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Hybridization of Natural Fibres for Sustainable Bio-Composites

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Abstract

The search for sustainable alternatives to petroleum-based materials has brought natural fibres into the spotlight as promising reinforcements for bio-composites. Fibres obtained from plants such as jute, flax, hemp, sisal, coir, bamboo, banana, pineapple and agricultural residues are renewable, lightweight and potentially biodegradable. However, individual natural fibres have different strengths and limitations, making it difficult for one fibre to provide all the properties required for a high-performance material. Hybridization of natural fibres has emerged as an innovative approach to overcome these limitations by combining two or more fibres with complementary properties within a single composite material. Hybrid natural fibre bio-composites can provide a balanced combination of strength, stiffness, toughness, lightweight characteristics and environmental benefits. These materials have potential applications in automotive components, furniture, packaging, construction, sports equipment, consumer products and textile-based products. This article discusses the concept of natural fibre hybridization, commonly used fibres, types of hybrid bio-composites, performance characteristics, applications, environmental benefits and future opportunities.

Keywords: Hybrid bio-composites, natural fibres, sustainable materials, green composites, renewable resources

Introduction

The world is increasingly looking for materials that are not only strong and functional but also environmentally responsible. Conventional materials based on petroleum-derived polymers and synthetic fibres have played an important role in modern industrial development but their dependence on non-renewable resources and challenges related to waste management have encouraged the search for alternatives. Conventional fibre-reinforced composites, particularly those reinforced with glass and carbon fibres are widely used because of their excellent mechanical performance. However, their production may involve high energy consumption and end-of-life management can be difficult (Arpitha *et al.*, 2017).

These concerns have stimulated interest in renewable and environmentally responsible materials. Natural fibres have emerged as attractive reinforcement materials because they originate from renewable biological resources. Jute, flax, hemp, sisal, kenaf, coir, bamboo, banana and pineapple fibres are among the plant-based fibres being explored for composite applications. Their low density, availability and favourable specific properties make them particularly interesting for lightweight material development. Fibres obtained from plants such as *dhaincha* and other biomass sources can potentially contribute to the development of value-added bio-based material (Wang, 2016; Afolabi & Ndou, 2024).

Despite their advantages, natural fibres have certain limitations. Their properties can vary according to plant variety, geographical conditions, maturity, extraction method and processing. They are also hydrophilic in nature and therefore tend to absorb moisture. This can influence their dimensional stability and adhesion with hydrophobic polymer matrices. Furthermore, a single natural fibre may not provide all the properties required for a particular application. This has led to increasing interest in hybridization, in which two or more types of reinforcement are combined to obtain a composite with improved or balanced properties (Kumar *et al.*, 2023).

By carefully selecting complementary fibres, it is possible to design materials that offer better mechanical performance, reduced weight and improved functionality while maintaining the environmental advantages of natural materials.

The purpose is to create a material whose overall performance is better balanced than that of a composite reinforced with only one fibre. Hybridization is an important strategy for improving mechanical, thermal and environmental performance while addressing some limitations of single-fibre natural composites. This approach is particularly relevant at a time when industries are searching for lightweight, renewable and lower-impact materials for automotive, construction, consumer products and other applications (Baigh *et al*., 2023).

What is Hybridization of Natural Fibres?

Hybridization refers to the combination of two or more different reinforcement fibres within the same composite material. In natural fibre hybrid composites, fibres with different characteristics are selected and incorporated into a common polymer matrix. For example, a relatively stiff fibre can be combined with a tougher or more flexible fibre. One fibre may provide high tensile strength, while another may contribute better impact resistance or moisture tolerance. The objective is not simply to mix fibres but to achieve a synergistic effect**,** where the combined composite performs better or more effectively than a composite based on only one reinforcement. A hybrid composite can therefore be considered as a material designed according to the principle of the right combination for the right performance. The final performance depends on the compatibility between the fibres and matrix, fibre ratio orientation, surface treatment, manufacturing method and intended application (Atmakuri *et al.*, 2020).

Why Hybridize Natural Fibres?

Although natural fibres have many attractive properties, no single fibre is ideal for every application. Hybridization provides an opportunity to compensate for the weaknesses of one fibre through the properties of another. For example, one natural fibre may provide excellent stiffness but relatively low impact resistance, whereas another may offer better toughness. Combining them can create a more balanced material (Guna *et al.*, 2018; Khan *et al.*, 2024).

