied to natural fibers, enhances surface roughness and removes lignin, hemicellulose, and other impurities, thereby improving fiber–matrix interfacial adhesion and significantly boosting mechanical performance [2].In composite systems, reinforcement morphology plays a crucial role. Particle-reinforced composites often involve fillers with defined geometries (e.g., spherical, cubic, or tetragonal), while fiber-reinforced composites utilize either continuous or discontinuous fibers, which may be unidirectionally or bidirectionally aligned [3]. Research by Sandhyarani Biswas [4] highlighted the structural potential of bamboo fiber composites enhanced with particle fillers, producing high-strength and lightweight materials. Hybrid composites, which integrate multiple types of fibers or fillers, have also shown superior mechanical properties compared to single-fiber systems [5]. Additionally, the incorporation of nanocellulose and cellulose nanocrystals into natural fiber composites has demonstrated significant promise, particularly for automotive applications [6].The demand for natural fiber-reinforced composites is rapidly growing across sectors such as automotive, construction, consumer goods, and packaging, owing to their environmental benefits and competitive mechanical characteristics[7]. For example, Maries Idiculla et al. [8] demonstrated that short, randomly oriented sisal fibers (~15 mm) considerably enhanced the mechanical performance of epoxy-based composites. However, several studies have also reported that beyond a certain fiber loading, as in bamboo–epoxy systems, the mechanical performance deteriorates due to poor resin dispersion and fiber agglomeration [9].Amid escalating concerns over environmental pollution and the depletion of non-renewable resources, there is a growing emphasis on developing sustainable, biodegradable, and renewable materials [10]. Natural fibers, such as banana pseudostem fibers, offer significant advantages over synthetic alternatives, including lower density, cost- effectiveness, biodegradability, and renewability [11,12].This study investigates the fabrication and mechanical performance of chopped, alkali-treated banana pseudostem fiber-reinforced epoxy composites[13]. The fibers, measuring 10–15 mm in length, were treated with 10% sodium hydroxide (NaOH) to enhance interfacial bonding between the fiber and matrix. Composite specimens were fabricated using the compression molding technique, incorporating various fiber volume fractions[14,15].

Mechanical tests, including tensile, flexural, impact, and hardness evaluations, were conducted to assess the composites' performance. The results indicated that the incorporation of alkali-treated banana pseudostem fibers significantly improved the mechanical properties of the epoxy matrix. The optimal performance was observed at a 20% fiber volume fraction, with tensile strength reaching approximately 68 MPa, flexural strength around 90 MPa, and impact toughness near 13 kJ/m2. Beyond this point, further increases in fiber content led to a gradual decline in mechanical properties, confirming 20% as the optimal reinforcement level.

2. MATERIAL ANALYSIS AND EXPERIMENTAL EVALUATION

2.1. Material Characterisation

The matrix material selected for this study was a bio-based epoxy system, FormuLITE™ amine-cured epoxy resin supplied by Cardolite LLC, United States. This resin was chosen for its low viscosity, efficient fiber wetting, extended pot life, and balanced mechanical properties. The hardener used was HY951, and a resin-to-hardener ratio of 10:1 by weight was adopted, as this ratio has been found to yield optimal results in similar composite applications. The banana pseudostem fibers utilized in this research were sourced from Vruksha Composites & Services, Andhra Pradesh, India. These fibers were extracted from the pseudostems of mature Musa acuminata (banana) plants, a byproduct of banana cultivation. The fibers were alkali-treated with a 10% sodium hydroxide (NaOH) solution for 1 hour to enhance interfacial bonding between the fiber and the matrix. After treatment, the fibers were thoroughly washed with distilled water, dried at room temperature, and cut to lengths of 10–15 mm [17, 18, 19, 20].

