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Bibliographic Overview of Lignocellulose Fiber Reinforced Polymer Composites: A Comparative Analysis of Recent Research Trends, Processing Techniques and Emerging Applications

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Abstract – Natural fiber-reinforced composites (NFRCs) have gained prominence as an environmentally sustainable replacement for synthetic composites, driven by rising ecological concerns. This study conducts a unique bibliographic analysis of NFRCs, concentrating on significant fibers like flax, jute, hemp, and sisal. It thoroughly reviews their mechanical properties, fabrication processes, and applications across various industries. The study uses bibliometric data to track evolving research trends, including advancements in fiber treatment, hybridization, and the development of biodegradable resins. Although NFRCs offer several benefits, they face issues such as fiber–matrix incompatibility, moisture sensitivity, and reduced mechanical durability. This review examines innovative solutions, such as advanced surface treatments, the integration of nanotechnology, and multi-scale reinforcement. The study also offers a forward-looking perspective on the potential of NFRCs in next-generation sustainable materials, highlighting their role in automotive, aerospace, construction, and biomedical sectors. By addressing knowledge gaps, this review provides a resource for researchers, manufacturers, and policymakers, contributing to the future adoption of NFRCs in various industries and fostering sustainable material innovations.

Key words: Biodegradable resins, Biorefinery, Fiber treatment, Mechanical durability, Natural fiber-reinforced composites, Sustainable materials.

1. Introduction

The rising demand for environmentally sustainable materials has led to a growing interest in natural fiber composites, largely due to their lightweight nature, biodegradability, and renewability. But many researchers have also produced fiber-reinforced polymer composites from resins and polymers, which have gained application in many construction areas. The resins, like epoxy and vinyl, are most commonly used for their excellent properties. In some cases, especially, the mechanical properties provide lower stress due to absorption of water molecules. Thus, the focus was shifted towards the usage of natural based fibers produced from plants. This study traces the development of NFRCs over the past decade, highlighting key advancements, contributions, and challenges [1]. Additionally, it explores the expanding applications of these composites across industries like aerospace, automotive, and packaging.

Between 2012 and 2024, significant progress has been made in the development of lignocellulosic fiber-reinforced polymers and hybrid composites, driven by the need for sustainable alternatives. This progress has notably affected industries such as automotive, aerospace, construction, and manufacturing [2]. Lignocellulosic fibers, including flax, hemp, jute, sisal, and kenaf, have risen in prominence due to their mechanical properties, which are comparable to traditional synthetic fibers, like glass and carbon [3]. These natural fibers enhance key mechanical attributes, such as tensile strength, modulus, impact resistance, and weight reduction. Continuous improvements in fiber treatment methods, matrix formulations, and composite fabrication techniques have further elevated their mechanical performance, reinforcing their potential for various industrial applications [4].

To maintain fiber integrity during composite processing, advancements in manufacturing techniques have been crucial. Processes such as resin transfer molding, compression molding, and extrusion have been optimized to meet the unique requirements of natural fibers [5,6]. Furthermore, innovations in fiber extraction methods, such as enzymatic treatments and steam explosion, have improved fiber compatibility with polymer matrices, facilitating more efficient composite production and enabling complex structural applications [7]. The lignocellulose fibers, derived from renewable plant biomass, provide a sustainable and widely available raw material base, including fibers like kenaf, hemp, wood, jute, and flax, for producing reinforced composites utilized in aerodynamic industries based on their performance [8].

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Their stable supply chain, driven by agricultural production, presents a cost-effective alternative to synthetic fibers, reducing transportation emissions and overall manufacturing costs.

The growing demand for eco-friendly materials has reinforced the economic viability of these fibers, fostering job creation and economic diversification, particularly in rural areas [9]. Moreover, NFRCs have a significantly lower environmental footprint than conventional fibers, like glass and carbon, largely due to reduced CO_2 emissions during production and the reliance on renewable resources, which aligns with circular economy principles [10,11]. The kenaf lignocellulosic is one natural fiber, which is cultivated from United States of America, will be an alternative to synthetic materials. Its higher mechanical properties compare to other natural fibers like jute, sisal, cotton, banana, and bamboo. This lignocellulosic will be a better alternative as well as a protecting agent to polymer composite.

The increasing adoption of NFRCs has been further accelerated by regulatory frameworks and shifting consumer preferences toward sustainable materials, positively influencing economic growth and employment, particularly in rural communities [12]. The cultivation and use of these fibers align with Environmental, Social, and Governance principles and support the United Nations' Sustainable Development Goals [13,14]. Additionally, fiber cultivation aids in carbon sequestration, amplifying its environmental advantages. Strong governance measures ensure the sustainable sourcing, production, and disposal of NFRCs, promoting ethical consumption and responsible manufacturing practices. The integration of lignocellulosic fibers into composite materials represents a convergence of technological innovation, economic opportunity, and environmental responsibility, contributing to a shift in industrial practices toward greener alternatives to conventional composites [15,16].

This study offers a comprehensive review of lignocellulosic fiber–reinforced polymer hybrid composites (LCF–PHC) research from 2012 to 2024, identifying major trends and developments [17,18]. By using quantitative bibliometric analysis, the study investigates research publication patterns and applies advanced analytical methods, like topic cluster, salience indicators, and knowledge mapping, to identify key research themes.

The goal is to present a holistic overview of the research landscape, intellectual development, and emerging areas of interest within NRF's studies [19,20]. The following sections of this paper present a structured analysis, detailing the methodology and bibliometric approach, followed by an in-depth discussion on lignocellulosic fibers and the treatments used to enhance fiber–matrix adhesion [21, 22]. Additionally, the study explores fiber surface treatments, analyzes publication trends, and discusses various composite manufacturing techniques [23,24].

The paper concludes with a synthesis of key findings and offers recommendations for future research directions in lignocellulosic fiber composites [25,26]. Table 1 compares widely used surface treatment methods, their principles, advantages, limitations, and application sectors. The increasing industrial adoption of natural fiber composites is further supported by market trends (Figure 1), which illustrates the publication growth of natural fiber composites, segmented by raw material (Wood, Flax, Hemp). Projecting a market value of $9.48 billion by 2030, with a compound annual growth rate (CAGR) of 12.0% from 2025 to 2030 [27]. This market growth reflects the rising demand for sustainable materials in industries like automotive and packaging, where materials such as flax and hemp are gaining prominence due to their eco-friendly properties.

Although many studies have reviewed the mechanical properties, surface modification methods, and application areas of NFRCs, most of this literature remains mainly descriptive. As a result, it often does not clearly explain why certain research topics become popular, dominate the field, or decline over time. In recent years, review articles are increasingly expected to go beyond listing results and instead provide clear interpretation that links experimental findings with research trends and technology readiness. To meet this expectation, the present review adopts a structured analytical approach that

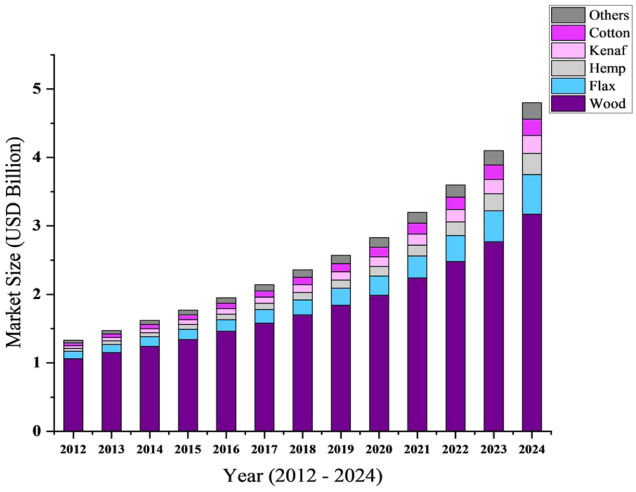

Fig. 1. Growth of natural fiber composite publications.

