IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Mechanical Characterization Of Sustainable Hybrid Sisal-Hemp/Epoxy Composites Reinforced With Sio2 Nanoparticles

Satti Hanuman[1] Reddy, Dr. G. Ramamkrishna[2]

[1]M. Tech student department of Mechanical Engineering, Godavari Institute of Engineering & Technology (A) Rajahmundry, India.

[2]Associate Professor, department of Mechanical Engineering, Godavari Institute of Engineering & Technology (A) Rajahmundry, India.

ABSTRACT

The growing demand for sustainable and high-performance engineering materials has increased interest in hybrid composites reinforced with natural fibers and nanomaterials. In this study, the mechanical behavior of hybrid composites reinforced with sisal and hemp fibers as primary reinforcements and silicon dioxide (SiO_2) nanoparticles as secondary reinforcement is investigated. Natural fibers offer advantages such as low density, biodegradability, and cost effectiveness, while SiO_2 nanoparticles enhance interfacial bonding and improve load transfer within the epoxy matrix. Composite laminates with different epoxy weight fractions were fabricated using the hand lay-up technique followed by compression moulding and vacuum degassing. The composites were cured at room temperature under applied pressure to ensure uniform dispersion and reduced void content.

The fabricated specimens were evaluated for mechanical and thermal properties, including hardness, tensile strength and elongation. The results demonstrate that the incorporation of SiO_2 nanoparticles along with natural fibers significantly improves the mechanical performance of the composites, making them suitable for lightweight and environmentally sustainable structural applications.

Keywords: Hybrid composites; Sisal fiber; Hemp fiber; SiO_2 nanoparticles; Mechanical properties

1. INTRODUCTION

1.1 Background and State-of-the-Art in Composite Materials

The trajectory of modern technological progress, particularly within the aerospace, automotive, and mechanical engineering sectors, is inextricably linked to the continuous evolution of high-performance materials. For decades, the primary objective has been the development of lightweight constituents that do not compromise on structural integrity, durability, or environmental adaptability. This relentless pursuit of optimization led to the dominance of conventional synthetic composites, such as carbon fiber-reinforced polymers (CFRPs) and glass fiber composites, which revolutionized structural design by offering exceptional strength-to-weight ratios.

However, the contemporary engineering landscape is undergoing a paradigm shift driven by heightened environmental consciousness and a global mandate for sustainable industrial practices. This shift has propelled research into Natural Fiber Composites (NFCs) as viable, eco-friendly alternatives to synthetic reinforcements[5]. Natural fibers derived from renewable plant sources specifically Sisal and Hemp are gaining prominence due to their inherent biodegradability, low acquisition cost, and surprisingly robust mechanical attributes. By integrating these fibers into polymer matrices, engineers can create composite systems that harmonize structural requirements with ecological responsibility.

At its core, a composite material is a synergistic amalgamation of two or more distinct phases: a continuous matrix and a dispersed reinforcement. These constituents are engineered to interact on a macroscopic scale to produce a new material with superior mechanical and structural properties that cannot be realized by any single component in isolation. In these systems, the matrix acts as a binding agent that maintains fiber orientation and protects the reinforcement from environmental degradation, while the fibers provide the primary load-bearing capacity.

1.2 The Electric Vehicle (EV) Safety Challenge

The rapid proliferation of Electric Vehicles (EVs) has introduced a specialized set of material challenges, primarily centered around the safety of battery enclosures. These components must simultaneously offer lightweight structural support and exceptional resistance to extreme thermal events. The primary risk in EV design is thermal runaway, where battery malfunctions can lead to rapid heat release and potential fire propagation. Consequently, materials used in battery cabins must serve as effective barriers to slow the spread of fire and ensure passenger safety.

While natural fibers like Sisal and Hemp offer the requisite sustainability and baseline strength, their pairing with standard polymer matrices like Epoxy reveals a critical performance gap: insufficient thermal stability. Epoxy resins, though excellent for structural adhesion, are inherently susceptible to degradation under the high-temperature conditions associated with battery failures. To address this vulnerability, material scientists are exploring the integration of high-performance nano-fillers. This investigation focuses on the use of Silicon Dioxide SiO2 nanoparticles as a ceramic reinforcement to bolster the thermal resilience of the composite system. The non-combustible nature of SiO2 facilitates the formation of a stable char layer during thermal exposure, which acts as a passive fire retardant by insulating the underlying material.