Table 1. Major Characteristics of Banana Psuedostem fibers

Property	Values
Lignin [wt%]	5-10
Hemicellulose [wt%]	9 - 16
Density [g/ccm]	1.30
Pectin [%]	3 – 5
Ash Content [%]	1 – 3
Tensile Strength [MPa]	521 – 914
Youngs Modulus [GPa]	27 – 32
Elongation [%]	1 – 3

2.2. Alkali Treatment on Banana Pseudostem Fibers

Banana pseudostem fibers are natural lignocellulosic fibers extracted from the trunk-like stalk (pseudostem) of the banana plant, which is typically discarded after fruit harvest. These fibers are lightweight, biodegradable, and renewable, making them an eco-friendly alternative to synthetic reinforcements in composite materials. They possess moderate tensile strength and stiffness, good moisture absorption, and a relatively high cellulose content, which contributes to their mechanical performance. Due to their availability and low cost, banana pseudostem fibers have gained attention for use in sustainable polymer composites, especially in automotive, packaging, and construction applications. When treated chemically (e.g., with alkali solutions), their interfacial bonding with polymer matrices is significantly improved, enhancing the overall mechanical properties of the composites.Alkali treatment, commonly using sodium hydroxide (NaOH), is essential for enhancing the performance of banana pseudostem fibers in composite applications. Raw fibers contain impurities such as lignin, hemicellulose, waxes, and other non-cellulosic materials that hinder effective bonding with polymer matrices. The alkali treatment removes these surface impurities and partially dissolves amorphous components, thereby increasing surface roughness and exposing more hydroxyl groups. This results in improved interfacial adhesion between the fiber and the matrix, leading to enhanced mechanical properties such as tensile strength, flexural strength, and impact resistance. Additionally, alkali treatment can reduce fiber moisture absorption and improve dimensional stability, making the treated fibers more suitable for structural composite applications.When banana pseudostem fibres are treated with an alkaline solution, the interfacial bonding between the fibres and epoxy resin is significantly improved. In this study, the fibres were soaked in a 5% sodium hydroxide (NaOH) solution for two hours. This alkali treatment helps remove surface impurities and non-cellulosic materials such as lignin and hemicellulose, enhancing the fibre-matrix adhesion. Figure 1 shows the banana pseudostem extraction process as a whole.

