RESEARCH ARTICLE OPEN ACCESS

Role of Stacking Sequence in Determining the Mechanical Properties of Hybrid Natural Fiber–Steel Mesh Composites

Lingeshwaran R, Soundararajan R, Babu M, Sugan V

Department of Mechanical Engineering, Mahendra Engineering College, Mallasamudram, Namakkal, Tamilnadu, India.

(Corresponding author : suganv@mahendra.info)

--************************----------------------------------

Abstract:

This study investigates the influence of stacking sequence on the mechanical properties of hybrid composites made from natural fibers (sisal, jute, and banana) and a stainless steel mesh core. Five different stacking configurations were evaluated through tensile, flexural, impact, and hardness tests. The results demonstrate that the stacking sequence significantly affects the composite's mechanical performance. Specifically, the configuration with sisal and banana fibers in the outer layers and steel mesh at the core exhibited the highest tensile and flexural strengths. The inclusion of steel mesh enhanced the overall structural integrity and energy absorption capacity of the composites. These findings highlight the importance of optimizing stacking sequence in the design of high-performance, sustainable hybrid composites for various structural applications.

Keywords: Stacking sequence, natural fiber composites, steel mesh, mechanical properties, hybrid composites

--************************----------------------------------

1. Introduction

In the quest for sustainable and high-performance materials, hybrid composites have emerged as a compelling alternative to conventional materials in various engineering and industrial applications. Composites, by definition, consist of two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. Among these, natural fiber-reinforced polymer composites have drawn increasing attention due to their environmental friendliness, renewability, cost-effectiveness, and favorable strength-to-weight ratios. However, one of the critical limitations of natural fiber composites is their relatively lower mechanical performance compared to synthetic composites, particularly in structural applications. As a response to these limitations, researchers have explored hybridization strategies—most notably, the combination of natural fibers with other reinforcement materials such as synthetic fibers or metallic meshes to enhance mechanical performance while preserving ecological benefits [1].

The incorporation of steel mesh as a secondary reinforcement in natural fiber composites has shown considerable potential in addressing some of the mechanical limitations of natural fiber-based materials. Steel, known for its superior tensile strength, stiffness, and impact resistance, can significantly bolster the structural integrity of composites when strategically embedded within the laminate structure. This combination of ductile metal reinforcement with renewable natural fibers enables the development of novel hybrid composites that are not only strong and durable but also relatively lightweight and environmentally benign. Among the various structural parameters influencing the performance of such hybrid

composites, the stacking sequence of the reinforcing layers plays a pivotal role [2].
The stacking sequence refers to the specific order and orientation in which different reinforcement layers—natural fibers and steel mesh in this case—are arranged within a composite laminate. This sequence determines how external loads are distributed among the layers and governs the overall mechanical response of the composite under tensile, compressive, flexural, and impact loading. An optimized stacking sequence can lead to substantial improvements in load-bearing capacity, energy absorption, interlaminar shear strength, and resistance to delamination. Conversely, a poorly designed stacking arrangement may result in suboptimal performance, premature failure, or inefficient use of reinforcement materials. Therefore, understanding and optimizing the stacking sequence is critical to maximizing the mechanical potential of hybrid natural fiber composites reinforced with steel mesh [3].

Natural fibers such as jute, hemp, flax, sisal, coir, and kenaf have been widely used in polymer composites due to their biodegradable nature, low density, moderate mechanical strength, and availability[4,5]. However, their hydrophilic nature and variability in mechanical properties often pose challenges in achieving consistent and reliable performance. To overcome these challenges, hybridization with stronger reinforcements such as steel mesh provides a viable pathway to improve dimensional stability, enhance stiffness, and boost impact resistance. When the steel mesh is integrated into the laminate at strategic locations—either on the outermost layers, inner core, or interleaved between natural fiber layers—it can significantly alter the stress distribution patterns and arrest crack propagation, thereby improving the composite's damage tolerance.

