STM JOURNALS

Journal of
Materials & Metallurgical Engineering

https://journals.stmjournals.com/jomme

ISSN: 2231-3818 (Online)
ISSN: 2321-4236 (Print)
Volume 15, Issue 3, 2025
September–December
DOI (Journal): 10.37591/JoMME

Research JoMME

Comparative Analysis of Natural and Synthetic Fiber-Reinforced Composites: Mechanical Properties, Processing, and Sustainability Considerations

Gurushanth B Vaggar[1], Ananthesh D Kamath[2,*], Elvin Chris DSouza[3], Shyam[4], Pradeep[5]

Abstract

The development of fiber-reinforced composites has significantly advanced engineering applications due to their excellent strength-to-weight ratio, corrosion resistance, and versatility. Synthetic fibers such as glass and carbon provide superior mechanical performance, but their production is energy-intensive and environmentally harmful. Natural fibers, including jute, flax, banana, and hemp, offer biodegradability, lower cost, and sustainability benefits, though they often fall short in strength and durability. Hybrid composites frequently demonstrate improved performance by combining the strength of synthetic fibers with the eco-friendly characteristics of natural fibers. Sustainability considerations reveal that the use of natural fibers can reduce costs and environmental impacts by up to 30%, highlighting their growing relevance in aerospace, automotive, and civil engineering. This paper consolidates findings from ten key studies, emphasizing mechanical properties, processing methods, and sustainability perspectives. Future research directions in fiber treatment, matrix modification, and recycling are also discussed.

Keywords: Hybrid composites, mechanical properties, natural fibers, processing, sustainability, synthetic fibers

INTRODUCTION

Fiber-reinforced composites (FRC) are materials engineered for improved mechanical performance whose properties are intricately connected with key factors such as the fiber type, the adhesion between the fiber and the matrix material, the orientation of the fibers in the composite, and the processing conditions of the composite [1]. Classical synthetic fibers of glass and carbon have been favored more on account of their tensile strength, compressive strength, and flexural strength. However, environmental issues have given rise to more research into natural fiber and hybrid composites to balance performance with sustainability.

Since they offer excellent mechanical strength, lightweight characteristics, corrosion resistance, and design flexibility, FRCs have gained importance in modern engineering. Their widespread application in aerospace, automobile, civil, and marine industries speaks loudly about their versatility and reliability in rigorous environments [2]. These characteristics have made synthetic fibers such as glass, carbon, and aramid more prominent in this field. They have traditionally been used due to their superior tensile strength, stiffness, and thermal stability [3].

***Author for Correspondence**
Ananthesh D Kamath
E-mail: anantheshkamath2004@gmail.com

[1]Associate Professor, Department of Mechanical Engineering, Alva's Institute of Engineering and Technology, Moodbidri, Karnataka, India
[2,3,45]UG students, Department of Mechanical Engineering, Alva's Institute of Engineering and Technology, Moodbidri, Karnataka, India

Received Date: December 03, 2025
Accepted Date: December 27, 2025
Published Date: December 30, 2025

Citation: Gurushanth B Vaggar, Ananthesh D Kamath, Elvin Chris DSouza, Shyam, Pradeep. Comparative Analysis of Natural and Synthetic Fiber-Reinforced Composites: Mechanical Properties, Processing, and Sustainability Considerations. Journal of Materials & Metallurgical Engineering. 2025; 15(3): 77–95p.

The manufacturing of synthetic fibers, however, faces disadvantages. High amounts of energy consumption and non-biodegradability, along with the challenges in recycling, contribute greatly to environmental concerns, thus the chances of their large-scale utilization are getting slim [4]. Production costs are also a major problem preventing synthetic fibers, especially carbon and aramid fibers, from widespread use in cost-sensitive industries [5].

Natural fibers have been the subjects of increased interest as reinforcement materials in recent decades. Jute, flax, banana, hemp, and sisal rank among the most studied natural fibers since they are abundant, renewable, and biodegradable [6]. Their fiber characteristics define the low density, allowing the production of lightweight composites. Besides, the cultivation itself requires very little energy compared with energy needed for the manufacture of synthetic fibers [7]. Added to this benefit is the promotion of socioeconomic development, especially in developing countries where fiber cultivation aids agricultural livelihoods [8].

However, natural fibers face inherent limitations such as lower tensile and compressive strength, higher moisture absorption, and weaker adhesion with polymer matrices compared to synthetic fibers [9]. These issues often restrict their use in high-performance applications where structural integrity and durability are critical [10].

The researchers started looking into hybrid composites, i.e., composites having natural and synthetic fibers in a polymer matrix to cater to these limitations. Hybridization allows the strength of synthetic fibers such as glass to make up for the weakness of natural fibers while keeping the costs down and environment-friendly. For example, jute-glass hybrid composites showed better tensile, flexural, and impact resistances than those reinforced only with natural fibers. Likewise, the flax-glass hybrid composites showed improved interlaminar shear strength and toughness, thereby being apt for structural applications.

With an upsurge in demand for sustainable engineering materials, the research has come shifting gear in eyeing the balance between performance and eco-friendliness. Synthetic fibers still lead in terms of strength, but natural fibers have definite advantages in biodegradability, recyclability, and cost-effectiveness. An integrated review of natural and synthetic fiber composites is necessary to assess their comparative performance, identify process problems, and highlight opportunities

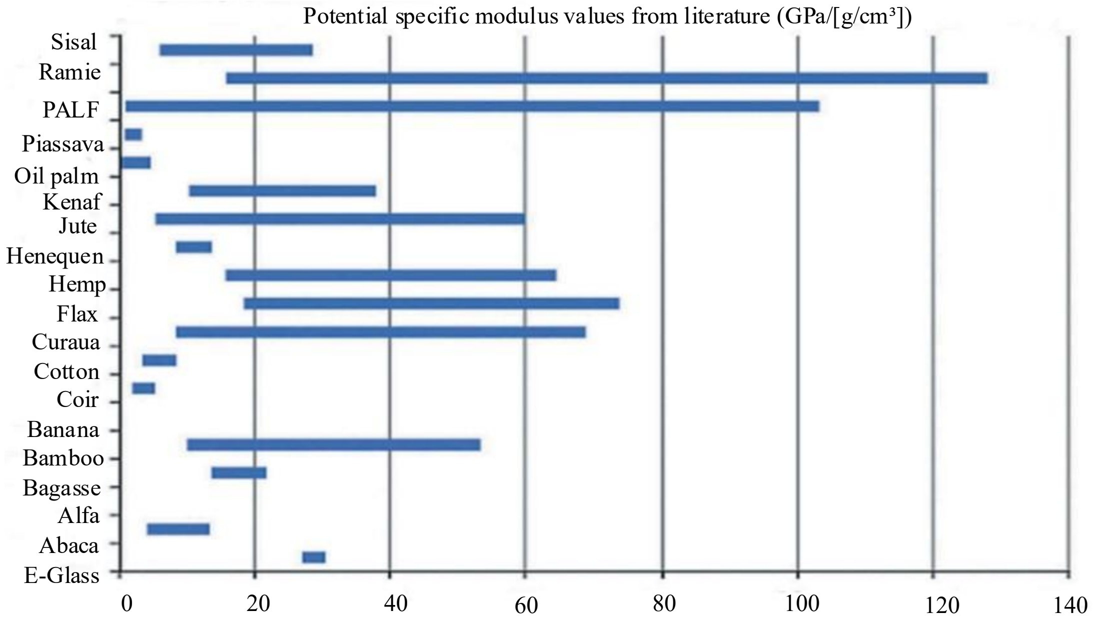


Figure 1. Comparison of potential specific modulus values and ranges between natural fibers and glass fiber.

Table 1. Physio-mechanical properties of natural and synthetic fibers.

	Fibre	**Density(gm/cc)**	**Tensile strength (MPa)**	**Young's modulus (GPa)**
Synthetic fibre	Aramid	1.40	300	124
	Kevlar (29)	1.30–1.44	2900–3620	70–83
	Nylon	1.14	54	0.94–3
	Glass (E)	2.50	2000=3000	70
	Carbon	1.40	4000	230-240
	Boron	2800	385	2.5-2.6
Natural fibre	Jute	1.30–1.45	393–773	13-27
	Coir	0.67–1.15	220	6
	Banana	1.35	335	33.8
	Bamboo	1.32	140–230	11-17
	Sisal	1.45–1.50	67	3.7
	Flax	1.54	28-85	0.3-2

Mechanical Properties of Natural and Synthetic Fiber Composites

The mechanical performance of fiber-reinforced composites strongly depends on fiber type, fiber-matrix adhesion, fiber orientation, and processing conditions in Figure 1. Synthetic fibers such as glass and carbon generally exhibit higher tensile, compressive, and flexural strength compared to natural fibers, but their environmental drawbacks have motivated extensive studies on natural and hybrid alternatives in Table 1 [11].

Tensile Properties

Tensile strength is a critical property for use in load-bearing applications, and generally, synthetic fiber composites have been found to score better on this property compared to natural fiber composites. Hybrid composites containing sisal, jute, and glass fibers surpassed tensile strength levels of pure natural fiber composites, thus showing that synthetic fibers do offer reinforcement. Whereas jute fiber composites showed better tensile performance than sisal fiber composites, this also emphasizes the role that fiber type plays under the natural fiber category.

While synthetic fiber options tend to have higher tensile strength, research into natural and hybrid alternatives is steadily closing this gap. Incorporation of synthetic fibers has been found to enhance tensile performance of natural fiber composites. For example, hybrid composites containing sisal, jute, and glass fibers have higher tensile strength than pure natural fiber composites, emphasizing the reinforcement potential of synthetic fibers. Another point is the natural fiber used for reinforcement, which greatly influences tensile performance. Jute fiber composites exhibited better tensile properties than sisal fiber composites, stressing the importance of selecting the appropriate natural fiber for the intended application. Tensile strength is a key property for materials subjected to pulling forces on load applications. While synthetic fiber composites usually possess higher tensile strength, continuous research regarding natural and hybrid variants is steadily closing this margin [12].