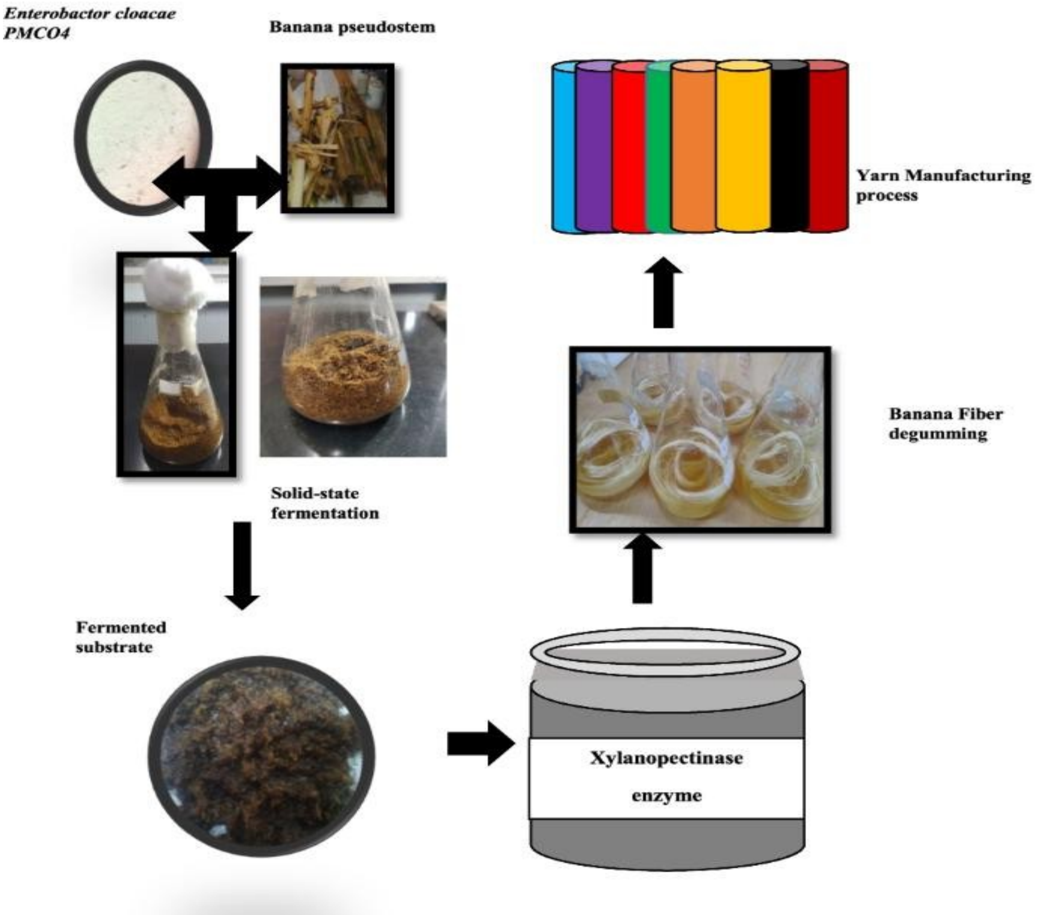

Fig 1. Banana Pseudostem Fibre Extraction

2.3. Composite Fabrication

Each composite was fabricated using approximately 300 grams of epoxy resin and 30 grams of hardener, maintaining a 10:1 ratio as specified by the manufacturer. Compression moulding was employed for fabrication due to its simplicity and versatility. The chemical composition of the developed composites is detailed in the accompanying table. In this study, 300 g of epoxy and 30 g of hardener were used to determine the optimal banana pseudostem fibre volume fraction, which was found to be 5%. The liquid resin-hardener mixture was poured over chopped NaOH-treated banana pseudostem fibres. The mixture was then placed into a metal mould, compressed, and cured for three hours, after which the mould was removed [21]. The final composite sheets were limited to dimensions of 200 mm × 200 mm and a maximum thickness of 6 mm. After curing, the samples were cut into standard ASTM test specimen sizes using water jet cutting. Figure 2 shows a photographic view of the various composite samples produced during fabrication.

Table 2 List depicting the codes of the present study's composite laminates

Laminate Code	**Epoxy Quantity**	**Hardener Quantity**	**Banana Pseudostem Fiber Volume Fraction**
I	300 g	30 g	10 wt %
II	300 g	30 g	15 wt %
III	300 g	30 g	20 wt %
IV	300 g	30 g	25 wt %
V	300 g	30 g	30 wt %

Fig. 2 Laminates prepared for doing the Mechanical Interpretation

2.4. Mechanical Evaluation

A comprehensive evaluation of the mechanical performance of fiber-reinforced epoxy polymer composites was carried out through a series of standardized tests. These assessments offered valuable insights into the material's response under both static and dynamic loading conditions. The mechanical characterization included flexural, impact, hardness, and tensile tests, each aimed at measuring specific strength and durability properties of the composites. For every test, three specimens were prepared and tested under consistent conditions to ensure reliability. The average values of these replicates were used for analysis, with error margins calculated to indicate the precision and repeatability of the results.. [22, 23]

2.4.1. Tensile Testing

Tensile specimens were fabricated in accordance with ASTM D638, which specifies the geometry, gauge length, and crosshead speed for accurate tensile evaluation of polymer materials. Testing was performed using a Universal Testing Machine (UTM) to determine tensile strength, elongation at break, and cohesion characteristics. Compliance with ASTM D638 ensured reproducible and comparable results across the composite specimens.

2.4.2. Flexural Testing

Flexural tests were conducted following ASTM D790 standards, which define specimen size and testing procedures for polymer matrix composites. A three-point bending configuration was employed using a UTM, applying load at the midpoint of specimens supported at both ends until failure. This method provided measurements of flexural strength, modulus of elasticity, and strain at break.

2.4.3. Impact Testing

Impact resistance was assessed using specimens prepared as per ASTM D256 for notched Izod impact testing. Each specimen included a 2.5 mm deep notch to concentrate stress and promote fracture initiation. Tests were performed on a pendulum impact tester, recording the energy absorbed upon fracture to evaluate the composite's dynamic load-bearing capacity.

2.4.4. Hardness Testing

Hardness measurements were obtained with a Shore D durometer in accordance with ASTM D2240, the standard for polymer and composite hardness testing. The durometer's indenter was pressed onto the sample surface under a controlled force, and the resistance to indentation was recorded as the Shore D hardness value, reflecting the material's surface hardness and resistance to localized deformation.

