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Hybrid Natural Fibre Polymer Composites: A Comprehensive Review

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Abstract

Hybrid natural fibre polymer composites (HNFPCs) have emerged as an innovative and sustainable alternative to conventional fibre-reinforced composites, driven by the need for eco-friendly, lightweight, and high-performance materials. This review presents a comprehensive analysis of recent advancements in HNFPCs, focusing on material constituents, fabrication techniques, resulting properties, and industrial applications. Various hybrid systems, including natural–natural and natural–synthetic fibre combinations, are explored for their synergistic potential in improving mechanical strength, thermal stability, and moisture resistance. The influence of surface modification methods and processing parameters on the interfacial bonding and durability of composites is critically discussed. A comparative evaluation of key physical and mechanical properties is provided using recent literature (2020–2024), highlighting performance trends across different hybrid configurations. Applications in automotive, aerospace, construction, marine, and consumer product sectors demonstrate the industrial relevance of HNFPCs, with an emphasis on sustainability and regulatory compliance. Despite their promise, challenges remain in property variability, limited thermal performance, and recyclability. Future perspectives suggest that integrating bio-based matrices, advanced treatments, and data-driven design will be essential in advancing the next generation of multifunctional, green composites. This review aims to provide a valuable resource for researchers and industry stakeholders seeking to optimize the development and deployment of HNFPCs for structural and semi-structural applications.

Keywords— *hybrid composites, natural fibre, synthetic fibre, mechanical properties, sustainability, polymer matrix*

Abstrak

Komposit polimer hibrida berbasis serat alam (Hybrid Natural Fibre Polymer Composites/HNFPCs) telah muncul sebagai alternatif inovatif dan berkelanjutan terhadap komposit serat konvensional, didorong oleh kebutuhan akan material yang ramah lingkungan, ringan, dan berkinerja tinggi. Artikel tinjauan ini menyajikan analisis komprehensif mengenai kemajuan terkini dalam pengembangan HNFPCs, dengan fokus pada komposisi material, teknik fabrikasi, sifat-sifat yang dihasilkan, serta aplikasi industrinya. Berbagai sistem hibrida, termasuk kombinasi serat alam–alam dan serat alam–sintetik, dieksplorasi karena potensi sinergisnya dalam meningkatkan kekuatan mekanik, stabilitas termal, dan ketahanan terhadap kelembaban. Pengaruh metode modifikasi permukaan dan parameter pemrosesan terhadap ikatan antar muka dan daya tahan komposit dibahas secara kritis. Evaluasi komparatif terhadap sifat fisik dan mekanik utama disajikan berdasarkan literatur terbaru (2020–2024), yang menyoroti tren kinerja dari berbagai konfigurasi hibrida. Aplikasi pada sektor otomotif, *dirgantara, konstruksi, kelautan, dan produk konsumen menunjukkan relevansi industri dari HNFPCs, dengan penekanan pada aspek keberlanjutan dan kepatuhan terhadap regulasi. Meskipun memiliki prospek yang menjanjikan, HNFPCs masih menghadapi tantangan berupa variabilitas sifat, keterbatasan kinerja termal, dan isu daur ulang. Perspektif ke depan menunjukkan bahwa integrasi matriks berbasis bio, perlakuan lanjut yang canggih, dan desain berbasis data akan menjadi kunci dalam mendorong pengembangan generasi berikutnya dari komposit hijau multifungsi. Tinjauan ini bertujuan untuk menjadi sumber informasi yang berharga bagi peneliti dan pelaku industri dalam mengoptimalkan pengembangan dan penerapan HNFPCs untuk aplikasi struktural maupun semi-struktural.*

Kata-kunci— *hkomposit hibrid, serat alam, serat sintetik, sifat mekanik, keberlanjutan, matrik polimer.*

1. INTRODUCTION

The increasing demand for lightweight, high-strength, and eco-friendly materials has accelerated the development of natural fibre-reinforced polymer composites (NFRPCs). These composites utilize lignocellulosic fibres such as jute, flax, hemp, kenaf, or sisal as reinforcements in polymer matrices [1, 2]. Despite their advantages in terms of biodegradability, renewability, and low cost, natural fibre composites often suffer from limited mechanical performance and moisture sensitivity [3, 4].