Table 1. Comparison of existing treatment methods for natural fibers and their potential applications

Method	Principle	Advantages	Limitations	Applications	References
Alkaline (NaOH) Treatment	Removes lignin and hemicellulose, improving fiber-matrix bonding	Enhances mechanical properties, increases fiber surface roughness	Can weaken fibers if over-treated	Automotive, aerospace, construction	[36, 39, 40, 41]
Silane Treatment	Forms covalent bonds between fiber and matrix	Improves interfacial adhesion, reduces water absorption	Costly, requires controlled processing	Structural applications, marine composites	[37, 45]
Steam Explosion	Uses high-pressure steam to break lignin structure	Eco-friendly, increases fiber compatibility	High energy consumption	Biodegradable packaging, automotive	[7]

combines bibliometric analysis with materials science understanding and data-based modeling to examine how NFRC research has evolved.

Within this approach, fuzzy logic–based modeling is used only as a supporting tool, not as a standalone prediction method. It helps combine experimental information on fiber properties, such as cellulose content (55–75%), tensile strength of raw fibers (200 MPa for coir and jute, up to more than 1500 MPa for flax and hemp), and strength improvements after surface treatment (15–45% for optimized alkali or silane treatment), with publication trends and application focus. This combined analysis allows a clear and logical interpretation of how factors such as processing ease, fiber–matrix bonding, durability, scalability, cost–performance balance, and long-term reliability have influenced the direction of NFRC research. As a result, this review not only identifies areas where research has grown rapidly, but also points out topics that have progressed slowly or remain insufficiently studied, in line with the current editorial preference for reviews that provide practical insight and future direction, rather than simply reporting publication growth.

2. Data Collection and Evaluation

2-1. Data and sources

To comprehensively assess the research landscape on NFRCs, a bibliometric analysis was carried out utilizing Scopus and Web of Science, two highly regarded academic databases. These platforms were selected for their broad coverage of high-quality, peer-reviewed literature in fields such as materials science, engineering, and sustainable composites. The analysis focused on research articles published from 2001 to 2025, aiming to capture technological advancements in NFRCs, particularly in terms of mechanical performance, manufacturing methods, and industrial applications.

Figure 2 illustrates the workflow adopted for bibliometric filtering, screening, and mapping. Terms like natural fiber composites, lignocellulosic fiber composites, mechanical properties, processing methods, bio-based composites, and sustainable polymer composites were employed. Boolean operators (AND, OR) were utilized to narrow the search results, ensuring a well-rounded, yet focused, collection of studies. To uphold academic integrity, only peer-reviewed journal articles, conference papers, and review articles were selected, while non-peer-reviewed sources, patents, and industry reports were excluded.

2-2. Data processing and visualization

The bibliometric data were analyzed using VOSviewer, Biblioshiny (R-based software), and Microsoft Excel. Visual representations of the citation network, co-authorship patterns, and thematic clusters were created to offer insights into the collaborative and thematic structure of FRC research. A comparative analysis was performed to assess technological advancements across various industries and material compositions. This approach provided a thorough understanding of the evolution of NFRCs over the past decade.

2-3. Selection criteria

The literature selection was based on specific inclusion and exclusion criteria. Studies were included if they:

Criteria I: Focused primarily on NFRCs, covering their mechanical properties, processing techniques, and industrial applications.

Criteria II: Offered experimental or theoretical insights into the performance of NFRCs and advancements in composite technology.

Criteria III: Examined natural fibers, like flax, hemp, jute, sisal, kenaf, and coir, among others.

Criteria IV: Addressed innovative methods, such as fiber surface treatments, hybridization, and bio-based polymer matrices.

Criteria V: Investigated the use of NFRCs in sectors like automotive, aerospace, construction, and packaging.

Studies that concentrated exclusively on synthetic or inorganic fiber composites were excluded to ensure the focus on sustainable materials. Additionally, research published in languages other than English was not included due to accessibility limitations.

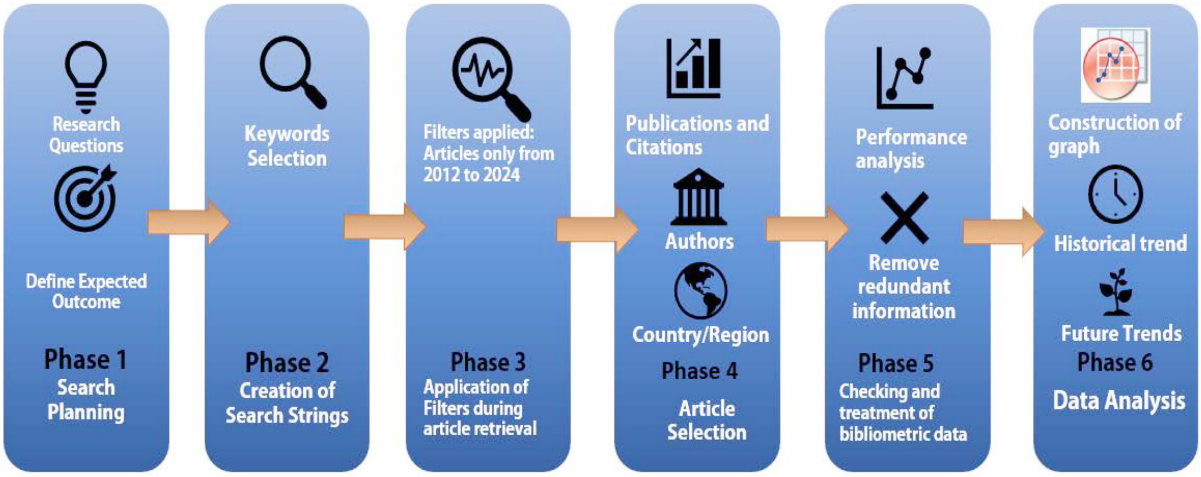

Fig. 2. Workflow of the bibliometric analysis process.

2-4. Bibliometric analysis

A bibliometric analysis was conducted using a structured, multi-step approach to examine publication growth, citation dynamics, thematic evolution, and collaboration patterns in FRCs research. Annual publication trends and citation metrics were analyzed to identify the major developmental phases of the field (Figure 3), and journal impact analysis was used to determine the dominant dissemination platforms. Keyword co-occurrence and thematic clustering were performed using VOSviewer and Biblioshiny to map the research focus areas and their interconnections. Collaboration networks among authors and institutions were evaluated to assess the global and interdisciplinary nature of NFRCs research. Together, these tools enabled not only quantitative mapping, but also an interpretative assessment of how experimental constraints and application demands have shaped research trajectories.

Figure 3 reveals a distinct decoupling between publication volume and citation impact, indicating that FRC research has progressed through identifiable knowledge phases rather than through linear expansion. During the early exploratory stage (2001–2008), publication output was limited; however, the citation density per article was high, reflecting the foundational influence of early studies focused on fiber characterization, fiber–matrix compatibility, and baseline processing routes. These studies established reference mechanical properties, typically composite tensile strengths in the range of 35–55 MPa for untreated or mildly treated systems, and documented critical limitations, such as high moisture uptake, exceeding 8–12 wt.%, which strongly influenced subsequent research directions.