Tables 3 and 4 shows the comparative properties of the banana pseudostem fiber reinforced epoxy polymer composites when they are in untreated form and in the treated form. A significant increase in the properties is found when the fibers are treated with sodium hydroxide solution.

Table 3. Mechanical Properties of Epoxy/Untreated (UT) Pseudostem fibre reinforced composites

Composition	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Impact Strength (KJ/m²)	Hardness (Shore D)
Epoxy/15% UT Pseudostem	20	37250.0	40	2810.0	2.12	79
Epoxy/20% UT Pseudostem	22	4120.0	45	3410.0	2.90	80
Epoxy/25% UT Pseudostem	25	4770.0	49	4760.0	2.85	81

Table 4. Mechanical Properties of Epoxy/Treated Pseudostem fibre reinforced composites

Composition	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Impact Strength (KJ/m²)	Hardness (Shore D)
Epoxy/15% Treated Pseudostem	22	3850.0	42	2920.0	2.42	81
Epoxy/20% Treated Pseudostem	24	4220.0	48	3520.0	3.10	83
Epoxy/25% Treated Pseudostem	28	4970.0	51	4880.0	3.35	84

3. OUTCOME AND DELIBERATION

3.1. Evaluation of Tensile Characteristics

The tensile strength and tensile modulus values for banana pseudostem fiber-reinforced epoxy composites are presented in Figure 3 and Figure 4, respectively. Among the various compositions tested, Combination III, containing 20% banana pseudostem fiber, exhibited the highest mechanical performance, with a tensile strength of 24 MPa and a tensile modulus of 4220 MPa. These findings suggest that incorporating 20% banana pseudostem fiber significantly enhances the tensile properties of the composite when compared to other formulations.