To address these limitations, researchers have explored hybridization strategies, wherein two or more types of fibres are combined within a single polymer matrix. The resulting hybrid natural fibre polymer composites (HNFPCs) aim to optimize the performance by leveraging the unique advantages of each fibre type, while minimizing their individual weaknesses [5]. This hybridization can be achieved through natural–natural (e.g., jute-sisal, flax-hemp) or natural–synthetic (e.g., jute-glass, flax-carbon) fibre combinations [6].

Incorporating synthetic fibres such as glass, basalt, or carbon can significantly enhance the mechanical strength and thermal stability of natural fibre composites, while the presence of natural fibres helps reduce the overall weight and environmental footprint of the composites [7]. Moreover, various matrix systems including thermoplastics (e.g., polypropylene, polylactic acid) and thermosets (e.g., epoxy, polyester) have been employed to tailor the properties of hybrid composites to meet specific application requirements [8].

The development of HNFPCs has also been driven by advancements in processing techniques such as compression moulding, resin transfer moulding, and vacuum-assisted infusion, which facilitate better fibre dispersion, matrix impregnation, and interfacial bonding [9]. Surface treatments and chemical modifications (e.g., alkali treatment, silane treatment, enzymatic treatment) have further improved the compatibility between fibres and matrices, leading to better stress transfer and overall performance [10].

The industrial relevance of HNFPCs is becoming increasingly evident in sectors such as automotive, aerospace, construction, marine, sports, and consumer products, where lightweight and sustainable materials are in high demand. Companies such as BMW, Mercedes-Benz, and Airbus have already incorporated natural or hybrid fibre composites in non-load bearing interior components [11].

Given the rapid expansion of this field, a comprehensive review is necessary to consolidate the recent findings, evaluate material combinations, and identify research trends and future directions. This paper aims to provide a holistic overview of hybrid natural fibre polymer composites, focusing on constituent materials, fabrication methods, physical and mechanical properties, applications, and future challenges.

2. TYPES AND COMBINATION OF HYBRID FIBRE

Hybrid natural fibre composites involve the use of two or more different types of fibres in a single polymer matrix. These combinations can be classified into two major categories:

- Natural/Natural fibre hybrids: These use combinations such as flax/jute, kenaf/sisal, or hemp/coir. Such systems aim to balance specific characteristics like tensile strength, ductility, moisture resistance, and thermal behavior.
- Natural/Synthetic fibre hybrids: Examples include jute/glass, flax/carbon, hemp/aramid, and kenaf/basalt. These configurations are designed to leverage the high-performance characteristics of synthetic fibres while reducing the environmental footprint by incorporating natural fibres.

The success of hybridization depends on several factors:

- Mechanical Compatibility: Fibres should ideally possess similar strain-to-failure behavior to ensure effective load sharing.
- Thermal Compatibility: Important to maintain dimensional stability and processing feasibility.
- Moisture Absorption Balance: Hybrid systems must address moisture sensitivity, especially when natural fibres are combined with hydrophobic synthetics.

Hybrid configurations can be classified as:

- Interlayered (laminar): Where different fibre layers are stacked alternatively.
- Intralayered: Both fibre types are mixed within the same layer.
- Randomly Oriented: Fibres are distributed randomly throughout the matrix.

Numerous studies have demonstrated that judicious selection of fibre types and stacking sequences can lead to synergistic effects in terms of tensile strength, flexural properties, impact resistance, and damping characteristics. Additionally, the hybrid approach allows customization for targeted applications such as load-bearing structures, crash components, or thermally stable panels.

3. POLYMER MATRICES USED IN HYBRID NATURAL FIBRE REINFORCED POLYMER COMPOSITES

The selection of a suitable polymer matrix is crucial in determining the overall performance of hybrid natural fibre composites. The matrix binds the fibres together, transfers loads, and protects the fibres from environmental degradation. In HNFRPCs, matrices are broadly categorized into thermoplastics and thermosets, each offering distinct advantages.