One can raise the tensile strength of natural fibers using synthetic fibers. For example, hybrid composites of sisal, jute, and glass fibers attained better tensile strength than pure natural fiber composites, thus validating the reinforcement by synthetics in Figure 2.

Even within the natural fiber range, fiber selection can have a profound effect on tensile performance in Table 2.

Table 2. Experimental values.

Composite material	Maximum force(N)
Glass epoxy	2805.77
Jute epoxy	4977.84
Glass-Jute epoxy	6953.42

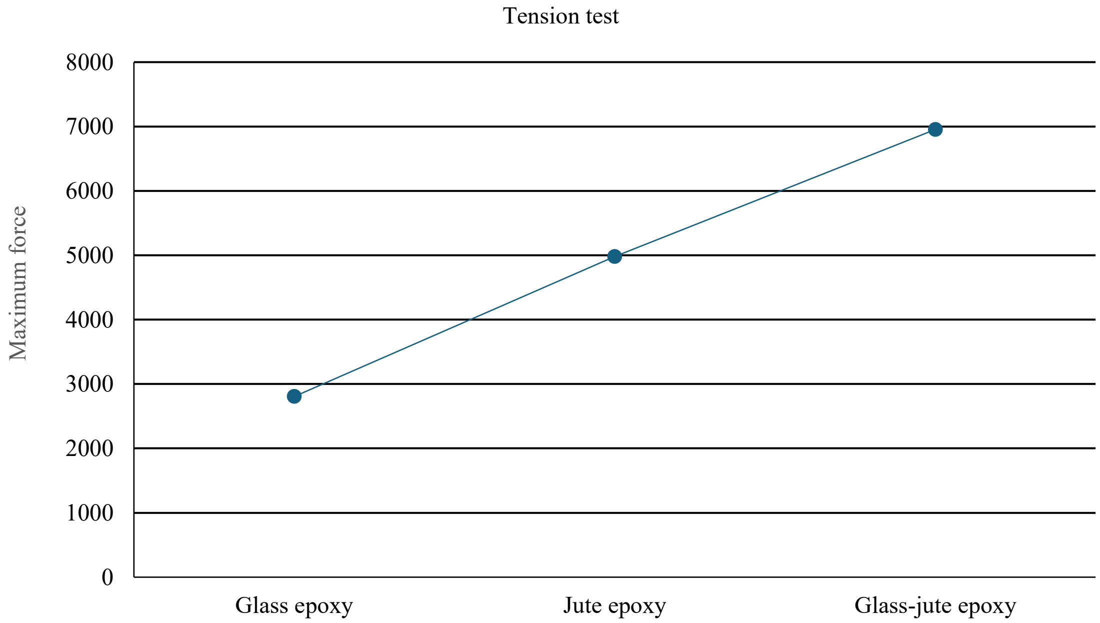


Figure 2. Comparative stress-strain curves for tensile test.

Compressive Properties

Compression strength really plays a critical role in structural applications. Dropping the glass fiber content in hybrid composites takes a serious toll on compressive performance, which points to synthetic fibers being necessary if you want reliable structural stability. Jute/polyester composites, sure, they aren’t on par with straight-up synthetic composites when it comes to compression. Still, they're outperforming wood-based materials and a handful of plastics in terms of compressive strength.

So, when you reduce the amount of synthetic fibers – like glass fibers – in hybrid composites, the compressive strength really takes a hit. There’s a clear link here: less glass fiber basically means you sacrifice compressive performance, which drives home how important these synthetic fibers are for keeping everything structurally sound. Sure, natural fiber composites such as jute/polyester aren’t always on par with fully synthetic ones in terms of compressive strength, but they’re actually still a step up over classic materials like wood-based products and some plastics. That makes them a legit option if you’re after a mix of performance and sustainability in Figure 3–6.

In any structural application, compression strength matters – a lot. Drop the glass fiber content in your hybrid composite, and you’ll see a pretty obvious dip in compressive capability, again underscoring the central role that synthetic fibers play in supporting structural stability in Table 3.

Table 3. Experimental value.

Composite material	Maximum force(N)
Glass epoxy	11221.1
Jute epoxy	6657.24
Glass-jute epoxy	10762.9

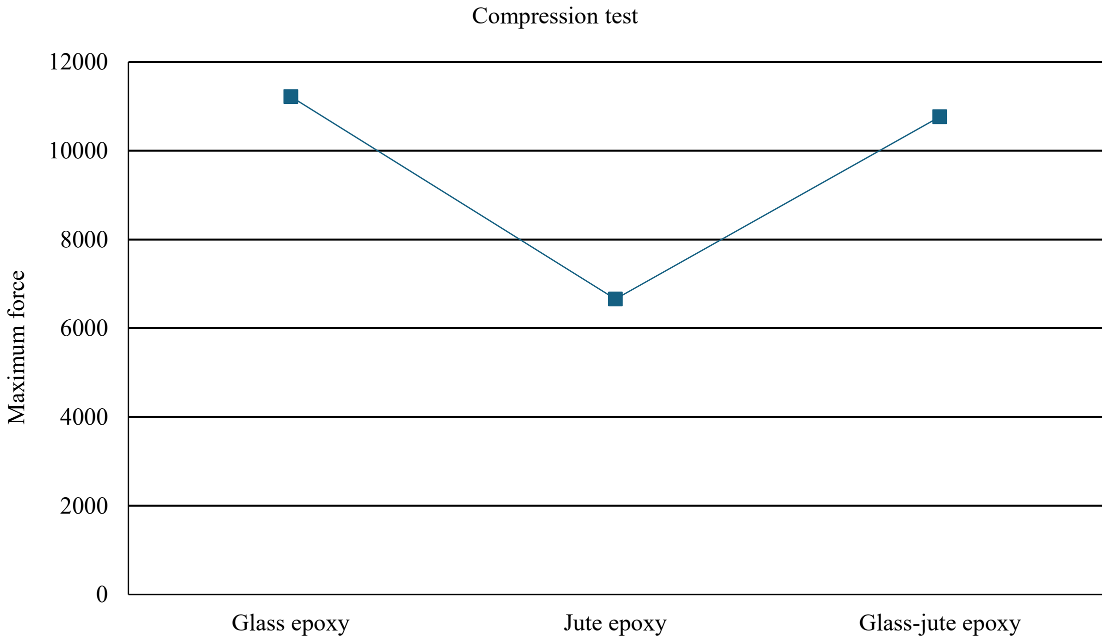


Figure 3. Comparative stress-strain curves for compressive test.

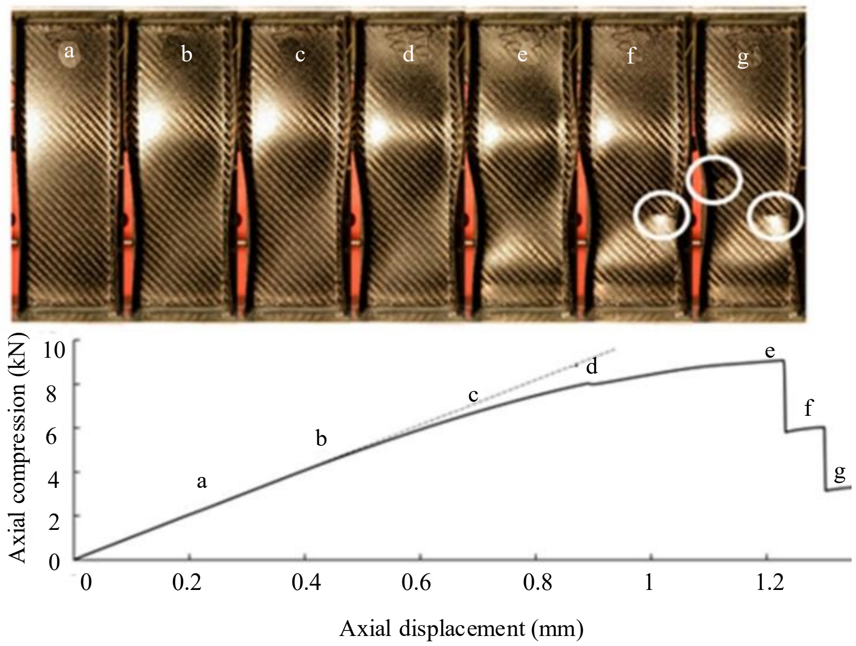


Figure 4. Exemplar carbon fiber composite channel (960 gsm) compression test (dashed line indicates the channel compression stiffness; circles indicate fractures; all column heights are 300 mm).

Flexural Properties

Flexural strength and modulus basically measure how well a composite resists bending – pretty much, how much it can flex without failing. Fiber length is a big deal here: longer natural fibers straight-up boost the material's ability to take bending loads. But, when you keep adding more fiber past a certain point, things go downhill – too many fibers can cause poor dispersion and weak bonding at the interfaces, dragging flexural strength down. Now, there's this hybrid setup with 60% glass fibers and 40% jute fibers, and that blend delivers the top flexural strength. So, hybridization here clearly plays a key role in boosting bending resistance [13].