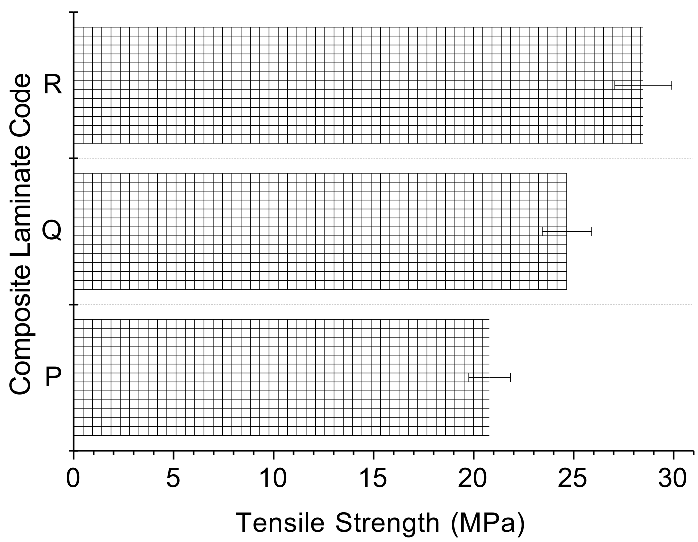

Fig 3. Tensile Strength of Composites

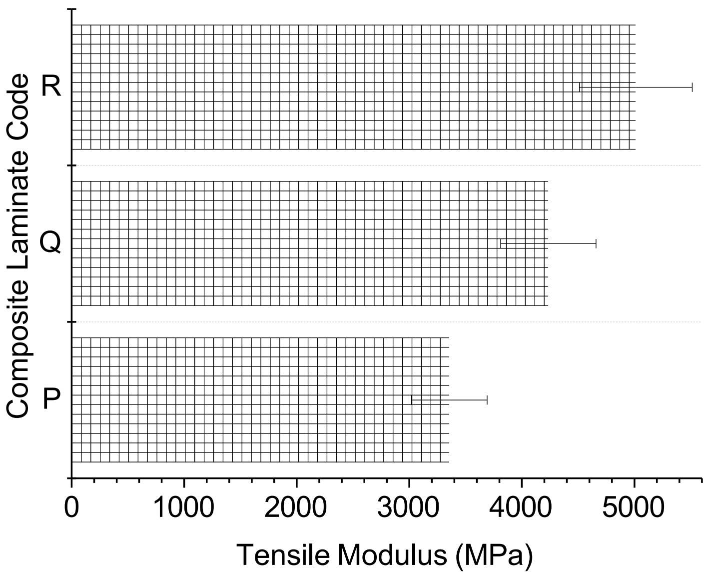

Fig 4. Tensile Modulus of Composites

3.2. Evaluation of Flexural Characteristics

Figures 5 and 6 present the flexural strength and flexural modulus results for banana pseudostem fiber-reinforced epoxy polymer composites. Among the different compositions evaluated, Combination III, incorporating 20% banana pseudostem fiber, demonstrated the highest flexural performance. This combination achieved a flexural strength of 48 MPa and a flexural modulus of 3520 MPa, outperforming all other formulations. These findings confirm that 20% banana pseudostem fiber reinforcement provides an optimal balance of strength and stiffness under flexural loading conditions.

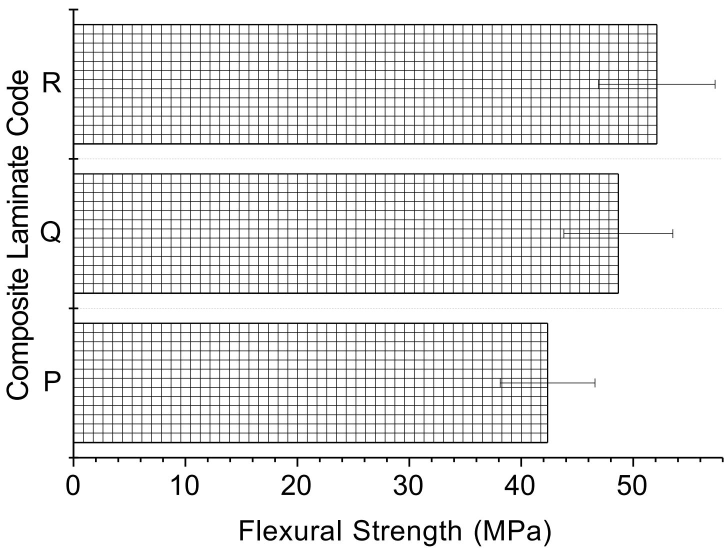

Fig 5. Flexural Strength of Composites

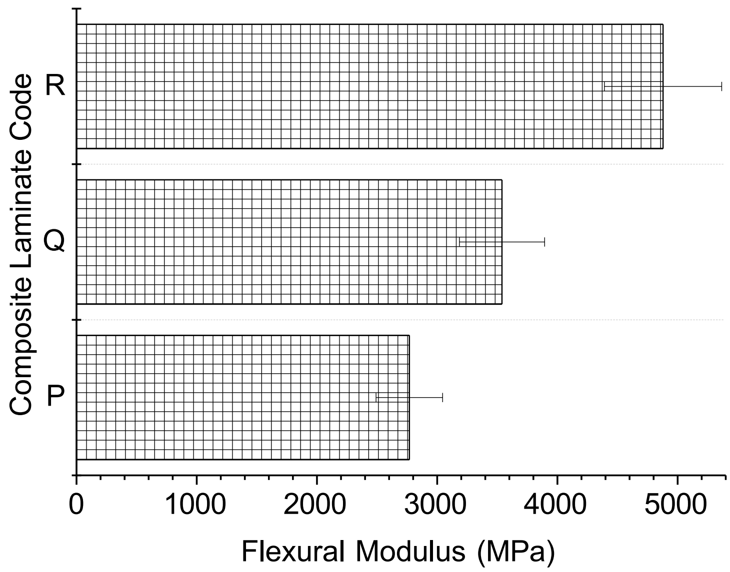

Fig 6. Flexural Modulus of Composites

3.3. Evaluation of Impact Characteristics

The impact toughness of the banana pseudostem fiber–reinforced epoxy composites was evaluated using standardized impact testing, with the results illustrated in Figure 7. Among the various composite formulations, Combination III, incorporating 20% banana pseudostem fiber, exhibited the highest impact strength, measuring 3.10 kJ/m2**.** This superior performance compared to other combinations indicates that a 20% fiber content provides the most effective configuration for absorbing energy under sudden impact or dynamic loading conditions.