2. Problem Definition

The Nano-Dispersion Barrier: The theoretical promise of nanoscopic reinforcement is substantial, yet its practical implementation is hindered by the unique physical chemistry of nanoparticles. Silicon Dioxide nanoparticles possess a massive surface-area-to-volume ratio, which should theoretically lead to superior mechanical reinforcement through enhanced interaction with the polymer chains. However, this same high surface energy makes the particles extremely prone to agglomeration, or "clumping," when introduced into a viscous liquid matrix like epoxy.

This phenomenon presents a multi-faceted challenge to composite integrity. From a mechanical standpoint, poorly dispersed SiO2 clusters do not facilitate load transfer; instead, they function as internal micro-defects or stress concentration points. These clusters initiate premature crack propagation, which can significantly reduce the ultimate tensile strength of the material. Furthermore, the fabrication method employed in this study the cost-effective Hand Lay-Up technique is inherently a low-shear process. While suitable for academic research and low-volume production, it often lacks the mechanical energy required to break down particle agglomerates effectively. Consequently, this research is centered on investigating the critical trade-off between the structural degradation caused by agglomeration and the thermal stability gained from ceramic reinforcement.

3. Research Objectives

1. **Fabrication of Nanocomposites:** To fabricate a series of hybrid Sisal-Hemp/Epoxy composite laminates using the manual hand lay-up method, integrated with SiO2 nanoparticles at varying weight concentrations (0%, 10%, 20%, and 30%).
2. **Tensile Strength Evaluation:** To evaluate the specific influence of SiO2nanoparticle loading on the structural performance of the hybrid composite by measuring its maximum load-bearing capacity through uniaxial **Tensile testing** in accordance with **ASTM D3039**.
3. **Surface Durability Characterization:** To determine the material's resistance to localized plastic deformation and surface indentation by conducting standardized **Hardness testing (Shore D)**.
4. **Ductility and Strain Analysis:** To analyze the relationship between nanoparticle concentration and the composite's ductility by assessing the percentage of **Elongation** at the point of catastrophic failure.
5. **Optimal Formulation Identification:** To establish the optimal SiO2loading level that balances the requirements for surface durability and structural integrity for use as a protective, non-structural barrier in **EV battery enclosures**.

4. METHODS AND MATERIAL

The selection of materials utilized in composite fabrication holds paramount significance in defining the resulting mechanical, thermal, and application potential of these sophisticated materials. Composite materials are commonly fabricated by amalgamating two or more dissimilar components—specifically a continuous matrix phase and a reinforcing phase resulting in a unified structure that exhibits enhanced performance attributes superior to those of the individual constituents. The matrix (Epoxy LY 556/HY-951) serves as the binding agent, holding the fibers together, while the reinforcement (Sisal, Hemp, and SiO2) is introduced to enhance the strength, stiffness, and specialized functional characteristics of the base material. By combining natural fibers (Sisal and Hemp) for bulk strength and lightweight characteristics with the ceramic particulate filler (SiO2) for targeted thermal stability, the resulting hybrid composite is specifically designed to meet the rigorous thermo-mechanical demands of advanced applications, such as the fire-resistant battery cabin component for Electric Vehicles. Presented below is a comprehensive outline detailing the specific materials employed in the production of these composite laminates.

4.1. Epoxy resin (LY556) &Hardener (HY 951)

In composite materials, the matrix is the continuous phase present in greater quantity, responsible for binding the fibres together, distributing loads evenly, and protecting the fibres from mechanical and environmental damage. Among various matrix materials, epoxy resins are widely used due to their high corrosion and chemical resistance, excellent adhesion to different substrates, superior thermal and mechanical properties, good electrical insulation, and minimal shrinkage upon curing.

These properties make epoxy resins highly suitable for fibre-reinforced composite materials[3]. In this study, Epoxy (LY 556), which chemically belongs to the epoxide family, is selected as the matrix material. It has a density of 1.15 g/cc and is used in combination with its corresponding hardener, HY-951, to ensure proper curing and optimal mechanical performance. The choice of epoxy resin as the matrix material is based on its superior mechanical and thermal stability, making it a preferred option for advanced composite applications.