Numerous studies have emphasized the significance of stacking sequence in fiber-reinforced composites[6,7]. For instance, in synthetic composites involving glass, carbon, or aramid fibers, strategic placement of stiffer or stronger layers near the surfaces has been shown to increase bending stiffness and delay failure. Translating these principles to natural fiber-metal hybrid systems involves additional considerations, such as the mismatch in stiffness, interfacial bonding characteristics, and thermal expansion coefficients between natural fibers and metallic reinforcements. These factors must be carefully managed through thoughtful design of the stacking sequence, selection of appropriate matrix materials, and implementation of surface treatments to ensure compatibility and effective load transfer across interfaces.

In hybrid natural fiber composites reinforced with steel mesh, the role of the matrix is equally vital. Thermoset resins such as epoxy, polyester, and vinyl ester are commonly used due to their good mechanical properties and strong adhesion to both natural fibers and steel. The matrix binds the fibers and mesh together, transfers loads among the reinforcing phases, and protects them from environmental degradation. The interface between the matrix and the reinforcing elements, particularly the natural fibers and steel mesh, is crucial for effective stress transfer. Surface treatments such as alkali treatment for fibers and chemical coatings or primers for steel mesh can significantly enhance interfacial bonding, leading to improved mechanical performance[4].

In addition to stacking sequence, other design parameters such as fiber orientation, volume fraction, layer thickness, and fiber-matrix adhesion influence the mechanical behavior of hybrid composites. However, the stacking sequence remains a primary design tool because it allows for the tailoring of properties without changing the constituent materials. For instance, placing steel mesh layers at the outermost surfaces can improve surface hardness and impact resistance, while positioning them at mid-thickness may enhance energy absorption during flexural loading. Similarly, alternating layers of natural fibers and steel mesh can yield a balance between stiffness, ductility, and strength, suitable for applications requiring both structural integrity and energy dissipation [8–10].

The performance of a composite is often evaluated through mechanical tests such as tensile, flexural, impact, and interlaminar shear tests. These tests provide insights into how stacking sequence affects failure mechanisms such as fiber breakage, matrix cracking, delamination, and debonding. For example, under tensile loading, the load is primarily borne by the stiffer reinforcement layers, and the sequence in which these layers are arranged determines the load path and failure mode. Under flexural loading, outermost layers experience maximum stress; thus, placing high-strength materials like steel mesh in these positions can enhance bending resistance. Impact tests reveal how energy is absorbed and dissipated during sudden loading, highlighting the role of tough steel layers in preventing catastrophic failure[11].

In addition to mechanical benefits, the strategic use of steel mesh in natural fiber composites can impart multifunctional properties. Steel mesh can serve as a conductive path for electromagnetic shielding, grounding, or heating applications. It can also enhance fire resistance, which is often a limitation in purely organic composites. Moreover, the hybrid structure can be designed for specific anisotropic properties, where stiffness and strength vary in different directions based on the orientation of the reinforcing layers. This flexibility in design is especially useful in automotive, aerospace, marine, and civil engineering applications where material properties must be tailored to specific loading conditions and environmental factors.

Despite the potential advantages, the development of hybrid natural fiber composites with embedded steel mesh presents several challenges. One key issue is ensuring adequate bonding between the steel mesh and the polymer matrix, particularly given the difference in surface energy and thermal behavior between metal and polymer. Improper bonding can lead to stress concentrations and delamination under load. Another challenge is the increased weight and reduced flexibility introduced by the metallic component, which may counteract some of the benefits of using natural fibers. Therefore, a balanced approach is required in selecting the number, position, and orientation of steel mesh layers to optimize mechanical performance without compromising other desirable properties.

The environmental implications of using hybrid composites must also be considered. While natural fibers are biodegradable and renewable, the inclusion of steel makes end-of-life disposal more complex. However, if designed for durability and long service life, such composites can still offer significant environmental benefits by reducing the use of non-renewable materials and extending product lifespan. Recycling and reuse strategies, such as mechanical separation of layers or repurposing of composite components, can further enhance the sustainability of these hybrid systems. In conclusion, the stacking sequence is a critical parameter in the design of hybrid natural fiber composites reinforced with steel mesh. It influences not only the mechanical properties but also the overall performance, reliability, and application potential of the composite. By carefully selecting and optimizing the arrangement of natural fiber and steel mesh layers, engineers can develop advanced composite materials that combine the ecological benefits of natural fibers with the strength and durability of steel. This research aims to systematically investigate the impact of different stacking sequences on the mechanical properties of such hybrid composites through experimental testing and analysis. The findings will contribute to the development of high-performance, sustainable materials for structural and semi-structural applications in various industries.