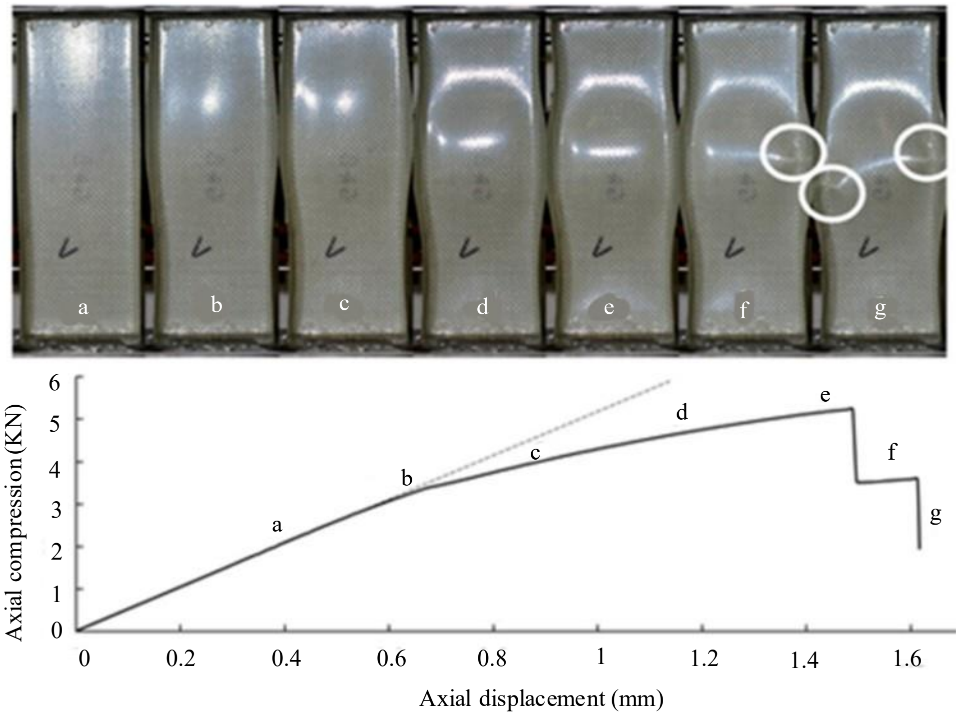
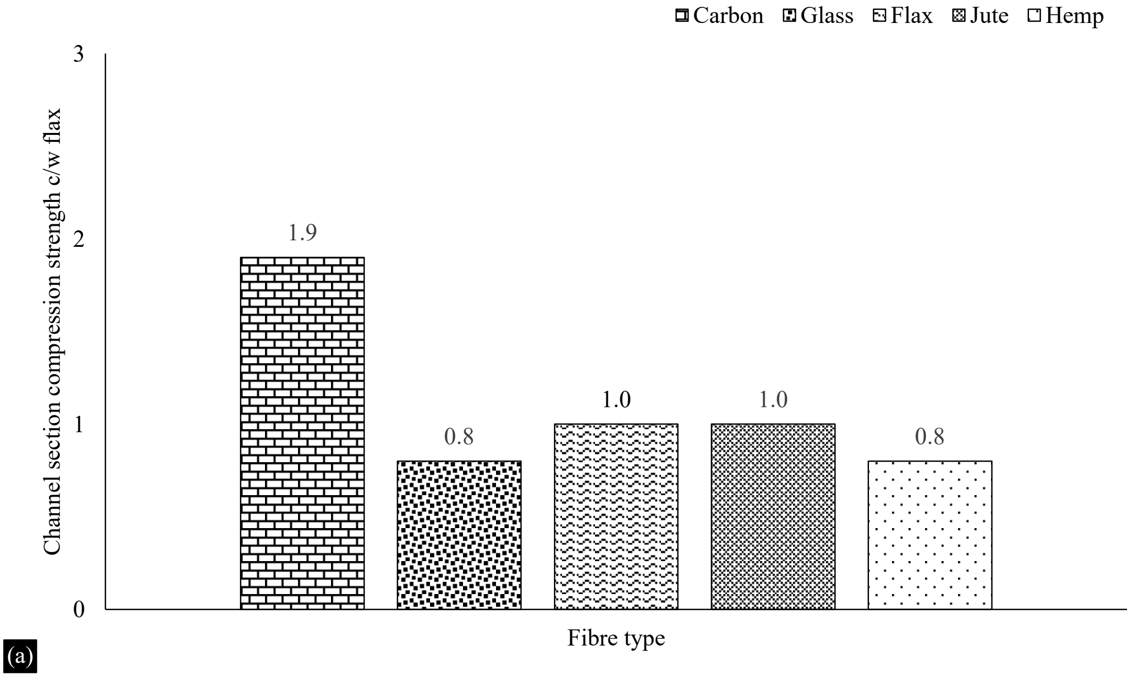


Figure 5. Exemplar glass fiber composite channel (1200 gsm) compression test (dashed line indicates the channel compression stiffness; circles indicate fractures; all column heights are 300 mm).

Fiber length and loading both have a big impact on these properties. Longer fibers are especially important – they improve flexural strength, mainly because they help distribute stress and transfer loads better within the composite. But, if you push fiber loading past a certain point, the flexural strength can actually drop. Overloading leads to poor fiber dispersion and creates weak bonds at the interface between fibers and the matrix, which really hurts the composite's ability to handle bending in figure 7 and 8.



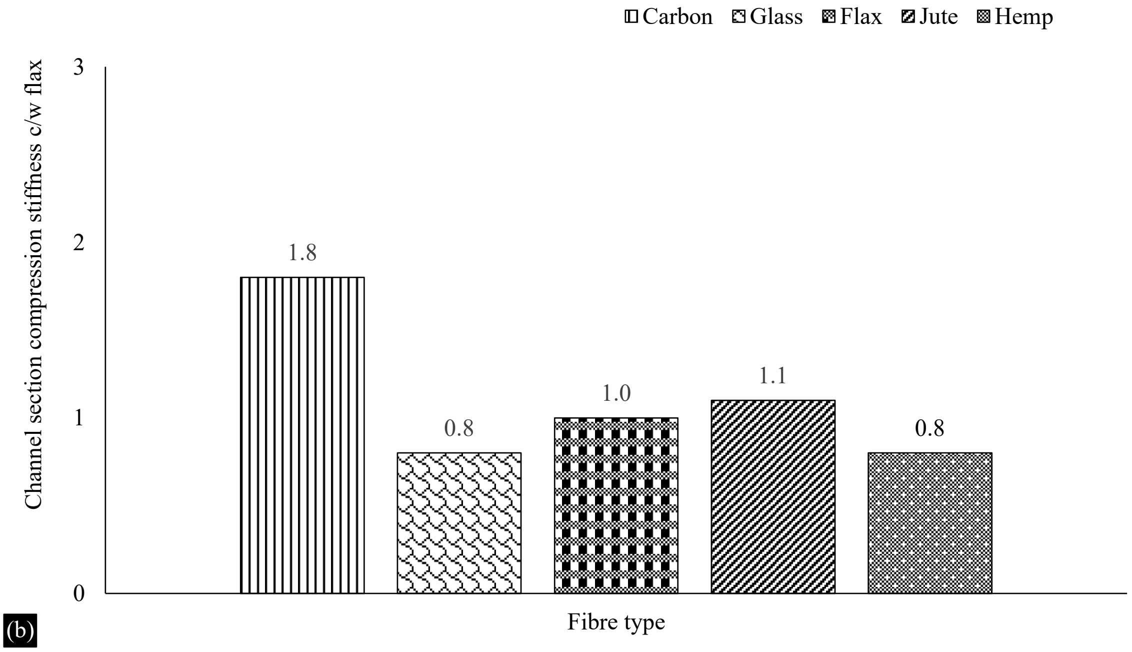


Figure 6. Mean compression strength and stiffness efficiency of structural columns from channel tests: (a) strength and (b) compression stiffness (EA/L), where E is the elastic modulus, A is the cross-section area, and L is the channel length, compared with values for flax.

Table 4. Experimental value.

Composite material	Maximum force(N)
Glass epoxy	98.1808
Jute epoxy	204.285
Glass-jute epoxy	317.955

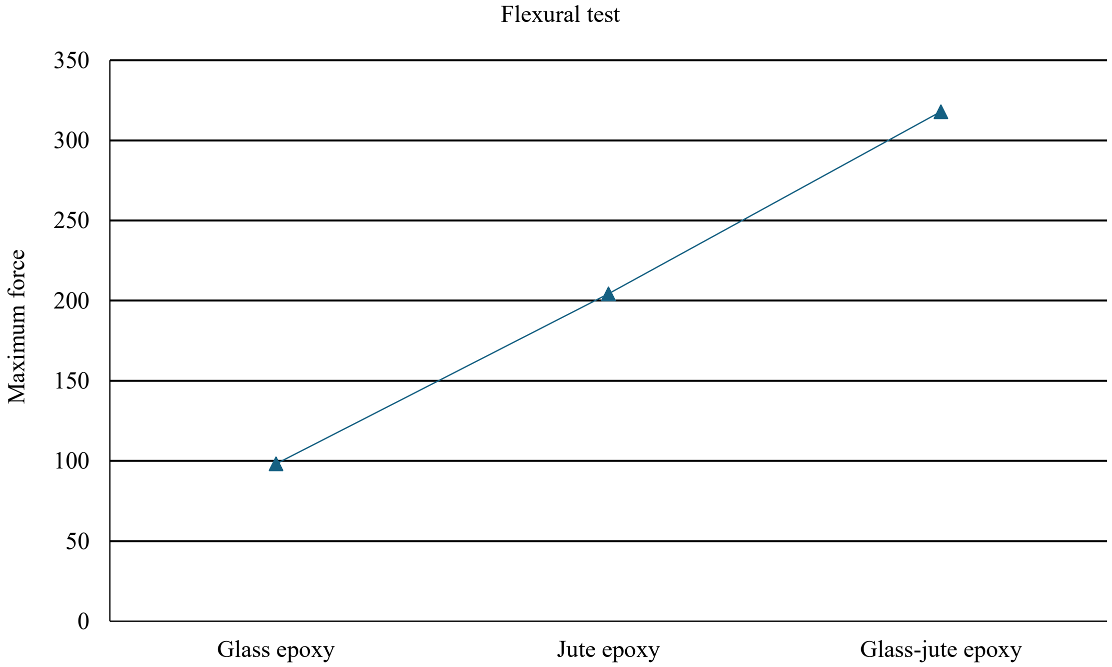


Figure 7. Comparative stress-strain curves for flexural test.