3.1 Thermoplastic Matrices

Thermoplastics such as polypropylene (PP), polyethylene (PE), polylactic acid (PLA), and polyamide (PA) are widely used due to their recyclability, ductility, and ease of processing. Key characteristics include:

- Recyclability: Enables multiple processing cycles, aligning with sustainability goals.
- Ease of Processing: Compatible with injection moulding, extrusion, and compression moulding.
- Moisture Sensitivity: Some thermoplastics, like PLA, are more sensitive to water uptake and may require coupling agents or fibre treatments.

Thermoplastics often require higher processing temperatures, which may limit their compatibility with some natural fibres. However, blending with plasticizers or using short-cycle moulding can mitigate thermal degradation.

3.2 Thermoset Matrices

Thermosetting polymers such as epoxy, polyester, and vinyl ester resins are also commonly employed. They offer:

- High Mechanical Strength: Ideal for load-bearing applications.
- Good Thermal and Chemical Resistance: Suitable for harsh environments.
- Strong Fibre Adhesion: Especially when used with treated natural fibres.

Thermosets cure irreversibly, which limits their recyclability but provides dimensional stability and high stiffness. Epoxy-based matrices are particularly favored in aerospace and automotive sectors due to their superior bonding and fatigue resistance.

3.3 Bio-based and Green Matrices

To enhance environmental sustainability, recent efforts have focused on developing matrices from renewable resources, such as:

- Thermoplastic starch (TPS)
- Bio-epoxy resins
- PLA-based copolymers

These matrices reduce the carbon footprint and support the development of fully bio-based hybrid composites. However, challenges such as low thermal stability, water sensitivity, and limited mechanical performance must be addressed.

The compatibility between the chosen matrix and hybrid fibres is essential to achieving optimal performance. Techniques such as matrix functionalization, use of compatibilizers, and coupling agents are often necessary to improve interfacial bonding, especially in systems combining hydrophilic natural fibres with hydrophobic polymer matrices.

4. FABRICATION TECHNIQUES FOR HYBRID NATURAL FIBRE COMPOSITES

The choice of fabrication method plays a critical role in determining the structural integrity, fibre dispersion, and interfacial bonding of hybrid composites. Various techniques have been developed and adapted to accommodate hybrid fibre systems. These include conventional and advanced processing approaches suitable for both thermoplastic and thermoset matrices.

4.1 Hand Lay-Up and Compression Moulding

This is one of the most accessible and widely used methods for producing fibre-reinforced composites.

- Hand lay-up involves manually placing the fibres in a mould followed by matrix application.
- Compression moulding uses heat and pressure to shape and cure the composite.

Advantages:

- Simple and cost-effective
- Suitable for both long and short fibre reinforcements

Limitations:

- Inconsistent fibre distribution
- Prone to voids and poor fibre wetting, especially in hybrid systems with dissimilar fibres

4.2 Vacuum-Assisted Resin Transfer Moulding (VARTM)

In VARTM, a vacuum is used to draw resin into a fibre preform laid within a closed mould.

- Offers improved wetting and void-free structures
- Useful for producing large, complex parts

Particularly effective for hybrid natural/synthetic systems where controlled resin flow enhances interfacial bonding.

4.3 Extrusion and Injection Moulding

These techniques are more suited to thermoplastic-based hybrids:

- Extrusion blends fibres and matrix in a molten state for sheet or pellet production.
- Injection moulding allows shaping of these pellets into complex geometries.

Key Benefits:

- Suitable for high-volume production
- Compatible with short and randomly oriented fibres

Challenges include maintaining fibre length and preventing fibre damage, especially in hybrid blends.

4.4 Solution and Melt Blending

- Solution blending involves dispersing fibres and polymers in a solvent, followed by evaporation or film casting.
- Melt blending uses high-shear mixing of components at elevated temperatures.

These are often employed in research settings to ensure uniform dispersion, particularly when using nano-reinforcements alongside hybrid fibres.