Between approximately 2009 and 2015, the field entered a consolidation phase, marked by a gradual increase in publications and citations. This period corresponds to systematic investigations of surface treatment strategies and thermoplastic processing routes, during which alkali (5–8% NaOH) and silane treatments were widely adopted. Experimental studies from this phase consistently reported 20–40% improvements in tensile strength, enabling values of 70–90 MPa in optimized flax-, hemp-, and jute-based systems, alongside reductions in water absorption to below 4–6 wt.%. The sustained citation growth during this stage indicates that these studies retained long-term relevance by offering comparative insights into the mechanical performance, moisture sensitivity, and recyclability of these materials.

After 2016, Figure 3 shows a pronounced surge in the number of publications, peaking between 2022 and 2024. However, this rapid expansion is not matched by a proportional rise in citation impact, suggesting the dilution of the average scholarly influence. This divergence reflects a shift toward application-driven and optimization-focused studies, often addressing specific fibers, surface treatments, or processing parameters, rather than fundamentally new concepts. Such behavior is characteristic of a maturing research field, where breadth expands more rapidly than conceptual depth. This period also aligns with the expansion of NFRC applications, from non-structural automotive interior components to semi-structural panels, packaging materials, and vibration or thermal–acoustic elements, driven by improved interfacial bonding but constrained by durability requirements.

The observed bibliometric trends also reflect a qualitative transition in the scientific and technological development of lignocellulosic fiber–reinforced polymer composites. Early research primarily established the fundamental understanding of fiber characteristics, mechanical properties, and fiber–matrix interactions. Subsequent studies increasingly focused on improving interfacial adhesion, reducing moisture absorption, and optimizing surface modification and composite processing techniques. More recent research has broadened these investigations toward hybrid reinforcement systems, modified polymer matrices, sustainable manufacturing, and application-oriented performance evaluation. This progression indicates that the field has moved beyond basic material characterization toward the development of composites with tailored properties for specific engineering applications. Nevertheless, increased publication activity and a wider range of proposed applications should not be interpreted as evidence of complete technological maturity. Challenges related

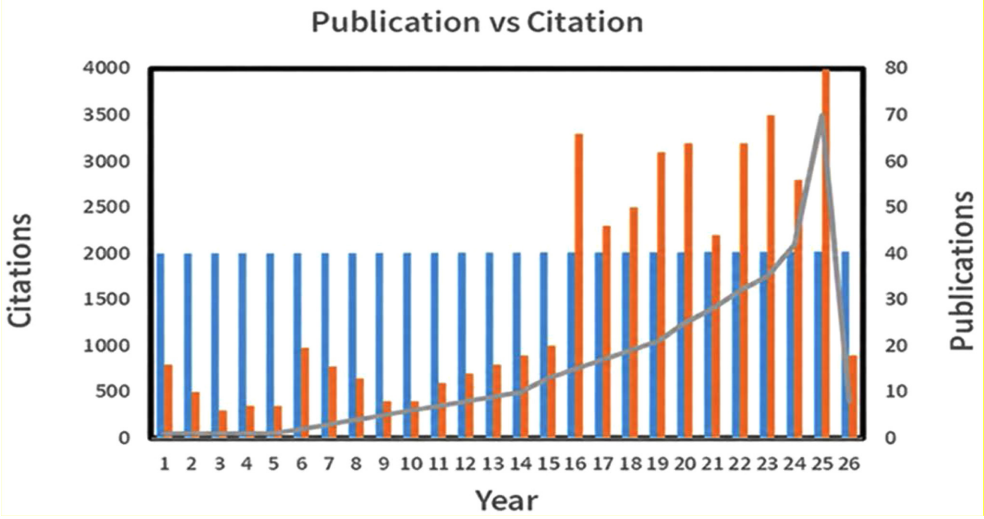

Fig. 3. Annual number of studies on natural fiber reinforced thermoplastic composites from the year 2001 to 2025.

to long-term durability, variability in natural fiber properties, manufacturing consistency, recyclability, and industrial-scale validation remain important barriers to wider commercialization.

Citation-based indicators should therefore be interpreted alongside the scientific contributions and experimental evidence reported in individual studies. Review articles may accumulate citations because they consolidate existing knowledge and provide convenient entry points to a research topic, whereas original experimental studies may contribute important advances without achieving comparable citation counts. Consequently, a high citation count does not necessarily indicate greater experimental novelty, practical applicability, or technological readiness. Similarly, the increasing frequency of keywords related to surface treatment, hybridization, and sustainable composites indicates growing research attention but does not independently demonstrate that these approaches have achieved superior or commercially validated performance. Accordingly, the bibliometric findings in this study are interpreted in conjunction with the reviewed material properties, processing developments, and application-related evidence to distinguish research popularity from demonstrated scientific progress. This combined interpretation provides a more balanced assessment of the evolution, current limitations, and future development priorities of lignocellulosic fiber-reinforced polymer composites.

Notably, the steep rise in publications after 2020 coincided with the emergence of keywords related to artificial intelligence, fuzzy logic, and optimization techniques, reflecting the growing recognition of nonlinear interactions among fiber chemistry, surface treatment severity, aspect ratio, and durability. Although these data-driven approaches have enhanced short-term property prediction and parameter screening, citation trends indicate that many such studies are exploratory and have limited long-term impact.

Experimental evidence shows that even chemically treated NFRCs may suffer 20–35% tensile strength loss under prolonged moisture exposure or thermal cycling, highlighting persistent gaps in durability modeling, interfacial aging, and industrial qualification. Overall, Figure 3 demonstrates that NFRC research has transitioned from a high-impact, low-volume knowledge formation stage to a high-volume, application-oriented stage, with an increasing reliance on data-driven tools. Therefore, bibliometric trends should not be interpreted as indicators of technological maturity alone. Instead, they underscore the need for integrative, analytical frameworks, such as the fuzzy logic–based synthesis adopted in this review, which connects publication growth with experimentally validated performance thresholds, degradation mechanisms, and application constraints. This perspective enables a more realistic assessment of research progress and highlights durability-centered investigations as a critical yet underrepresented frontier in NFRC development.

2-4-1. Leading researchers

Between 2012 and 2024, the field of lignocellulosic fiber composites has seen significant advancements, largely driven by a group of influential researchers (Figure 4). These experts have made substantial contributions to both scientific knowledge and industrial applications, playing a vital role in driving innovation in the field. Dr. Jawaid M., from Universiti Putra Malaysia, is among the most cited researchers, with over 600 publications and a remarkable citation count of 34,973, highlighting his significant impact. Dr. Sapuan S.M., also from Universiti Putra Malaysia, has published over 1,000 works and earned 34,048 citations, further cementing his importance in the field. Dr. Sanjay M. R., from King Mongkut's University of Technology North Bangkok, ranks third, with 17,010 citations, reflecting his