Hybridizing – combining, for example, glass, and jute fibers – has shown to be a practical way to dial in the flexural strength. In particular, using a hybrid mix of 60% glass fibers to 40% jute fibers resulted in the highest flexural strength. This highlights how a targeted mix of synthetic and natural fibers can seriously improve mechanical performance in Table 4.

Impact Resistance

Natural fiber composites strike a balance between impact resistance and cost efficiency. For instance, jute-banana composites deliver moderate impact resistance at an economical price point, making them practical for lightweight, budget-conscious applications where the highest possible impact strength isn't critical, but some resilience is required.

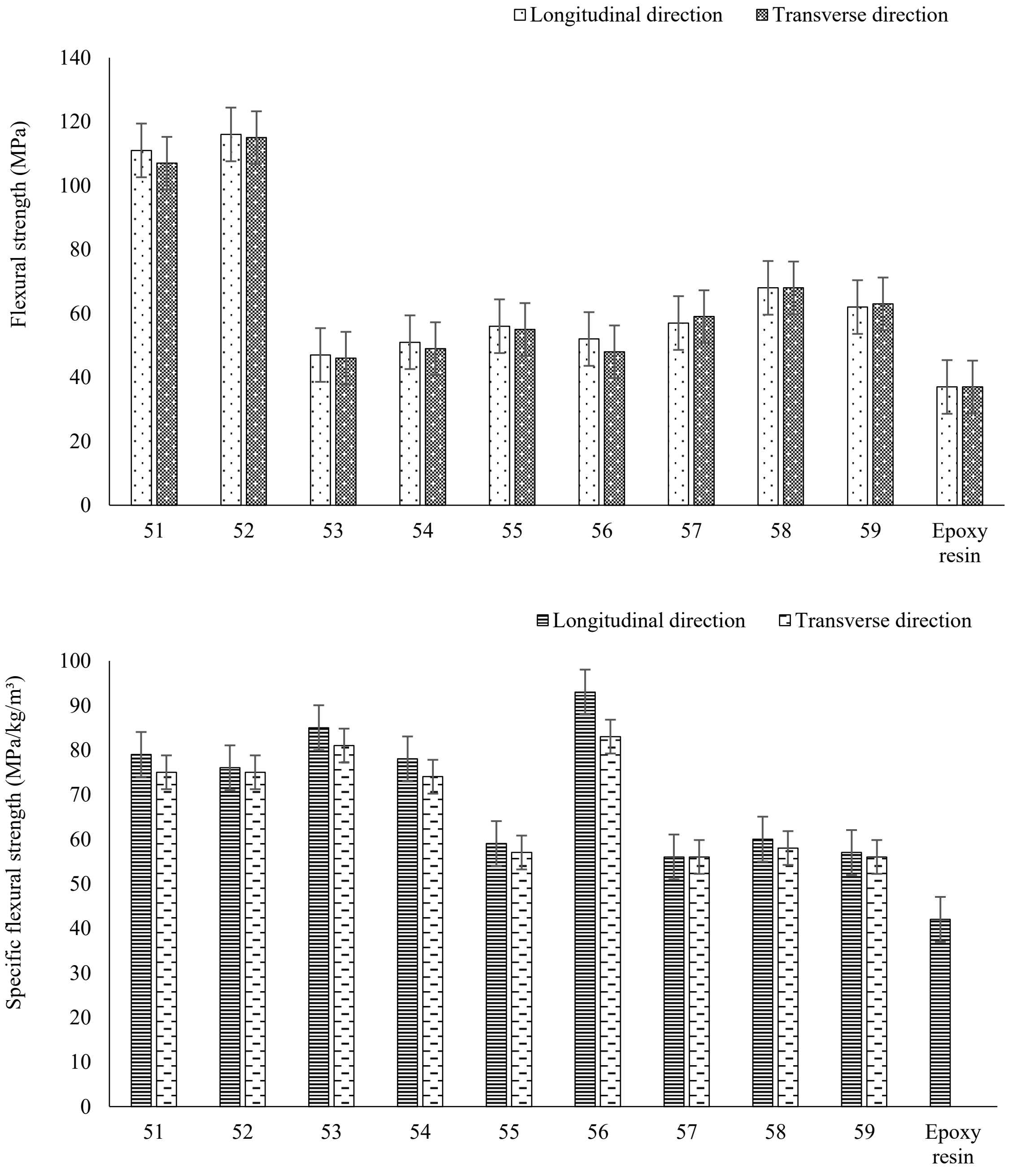


Figure 8. Flexural strength and specific flexural strength of flax, jute, glass fabric reinforced composites and epoxy resin.

Hybridization further boosts the performance ceiling. Research by Rafiquzzaman demonstrates that glass–jute hybrid composites outperform pure natural fiber types in impact resistance, showing that the right combination of materials can raise strength levels while retaining sustainability benefits in figure 9a and 9b.

Essentially, impact strength – meaning the material's ability to absorb sudden shock loads – remains a key property where unexpected impacts are likely. With strategic fiber selection and hybrid approaches, engineers can tailor composites to specific functional and environmental requirements [14].

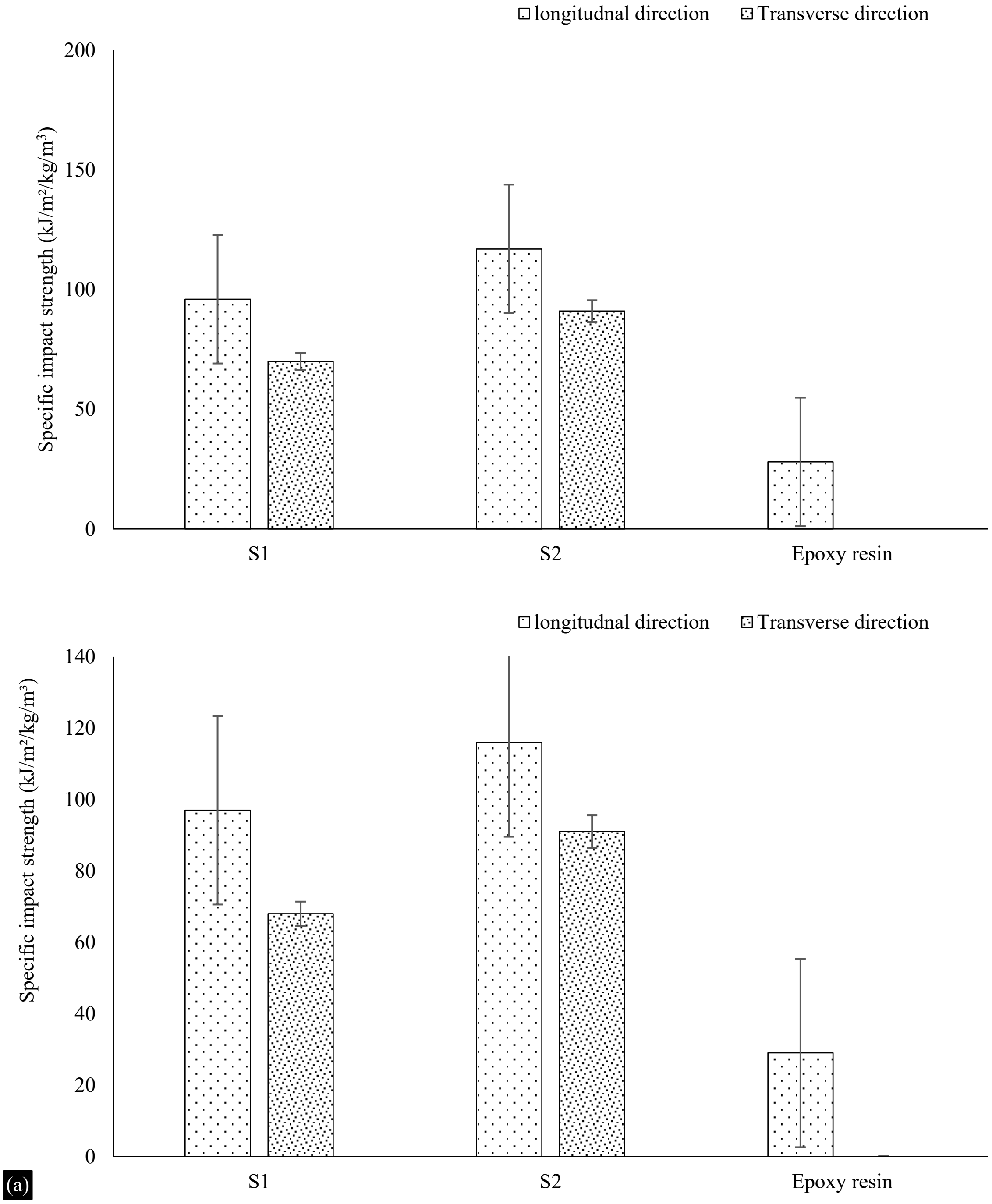


Figure 9. a: Impact strength and specific impact strength of the glass fabric reinforced composites and epoxy resin.