2. Material & Selections

2.1 Materials

Composite laminates were fabricated using three types of natural fibers: sisal (362 gsm), jute (350 gsm), and banana fiber (300 gsm). For structural enhancement, a core layer of SS 303 stainless steel mesh with a mesh opening of 100 mm and a density of 8.03 g/cm³ was incorporated. The matrix system comprised epoxy resin LY556, cured with hardener HY951, selected for its compatibility and effective bonding with the reinforcing materials.

2.2 Composite Fabrication

The composite specimens were produced using a mold with dimensions of 200 mm × 200 mm × 3 mm. To prevent resin leakage during fabrication, an aluminum foil barrier was placed on the mold surface. In the initial phase of manufacturing, the epoxy system—comprising LY556 resin and HY951 hardener—was poured into the mold cavity without the addition of hBN particles. Sufficient resin was applied to each layer of the woven natural fibers to ensure compactness and minimize voids within the laminate. This investigation focused on assessing the influence of stacking sequence by varying the fiber layer arrangements, as detailed in Tables 1. A steel mesh was incorporated at the core of the composite structure to enhance its mechanical strength and load-bearing capacity. In the subsequent phase, composite panels were fabricated using epoxy resin blended with hBN particles, applying the most effective fiber stacking sequence identified from earlier tests. After layer assembly, the mold was transferred to a compression molding unit and processed under a pressure of 30 bar. The fabrication steps and a representative image of the composite specimen are presented in Figure 1.

Table 1. Stacking sequences of hybrid composites.

Sample	Stacking Sequences						
S1	Sisal	Banana	Jute	Wire mesh	Sisal	Banana	Jute
S2	Jute	Banana	Sisal	Wire mesh	Jute	Banana	Sisal
S3	Banana	Sisal	Jute	Wire mesh	Banana	Sisal	Jute
S4	Sisal	Jute	Banana	Wire mesh	Sisal	Jute	Banana
S5	Jute	Sisal	Banana	Wire mesh	Jute	Sisal	Banana