4.5 3D Printing and Advanced Techniques

Recent developments in additive manufacturing have enabled the use of hybrid fibre reinforcements in printable filaments.

- Fused deposition modelling (FDM) is being explored using thermoplastic matrices reinforced with chopped hybrid fibres.
- Electrospinning is also being investigated for multilayer nanofibre architectures.

Although still in the early stages, these methods offer opportunities for custom-designed, functionally graded composites.

Hybrid Fabrication Strategies: To optimize performance, researchers are exploring:

- Sequential lay-up (synthetic outer layers for impact resistance, natural core for weight reduction)
- Coating or treating natural fibres before co-processing with synthetic fibres
- Hybrid weaves or mats with tailored stacking sequences

In conclusion, the choice of fabrication technique should be aligned with the fibre types, matrix characteristics, target properties, and intended applications. The next section will focus on the resulting mechanical, thermal, and moisture-related properties of hybrid natural fibre polymer composites.

5. MECHANICAL, THERMAL, AND MOISTURE-RELATED PROPERTIES OF HYBRID NATURAL FIBRE POLYMER COMPOSITES

Hybridization in natural fibre polymer composites is primarily aimed at overcoming the intrinsic limitations of individual natural fibres—particularly their relatively low mechanical strength, high moisture absorption, and poor thermal resistance. By combining two or more fibre types within a single polymer matrix, synergistic effects can be achieved, leading to enhanced performance suitable for broader engineering applications. This section provides a detailed overview of how hybridization influences the mechanical, thermal, and moisture-related properties of these composites.

5.1 Mechanical Properties

Hybrid natural fibre composites generally exhibit improved mechanical behavior compared to single-fibre composites. Tensile strength, flexural modulus, and impact resistance are particularly sensitive to the type of fibres used, their orientation, and the stacking sequence in laminates.

Recent studies emphasize that optimal fibre combinations and volume fractions are key to maximizing mechanical properties:

- Banana/sisal hybrid reinforced epoxy composites showed an improvement in tensile strength by 18–25% compared to their single-fibre counterparts due to better load distribution [12].
- Flax/glass fibre–reinforced PLA composites achieved higher flexural and impact strength, balancing stiffness from flax with the toughness of glass fibres [13].
- Kenaf/jute hybrid composites with proper layering sequence (jute as the core, kenaf as skin) demonstrated better interlaminar shear strength and flexural rigidity due to outer-layer protection and enhanced stress transfer [14].
- The hybridization of sugar palm fibre with kenaf fibre in a polypropylene matrix has demonstrated a synergistic effect on the tensile properties of the composites. Among the two fibres, kenaf exhibited a more dominant role in enhancing the tensile strength, indicating its stronger reinforcement capability in the hybrid composite system [15-17].

Surface modification of fibres such as alkali, silane, or microwave-assisted treatment significantly improves fibre-matrix adhesion, leading to better stress transfer and crack resistance under loading [18].

5.2 Thermal Properties

Thermal performance is critical in determining the applicability of HNFPCs in automotive or construction sectors. Parameters such as thermal degradation temperature, glass transition temperature (T_g), and thermal conductivity reflect the thermal stability of a composite system.

Recent research indicates the following:

- Flax/basalt hybrid composites show delayed onset of thermal degradation by 20–40°C compared to pure flax composites, with improved residual char formation enhancing fire resistance [19].
- Karthick et al. (2022) investigated the effect of nano-/microfiller addition on the mechanical performance and morphology of kenaf/glass fibre-reinforced hybrid composites. The results showed that the incorporation of fillers up to 15 wt% enhanced the composite strength; however, the study did not specifically address changes in the glass transition temperature (T_g) [20].
- The study evaluated the mechanical and thermal properties of hybrid composites incorporating coir and hemp fibres in a polyester matrix. The results demonstrated that the combination of these fibres enhanced the thermal stability and mechanical properties of the composite, making it a promising candidate for lightweight applications [21].