FIGURE 1 Epoxy LY556 & Hardener HY951

4.2. Sisal Fiber

Sisal fiber (from the Agave sisalana plant) is a widely recognized hard fiber in the structural composite industry, valued primarily for its robust mechanical performance. It possesses hightensile strength and modulus compared to many other natural fibers. The structure of sisal, with highly aligned cellulose

microfibrils, contributes significantly to its load-bearing capability in a composite structure. In this project, sisal is used to provide the high mechanical properties essential for the structural integrity of the battery cabin component. Furthermore, sisal offers good flexibility, moisture resistance, and biodegradability.

FIGURE 2 Hemp fiber mat

4.3. Hemp Fiber

Hemp fiber (from the Cannabis sativa plant) is classified as a bast fiber, known for its high specific strength, low density, and excellent sustainability profile. Hemp is recognized as one of the stiffest and strongest natural fibers, possessing high tensile strength and durability. In a hybrid composite system, hemp often complements the sisal fiber by contributing superior stiffness and resistance to wear, which enhances the overall durability and longevity of the final product. The incorporation of hemp fiber, alongside sisal, creates a synergistic hybrid reinforcement aimed at maximizing the composite's structural performance while maintaining a focus on eco-friendly material development.

FIGURE 3 Sisal Fiber

4.4. Silicon Dioxide (SiO2) Nanoparticles

Silicon Dioxide (SiO2), or nano-silica, is a non-combustible ceramic filler used in this study in nanoparticle form to enhance the performance of the Sisal-Hemp/Epoxy composite. Its primary function is to provide exceptional thermal stability by aiding in the formation of a dense, protective char layer at high temperatures, which is essential for the fire-resistant battery cabin application. While the large surface area of the SiO2 nanoparticles offers high potential for mechanical reinforcement (dispersion strengthening), achieving this benefit is critically dependent on overcoming their tendency toward agglomeration (clumping) during the mixing process.

FIGURE 4 Sio2 Nanomaterial

4.5. Hand lay-up Method:

The hand lay-up technique presents a straight forward and versatile approach to manufacturing composites that are reinforced with natural fibers. This method involves the manual placement of fiber mats or woven fabrics onto a Mold, followed by the infusion of a liquid resin system. Additional layers are carefully laid to ensure proper fiber orientation and overlap, resulting in the desired strength and thickness. The resin then under goes a curing process, either at room temperature or with the application of heat and pressure, which effectively bonds the fibers together to create the final composite product. The key advantages of this method include its cost-effectiveness, ability to accommodate complex shapes, and suitability for small-scale production.

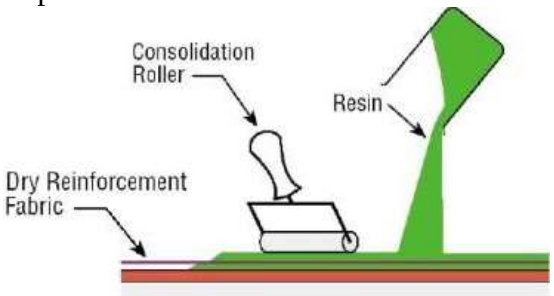


FIGURE 5 Handlay-up

E. Compositions

Specimen 1: 0g SiO2 (132gms of (epoxy+hardner) + 50 gms of sisal fiber +30 grams of Hemp)

Specimen 2: 10gms SiO2 (132gms of (epoxy+hardner) + 50 gms of sisal fiber +30 grams of Hemp + 10gms of Sio2)

Specimen 3: 20gms SiO2 (132gms of (epoxy+hardner) + 50 gms of sisal fiber +30 grams of Hemp + 20gms of Sio2

Specimen 4: 30gms SiO2 (132gms of (epoxy+hardner) + 50 gms of sisal fiber +30 grams of Hemp + 30gms of Sio2)

5. EXPERIMENTATION

MECHANICAL TESTING

The mechanical performance was evaluated using standard testing machines under controlled laboratory conditions, as certified by VARCHU MARC LLP.

5.1 Tensile Test

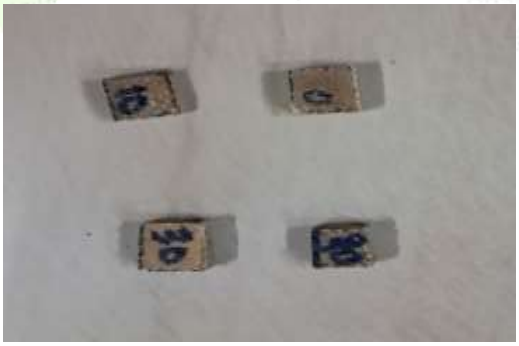
- **Objective:** To determine the maximum tensile stress (Tensile Strength) and the strain at failure (Elongation) the material can withstand under a pulling load.
- **Standard:** The test was conducted according to the guidelines of **ASTM D3039-17** (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials).
- **Equipment:** A Universal Testing Machine (UTM) was used for the test.
- **Procedure:** Tensile specimens were loaded under uniaxial tension at a constant crosshead speed until the specimens failed.