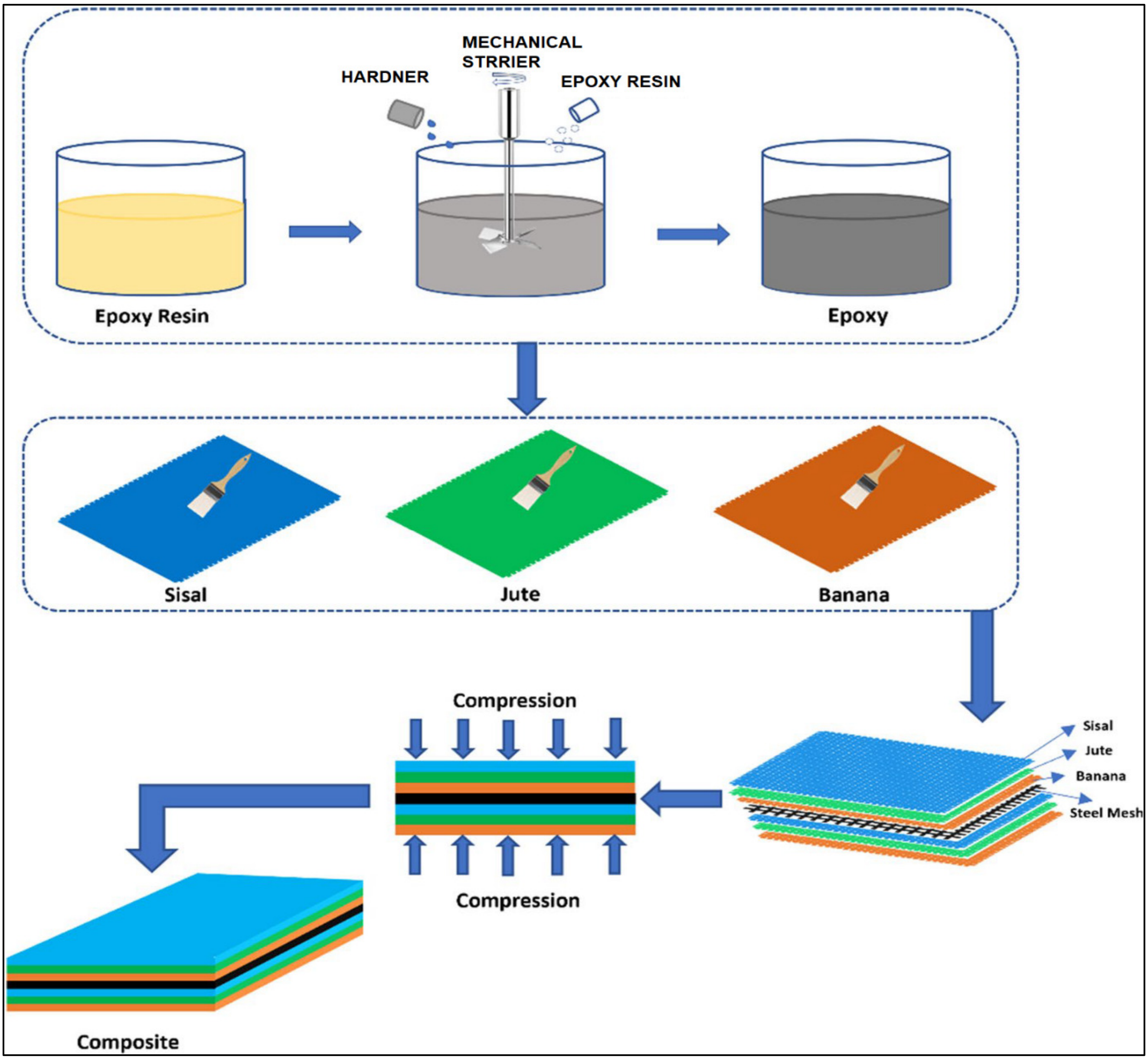

Figure 1. Illustration of the Fabrication Process for Hybrid Composite.

2.3 Mechanical characterization

2.3.1 Tensile Strength

The tensile properties of the hybrid natural fiber composites were evaluated using an Instron universal testing machine (Model 8801, Instron, Germany) operated at a constant strain rate of 1 mm/min. The test results included measurements of ultimate tensile strength and yield strength, which were recorded directly from the testing system. Prior to testing, all specimens were prepared in accordance with ASTM D3039 standards to ensure consistency and reliability in the results.

2.3.2 Flexural Strength

Flexural behavior was assessed through a three-point bending test, also performed using the

Instron 8801 machine at a strain rate of 1 mm/min. Specimens with dimensions of 125 mm × 12.7 mm × 3 mm were fabricated and tested according to ASTM D790 guidelines. During testing, some samples exhibited failure modes such as fracture and breakage, providing insight into the material's bending resistance and toughness.

2.3.3 Hardness

The Shore D hardness of the fabricated hybrid natural fiber nanocomposites was measured at 1.00 mm intervals, with each measurement held for a dwell time of 20 seconds. This method quantifies the material's resistance to surface indentation. A Shore D durometer was used to perform the test, where the hardness value is inversely proportional to the depth of penetration by the indenter's foot, offering a clear indication of surface hardness.

2.3.4 Impact Energy

The energy absorbed during fracture of the natural fiber composite was evaluated using the Izod impact test, in accordance with ASTM D256 standards, utilizing a FIT-300-D testing machine (Fine Testing Machine, India). Test specimens measured 63.5 mm in length, 12.5 mm in width, and 7 mm in thickness. An H2 hammer, capable of delivering a maximum impact energy of 5.42 J at a velocity of 3.46 m/s, was employed to perform the test.