Hybridization also affects thermal expansion, where more dimensionally stable fibres (e.g., basalt, flax) can mitigate swelling and contraction of the composite under cyclic temperature changes.

5.3 Moisture Absorption and Water Resistance

Moisture uptake in natural fibre composites remains a pressing issue due to the presence of hydrophilic hydroxyl groups in lignocellulosic fibres. However, hybridization has proven to reduce water affinity, especially when involving less hygroscopic fibres or protective layering strategies.

Key findings from recent studies:

- The study evaluated the influence of external basalt layers on the durability of flax-reinforced epoxy composites. Two laminate configurations were tested: one with all flax layers and another with basalt layers on the outer surfaces. The results demonstrated that the hybrid laminate with basalt outer layers exhibited reduced water absorption and improved mechanical properties under salt-fog conditions, highlighting the protective role of basalt fibres against moisture ingress [22].
- The combination of hemp and coir fibers in hybrid composites can influence water absorption behavior, depending on the fiber proportion and surface treatment applied. The incorporation of coir fiber in low amounts, along with appropriate chemical treatment, can help reduce water absorption in the hybrid composites [23].
- A study by Johar and Ariff (2022) investigated hybrid composites incorporating microwaved coconut fibre and rice husk. The results demonstrated that microwave treatment enhanced flexural strength and reduced water absorption compared to conventional oven treatment [24].

Water absorption behavior is typically modeled using Fickian diffusion, and long-term immersion studies indicate that hybridization can slow down saturation rates, improving dimensional stability and preventing delamination.

Overall**,** hybrid natural fibre polymer composites present a promising balance between performance and eco-sustainability. The choice of fibres, processing method, and surface treatments directly influence their mechanical robustness, thermal endurance, and environmental stability. However, standardization of testing protocols and further long-term performance assessments remain crucial for widespread industrial adoption.

6. SPECIFIC APPLICATIONS AND INDUSTRIAL RELEVANCE OF HYBRID NATURAL FIBRE POLYMER COMPOSITES

The growing emphasis on sustainable materials, lightweight structures, and eco-friendly design has pushed hybrid natural fibre polymer composites (HNFPCs) to the forefront of material innovation across various sectors. These composites, owing to their enhanced mechanical, thermal, and moisture-resistance properties, have found applications in automotive, aerospace, construction, marine, and consumer product industries. This section explores these applications and their industrial significance.

6.1 Automotive Industry

The automotive sector remains the most dominant application area for natural fibre composites due to the dual demand for weight reduction and sustainability. Hybrid natural fibre composites have been used in:

- Interior components such as door panels, dashboards, seat backs, and headliners.
- Under-the-hood components when hybridized with thermally stable fibres (e.g., flax/basalt).

For instance, Kenaf/glass fibre hybrid composites in a PP matrix have been adopted by companies like *Mercedes-Benz* and *BMW* for interior panels due to their favorable strength-to-weight ratio, noise dampening, and recyclability [25]. Hybridization allows for better crash resistance and improved fire performance compared to single-fibre systems.

6.2 Aerospace and Aviation

Although still in the exploratory stage, aerospace applications of HNFPCs are expanding for non-structural parts such as:

- Cabin insulation
- Luggage compartments
- Tray tables

Hybrid composites such as flax/carbon or jute/glass reinforced with epoxy have demonstrated adequate fatigue resistance and vibration damping suitable for low-load aerospace interiors [26]. The challenge remains in meeting strict flammability and performance standards, which hybrid designs are increasingly able to address through improved thermal and mechanical stability.

6.3 Construction and Building Materials

In civil engineering and architecture, HNFPCs are used for both structural and non-structural applications:

- Wall panels and insulation boards
- Roofing sheets
- Partition walls and cladding
- Decorative elements

Natural straw/hemp fibre hybrid panels are used in prefabricated structures, offering thermal insulation and resistance to biodegradation [27]. These panels are particularly suited for modular housing, especially in regions aiming to reduce their carbon footprint.