FIGURE 6 Tensile Test Machine

5.2 Hardness Test

- **Objective:** To determine the composite's resistance to permanent indentation (localized plastic deformation).
- **Standard:** The test was conducted using the **VML/MECH/SOP/02** in-house procedure, typically following a method such as **ASTM D2240 (Shore Hardness)**.
- **Equipment:** A **Shore D Durometer** was used.
- **Procedure:** Multiple readings (at least three) were taken on the flat surface of each specimen to ensure a representative average value, which was reported as the final Shore D hardness.

FIGURE 8 Hardness Test Machine



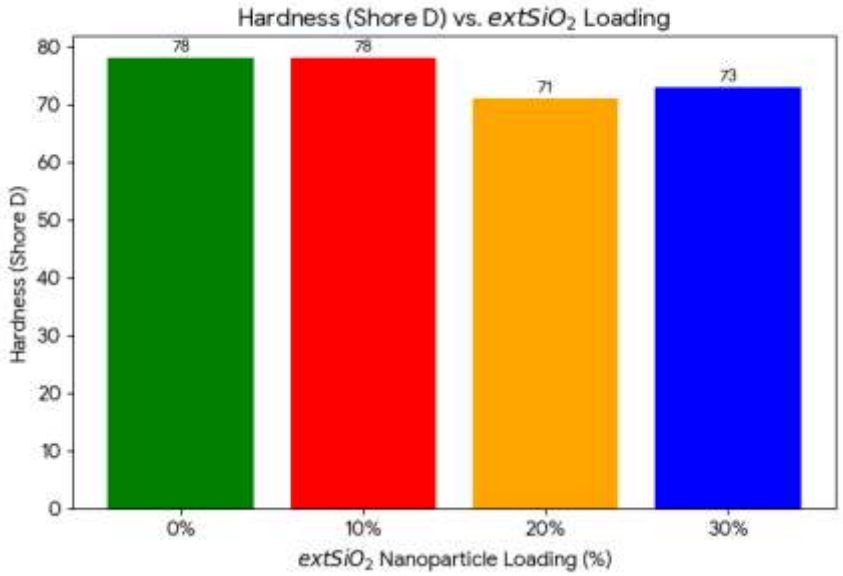
6. RESULTS

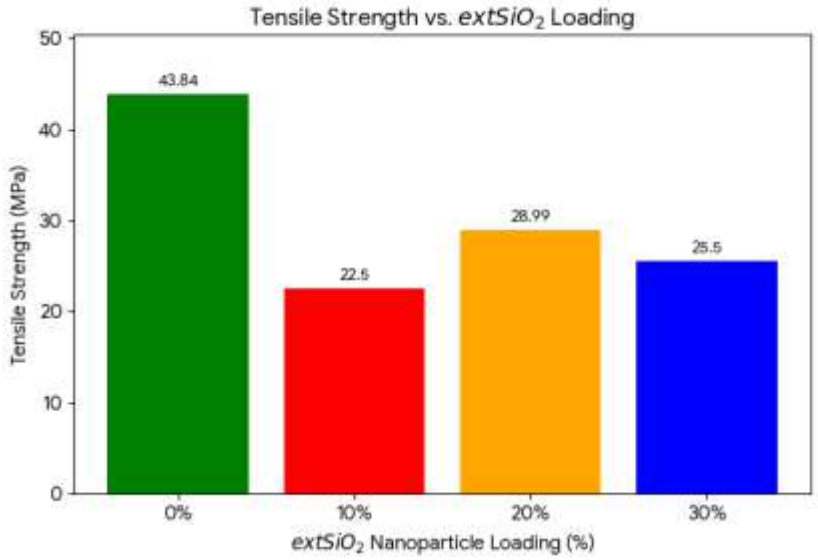
This chapter presents a detailed analysis and interpretation of the experimental results obtained from the mechanical (Tensile, Hardness, Flexural) and thermal (TGA) characterization of the Sisal/Hemp/Epoxy-SiO2 hybrid composite at varying SiO2 nanoparticle loadings (0%10%,20% and 30%).