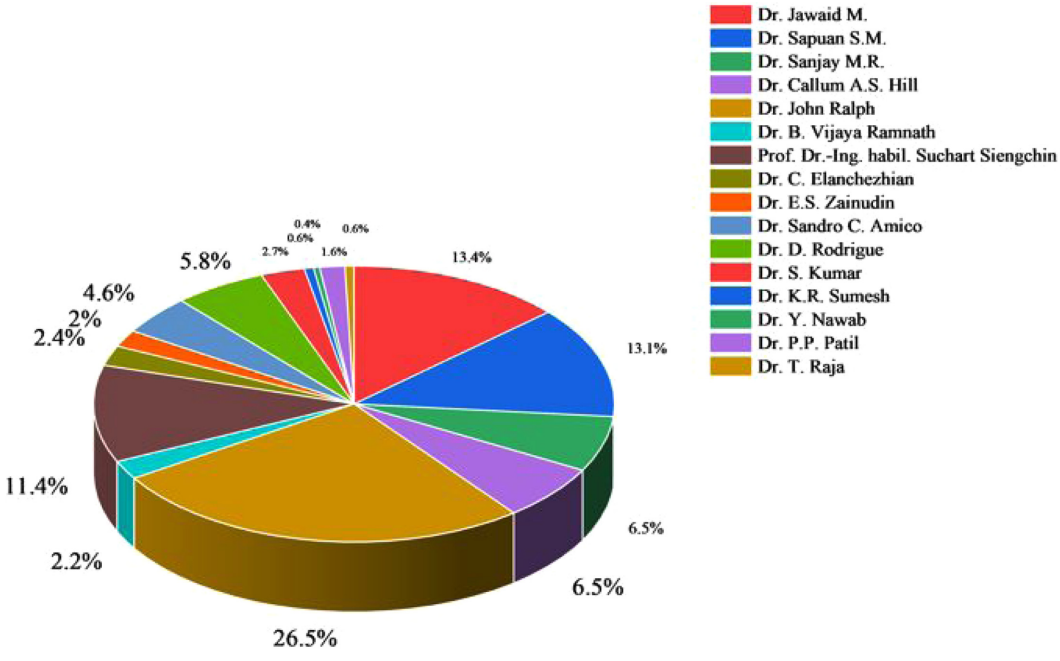

Fig. 4. Leading researchers in lignocellulosic fiber composites.

influential contributions to mechanical engineering and the development of lignocellulosic fiber composites for sustainable materials.

In the field of wood science and fiber modification, Dr. Callum A.S. Hill has made essential contributions, particularly in wood modification techniques and lignocellulosic materials. His research has earned him nearly 17,000 citations by 2024, underscoring his impact in this area. Dr. John Ralph, a prominent figure in lignin chemistry, has also made significant strides. His extensive research, which has garnered over 69,000 citations by 2024, has greatly advanced the understanding of lignin's role in fiber composites, driving both theoretical and practical progress.

Together, the collective efforts of these researchers have greatly advanced the field of lignocellulosic fiber composites, expanding their use across industries like construction, automotive, and aerospace. Their work has helped shape the future of sustainable composite materials, influencing both academic inquiry and industrial practices.

2-4-2. Prominent countries

The global research landscape for lignocellulosic fiber composites has been significantly shaped by various countries, with a strong focus on sustainability and material science innovations. These efforts are closely aligned with the 2030 Agenda for Sustainable Development, which emphasizes the promotion of eco-friendly materials, reducing carbon emissions, and enhancing industrial applications. Over the last decade, several nations have emerged as leaders in this field, driven by policy support, technological advancements, and investments that foster innovation in lignocellulosic fiber composites. The research output from these countries, along with international collaborations and industrial applications, has greatly influenced the development of sustainable composite materials.

India has emerged as the top contributor in lignocellulosic fiber composite research, with 580 published articles, 11,560 citations, and an h-index of 160. The country’s research primarily focuses on utilizing agricultural waste, hybrid composites, and bio-based polymers. Malaysia, with 145 articles, 4,350 citations, and an h-index of 54, has made notable strides in palm fiber composites and biodegradable materials. China, as a key global research hub, has contributed 82 publications, receiving 1,850 citations and an h-index of 26, with a focus on nano-cellulose composites and high-strength fiber reinforcements. Brazil has also made significant progress, publishing 60 articles, garnering 1,650 citations, and an h-index of 20, particularly in bio-composites for packaging and construction.

Saudi Arabia has increased its research output, with 50 articles, 800 citations, and an h-index of 18, concentrating on date palm fiber composites and structural applications. The United States, ranking sixth, has contributed 48 articles, accumulating 1,250 citations and an h-index of 16, excelling in high-performance bio-composites for industrial-scale production. The United Kingdom has maintained a strong research presence with 45 articles, 1,300 citations, and an h-index of 18, focusing on advanced manufacturing techniques and hybrid composites. Ethiopia’s research sector has expanded, with 42 articles, 400 citations, and an h-index of 15, mainly targeting agricultural fiber use in construction. Iran has made valuable contributions with 38 articles, 800 citations, and an h-index of 17, focusing on natural fiber modifications and polymer integration. Italy rounds out the top ten with 35 publications, 1,600 citations, and an h-index of 14, advancing biopolymer composites for aerospace and automotive sectors.

These countries play a crucial role in advancing the science of polymeric composites, with their sustained efforts pushing forward material science in line with global sustainability goals. Through collaborative research, increased funding, and industrial partnerships, progress in lignocellulosic fiber composites is expected to accelerate, supporting greener and more efficient material solutions across industries. As demand for sustainable materials continues to rise, these nations will likely lead the way in addressing challenges in scalability, mechanical performance, and recyclability, reducing reliance on synthetic materials and fostering a more circular economy in composite manufacturing.

2-4-3. The most researched areas

The research landscape for LCF–PHC has grown substantially between 2012 and 2024, as shown in Figure 5, illustrating the multidisciplinary nature of this field. These composites combine principles from various disciplines, such as materials science, engineering, chemistry, and environmental science, positioning them at the forefront of sustainable material development. The spread of research publications across these diverse domains reflects the wide range of expertise contributing to advancements in LCF-PHC. The primary research areas in LCF-PHC include Materials Science, Engineering, Chemistry, Chemical Engineering, Physics, and Environmental Science. The interdisciplinary nature of these composites has resulted in a wide array of scientific contributions.

Materials Science (72.1%) remains the dominant field, focusing on the development, characterization, and enhancement of lignocellulosic fiber composites. Research in this area primarily addresses fiber-matrix interactions, improving mechanical performance, and increasing durability. Engineering (46.8%), which includes mechanical, civil, and aerospace engineering, closely follows. This domain concentrates on the application of LCF–PHC in structural components, automotive manufacturing, and other high-performance industrial applications. Chemistry (22.3%) plays an essential role in understanding the chemical properties of polymer matrices and fiber reinforcements, helping researchers to optimize the composite properties for various uses.

Chemical Engineering (15.7%) significantly contributes by enhancing processing methods, manufacturing techniques, and scaling up production, ensuring efficient material synthesis and overall sustainability. Physics (8.1%) focuses on investigating the mechanical and thermal properties of these composites, supporting improvements in performance and material stability. Environmental Science (6.4%) has become an increasingly prominent field, driven by the sustainable nature of lignocellulosic fiber composites. Research in this domain evaluates the life-cycle impacts, biodegradability, and ecological benefits

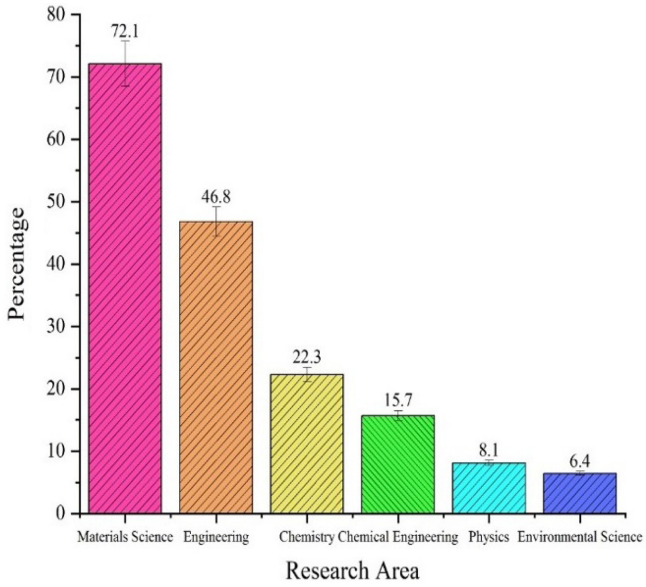

Fig. 5. The most researched areas in lignocellulosic fiber composite research.

of replacing synthetic composites with natural fiber alternatives. This growing interdisciplinary research landscape underscores the broad interest and collaborative efforts aimed at advancing lignocellulosic fiber–based composites for a more sustainable future.