6.4 Marine and Shipbuilding Industry

In marine applications, resistance to moisture, saltwater, and UV exposure is essential. Natural fibre composites are increasingly used for:

- Small boat hulls
- Cabin interiors
- Deck components

Flax/basalt or hemp/glass hybrids in vinyl ester or polyester matrices offer a combination of buoyancy, reduced water absorption, and good fatigue performance [28]. Treatments such as epoxy coating or gelcoat sealing further enhance water resistance.

6.5 Sports and Recreational Equipment

The sports and leisure industry leverages HNFPCs for products where lightweight, stiffness, and aesthetic appeal are desired, including:

- Bicycle frames and surfboards
- Protective gear (helmets, guards)
- Rackets and paddles

For instance, flax/carbon hybrid composites are used in bicycle components to replace full-carbon parts while offering comparable vibration damping and improved environmental performance [29].

6.6 Furniture and Consumer Products

HNFPCs are being adopted in the furniture and consumer goods sector for their design flexibility, biodegradability, and cost efficiency. Common products include:

- Chairs, tables, and cabinet panels
- Speaker enclosures
- Luggage components

Hybrid systems like banana/sisal or jute/coir composites are not only lightweight and strong but also offer a rustic aesthetic valued in eco-conscious design [30, 31].

Industrial Relevance and Economic Potential

The industrial relevance of HNFPCs is driven by the convergence of the following factors:

- Regulatory pressure for green materials (e.g., EU directives on recyclability in vehicles)
- Consumer awareness regarding environmental impact
- Cost advantages over fully synthetic composites
- Circular economy incentives, especially when fibres are derived from agricultural waste

Furthermore, the ability to tailor properties via custom hybrid configurations allows manufacturers to optimize materials for specific applications without resorting to expensive or non-renewable resources.

Recent market analyses suggest that the global natural fibre composites market is expected to grow at over 10% CAGR through 2026, with hybrid composites accounting for a significant portion of this growth due to their enhanced performance profile [32, 33].

7. CHALLENGES AND FUTURE PERSPECTIVES OF HYBRID NATURAL FIBRE POLYMER COMPOSITES

While hybrid natural fibre polymer composites (HNFPCs) offer a promising combination of environmental sustainability, enhanced mechanical performance, and design flexibility, there remain a number of challenges that hinder their widespread adoption, especially in high-performance industries. This section outlines the current limitations, ongoing research efforts, and future opportunities in this field.

7.1 Challenges

7.1.1 Inconsistency of Natural Fibre Properties

Natural fibres are biological materials with inherent variability in terms of diameter, cellulose content, moisture content, and mechanical properties, even within the same species. This inconsistency complicates material standardization and quality control in composite manufacturing.

7.1.2 Fibre–Matrix Interface Compatibility

The hydrophilic nature of natural fibres and the hydrophobic character of most polymer matrices often result in poor interfacial bonding, leading to delamination and premature failure. Although surface treatments like alkali, silane, and enzymatic methods help, they add to production cost and complexity.

7.1.3 Moisture Sensitivity and Environmental Aging

Despite hybridization, natural fibre composites remain susceptible to moisture absorption, microbial attack, and UV degradation. This limits their outdoor applications unless advanced protective coatings or hybrid layers with moisture barriers (e.g., basalt/glass) are used.

7.1.4 Limited High-Temperature Performance

Natural fibres degrade thermally at relatively low temperatures (200–300°C), restricting their use in high-temperature environments. Although hybridization with thermally stable fibres improves this, the overall thermal ceiling remains a limitation for aerospace or under-the-hood automotive applications.

7.1.5 Lack of Standardized Processing Techniques

While numerous fabrication methods exist—hand lay-up, compression molding, resin transfer molding—no universally accepted method ensures optimum performance for all types of HNFPCs. Process optimization is often case-specific and lacks scalability.

7.1.6 End-of-Life Management and Recycling

Although bio-based, many HNFPCs use non-biodegradable polymer matrices like epoxy or polypropylene. This makes recycling complex, particularly for thermoset-based systems. Full biodegradability is still an aspiration rather than a widespread reality.