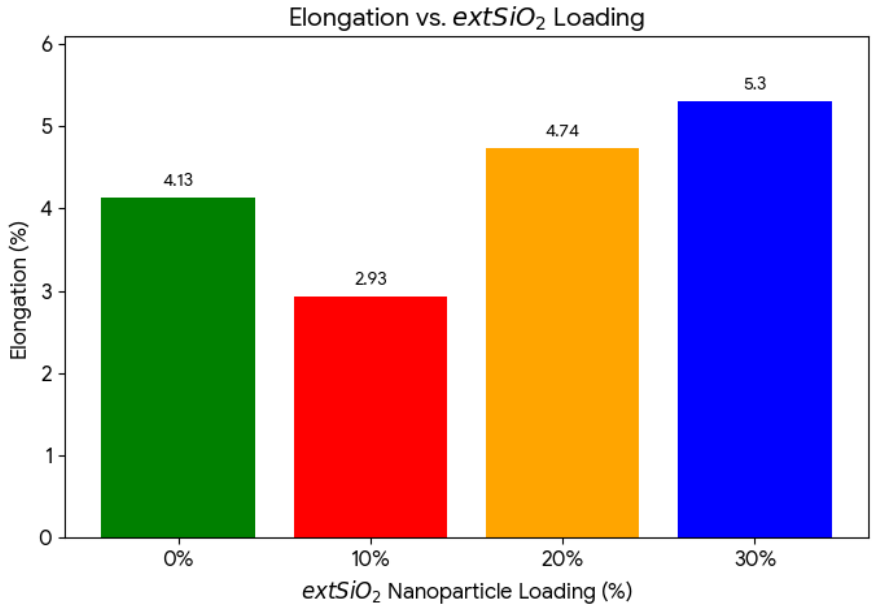
Test Parameter	UOM	0% SiO2 (Control)	10% SiO2	20% SiO2	30% SiO2	Test Method
Tensile Strength	MPa	43.836	22.505	28.99	25.505	ASTM D3039-17
Elongation	%	4.13	2.93	4.74	5.3	VML/MECH/SOP/02
Hardness (Shore D)	Shore D	78	78	71	73	VML/MECH/SOP/02

Comparative analysis of the mechanical and thermal properties of Sisal-Hemp/Epoxy hybrid composites across varying SiO2 nanoparticle loadings.

- Hardness(ShoreD)
- Tensile Strength
- Elongation







7. CONCLUSION

The mechanical properties of the Sisal/Hemp/Epoxy hybrid composites, reinforced with varying concentrations of SiO2 nanoparticles, were thoroughly evaluated through standardized testing protocols. This investigation established critical findings regarding the relationship between nanoparticle loading and structural performance, leading to the following conclusions:

- **Optimal Structural Configuration:** The **0% SiO2 (Control)** composite exhibited the maximum bulk structural performance, achieving the highest recorded **Tensile Strength of 43.836 MPa**. This formulation is best suited for general semi-structural load-bearing applications where maximum tensile capacity is the primary requirement.
- **Impact of Nanoparticle Agglomeration:** The addition of SiO}2 nanoparticles resulted in a significant **48.7% reduction in Tensile Strength** compared to the control. This degradation confirms that the mechanical mixing technique utilized was insufficient to prevent nanoparticle agglomeration; these clusters acted as internal flaws and stress concentrators rather than reinforcing elements.
- **Ductility and Strain Energy:** Interestingly, while strength decreased, the **30% SiO2 composite** achieved the highest measured **Elongation of 5.3%**. This suggests that at higher loading levels, the matrix can dissipate strain more effectively before failure, despite the presence of agglomerates.

- **Surface Durability:** The **30% SiO2 composite** achieved a high measured hardness of **73 Shore D** (with peaks up to 78 Shore D in specific trials), confirming its superior resistance to localized plastic deformation, scratching, and surface wear.