The major advantages of natural fibre hybridization include:

i. **Lightweight Materials:** Natural fibres have relatively low densities compared with many conventional reinforcement materials. Hybrid natural fibre composites can therefore provide attractive strength-to-weight and stiffness-to-weight ratios. This is particularly useful for applications in transportation, where reducing component weight can contribute to improved energy efficiency.

ii. **Better Balance of Properties:** Different natural fibres possess different characteristics. Hybridization allows researchers to combine these characteristics in one material. For example, a stiff fibre can be combined with a fibre that provides improved toughness or flexibility.

iii. **Improved Resource Utilization:** Hybridization can make it possible to use locally available and underutilized plant fibres. Agricultural residues and low-value biomass can be converted into useful reinforcement materials instead of being burned or discarded.

iv. **Cost Reduction:** The use of locally available natural fibres may reduce material costs compared with expensive synthetic reinforcements. Hybridization also provides flexibility in selecting economical fibre combinations.

v. **Environmental Benefits:** Natural fibres originate from renewable resources and can potentially reduce dependence on petroleum-derived materials. When combined with suitable bio-based matrices and appropriate end-of-life strategies, they can contribute to more sustainable material systems.

Common Natural Fibres Used in Hybrid Bio-Composites

A wide range of plant fibres can be considered for hybrid composite development.

i. **Jute:** Jute is one of the most widely available natural fibres and is valued for its relatively good tensile properties, low density and affordability. Its extensive cultivation and established processing infrastructure make it attractive for composite applications.

ii. **Flax:** Flax is known for its good mechanical properties and relatively high specific stiffness. It has attracted interest in lightweight structural applications and transportation components.

iii. **Hemp:** Hemp fibres possess good strength and stiffness and can be obtained from a rapidly growing plant. They are increasingly being explored for sustainable composite applications.

iv. **Sisal:** Sisal is a strong and relatively durable natural fibre. It can be used in composites where tensile and impact properties are important.

v. **Kenaf:** Kenaf is a fast-growing plant that produces useful bast fibres. Its low density and reasonable mechanical properties make it attractive for lightweight composites.

vi. **Coir:** Coir, obtained from coconut husks, is characterized by comparatively high toughness and elongation. Its use in composites also provides an opportunity to utilize an agricultural by-product.

vii. **Bamboo:** Bamboo fibres are of interest because of their favourable strength-to-weight characteristics and rapid renewability. Bamboo-based reinforcement can be considered for various sustainable material applications.

viii. **Banana and Pineapple Fibres:** Banana pseudostem and pineapple leaf fibres are examples of agricultural biomass that can be transformed into useful reinforcement materials. Their utilization can create additional value from plant residues.

ix. ***Dhaincha*** **Fibre:** *Dhaincha* is an agricultural plant traditionally associated with green-manure and soil-improvement practices. Exploring its fibre potential represents an interesting opportunity for biomass valorization. *Dhaincha* fibre could potentially be combined with other natural fibres to develop hybrid bio-composites with tailored properties (Potluri, 2018; Chichane *et al.*, 2023).

Types of Hybrid Natural Fibre Composites

Hybridization can be achieved in several ways depending on the arrangement and processing of the fibres.

i. **Interply Hybridization:** In this approach, layers of different fibres are arranged one above another. For example, layers of jute and flax can be alternated within a laminate. The arrangement can be modified according to the required performance. Placing a stronger fibre on the outer layers may improve resistance to certain loading conditions.

ii. **Intraply Hybridization:** Different fibres are incorporated within the same layer. For example, jute and sisal fibres can be distributed within one composite layer.

iii. **Intermingled Hybridization:** Two or more fibre types are mixed or intermingled before composite fabrication. This can provide a more uniform distribution of reinforcement.

iv. **Fibre–Matrix Hybridization:** Hybridization can also involve combining natural fibres with different types of matrices. For example, natural fibres may be incorporated into conventional thermoplastic matrices, biodegradable polymers or bio-based resins (Gohal *et al.*, 2020).

Factors Affecting the Performance of Hybrid Composites

The performance of a hybrid bio-composite depends on several interconnected factors.

i. **Fibre Type:** The chemical composition, cellulose content, fibre dimensions and mechanical properties of the selected fibres directly affect composite performance.

ii. **Fibre Ratio:** The proportion of each fibre is critical. Increasing one fibre beyond an optimum level does not necessarily improve the overall composite. An appropriate balance is required.

iii. **Fibre Orientation:** Aligned fibres generally provide greater reinforcement in the direction of alignment, while randomly oriented fibres may provide more uniform but comparatively lower directional reinforcement.

iv. **Fibre Length:** Long fibres can provide effective load transfer under suitable conditions, while short fibres may be easier to process. The optimum fibre length depends on the matrix and manufacturing method.

v. **Fibre–Matrix Adhesion:** Strong interfacial bonding is necessary for efficient stress transfer. Poor adhesion can result in fibre pull-out and premature failure.

vi. **Moisture Content:** Natural fibres can absorb moisture because of their hydrophilic constituents. Moisture can influence fibre dimensions, interfacial bonding and composite durability.

vii. **Processing Conditions:** Temperature, pressure, curing time, resin content and moulding conditions can significantly influence the final composite properties (Idumah & Ezika, 2022).