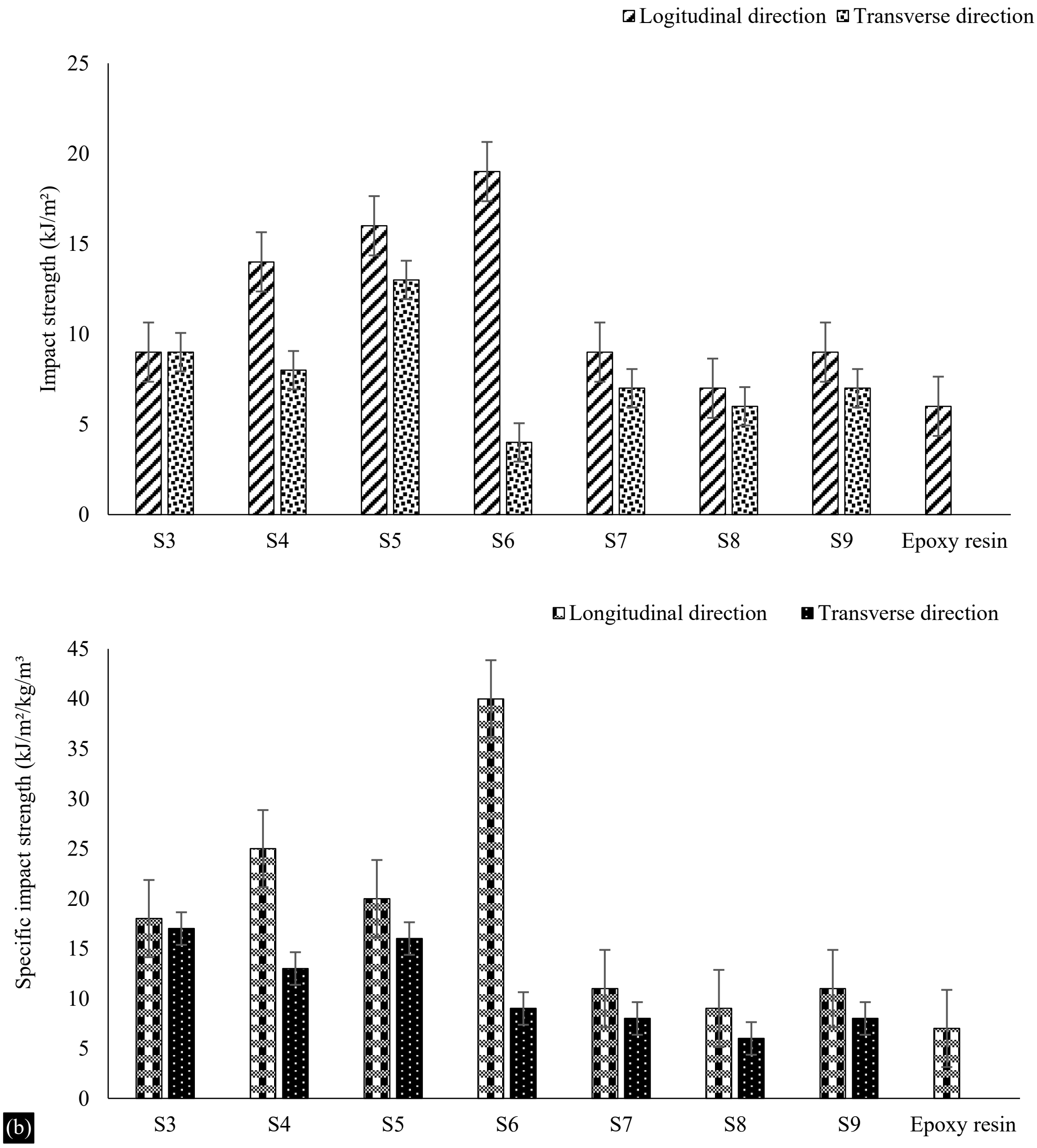


Figure 9. b: Impact strength and specific impact strength of the flax and jute fabric reinforced composites and epoxy resin.

Vibration Properties

Vibrational performance is a big deal, especially if you're talking aerospace or auto applications – dynamic stability and vibration damping aren't just nice-to-haves, they're deal-breakers. Hybrid composites, like jute-glass, regularly outperform their single-fiber cousins. You'll see higher natural frequencies, better damping characteristics – the works. That's down to the increased stiffness and superior energy absorption you get with these hybrids, letting them eat up and dissipate vibrational energy far more effectively. Same logic goes for flax-glass hybrids in Figure 10–12. They show higher interlaminar fracture toughness, meaning they put up a better fight against delamination from vibration – a classic failure mode with dynamic loading. Basically, this all adds up to longer life and better reliability for components getting stressed in tough environments in table 5. Bottom line: when it comes to vibrational performance in demanding aerospace and automotive structures, hybrid composites set the standard with their superior damping and resistance to vibration-induced damage [15].

Table 5. Experimental values.

Composite material	Natural frequency	Damping ratio
Glass epoxy	655	0.1445
Jute epoxy	799	0.1446
Glass-jute epoxy	843	0.0045

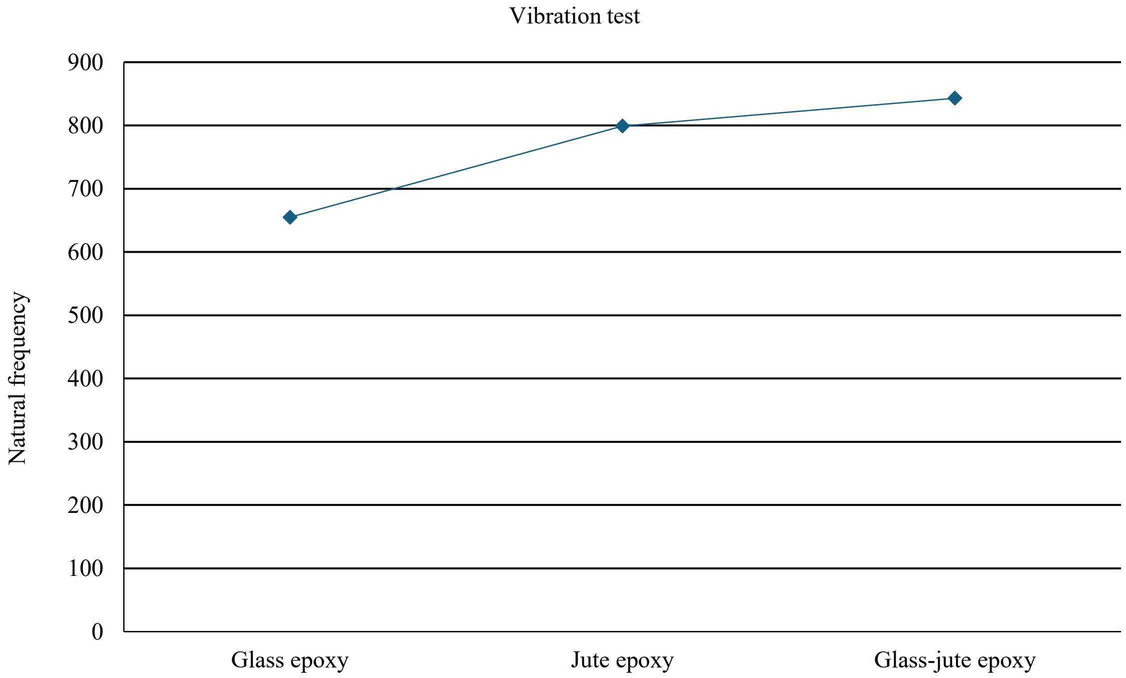


Figure 10. Comparative graph on natural frequency.

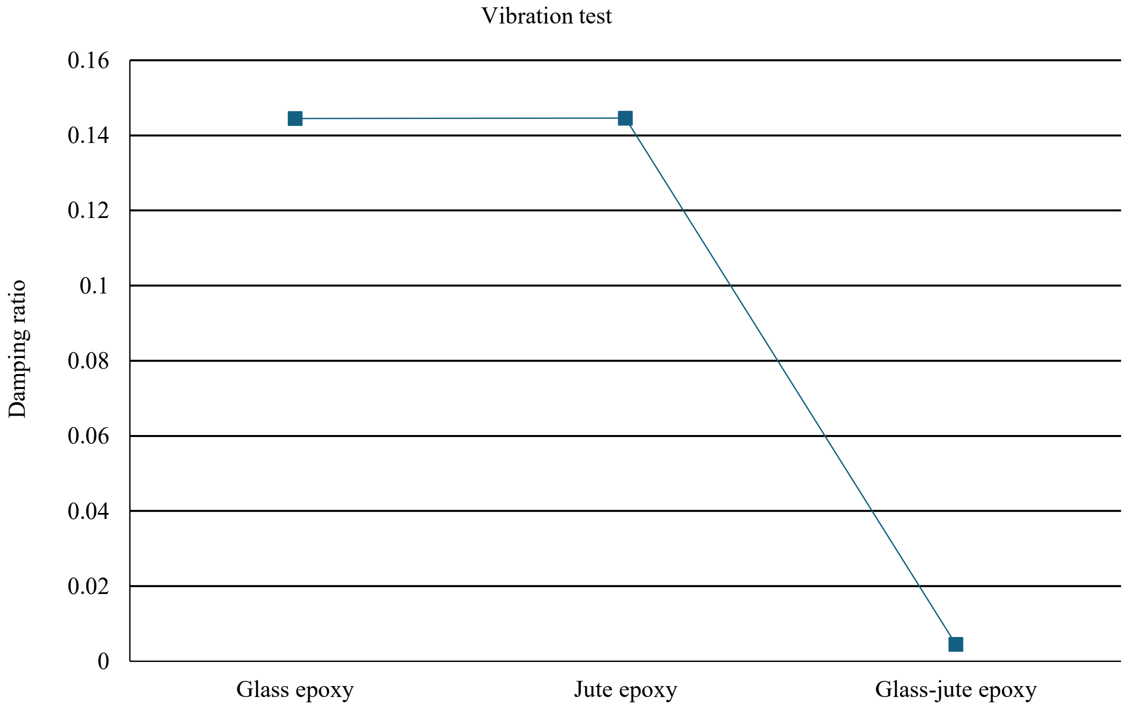


Figure 11. Comparative graph on damping ratio.