3 Result and discussion

3.1.1 Tensile Properties

Figure 2 illustrates the tensile strength results corresponding to various stacking sequences in sisal-jute-banana-steel mesh epoxy hybrid composites. Among these configurations, the S4 laminate exhibited the highest tensile strength, reaching 67 MPa, significantly outperforming the other stacking arrangements. This remarkable improvement is attributed to the synergistic effect of sisal and banana fibers used in both the outer and core layers, which contributed to an overall enhancement in the composite's stiffness [12]. The superior bonding of sisal and banana fibers with the epoxy matrix is believed to play a key role in reinforcing the material's tensile capacity.

The incorporation of a steel mesh layer further amplified the composite's structural integrity by promoting uniform load distribution throughout the laminate. This addition mitigated the formation of localized stress concentrations, thereby increasing the material's ability to withstand higher applied loads without premature failure. The steel mesh effectively acted as a critical reinforcement component, leading to tensile strength improvements of at least 30% compared to mesh-free composites. A comparative evaluation of tensile strength among epoxy hybrid composites reinforced with jute, kenaf, and banana fibers showed a significant increase up to 39% in the S4 configuration, further confirming its mechanical superiority.

Figure 2 presents the tensile modulus values for the different stacking sequences. The S4 configuration again stood out, achieving a maximum tensile modulus of 0.72 GPa. This increase is primarily due to enhanced interfacial adhesion between the fiber reinforcements and the epoxy matrix. When comparing hybrid and pure composites, it was evident that the pure composites displayed lower tensile modulus values, indicating a reduced resistance to elastic deformation. The optimized outer-layer arrangement of sisal and banana fibers in S4 contributed to the improved load transfer characteristics, resulting in the highest tensile stiffness among all tested configurations.

In contrast, the S5 stacking sequence recorded the lowest tensile modulus at 0.5 GPa, highlighting its comparatively inferior performance in stiffness. The overall trend in tensile modulus among the composite configurations followed the order: S5 < S1 < S2 < S3 < S4. These findings emphasize the critical role of fiber arrangement and interfacial bonding in determining the tensile behavior of hybrid composites.

3.1.2 Flexural Properties

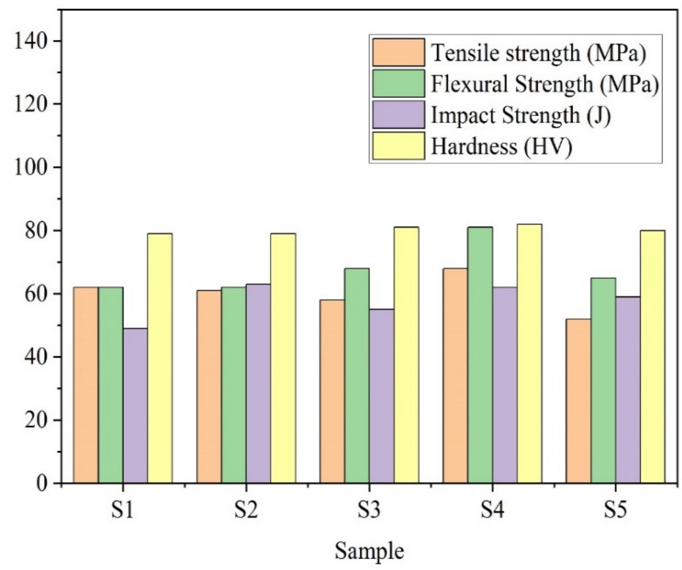

Figure 2. Results for Mechanical Characterization.

Figure 2 displays the flexural strength values for different stacking sequences of sisal-jute-banana-steel mesh epoxy hybrid composites. Among all configurations, the S4 laminate achieved the highest flexural strength at 80 MPa, significantly outperforming the other combinations. This enhanced bending performance can be attributed to two primary factors: first, the high tensile strength of sisal and banana fibers positioned in the outer layers contributes effectively to resisting bending stresses; second, the presence of a centrally embedded steel mesh enables more uniform stress distribution, reducing the risk of localized damage or failure.

The strategic inclusion of steel mesh at the core not only reinforces the composite but also substantially increases its structural stiffness. This reinforcement method markedly boosts the composite's load-bearing capacity and rigidity, leading to an improvement in flexural strength by at least 33% when compared to composites without mesh reinforcement. Further comparative evaluation involving jute, kenaf, and banana fiber-reinforced epoxy hybrids confirmed a peak increase of 16% in flexural strength for the NC4 stacking sequence.