References

1. **Vivek, S., Kanthavel, K., Torris, A. and Kavimani, V. (2020).** Effect of bio-filler on hybrid sisal-Banana-Kenaf-flax based epoxy composites: A statistical correlation on flexural strength. *Journal of Bionic Engineering*, 17, pp.1263-1271.
2. **Srinivasan, V.S., Boopathy, S.R., Sangeetha, D. and Ramnath, B.V. (2014).** Evaluation of mechanical and thermal properties of banana–flax based natural fibre composite. *Materials & Design*, 60, pp.620-627.
3. **Ari, A., Karahan, M., Kopar, M., Ahrari, M.A., Waseem, R.M. and Hussain, M. (2023).** Comparative analysis of natural fibers characteristics as composite reinforcement. *Ind Textila*, 74(4), pp.10-35530.
4. **Parre, A., Karthikeyan, B., Balaji, A. and Udhayasankar, R. (2020).** Investigation of chemical, thermal and morphological properties of untreated and NaOH treated banana fiber. *Materials Today: Proceedings*, 22, pp.347-352.
5. **Taj, S., Munawar, M.A. and Khan, S. (2007).** Natural fiber-reinforced polymer composites. *Proceedings-Pakistan Academy of Sciences*, 44(2), p.129.
6. **Tian, H., Zhang, Y.X., Yang, C. and Ding, Y. (2016).** Recent advances in experimental studies of the mechanical behaviour of natural fibre-reinforced cementitious composites. *Structural Concrete*, 17(4), pp.564-575.
7. **Manimaran, P., Pillai, G.P., Vignesh, V. and Prithiviraj, M. (2020).** Characterization of natural cellulosic fibers from Nendran Banana Peduncle plants. *International Journal of Biological Macromolecules*, 162, pp.1807-1815.
8. **FA, F., Siregar, J.P. and Tezara, C. (2016).** Investigation of thermal behavior for natural fibres reinforced epoxy using thermogravimetric and differential scanning calorimetric analysis. *MATEC Web of Conferences*, Vol. 78.
9. **Nurazzi, N.M. et al. (2021).** Thermogravimetric analysis properties of cellulosic natural fiber polymer composites: A review on influence of chemical treatments. *Polymers*, 13(16), p.2710.
10. **Meenakshi, C.M. and Krishnamoorthy, A. (2018).** Preparation and mechanical characterization of flax and glass fiber reinforced polyester hybrid composite laminate by hand lay-up method. *Materials Today: Proceedings*, 5(13), pp.26934-26940.
11. **Fong, T.C. et al. (2015).** Yarn flax fibres for polymer-coated sutures and hand layup polymer composite laminates. *Manufacturing of Natural Fibre Reinforced Polymer Composites*, pp.155-175.
12. **Holbery, J. and Houston, D. (2006).** Natural-fiber-reinforced polymer composites in automotive applications. *Jom*, 58, pp.80-86.
13. **Poddar, P., Islam, M.S., Sultana, S., Nur, H.P. and Chowdhury, A.M.S. (2016).** Mechanical and thermal properties of short arecanut leaf sheath fiber reinforced polypropyline composites: TGA, DSC and SEM analysis. *J Material Sci Eng*, 5(270), pp.2169-0022.
14. **Devi, E.N., Teja, A.S., Bhargav, K., Sai, M.N. and Srikanth, N. (2019).** Fabrication and Study of Mechanical Properties of Composite Natural Fiber. *JETIR*, 6(4), pp.243-247.
15. **Maneendra, P.V.V.S. et al. (2022).** Determination and Analysis of Tensile Strength for Epoxy Refined Coconut Fiber Composite with Rice Hulls and Sawdust as Refinements. *International Journal of Mechanical Engineering*, 7(4), pp.1716-1719.
16. **Ismail, M. et al. (2020).** Mechanical properties of hybrid glass fiber/rice husk reinforced polymer composite. *Materials Today: Proceedings*, 27, pp.1749-1755.
17. **Fuqua, M.A., Huo, S. and Ulven, C.A. (2012).** Natural fiber reinforced composites. *Polymer Reviews*, 52(3), pp.259-320.
18. **Prabhu, L. et al. (2021).** Experimental investigation on mechanical properties of flax/banana/industrial waste tea leaf fiber reinforced hybrid polymer composites. *Materials Today: Proceedings*, 45, pp.8136-8143.

19. **Siregar, J.P., Salit, M.S., Rahman, M.Z.A. and Dahlan, K.Z.H.M. (2011).** Thermogravimetric analysis (TGA) and differential scanning calometric (DSC) analysis of pineapple leaf fibre (PALF) reinforced high impact polystyrene (HIPS) composites. *Pertanika Journal of Science and Technology*, 19(1), pp.161-170.
20. **Domke, P.V. and Mude, V.D. (2015).** Natural fiber reinforced building materials. *IOSR Journal of Mechanical and Civil Engineering*, 12(3), pp.2320-2334.