2-4-4. Top contributing countries

Global contributions to LCF–PHC research have been spearheaded by several key nations, each contributing uniquely to the progress of this field. Table 2 provides updated information on the top ten most productive countries based on total publications, h-index, and citation impact. These countries have made significant strides in LCF-PHC research, with India, Malaysia, and China emerging as leaders in terms of total publications and research influence, as illustrated in Figure 6. The growing interest in sustainable composite materials has fostered international collaborations and investments, further accelerating advancements in this area.

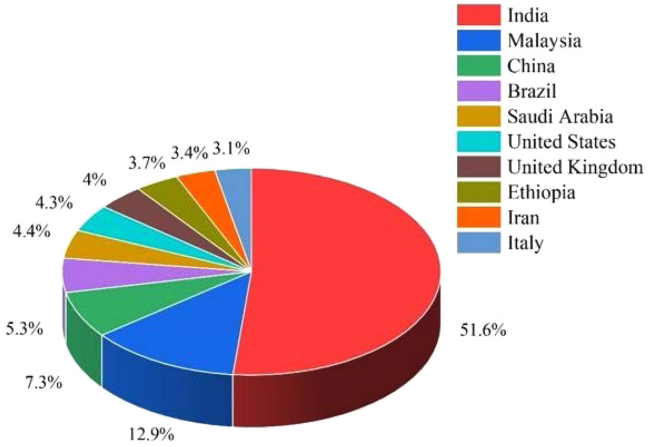

Fig. 6. Top contributing countries in LCF-PHC research.

2-4-5. Most influential research institutions

Institutional contributions are vital in advancing research in LCF-PHC. As shown in Table 3, the leading institutions in this field are ranked based on their total citations and their proportionate share in

Table 2. Top ten countries in LCF-PHC research

Rank	Country	Total Publications (TP)	h-index	Citations	Citations per TP
1	India	580	160	11,560	19.9
2	Malaysia	145	54	4,350	30.0
3	China	82	26	1,850	22.6
4	Brazil	60	20	1,650	27.5
5	Saudi Arabia	50	18	800	16.0
6	United States	48	16	1,250	26.0
7	United Kingdom	45	18	1,300	28.9
8	Ethiopia	42	15	400	9.5
9	Iran	38	17	800	21.1
10	Italy	35	14	1,600	45.7

Table 3. Top ten institutional affiliations in LCF-PHC research

Rank	Institution	Total Citations	% Weightage	Country
1	CNR ITAE	900	18.2%	Italy
2	Department of Ingegneria Civile	900	18.2%	India
3	Department of Mechanical Engineering (Anna University)	580	11.7%	India
4	Department of Mechanical Engineering (Dr. Mahalingam College of Engineering and Technology)	580	11.7%	India
5	Department of Mechanical Engineering (Jawaharlal Nehru Technological University)	580	11.7%	India
6	Department of Mechanical Engineering (Sri Sai Ram Institute of Technology)	420	8.5%	India
7	Department of Mechanical Engineering (Sri Sairam Engineering College)	320	6.5%	India
8	Jawaharlal Nehru Technological University	300	6.1%	India
9	School of Aerospace Engineering and Applied Mechanics	280	5.7%	China
10	School of Materials and Mineral Resources Engineering	270	5.5%	Malaysia

overall research contributions. These institutions are instrumental in driving the development and dissemination of knowledge in lignocellulosic, fiber-based, polymeric, and hybrid composites, underscoring their significant role in fostering innovation and progress in this area.

These institutions have played a pivotal role in advancing lignocellulosic fiber composite research, with Italy and India emerging as prominent contributors. The rising number of publications and citations in LCF–PHC research underscores the growing importance of these materials in sustainable development. As industrial demand for biodegradable, high-performance composites continues to rise, future research efforts are expected to concentrate on:

(a) Improving Mechanical and Thermal Properties: The focus will be on developing stronger, heat-resistant bio-composites suitable for aerospace and automotive applications.

(b) Optimizing Processing Techniques: Innovations in chemical modifications and manufacturing methods will enhance scalability and cost-efficiency.

(c) Sustainability and Circular Economy: Future studies will prioritize recyclability, biodegradability, and life-cycle assessments of LCF–PHC materials.

By encouraging global collaborations and integrating interdisciplinary expertise, researchers and industries can drive the continued advancement of sustainable composite technologies, aligning with the United Nations' Sustainable Development Goals and fostering environmentally responsible manufacturing practices.

2-5. Limitations

While this bibliometric study offers a structured and thorough analysis, there are some limitations to consider, as shown in Table 4. The study primarily used Scopus and Web of Science, which may have excluded relevant research from other databases, like Google Scholar, or institution-specific repositories. Only English-language publications were included, which could have overlooked significant contributions from non-English-speaking research communities. Another limitation is citation lag, as recently published studies with high potential impact may not yet have received enough citations to be recognized as influential. Additionally, patents and industry reports were excluded, even though they may contain valuable insights into the commercial applications and market trends of NFRCs.

This study employs a structured bibliometric approach to offer a detailed exploration of NFRC research, laying the groundwork for future progress in sustainable composite materials. The findings enhance the understanding of the evolution of NFRCs and highlight ways their potential can be better utilized in industrial applications.

2-6. Fuzzy logic–based decision framework for fiber property interpretation

A fuzzy logic–based decision framework was formulated by systematically extracting recurring and experimentally validated relationships reported in the NFRC literature. The purpose of this framework is to qualitatively interpret composite performance trends under varying material and processing conditions rather than to predict absolute property values or replace experimental characterization. Such an approach is particularly suitable for NFRCs, where strong nonlinearity and variability arise from natural fiber heterogeneity, surface chemistry, and processing sensitivity.

The input variables of the fuzzy model were defined using experimentally bounded and physically relevant ranges derived from multiple reported studies: cellulose content (low < 55%, medium 55–70%, high > 70%), surface treatment intensity (untreated, mild = 1–3% NaOH, moderate = 5–8% NaOH, or silane treatment = > 10% NaOH), and fiber aspect ratio (low < 50, medium 50–100, high > 100). These parameters are widely recognized as dominant factors governing stress transfer efficiency, interfacial adhesion, and overall mechanical performance in NFRCs and, therefore, provide a rational basis for rule-based inference.

The output responses of the model include the composite tensile strength, which is typically reported in the range of 30–50 MPa for untreated composites and 55–90 MPa for treated or hybrid systems, and qualitative interfacial bonding quality, which reflects the combined effects of chemical compatibility and surface morphology. Representative fuzzy inference rules, such as "IF cellulose content is high AND surface treatment is moderate, THEN tensile strength is high," are directly grounded in experimental observations, where optimized alkali or silane treatments have been shown to enhance the tensile strength by approximately 20–40%.