Figure 2 presents the flexural modulus for various fiber arrangements within the hybrid composites. The S4 configuration again delivered the highest performance, registering a flexural modulus of 3.3 GPa. These results underscore the superior bending stiffness achieved through the optimized placement of sisal and banana fibers, which enhanced fiber-matrix interaction and load transfer efficiency.

In general, all hybrid composites exhibited greater flexural stiffness than their single-fiber counterparts, regardless of the specific fiber types used. However, stacking sequences that placed sisal and banana in the outermost layers consistently produced composites with the highest modulus values. Conversely, arrangements where jute and banana occupied the skin layers resulted in relatively poor flexural performance, as evidenced by the noticeably lower modulus values. These findings highlight the importance of fiber type and layer positioning in tailoring the flexural characteristics of hybrid natural fiber composites.

3.1.3 Impact Strength

Figure 2 illustrates the impact strength performance of sisal-jute-banana-steel mesh epoxy hybrid composites, emphasizing the role of stacking sequence in resisting high-velocity impacts. The impact resistance of these materials is significantly influenced by the interaction between the fiber reinforcements and the epoxy matrix. Among the different configurations tested, the S2 and NC4 laminates demonstrated the highest impact strength, each reaching 63 KJ/m^3.

The improvement in impact resistance is largely attributed to the presence of a centrally embedded steel mesh, which acts as a crack arrester and reinforcement medium. By effectively dissipating and absorbing the energy from sudden impacts, the steel mesh helps prevent catastrophic failure and enhances the composite's ability to endure dynamic loading conditions. This reinforcement strategy improves overall toughness and durability, particularly in structures subjected to impact stresses.

3.1.4 Shore D Hardness

The surface hardness of fiber-reinforced composites is largely governed by the strength of adhesion between the fibers and the epoxy matrix. Figures 2 show the Shore D hardness measurements taken from both the top and bottom surfaces of different stacking sequences involving sisal, jute, banana fibers, and steel mesh, along with pure composite specimens. These measurements provide insights into how the outermost fiber layer influences hardness due to its bonding efficiency with the matrix.

For the S1 configuration, sisal forms the top layer while jute occupies the bottom, yielding Shore D hardness values of 79 and 76, respectively. In the S2 sequence, jute a fiber with relatively lower hardness is placed on the top, and sisal a harder fiber on the bottom. The S3 laminate features banana fiber on the top and jute on the bottom, where jute demonstrates a slightly higher hardness than banana. In S4 and S5, the combination of sisal and jute in the outer layers results in the highest recorded hardness values, whereas configurations involving banana fibers in the skin layers tend to yield lower values due to banana's inherently softer texture.

Despite these differences in outer-layer composition, the results showed no major variations in hardness between pure composites and hybrid composites with different stacking sequences. Moreover, the presence of steel mesh within the laminate had minimal influence on the Shore D hardness values.

Overall, when evaluating all hybrid configurations, the mechanical and surface hardness properties were relatively consistent. However, a closer analysis identified the S4 configuration as particularly well-balanced in terms of both mechanical performance and surface hardness.

4. Conclusion

The present investigation underscores the significant influence of stacking sequence on the mechanical behavior of hybrid natural fiber composites reinforced with a stainless steel mesh core. Five different stacking sequences involving sisal, jute, and banana fibers were fabricated and mechanically tested to evaluate their tensile, flexural, impact, and surface hardness properties. Among the evaluated configurations, the S4 laminate—featuring sisal and banana fibers in the outer layers with steel mesh embedded centrally—consistently outperformed other sequences across all mechanical metrics. It exhibited the highest tensile strength (67 MPa), flexural strength (80 MPa), and flexural modulus (3.3 GPa), confirming that optimal fiber placement and mesh integration significantly enhance load-bearing capacity and stiffness.