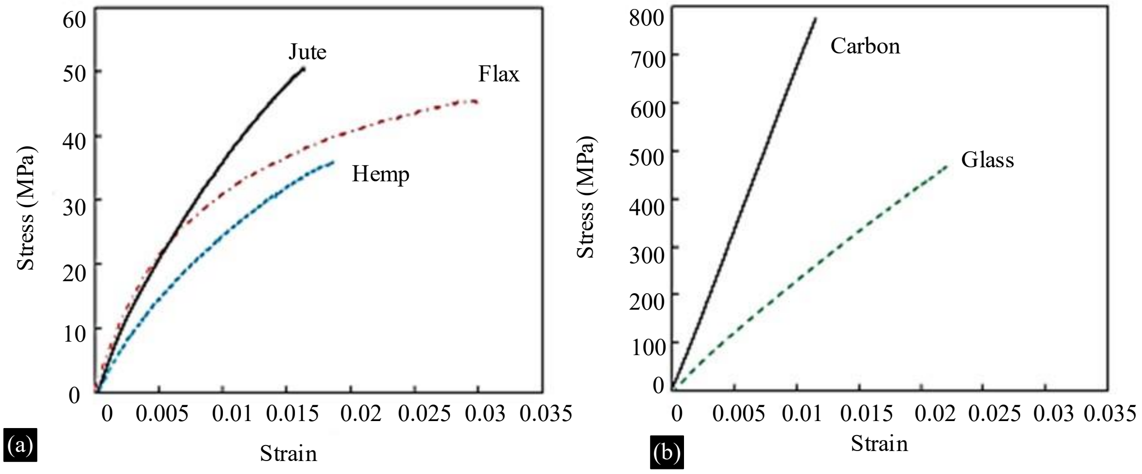


Figure 12. Exemplar uni-axial tension coupon material tests of the fiber composite laminates: (a) Natural fiber composite laminates and (b) Synthetic fiber composite laminates.

Figure 13. Hand lay-up technique.

Processing Techniques

The processing method used in the fabrication of fiber-reinforced composites plays an important role in determining fiber distribution, matrix bonding, and overall mechanical performance. The simplest and most widely used method is the hand lay-up technique, which involves manually arranging fibers in layers and impregnating them with resin. The hand lay-up process to fabricate jute, sisal, and glass fiber composites, demonstrating that it remains an effective technique for small-scale production despite some limitations in quality consistency in Figure 13.

The hand lay-up technique to produce hybrid composites, reporting that careful control of fiber length and orientation during processing significantly influenced tensile and flexural properties. Hybrid glass–jute composites prepared by hand lay-up performed well mechanically, although voids and uneven resin distribution were sometimes observed.

For improved quality, resin transfer molding (RTM) and vacuum infusion techniques have been adopted in recent studies. Treated jute fibers incorporated through controlled infusion techniques exhibited enhanced interfacial bonding, resulting in improved flexural performance compared to untreated counterparts. Vacuum-assisted resin infusion produced flax–glass composites with higher interlaminar shear strength and fracture toughness, reducing the risk of delamination under cyclic loads in Figure 14.

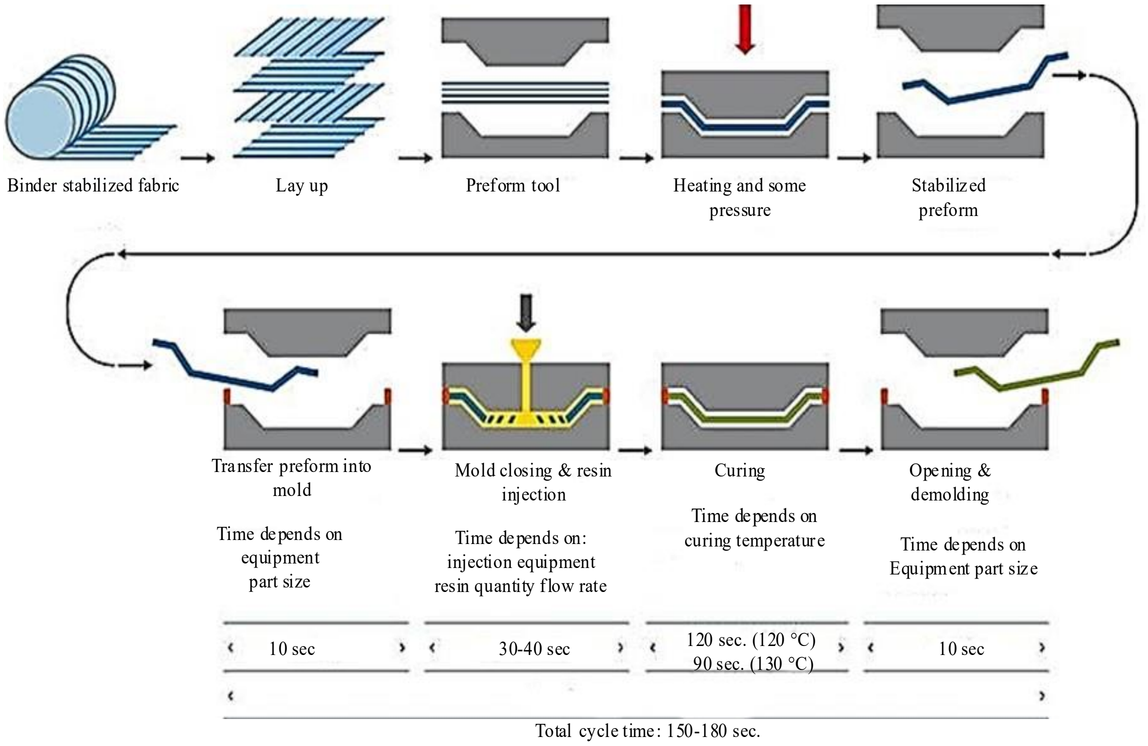


Figure 14. Resin transfer molding [RTM].

Advanced processing methods not only improve mechanical properties but also reduce variability between samples, making them more suitable for large-scale industrial applications. However, due to cost and equipment requirements, simpler techniques such as hand lay-up remain the most widely used method in developing regions, particularly for natural fiber composites.

In low-cost applications, simple fabrication methods such as hand lay-up are sufficient to produce composites with acceptable properties, particularly when sustainability and affordability are prioritized over maximum strength. Rafiquzzaman reported that hybrid composites prepared using controlled resin mixing achieved both cost reductions and mechanical improvements, reinforcing the importance of optimized processing. The selection of an appropriate processing method is a cornerstone in the successful fabrication of fiber-reinforced composites, as it directly impacts crucial characteristics such as fiber distribution, the integrity of the matrix-fiber interface, and ultimately, the comprehensive mechanical performance of the final product. Among the diverse array of available techniques, the hand lay-up method distinguishes itself through its inherent simplicity and widespread adoption across various industries and research settings. This technique is characterized by a largely manual process, where reinforcing fibers are meticulously arranged in successive layers and subsequently impregnated with a thermosetting resin system [16].

Further underscoring the remarkable versatility and utility of the hand lay-up technique, successfully employed it in the production of innovative hybrid composites. Their extensive work meticulously highlighted the profound influence that careful control over critical processing parameters, such as fiber length and precise orientation, exerts on the resultant tensile and flexural properties of the composite material. The commendable mechanical performance exhibited by hybrid glass–jute composites that were specifically prepared using the hand lay-up method. However, their comprehensive study also brought to light potential drawbacks associated with this technique, specifically noting the occasional presence of detrimental voids and an uneven distribution of resin throughout the composite structure. These imperfections can lead to stress concentrations and compromised mechanical integrity.

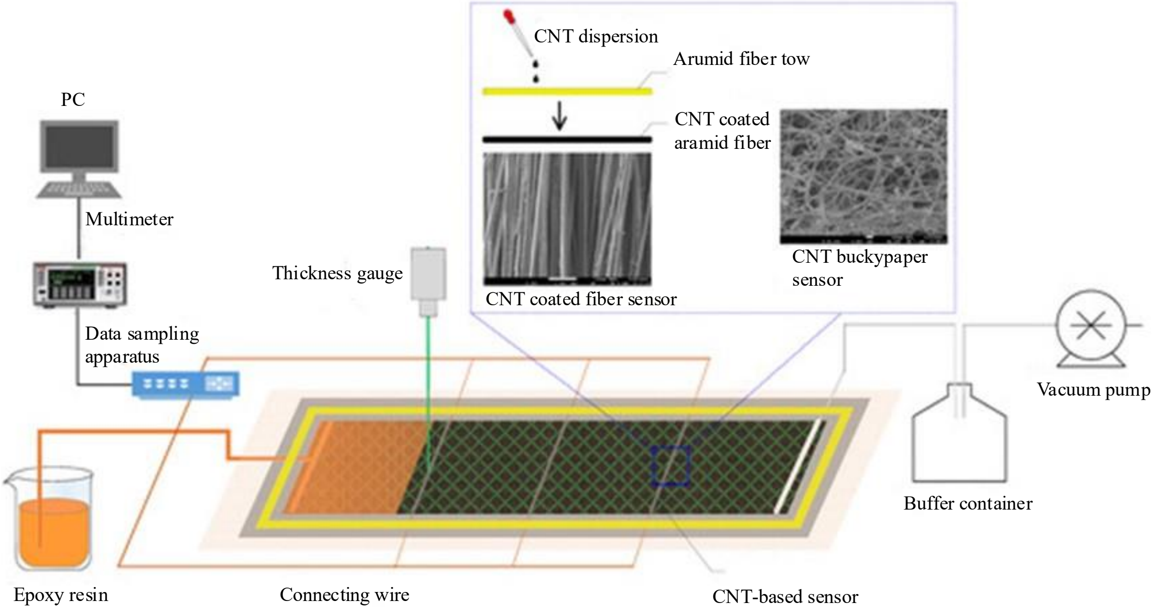


Figure 15. Schematic image of CNT-based sensor preparation and the monitoring application for VARI process.