Excessive treatment severity has been repeatedly reported to induce fiber damage, reduce load-bearing efficiency, and cause premature failure, highlighting the existence of clear performance thresholds. This fuzzy logic framework captures nonlinear and threshold-dependent behaviors that are difficult to represent using linear regression or purely

Table 4. Summary of data collection and analysis

Parameter	Details
Databases used	Scopus, Web of science
Time frame	2012-2024
Inclusion Criteria	Peer-reviewed articles, conference papers, and review articles.
Exclusion Criteria	Non-peer-reviewed sources, synthetic/inorganic fiber studies, non-English publications
Keywords Used	Natural fiber composites, lignocellulosic composites, mechanical properties, processing techniques, bio-based composites, sustainable polymer composites
Analytical Tools	VOS viewer, Biblioshiny, Microsoft Excel
Key Analyses Performed	Publication trends, citation analysis, journal impact assessment, keyword co-occurrence mapping, collaboration network analysis

statistical methods. By encoding experimentally observed trade-offs, such as the balance between improved interfacial bonding and fiber embrittlement at higher treatment levels, the framework functions as a decision-support tool that synthesizes dispersed experimental evidence into interpretable rules. Accordingly, the fuzzy logic model complements the bibliometric and materials science analyses presented in this review by enabling a structured interpretation of performance trends while explicitly avoiding claims of standalone predictive capability or methodological novelty.

It is positioned as a decision-support and synthesis tool that integrates dispersed experimental evidence into interpretable, rule-based relationships. Critical analyses of data-driven approaches in fiber-reinforced polymer systems consistently show that, while fuzzy logic and ANFIS models can effectively manage uncertainty and sparse datasets, their predictive accuracy is fundamentally constrained by experimental variability and degradation mechanisms that are often excluded from short-term testing.

For example, moisture diffusion and fiber–matrix debonding have been reported to reduce tensile strength retention by 20–40% after prolonged environmental exposure, even in systems that initially show 20–40% strength gains from optimized surface treatments. Such time-dependent degradation effects are not reliably captured by rule-based or machine-learning models trained on static mechanical data. Consequently, in the present review the fuzzy logic framework is deliberately restricted to trend interpretation, enabling analytical understanding of performance thresholds, trade-offs, and research evolution, while avoiding claims of predictive novelty or replacement of experimental validation.

The principal contribution of the fuzzy logic–based framework is its ability to organize dispersed findings from the literature into an interpretable set of conditional relationships between fiber characteristics, processing conditions, and composite performance. Unlike the qualitative review, which discusses individual studies and reported developments, the framework provides a common decision-support structure for examining how combinations of cellulose content, surface-treatment intensity, and fiber aspect ratio may influence tensile performance and interfacial bonding. For example, it highlights the trade-off between improving fiber–matrix adhesion through appropriate surface treatment and potentially reducing fiber integrity under excessive treatment conditions. It also makes explicit that composite performance depends on the combined effects of multiple parameters, rather than on a single material characteristic. Thus, the additional insight is not the prediction of new property values, but the systematic interpretation of relationships, potential performance thresholds, and competing effects reported across different studies. The framework should therefore be regarded as a qualitative synthesis tool that supports comparison and hypothesis generation. Since it has not been independently validated against a dedicated experimental dataset, its inferred relationships should not be interpreted as quantitative predictions or definitive rankings of composite systems.

3. Properties of Natural Fibers

3-1. Mechanical and thermal properties

Natural fibers like flax, hemp, jute, and sisal are well-known for their impressive strength-to-weight ratios, making them excellent reinforcements for polymer matrices. The mechanical properties of these fibers are influenced by factors such as fiber composition, microstructure, and cellulose content [28]. The tensile strength, Young's modulus and flexural strength of these fibers can vary significantly depending on cultivation conditions, extraction methods, and fiber treatments as well as dependent on fiber content and matrix compatibility [29]. For example, flax fibers, known for their high cellulose content and low microfibrillar angles, exhibit tensile strengths between 500 and 1500 MPa and Young's moduli ranging from 27.6 to 70 GPa [30,31].

Hemp fibers show tensile strengths between 550 and 900 MPa and moduli around 70 GPa, positioning them as a strong alternative to synthetic fibers [32]. Jute fibers, commonly used in industrial settings, have tensile strengths from 200 to 450 MPa, with Young's moduli between 20 and 55 GPa [33]. Sisal fibers, suited for medium-load applications, demonstrate tensile strengths between 468 and 700 MPa and moduli ranging from 9 to 28 GPa [34].

A comparison of these mechanical properties is summarized in Table 5, which illustrates the fiber content with respect to the variation in tensile strength, Young's modulus, and flexural strength across different natural fiber types, serving as a useful reference for selecting fibers based on specific mechanical needs in composite applications. Thermal properties are also crucial for determining the suitability of natural fibers in high-temperature environments.

Most natural fibers begin to degrade between 200°C and 300°C, due to the breakdown of hemicellulose and cellulose. Whereas, in case of utilizing the agro-industrial by product (date trunk fiber) for producing bio-derived composite, holding high thermal stability with minimum loss at 270°C. Flax and hemp fibers exhibit better thermal stability compared to jute and sisal, making them more suitable for thermally demanding applications [35]. However, the addition of fire retardants and hybridization techniques can further improve the heat resistance of natural fiber composites.

Table 5. Comparison of mechanical properties of selected natural fibers

Fiber Type	Fiber Content (wt%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Flexural Strength (GPa)	Reference
Flax	50	500–1500	27.6–70	5.80	[27, 28]
Hemp	50	550–900	~70	4.6	[29]
Jute	40	200–450	20–55	6.2	[30]
Sisal	50	468–700	9–28	3.4	[31, 32]

3-2. Moisture absorption and durability

A major limitation of natural fibers is their tendency to absorb moisture, which can negatively impact the durability and mechanical stability of composites. The hydrophilic nature of these fibers leads to issues such as dimensional swelling, fiber–matrix debonding, and degradation from microbial activity. The primary cause of moisture absorption is the hydroxyl groups in cellulose, which have a strong affinity for water molecules. To address these challenges, several chemical treatments have been explored to modify fiber surface properties and improve fiber-matrix adhesion. One of the most common methods is alkali treatment, or mercerization, where fibers are treated with sodium hydroxide (NaOH) to remove surface impurities, increase surface roughness, and enhance fiber–matrix interaction. Studies have shown that alkali-treated fibers exhibit improved mechanical properties and reduced moisture absorption due to better bonding with the polymer matrix [36].

Another widely used technique is silane treatment, which involves applying silane coupling agents that form covalent bonds between the fiber and the polymer matrix. This improves interfacial bonding and imparts hydrophobicity to the fiber surface. Research has shown that silane-treated fibers have lower water uptake and better durability in composite materials [37].

Acetylation is also a promising modification method, where the hydroxyl groups in the fibers react with acetic anhydride to form ester bonds, reducing hydrophilicity. Acetylated fibers are known to have enhanced water resistance, improved compatibility with hydrophobic polymers, and better dimensional stability [38]. The bio based composite provides a better retention of moisture during packing of the material, but this composite are preferable for food preservation wrapping. In conclusion, combining fiber surface treatments with optimized processing techniques can significantly improve the performance and longevity of natural fiber composites, making them more suitable for a variety of engineering applications.