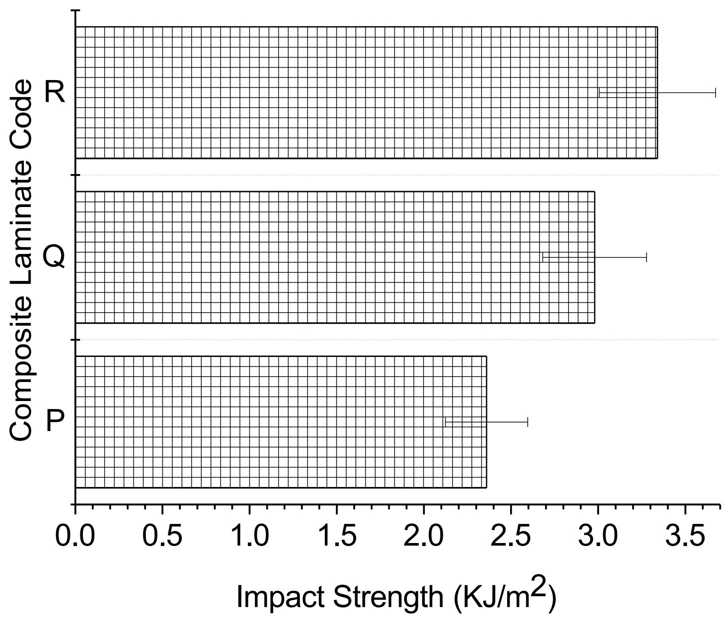

Fig 7. Impact Strength of Composites

3.4 Evaluation of Hardness Characteristics

Hardness refers to a composite material's resistance to deformation or surface indentation when subjected to an applied force. The results of the hardness test are shown in Figure 8. Among the tested samples, Combination III, containing 20% pseudostem fiber, exhibited the highest hardness value, recording 87 Shore D. This indicates enhanced surface integrity and resistance to localized damage, making it suitable for applications requiring improved wear and scratch resistance.

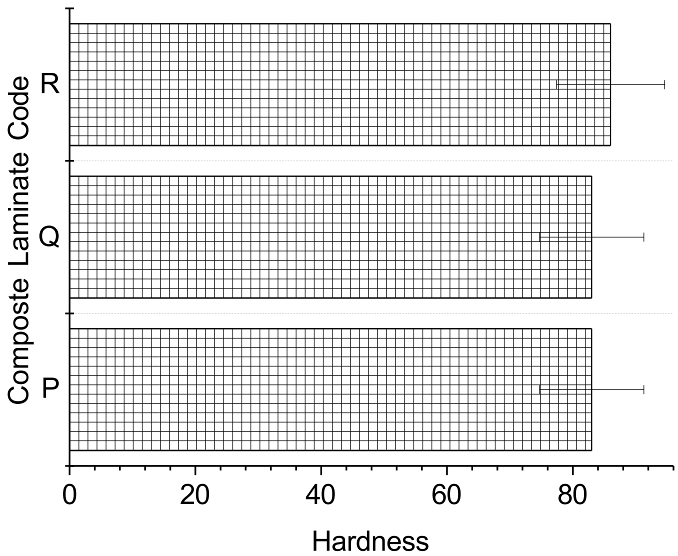

Fig 8. Hardness of Composites

4. APPLICATIONS

Banana pseudostem fiber–reinforced epoxy composites have gained significant attention as a sustainable alternative to synthetic fiber composites due to their eco-friendliness, renewability, and competitive mechanical properties. Their combination of low density, moderate strength, and biodegradability makes them well-suited for a range of applications, including:

- **Automotive Components**: These composites can be used in interior panels, dashboards, door trims, and seat backing due to their lightweight nature and good impact resistance, contributing to vehicle weight reduction and fuel efficiency.
- **Construction Materials**: Owing to their decent flexural and compressive properties, they are suitable for partition boards, roofing sheets, insulation panels, and decorative elements in green building systems.
- **Packaging**: Their biodegradability and sufficient strength make them suitable for reusable, recyclable, or compostable packaging solutions, especially in low-load applications.
- **Furniture and Household Items**: They can be used in manufacturing lightweight furniture panels, shelves, or decorative surfaces that demand moderate strength and durability.
- **Consumer Goods**: Items like luggage shells, casings for electronic devices, and sporting goods (e.g., helmets or protective gear) can benefit from their balance of stiffness and impact resistance.
- **Agricultural Tools and Equipment Housings**: Their resistance to wear and light environmental exposure makes them viable for non-structural parts of agricultural implements.