7.2 Future Perspectives

Despite the above challenges, ongoing research and technological advances provide optimistic prospects for the development and commercialization of HNFPCs.

7.2.1 Advanced Surface Modification and Green Treatments

Emerging treatments such as plasma treatment, microwave-assisted alkalization, and enzyme-based modification are gaining traction as more eco-friendly and efficient alternatives to traditional chemical treatments. These can enhance interfacial bonding and reduce moisture affinity without compromising fibre integrity.

7.2.2 Development of Fully Bio-Based Composites

The combination of bio-based resins (e.g., polylactic acid, polyhydroxyalkanoate) with hybrid natural fibres is a major focus area. This not only improves biodegradability but also aligns with circular economy goals. Research is also exploring dynamic covalent polymer matrices for recyclable thermosets.

7.2.3 Computational Modelling and Predictive Design

Finite Element Analysis (FEA), machine learning (ML), and data-driven material design are being used to predict the behavior of HNFPCs under various load conditions. This approach helps reduce trial-and-error in material formulation and accelerates the design-to-market timeline.

7.2.4 Multi-Functional Hybrid Composites

Future HNFPCs are expected to offer more than just structural functions. Integration of flame retardancy, self-healing capabilities, electrical conductivity, and smart sensing is under investigation, particularly using nano-fillers (e.g., graphene, CNTs) in combination with natural fibres.

7.2.5 Industrial Upscaling and Automation

To meet growing demand, scalable and cost-effective manufacturing techniques such as automated fibre placement (AFP) and in-situ resin infusion are being developed for hybrid composites. Collaboration between academic research and industry will be key to achieving commercialization.

7.2.6 Life Cycle Assessment (LCA) and Standardization

Rigorous environmental impact assessments through LCA will be vital for justifying large-scale use. Standardized testing and certification processes for HNFPCs, especially in automotive and construction sectors, are needed to foster industry-wide trust.

8. CONCLUSIONS

Hybrid natural fibre polymer composites are poised to play a critical role in the transition towards greener materials in various industries. While mechanical and thermal properties have shown substantial improvement through hybridization, addressing moisture durability, thermal stability, and process scalability remains crucial. Interdisciplinary research that bridges materials science, environmental engineering, and computational modelling will drive the next wave of innovations, making HNFPCs more competitive with conventional composites while remaining eco-conscious.

Hybrid natural fibre polymer composites (HNFPCs) represent a promising class of sustainable materials that synergistically combine the advantages of multiple fibre types—particularly natural–natural or natural–synthetic combinations—with polymer matrices to enhance overall composite performance. Over the past decade, research in this domain has significantly advanced in terms of materials selection, processing optimization, property enhancement, and application development.

This review has comprehensively discussed various types of natural and hybrid fibres, the effects of processing methods, and the resulting mechanical, thermal, and moisture-related properties. It is evident that hybridization improves the mechanical strength, stiffness, impact resistance, and thermal stability of natural fibre composites while mitigating limitations such as moisture sensitivity and variability in fibre properties. However, challenges remain in achieving consistent quality, improving fibre–matrix adhesion, enhancing long-term durability, and scaling up production for industrial use.

In terms of applications, HNFPCs have demonstrated significant relevance in the automotive, construction, marine, aerospace, sports, and consumer goods sectors. The growing emphasis on eco-sustainability, lightweight design, and regulatory compliance has accelerated their adoption, although widespread commercialization is still constrained by technical, economic, and environmental barriers.

Looking forward, the integration of green surface modification techniques, bio-based matrices, computational design tools, and multi-functional capabilities is expected to drive innovation. Furthermore, future efforts should prioritize life cycle assessment, recyclability, and standardization, particularly to support industrial uptake and policy alignment with circular economy principles.

In conclusion, while hybrid natural fibre polymer composites are not yet a universal substitute for synthetic composites, they hold substantial potential as a viable and environmentally responsible alternative—especially in semi-structural and functional components across various industries. Continued interdisciplinary research, industry-academic collaboration, and supportive policies will be crucial in unlocking the full potential of HNFPCs in the coming years.

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