3-3. Formulation of fuzzy logic model

The analytical study was carried out by a fuzzy logic system to possibly predict the mechanical properties of different natural fibers. Based on the fuzzy main four components such as Fuzzification Interface, Knowledge Base, Decision – Making Logic, and Defuzzification Interface, determine the maximum to minimum. This proposed model from the author has extremely utilized for validating the parameters, followed by analyzing the mechanical properties of the fiber for producing accurate results. The validation of data by fuzzy rulesets were shown in Table 6, which was produced through fuzzy logic model, as mentioned by the author. These results show that the mechanical properties of jute fiber impacted with high performance composite materials, which promotes wider applications in aerospace industries. Table 6 illustrates the fuzzy rules for data derivation of polymer composite analysis.

Table 6. Characterization data derived from fuzzy rulers

Fuzzy Rule No.	Jute Fiber (Wt%)
01	1.62
02	2.17
03	2.79
04	5.62
05	5.80
06	5.79
07	8.98
08	9.69
09	9.25

4. Surface Treatment of Fibers for Improved Bonding

4-1. Treatment with Alkali

In recent years, there has been a growing focus on enhancing the interfacial bonding between natural fibers and polymer matrices in composite materials. One of the most extensively studied techniques is alkaline treatment, also known as mercerization. This process involves immersing lignocellulosic fibers in a NaOH solution, which removes surface impurities, such as waxes, oils, and lignin, that hinder bonding with the polymer matrices. The key mechanism behind this treatment is the saponification of ester bonds in lignin and hemicellulose, which increases surface roughness and improves fiber-matrix adhesion [39].

NaOH surface treatment offers a narrow processing window, where fiber performance is improved before degradation begins. Mild to moderate alkali treatment in the range of 4–6 wt.% NaOH reliably removes hemicellulose and surface impurities, increasing cellulose crystallinity by 15–25% and reducing microfibril angle, which promotes stronger stress transfer [40]. Hemp/PP composites treated with 5% NaOH demonstrated tensile strength increases from 42 MPa to 63–68 MPa and stiffness gains of nearly 30%, while Sisal/Epoxy laminates showed a similar 22–35% strength improvement, accompanied by a 40–60% drop in water absorption [41,42]. These gains are reinforced by thermal analysis, where onset decomposition temperatures increase from 215–230°C up to 260–275°C, reflecting improved fiber stability.

However, studies report that treatment above 8–10 wt% NaOH begins to collapse cell walls and strip structural lignin, resulting in reduced elongation (15–25%), matrix debonding, and performance decay. In severe cases, initially high-strength laminates lose 30–35% tensile strength after 30–60 days of moisture exposure or thermal cycling, confirming that over-treatment accelerates damage mechanisms rather than strengthening the composite [40,43].

The effectiveness of alkaline treatment depends on several factors, such as NaOH concentration (typically ranging from 1% to 10%) [40], treatment duration (from a few minutes to several hours) [41], and processing temperature [42]. Research consistently shows that alkaline-treated fibers demonstrate improved mechanical properties, including higher tensile strength, flexural strength, and impact resistance

compared to untreated fibers [43]. The removal of non-cellulosic components enhances surface roughness, which increases mechanical interlocking and chemical bonding with the polymer matrix. Moreover, alkaline treatment reduces moisture absorption, an important factor for maintaining mechanical integrity in humid environments [44]. These threshold-sensitive outcomes strongly support the use of fuzzy logic in NFRC evaluation because treatment–property relationships do not change linearly. The same chemical modification can either improve or degrade composite performance depending on concentration, fiber type, and exposure history, meaning performance zones are better represented by linguistic rules (“low”, “optimum”, “excessive”) than by single-valued equations.

4-2. Treatment with Silane

Another widely studied method for improving fiber-matrix compatibility is silane treatment. Silane coupling agents have dual functionality, allowing them to bond hydrophilic fibers with hydrophobic polymer matrices. These agents undergo hydrolysis to form silanol groups, which then bond with hydroxyl groups on cellulose fibers. This process improves fiber dispersion, adhesion, and overall composite durability [45]. The treatment process includes hydrolysis, condensation, and grafting. During hydrolysis, silane monomers react with water, forming silanol groups while releasing alcohol byproducts [46]. Silane coupling offers a strong adhesion mechanism by enabling covalent bonding between hydroxyl groups on natural fibers and the polymer matrix, and its effect is strongly concentration-dependent.

Across multiple systems, 1–3 wt% silane consistently enhances interfacial shear strength by 30–55%, accompanied by tensile strength gains of 20–35% in flax-, ramie-, and hemp-based epoxy composites. Ramie/epoxy laminates treated with 2% γ-APS silane showed tensile strength improvements from 120 MPa to 158–165 MPa and a 50% increase in interlaminar shear strength due to stronger interfacial continuity (SEM studies showed complete removal of surface waxes and tighter matrix wrapping) [45, 46]. Similarly, jute–epoxy systems reported 40% interfacial shear strength improvement, with glass transition temperature shifting upward by 5–8°C, confirming improved fiber–matrix coupling [46,47].

Thermal analysis further supports this efficiency window: Silane-treated fibers display increases in onset decomposition temperature from 225–240 °C to 260–280 °C, and in some epoxy systems, char residue rises by 10–15 wt%, indicating enhanced microstructural stability and delayed thermal degradation. However, above 3–5 wt%, studies report diminishing returns, with unreacted silane residues forming weak interphases, leading to microcracking and moisture-assisted debonding.

Excess Silane has been linked to 10–20% post-aging strength decline under accelerated humidity exposure, confirming that surface coupling efficiency plateaus beyond optimal loading. Upon heating, these interactions form covalent Si–O–C bonds, which strengthen the fiber–matrix interface and enhance mechanical performance [47]. Silane-treated fibers exhibit superior moisture resistance and durability, making them ideal for high-performance applications in industries like automotive and aerospace [48].

4-3. Treatment with Esterification

Estherification is another effective chemical modification method aimed at improving fiber-matrix adhesion by reducing the hydrophilic nature of natural fibers. This process replaces hydroxyl (-OH) groups on fibers with carboxyl (-COOH) groups, which impart hydrophobic properties and enhance compatibility with polymer matrices [49]. Natural fibers contain hydroxyl groups in cellulose, hemicellulose, and lignin, which are responsible for their high moisture absorption. Esters address this by converting these reactive groups into hydrophobic acetyl groups, reducing water uptake and improving dimensional stability [50]. The process primarily targets hemicellulose and lignin, as cellulose's crystalline structure is less reactive.

Methanol is commonly used as the acetylating agent due to its efficiency in facilitating this transformation [51]. Acetylation and maleated coupling demonstrate a similar “processing window” to alkali treatment, where performance peaks at moderate reagent loading and exposure time. At optimized conditions, typically achieved with 5–10 wt% acetic anhydride or 3–5 wt% maleated coupling, esterified fibers show substantial reductions in surface hydroxyl content, producing 20–40% decreases in water uptake and 30–55% reductions in swelling strain, as reported for rice-husk and wood fiber systems. These chemical changes translate to significant mechanical improvements: acetylated jute/PP composites exhibit tensile strength gains from 48 MPa (untreated) to 60–68 MPa, while acetylated wood–PLA and bamboo–PP systems show stiffness increases of 25–45%, accompanied by a 10–20°C increase in glass-transition temperature (T_g) and improvements in thermal decomposition onset from 245°C to 270–290°C.