These composites are especially attractive in sectors aiming to reduce carbon footprints and utilize agro-waste efficiently, aligning with global trends in circular economy and sustainable material development.

5. FUTURE SCOPES

Banana pseudostem fiber–reinforced epoxy composites offer promising opportunities for future research and industrial applications due to their sustainable nature and favorable mechanical properties. Key areas for future exploration include:

- **Optimization of Fiber Treatment Techniques**: Further studies can focus on advanced chemical and physical treatments to improve fiber-matrix adhesion, durability, and moisture resistance, thereby enhancing composite performance in diverse environments.
- **Hybrid Composite Development**: Combining banana pseudostem fibers with other natural or synthetic fibers may yield hybrid composites with tailored mechanical and thermal properties for specialized applications.
- **Bio-Based Matrix Integration**: Research on fully bio-based composite systems using biodegradable or bio-derived resins can lead to environmentally friendly, fully sustainable materials.

- **Nano-Engineering and Surface Modification**: Incorporating nanomaterials such as nanocellulose or graphene oxide into the composite system can improve mechanical strength, thermal stability, and barrier properties.
- **Scaling Up and Manufacturing Techniques**: Developing scalable and cost-effective manufacturing processes such as automated compression molding, extrusion, or 3D printing will facilitate commercial adoption.
- **Life Cycle Assessment and Recycling**: Comprehensive life cycle analysis and recycling methods will support the environmental viability and circular economy integration of these composites.
- **Expanded Applications**: Exploring their use in high-performance sectors like aerospace, marine, and sports equipment where lightweight and strength are critical could open new markets.

Overall, banana pseudostem fiber composites hold significant potential to contribute to sustainable materials science, reducing reliance on non-renewable resources and promoting greener manufacturing practices.

6. CONCLUSIONS

The banana pseudostem fiber–reinforced epoxy composites were successfully fabricated using compression moulding, incorporating NaOH-treated chopped fibers to enhance interfacial bonding with the matrix. Following comprehensive mechanical testing and characterization, the following key findings were observed:

- **Tensile Properties**: The composite with 20 wt% banana pseudostem fiber (Combination III) demonstrated the highest tensile performance, with a tensile strength of 24 MPa and a tensile modulus of 4220 MPa. In contrast, the 15 wt% fiber composite exhibited lower values of 22 MPa and 3850 MPa, respectively, indicating the mechanical benefits of higher fiber content.
- **Flexural Properties**: The 20 wt% fiber composite also showed superior flexural strength **(**48 MPa**)** and modulus **(**3520 MPa**),** outperforming the 15 wt% variant, which recorded 42 MPa and 2920 MPa. This demonstrates enhanced stiffness and resistance to bending at higher fiber loadings.
- **Impact Strength**: The impact toughness of the 20 wt% composite reached 3.10 kJ/m2, significantly higher than the 2.42 kJ/m2 achieved by the 15 wt% formulation, confirming improved energy absorption under dynamic loading conditions with increased fiber content.
- **Hardness**: In hardness testing, the 20 wt% fiber composite recorded 83 Shore D, slightly higher than the 81 Shore D of the 15 wt% composite, suggesting better resistance to surface indentation and wear.

Based on these results, it can be concluded that NaOH-treated chopped banana pseudostem fiber–reinforced epoxy composites achieve optimal mechanical performance at a 20 wt% fiber loading. This composition offers a well-balanced enhancement of tensile, flexural, impact, and hardness properties, making it a viable and sustainable alternative for lightweight, high-performance engineering applications.

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Disclosure of Interests. The authors have no competing interests.

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