The improvements in mechanical performance can be primarily attributed to the synergistic effects of stiff outer fiber layers (sisal and banana), effective fiber–matrix bonding, and the structural reinforcement provided by the steel mesh core. The centrally embedded mesh played a crucial role in redistributing applied loads, arresting crack propagation, and increasing energy absorption under dynamic loading, as evidenced by the superior impact resistance observed in S2 and NC4 configurations. Additionally, the Shore D hardness results indicated that surface hardness was largely influenced by the type of fiber in the outermost layer, with sisal contributing to higher hardness values due to its denser structure.

These findings validate the critical role of stacking sequence as a design variable in tailoring the mechanical performance of hybrid composites. By strategically arranging natural fibers and integrating steel mesh reinforcement, it is possible to engineer composites that strike a balance between strength, stiffness, impact resistance, and environmental sustainability. Such hybrid systems show promise for applications in automotive, construction, aerospace, and marine industries, where both mechanical performance and ecological considerations are essential.

Future work could explore the long-term durability, moisture resistance, and thermal performance of these composites, as well as the potential integration of nanofillers or surface treatments to further enhance interfacial bonding. Overall, the study contributes valuable insights into the design and development of next-generation sustainable composite materials.

References

[1] Elayaraja R and Rajamurugan G 2024 Recent development and efficacy of wire mesh embedded natural fiber composite - A review *Results in Engineering* 24

[2] Radhakrishnan E and Govindasamy R 2025 Reinforcement of a novel woven pineapple yarn and wire mesh on natural fiber hybrid composite *Textile Research Journal*

[3] Singh C Q J and Rajamurugan G 2021 Effect of Resin on Mechanical and Wear Performance of Wire Mesh-Reinforced Hydrophilic Fiber Composite *Transactions of the Indian Institute of Metals* 74 2853–67
[4] Elayaraja R and Rajamurugan G 2024 Performance of Hybrid Composites Fabricated by Flax/Hemp Fibers Using Wire Mesh Plain Weaving Techniques *Fibers and Polymers* 25
[5] Suresh S, Velmurugan D, S S and Elayaraja R 2024 Advanced joining methods for lightweight materials in sustainable manufacturing *Futuristic Technology for Sustainable Manufacturing*
[6] Singh Q J and Rajamurugan G 2022 Experimental study on abrasive water jet machining of WCFC reinforced flax/wire mesh/hemp composite *Journal of Industrial Textiles* 52 152808372211219
[7] Krishnasamy P, Rajamurugan G and Thirumurugan M 2021 Dynamic mechanical characteristics of jute fiber and 304 wire mesh reinforced epoxy composite *Journal of Industrial Textiles* 51 540–58
[8] Elayaraja R, Sasikumar R, Gokul M and Gowrisankar T 2020 Experimental Investigation of Prosopis Juliflora and Mango Tree with Epoxy Resin *IOP Conference Series: Materials Science and Engineering* vol 923
[9] Rajamurugan G, Ramakrishnan ., Krishna P, Raj J and Elayaraja R 2024 Mechanical and dynamic response of epoxy based pineapple/flax fiber composites reinforced with steel and nylon wire meshes *Engineering Research Express* 6
[10] Rajamurugan G, Rithvik Athithya S, Krishnasamy P, Nadeem A, Kavinkumar L and Elayaraja R 2024 Mechanical and tribological performance of ramie composite reinforced with perforated Al/Cu foils *Engineering Research Express* 6
[11] Khalid M Y, Arif Z U, Al Rashid A, Shahid M I, Ahmed W, Tariq A F and Abbas Z 2021 Interlaminar shear strength (ILSS) characterization of fiber metal laminates (FMLs) manufactured through VARTM process *Forces in Mechanics* 4 100038
[12] Thiagamani S M K, Pulikkalparambil H, Siengchin S, Ilyas R A, Krishnasamy S, Muthukumar C, Radzi A M and Rangappa S M 2022 Mechanical, absorption, and swelling properties of jute/kenaf/banana reinforced epoxy hybrid composites: Influence of various stacking sequences *Polym Compos* 43 8297–307

Orcid id :
Babu M - https://orcid.org/0009-0001-4022-256X
Sugan V- https://orcid.org/0009-0002-1322-5009