In response to the acknowledged limitations of the hand lay-up method and with a view towards achieving significantly improved quality and consistency in composite fabrication, more sophisticated and advanced techniques such as resin transfer molding (RTM) and vacuum infusion have garnered substantial prominence in recent investigative efforts and industrial applications. Treated jute fibers, when precisely incorporated through controlled infusion techniques, exhibited notably enhanced interfacial bonding with the polymer matrix. This superior bonding, a direct consequence of the controlled processing environment, subsequently translated into markedly improved flexural performance when compared to their untreated counterparts, highlighting the critical role of fiber-matrix adhesion. Expanding upon the undeniable benefits afforded by these advanced manufacturing methods, vacuum-assisted resin infusion (VARI) consistently yielded flax–glass composites possessing superior interlaminar shear strength (ILSS) and enhanced fracture toughness in figure 15. This enhancement in ILSS is of paramount importance as it significantly mitigates the risk of catastrophic delamination, a common failure mode when composite materials are subjected to dynamic cyclic loading conditions in demanding applications [17].

Advantages of embracing advanced processing methods, articulating that these techniques not only contribute substantively to the attainment of improved mechanical properties but also effectively minimize the inherent variability observed between individual samples. This elevated level of consistency and reproducibility renders composites manufactured using these advanced methods far more suitable and reliable for large-scale industrial applications where stringent quality control and predictable performance are non-negotiable requirements. Despite these undeniable technological advancements and their associated benefits, crucial practical consideration: the substantial cost implications and extensive equipment requirements inherently associated with the adoption of such sophisticated manufacturing techniques. Consequently, simpler, and more accessible methods like hand lay-up continue to retain their status as the most widely utilized approaches in many developing regions globally, particularly for the fabrication of natural fiber composites, primarily due to their unparalleled accessibility and significantly lower initial investment costs [18].

The practical perspective, underscoring that for a vast array of low-cost applications, fundamental, and basic fabrication methods such as hand lay-up are frequently more than sufficient to achieve composites possessing entirely acceptable and adequate properties. This holds particularly true in scenarios where sustainability, environmental responsibility, and affordability are prioritized as key design drivers over the singular pursuit of achieving maximum possible strength or stiffness. The paramount importance of optimized processing, even when operating within the confines of simpler manufacturing frameworks, was further elucidated and emphasized by Rafiquzzaman, who reported that hybrid composites meticulously prepared using controlled resin mixing techniques achieved a desirable dual outcome: both significant cost reductions in production and substantial improvements in their overall mechanical performance. This collective and extensive body of research, encompassing contributions from numerous esteemed researchers, paints an unequivocally clear and comprehensive picture: while advanced manufacturing methods undoubtedly offer superior performance characteristics and unparalleled consistency for the most demanding and critical applications, simpler, and more traditional techniques remain absolutely vital for their economic viability, widespread applicability, and enduring relevance, particularly within specific industrial sectors and diverse regional contexts across the globe.

Sustainability Considerations

Sustainability is one of the key motivations for the increasing use of natural fibers in composite development.

Natural fibers such as jute, flax, and banana are renewable, biodegradable, and require less energy for cultivation and processing, making them more eco-friendly alternatives. Jute composites, though mechanically weaker than glass composites, provided a greener option with lower environmental impact.

In addition to their ecological benefits, natural fibers offer significant cost savings. Jute and banana fiber composites reduce overall material cost while maintaining acceptable mechanical properties for lightweight applications. Rafiquzzaman further demonstrated that incorporating natural fibers into glass composites can reduce production costs by up to 30%, making them highly attractive for cost-sensitive industries.

Hybrid composites have emerged as a practical solution to achieve both performance and sustainability. Jute–glass hybrids provided a balance of high mechanical strength and reduced reliance on synthetic fibers, making them a sustainable alternative for semi-structural applications. Flax–glass hybrid composites not only improved interlaminar strength but also reduced the environmental burden compared to pure synthetic composites.

Another sustainability factor is the circular economy potential of natural fibers. Chemical treatments of jute fibers improved compatibility with polymer matrices, extending their service life and reducing waste generation. Using simple hand lay-up methods with natural fibers allows for low-energy fabrication, contributing to sustainable production practices.

The escalating global focus on environmental stewardship has spurred a significant surge in the exploration and adoption of natural fibers for the development of advanced composite materials. This paradigm shift is primarily propelled by the inherent limitations and ecological burdens associated with conventional synthetic fibers, such as glass and carbon. While these synthetic counterparts have historically been favored for their exceptional strength-to-weight ratios and stiffness, their manufacturing processes are notoriously energy-intensive, contributing substantially to carbon emissions. Furthermore, their non-biodegradable nature results in their persistence in landfills for millennia, exacerbating waste management crises and posing long-term environmental hazards.

In stark contrast, natural fibers present themselves as compellingly sustainable and environmentally benign alternatives. Derived from renewable agricultural sources, fibers like jute, flax, and banana are not only inherently biodegradable, thus mitigating landfill accumulation, but also demand considerably less energy for their cultivation, harvesting, and initial processing compared to their synthetic counterparts. Research conducted by Gowda et al. serves as a crucial testament to this ecological advantage. While their findings acknowledge that jute composites might exhibit a marginally lower mechanical strength when directly compared to high-performance glass composites, the drastically reduced environmental footprint throughout the entire lifecycle of natural fiber composites firmly establishes them as a far "greener" and more ecologically responsible choice. This emphasis on reduced environmental impact positions natural fibers as a vital component in the transition towards a more sustainable materials economy.

Beyond their undeniable ecological merits, natural fibers offer substantial and often overlooked economic advantages that are increasingly appealing to industries seeking cost-effective solutions without compromising essential performance. The strategic integration of readily available jute and banana fibers into composite formulations can lead to a considerable reduction in overall material costs. Crucially, this cost reduction is achieved while still maintaining adequate mechanical properties, rendering these composites suitable for a wide array of lightweight applications where extreme strength is not the sole determinant of material selection. Reinforcing this economic benefit, Rafiquzzaman's comprehensive analysis indicated that the judicious inclusion of natural fibers even in hybrid glass composites can lead to remarkable production expense reductions, potentially slashing costs by up to 30%. This significant cost-saving potential makes natural fiber-reinforced composites highly attractive to industries where cost-efficiency and competitive pricing are paramount drivers for market penetration and sustained growth [19].

The innovative development of hybrid composites represents a highly pragmatic and effective strategy to concurrently address the twin objectives of achieving superior performance and enhancing overall sustainability. This approach involves judiciously combining natural fibers with synthetic fibers, leveraging the best attributes of both. Pioneering research in this domain showcased the efficacy of jute–glass hybrid composites. Their observations revealed that these hybrid materials effectively strike a delicate yet powerful balance, offering superior mechanical strength, often approaching that of purely synthetic composites, while simultaneously achieving a significantly decreased reliance on energy-intensive synthetic fibers. This strategic reduction in synthetic material content positions jute–glass hybrids as a viable and highly sustainable option for semi-structural applications where both strength and environmental considerations are critical. Flax–glass hybrid composites not only bolster crucial interlaminar strength – a common weakness in some natural fiber composites – but also contribute demonstrably to a reduced environmental footprint when benchmarked against composites composed purely of synthetic materials. This hybrid approach offers a pathway to bridge the performance gap while steadily increasing the bio-content and reducing the ecological impact of composite materials.

A pivotal and often understated aspect of the sustainability of natural fibers lies in their inherent potential to foster a circular economy. This concept emphasizes maximizing resource utilization and minimizing waste through closed-loop systems. Chemical treatments applied to natural fibers, such as jute, can dramatically enhance their compatibility and interfacial adhesion with a diverse range of polymer matrices. This improved compatibility is crucial for creating durable composites, thereby extending their service life and significantly mitigating waste generation at the end of their functional lifespan. Furthermore, fundamental advantage: the simplicity and widespread applicability of hand lay-up methods, which are commonly and effectively employed with natural fibers. These low-energy fabrication processes directly contribute to more sustainable production practices by reducing the energy consumption associated with composite manufacturing. This inherent ease of processing, coupled with the potential for enhanced material longevity and recyclability, further amplifies the appeal of natural fibers in a world increasingly driven by the imperative for resource efficiency, reduced environmental impact, and the overarching goal of achieving a truly circular economy across a product's entire lifecycle.

Challenges and Future Directions

Despite the significant progress in the development of natural and hybrid fiber composites, several challenges remain that limit their widespread application. One of the primary issues is the comparatively lower mechanical performance of natural fibers when evaluated against synthetic fibers such as glass and carbon. Jute fibers perform better than sisal in mechanical tests, both are still weaker than glass fiber composites.

Moisture absorption represents another critical drawback of natural fibers, as it weakens fiber–matrix adhesion and reduces long-term durability. The untreated jute composites showed reduced flexural strength due to poor bonding and moisture sensitivity, which could be partially improved through chemical treatments. The reducing synthetic fiber content in hybrids increases vulnerability to moisture and lowers compressive strength.

Another challenge lies in processing variability. The fiber length and distribution significantly affect tensile and flexural strength, and inconsistencies during fabrication can result in poor reproducibility of mechanical properties. The hand lay-up techniques, while cost-effective, often introduce voids and defects that compromise performance.

To overcome these challenges, researchers are exploring surface treatments, coupling agents, and chemical modifications to enhance fiber–matrix adhesion and reduce moisture absorption. Zhang et al. demonstrated that hybrid composites fabricated with controlled resin infusion methods displayed superior interlaminar shear strength and fracture toughness, suggesting that optimized processing is essential for improving natural fiber performance.