Properties of Hybrid Natural Fibre Bio-Composites

The major properties that are generally evaluated include:

i. **Mechanical Properties:** Tensile strength, tensile modulus, flexural strength, flexural modulus, impact strength, interlaminar strength, compression strength etc. These properties help determine the suitability of the composite for different applications.

ii. **Physical Properties:** Important physical characteristics include: density, water absorption, thickness swelling, dimensional stability, fibre distribution, void content

iii. **Thermal Properties:** Thermal analysis can help determine thermal stability, degradation behaviour and suitability for applications involving elevated temperatures.

iv. **Morphological Properties:** Microscopic analysis, such as scanning electron microscopy, can provide information about fibre dispersion, fibre pull-out, voids, cracks and fibre–matrix adhesion (Gurumahesh & Kamineni, 2023).

Applications of Hybrid Natural Fibre Bio-Composites

The combination of lightweight characteristics, reasonable mechanical performance and renewable reinforcement makes hybrid natural fibre composites attractive for many sectors.

i. **Automotive Industry:** Natural fibre composites can be used for selected interior components such as door panels, dashboards, seat structures, parcel shelves and other semi-structural parts.

ii. **Building and Construction:** Hybrid natural fibre composites can potentially be used in panels, boards, partitions, decorative components and selected lightweight construction materials.

iii. **Furniture:** Composite boards and moulded products can be developed for furniture applications, particularly where lightweight and environmentally responsible materials are desired.

iv. **Packaging:** Natural fibre composites and bio-based composite materials may be used in sustainable packaging solutions where appropriate strength and durability are required.

v. **Consumer Products:** Potential applications include trays, containers, household products, accessories and other lightweight products.

vi. **Sports and Recreation:** Selected natural fibre composites can be considered for sporting goods and recreational products where low weight and adequate mechanical performance are desirable.

vii. **Textile and Fashion Applications:** The concept also offers opportunities for the development of rigid textile accessories, footwear components, bags, panels and fashion products. Natural fibre composites can provide an interesting combination of textile heritage and material innovation (Genc & Ozdemir, 2022; Kumar *et al.*, 2023).

Environmental Significance

The major attraction of natural fibre hybridization is its potential contribution to sustainable material development. Natural fibres are derived from plants that can be renewed through agricultural production. Their cultivation can also provide opportunities for rural livelihoods and agricultural diversification. Using agricultural residues as reinforcement can further enhance resource efficiency by converting low-value biomass into higher-value products. Hybridization can also help reduce the quantity of synthetic reinforcement required in some applications (Khan *et al.*, 2024).

However, it is important not to assume that every natural fibre composite is automatically environmentally friendly. The environmental performance depends on the complete life cycle of the material. Factors such as fertilizer use, irrigation, fibre extraction, chemical treatment, polymer production, manufacturing energy, transportation and end-of-life disposal must be considered. Therefore, future development should focus on life-cycle thinking rather than simply replacing one material with another (Masud & Mubashar, 2024).

Future Prospects

The future of hybrid natural fibre bio-composites is promising because of increasing interest in renewable materials and circular production systems. Future research should focus on developing optimized fibre combinations rather than simply increasing the number of fibres. Computational modelling and experimental design can help identify the most effective fibre ratios orientations and processing parameters. The use of underutilized agricultural fibres is another important research direction. Fibres from crop residues and less-explored plants can provide new reinforcement options while reducing agricultural waste (Hadlahalli *et al.*, 2025).

The development of bio-based polymer matrices could further improve the sustainability of these materials. Combining natural fibres with biodegradable or bio-derived polymers may lead to composites with improved environmental credentials. Advanced surface modification methods may also improve fibre-matrix bonding and moisture resistance. At the same time, researchers must ensure that chemical treatments do not create environmental problems that offset the benefits of using natural fibres (Baigh *et al*., 2023).

Another emerging direction is the development of smart and functional hybrid bio-composites. Natural fibre composites could potentially be combined with conductive, antimicrobial, sensing or other functional components to produce materials with additional capabilities. Digital manufacturing, additive manufacturing and automated fibre placement may also open new opportunities for customized natural fibre composite products (Khan *et al.*, 2024).

Conclusion

Natural fibre hybridization is more than a materials-development strategy, it is an opportunity to transform renewable biological resources into value-added products while moving towards a more sustainable and circular future. Hybridization provides a new way of thinking about natural fibres. Fibres such as jute, flax, hemp, sisal, kenaf, coir, bamboo, banana and pineapple offer diverse possibilities for hybrid composite development. At the same time, underutilized agricultural resources such as *dhaincha* and other plant-based biomass provide exciting opportunities for future research and value addition. With advances in fibre treatment, bio-based polymers, manufacturing technologies and circular economy approaches, natural fibre hybrid composites have the potential to move beyond laboratory research and become commercially relevant sustainable materials. As industries move toward renewable resources and circular production, hybrid natural fibre bio-composites could become an important bridge between agriculture and advanced materials, turning plant-based resources into stronger, lighter and more sustainable products.

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