Future research directions should focus on the development of bio-based resins, which would complement natural fibers in creating fully biodegradable composites. Nanofillers such as nanocellulose, graphene, and nano-silica are also being investigated to enhance tensile, thermal, and barrier properties of natural fiber composites. Rafiquzzaman emphasized that cost savings of up to 30% can already be achieved with hybrid composites, and further innovations in recycling and reusability could strengthen the case for adopting them in large-scale industries.

In the long term, integrating sustainable processing techniques, renewable matrices, and advanced hybridization strategies will be essential for achieving composites that are both high-performance and environmentally responsible. Natural and hybrid fiber composites hold immense promise for sustainable engineering applications, yet their widespread adoption is hindered by several persistent challenges. A primary concern is their mechanical performance, which generally falls short when compared to traditional synthetic fibers like glass and carbon. For instance, while jute fibers show better mechanical properties than sisal, both still exhibit lower strength than glass fiber composites, as noted by Boopalan et al. This inherent limitation necessitates further research into fiber modification and composite design to bridge the performance gap with synthetic alternatives.

Another significant drawback is the susceptibility of natural fibers to moisture absorption, which can severely compromise the long-term durability and integrity of the composites. Moisture absorption weakens the crucial interface between the fiber and the matrix, leading to reduced adhesion. Kabir et al. demonstrated that untreated jute composites experienced a decline in flexural strength due to poor bonding and high moisture sensitivity, although chemical treatments offered a partial solution. Similarly, Dash et al. observed that reducing the synthetic fiber content in hybrid composites increased their vulnerability to moisture and lowered their compressive strength. This highlights the critical need for effective surface treatments and hydrophobic coatings to enhance moisture resistance.

Processing variability also poses a considerable challenge in the consistent production of high-performance natural fiber composites. Inconsistencies in fiber length and distribution during fabrication significantly impact the mechanical properties, leading to poor reproducibility of tensile and flexural strength. Furthermore, hand lay-up techniques often introduce undesirable voids and defects that compromise the overall performance of the composite. These findings emphasize the importance of developing more precise and controlled manufacturing processes to ensure consistent quality and performance.

To address these multifaceted challenges, researchers are actively pursuing various strategies. Surface treatments, coupling agents, and chemical modifications are being explored to enhance fiber–matrix adhesion and mitigate moisture absorption. Hybrid composites produced using controlled resin infusion methods exhibited superior interlaminar shear strength and fracture toughness, underscoring the vital role of optimized processing techniques in improving natural fiber composite performance.

Looking ahead, future research directions are centered on developing fully biodegradable composites that align with sustainability goals. This includes the development of bio-based resins that can complement natural fibers. The incorporation of nanofillers such as nanocellulose, graphene, and nano-silica is also being investigated to significantly enhance the tensile, thermal, and barrier properties of natural fiber composites. Rafiquzzaman highlighted that hybrid composites already offer cost savings of up to 30%, and further innovations in recycling and reusability could significantly bolster the economic case for their widespread adoption in various industries.

Natural and hybrid fiber composites hold immense promise for sustainable engineering applications, yet their widespread adoption is hindered by several persistent challenges. A primary concern is their mechanical performance, which generally falls short when compared to traditional synthetic fibers like glass and carbon. For instance, while jute fibers show better mechanical properties than sisal, both still exhibit lower strength than glass fiber composites. This inherent limitation necessitates further research into fiber modification and composite design to bridge the performance gap with synthetic alternatives [20].

CONCLUSION

This review has presented a comparative analysis of natural, synthetic, and hybrid fiber-reinforced composites, focusing on mechanical properties, processing methods, and sustainability considerations. Synthetic fibers such as glass and carbon continue to dominate in terms of tensile, compressive, and flexural strength, making them indispensable for high-load structural applications. However, their high production cost, energy consumption, and environmental drawbacks create a strong need for sustainable alternatives.

Natural fibers such as jute, flax, hemp, and banana provide significant advantages in terms of renewability, biodegradability, and affordability. Although their mechanical performance remains lower than that of synthetic fibers, they are suitable for lightweight and cost-sensitive applications. Hybrid composites have emerged as the most promising solution, combining the strength of synthetic fibers with the eco-friendly characteristics of natural fibers to achieve balanced performance.

Processing techniques play a crucial role in determining the performance of these composites. While hand lay-up remains the most accessible method, advanced techniques such as resin transfer molding and vacuum infusion improve fiber–matrix bonding and reduce defects, leading to better mechanical behavior.

From a sustainability perspective, natural, and hybrid composites offer reduced environmental footprint and cost savings of up to 30%, making them increasingly attractive for industries such as automotive, aerospace, and construction.

Looking forward, further research should focus on improving fiber–matrix adhesion, reducing moisture absorption, and developing bio-based resins and nanofiller reinforcements. Recycling strategies for composite waste must also be prioritized to align with circular economy principles. With these advancements, natural, and hybrid composites have the potential to become mainstream materials that offer both performance and sustainability for next-generation engineering applications.

REFERENCES

1. Abuthakeer SS, Vasudaa R, Nizamudeen A. Application of natural fiber composites in engineering industries: a comparative study. Appl Mech Mater. 2016;854:59–64. doi:10.4028/www.scientific.net/AMM.854.59
2. Adhikary SK, Rudzionis Z. Behavior of concrete under the addition of high volume of polyolefin macro fiber and fly ash. Fibers (Basel). 2018;6(2):38. doi:10.3390/fib6020038
3. Al-Oraimi S, Seibi A. Mechanical characterisation and impact behaviour of concrete reinforced with natural fibres. Compos Struct. 1995;32(1–4):165–171. doi:10.1016/0263-8223(95)00043-7
4. Bambach MR. Direct comparison of the structural compression characteristics of natural and synthetic fiber–epoxy composites: flax, jute, hemp, glass and carbon fibers. Fibers (Basel). 2020;8(10):62. doi: 10.3390/fib8100062
5. Begum S, Fawzia S, Hashmi MSJ. Polymer matrix composite with natural and synthetic fibres. Adv Mater Process Technol. 2020;6(3):547–564. doi:10.1080/2374068X.2020.1728645
6. Cavalcanti D, Banea M, Neto J, Lima R. Comparative analysis of the mechanical and thermal properties of polyester and epoxy natural fibre-reinforced hybrid composites. J Compos Mater. 2021;55(12):1683–1692. doi:10.1177/0021998320976811
7. Chakraborty S, Kundu SP, Roy A, Basak RK, Adhikari B, Majumder S. Improvement of the mechanical properties of jute fibre reinforced cement mortar: a statistical approach. Constr Build Mater. 2012;38:776–784. doi:10.1016/j.conbuildmat.2012.09.067
8. Deb S, Mitra N, Maitra S, Majumdar SB. Comparison of mechanical performance and life cycle cost of natural and synthetic fiber-reinforced cementitious composites. J Mater Civ Eng. 2020;32(6):04020125. doi:10.1061/(ASCE)MT.1943-5533.0003219
9. Halvaei M, Jamshidi M, Latifi M. Application of low modulus polymeric fibers in engineered cementitious composites. J Ind Text. 2014;43(4):511–524. doi:10.1177/1528083712465881
10. Husainie SM, Khattak SU, Robinson J, Naguib HE. A comparative study on the mechanical properties of different natural fiber reinforced free-rise polyurethane foam composites. Ind Eng Chem Res. 2020;59(50):21745–21755. doi:10.1021/acs.iecr.0c04006
11. Ilankeeran PK, Mohite PM, Kamle S. Axial tensile testing of single fibres. Mod Mech Eng. 2012;2(4):151–156. doi:10.4236/mme.2012.24020
12. Mishra R, Wiener J, Militky J, Petru M, Tomkova B, Novotna J. Bio-composites reinforced with natural fibers: comparative analysis of thermal, static and dynamic-mechanical properties. Fibers Polym. 2020;21(3):619–627. doi:10.1007/s12221-020-9804-0
13. Roy A, Chakraborty S, Kundu SP, Basak RK, Majumder SB, Adhikari B. Improvement in mechanical properties of jute fibres through mild alkali treatment as demonstrated by utilisation of the Weibull distribution model. Bioresour Technol. 2012;107:222–228. doi:10.1016/j.biortech.2011.11.073
14. Zhou X, Ghaffar SH, Dong W, Oladiran O, Fan M. Fracture and impact properties of short discrete jute fibre-reinforced cementitious composites. Mater Des. 2013;49:35–47. doi:10.1016/j.matdes.2013.01.029
15. Rajamurugu N, Karthikeyan P, Aakash A, Meshak AA, Ajithkumar K. Comparative study on mechanical behaviour of synthetic, natural and hybrid composite laminates. IOP Conf Ser Mater Sci Eng. 2020;923(1):012048. doi:10.1088/1757-899X/923/1/012048
16. Badyankal PV, Manjunatha T, Vaggar GB, Praveen K. Compression and water absorption behaviour of banana and sisal hybrid fiber polymer composites. Mater Today Proc. 2020;35:383–386. doi:10.1016/j.matpr.2020.02.695
17. Sanjay MR, Arpitha GR, Yogesha B. Study on mechanical properties of natural–glass fibre reinforced polymer hybrid composites: a review. Mater Today Proc. 2015;2:2959–2967.
18. Madhu P, Sanjay MR, Senthamaraikannan P, et al. A review on synthesis and characterization of commercially available natural fibers: part I. J Nat Fibers. 2019;16:1132–1144.
19. Ahmadova A. Numerical modelling of porosity generation, movement, and compaction during the RTM process [dissertation]. 2018.
20. Shi Y, Wang B, Du K, Liu Y, Kang R, Wang S, Zhang J, Gu Y, Li M. Process monitoring for vacuum-assisted resin infusion by using carbon nanotube-based sensors. Polymers (Basel). 2025;17(4):459. doi:10.3390/polym17040459