The FTIR and XRD analyses confirm these enhancements are linked to increased cellulose accessibility and stronger covalent bonding, rather than physical cleaning alone [49,50]. However, similar to NaOH, over-functionalization reduces performance. Excessive acetic anhydride (>12–15 wt%), prolonged reaction (>3 h), or high catalyst loading progressively disrupts cellulose molecular integrity, reducing crystallinity by 8–12%, lowering elongation at break (−20–30%), and accelerating interfacial cracking under cyclic stresses. Long-term durability evaluations show that aggressively esterified sisal and bamboo laminates lose 25–40% tensile strength after 30–90 days of wet–dry cycling, highlighting that hydrophobization alone cannot prevent moisture-induced microcracking once fiber walls become embrittled [51,52].

Esters improve fiber-matrix interlocking, resulting in composites with superior mechanical strength and environmental resistance. Acetylated fibers are widely used in industries such as automotive, construction, and packaging, where moisture resistance and mechanical durability are critical [52]. Performance outcomes depend not only on the treatment chemistry, but also on concentration, exposure duration, and fiber type, meaning composite gains fall into discrete

performance regimes: “insufficient,” “optimal,” and “over-treated.” This threshold behavior explains why esterification features strongly in bibliometric growth after 2018; its promise lies in balancing hydrophobicity and fiber integrity, a balance that rule-based fuzzy logic can capture more realistically than predictive equations.

4-4. Treatment by Enzyme

Enzymatic treatment has also emerged as a sustainable and eco-friendly method for modifying natural fibers for composite applications. Unlike chemical treatments, which often involve hazardous substances, enzymatic treatments utilize biological catalysts, such as cellulases, amylases, and proteases, to modify fiber surfaces under mild conditions [53]. A key advantage of enzymatic treatment is its ability to selectively degrade unwanted fiber components while preserving the cellulose structure.

For example, cellulase enzymes break down amorphous cellulose regions, increasing fiber surface roughness and improving adhesion to polymer matrices. Additionally, enzymatic treatment removes waxes and pectins, enhancing fiber wettability and bonding potential [54]. Moderate enzyme exposure typically 3–5 wt.% aqueous formulations with cellulase, pectinase, or amylase, has been shown to produce measurable gains in fiber–matrix compatibility.

Coir/PLA laminates treated with 5% amylase demonstrated steep mechanical improvements, with tensile strength increasing from 12–14 MPa for untreated composites to 55–60 MPa (+350–400%), and bending strength rising threefold, alongside a doubling in impact strength, due to enhanced interfacial shear transfer and fiber pull-out resistance. Similar magnitudes were observed in enzymatically retted hemp systems, where pectinase–xylanase mixtures increased fiber fineness, reduced bundle size, and increased single-fiber failure stress by 25–32%, while improving composite stiffness by 20–30% under PP matrices, confirming the microstructural role of matrix wetting and mechanical anchoring. Thermal and moisture behavior likewise improved within this treatment window.

Enzyme-conditioned fibers exhibit onset degradation temperatures that increase by 15–25°C, reflecting improved thermal stability and removal of thermally labile fractions, while water absorption reductions between 20–45% have been reported relative to untreated counterparts an effect linked to reduced hydroxyl-rich amorphous regions. However, exceeding optimal exposure thresholds (>6–8 wt.% enzyme concentration or prolonged treatment beyond 3–5 hours) results in cellulose chain scission and decreased crystallinity, manifesting as reductions in elongation at break by 15–20%, stiffness losses approaching 10–15%, and ultimate tensile strength declines of 10–25% depending on fiber species and matrix.

In accelerated aging assessments, enzyme-overprocessed coir and hemp composites showed up to 20–30% strength loss after cyclic humidity or thermal exposure, indicating that enzymatic hydrolysis of amorphous regions can undermine durability when overtreatment occurs [55]. However, excessive enzyme exposure can lead to fiber damage and reduced mechanical integrity. Therefore, optimizing enzymatic treatment parameters, such as enzyme concentration, reaction time, and temperature, is crucial to achieve the right balance between fiber purification and preservation [56]. Enzymatic treatments align with the global push for sustainable material processing by reducing chemical waste and energy consumption. Future research is expected to focus on tailoring enzyme formulations to achieve specific fiber modifications while minimizing environmental impact [57]. Table 7 shows the comparison analysis of various surface treatments used for natural fiber composites.

These outcomes confirm that enzyme treatments share the same processing-window constraint observed in alkali modification: substantial gains emerge only at moderate severity. Importantly, enzyme-treated systems demonstrate heightened sensitivity to interaction effects, treatment time, enzyme type, fiber chemistry, and matrix polarity, which vary across lignocellulosic sources. As such, enzyme treatment embodies a high-reward but high-specificity strategy, where strength gains are fundamentally limited by the preservation of native cellulose

Table 7. Comparison of surface treatment methods for enhancing fiber-matrix bonding in natural fiber composites

Treatment Method	Mechanism	Key Benefits	Limitations	Common Applications	References
Alkali Treatment (Mercerization)	Removal of surface impurities (waxes, oils, lignin) *via* NaOH, increasing surface roughness and improving adhesion	- Enhanced mechanical properties (tensile, flexural, impact strength) - Reduced moisture absorption - Better fiber-matrix interlocking	-Over treatment can weaken fibers - Involves strong chemicals (NaOH)	Aerospace, automotive, construction	[42, 43, 44]
Silane Treatment	Silane coupling agents bond hydrophilic fibers to hydrophobic matrices by forming Si-O-C bonds	- Improved fiber dispersion and adhesion - Superior moisture resistance - Higher composite durability	- High cost of silane agents - Requires controlled processing conditions	High-performance composites in aerospace and automotive	[46, 47, 48]
Acetylation	Replaces hydroxyl (-OH) groups with acetyl (-$COCH_3$) groups, making fibers more hydrophobic	- Reduced moisture absorption - Better dimensional stability - Enhanced environmental resistance	- Incomplete acetylation may not fully improve adhesion - Requires specialized chemicals (acetic anhydride)	Automotive, packaging, construction	[49, 50, 51, 52]
Enzymatic Treatment	Use of biological catalysts (cellulases, amylases, proteases) to selectively modify fiber surfaces	- Eco-friendly and sustainable - Preserves cellulose structure - Reduces chemical waste	- Requires precise control of enzyme concentration and reaction time - Over-treatment may damage fibers	Green composite applications, textiles, bioplastics	[53, 54, 55, 56, 57]

integrity, establishing clear thresholds that can be encoded into the fuzzy-logic ruleset employed later in this review ("IF enzyme intensity is moderate, THEN bonding is high; IF excessive, THEN durability decreases").

Across a wide range of lignocellulosic composites, optimized alkali treatment at approximately 5–6% NaOH consistently increases cellulose crystallinity, from 30–45% in untreated fibers to above 55–60%, while simultaneously reducing the amorphous hemicellulose content. These structural changes were accompanied by a clear thermal response, with the onset of thermal degradation shifting from 200–230°C to 260–280°C and peak degradation temperatures exceeding 350°C in treated bamboo, Derris scandens, and Pennisetum-based fibers. At the composite level, these microstructural improvements translated into 18–35% gains in tensile strength, with representative kenaf/epoxy systems reaching strengths of 55–60 MPa under optimized treatment, alongside improved strength retention under cyclic loading and moderate thermal exposure. However, experimental evidence has consistently revealed a critical upper threshold.

Aggressive chemical treatments exceeding 8–10% NaOH concentration induce fibrillation, lumen collapse, and excessive fiber swelling, leading to reduced elongation at break and premature interfacial debonding of the fibers. Consequently, even initially high-strength laminates can experience a 30–35% tensile strength loss after prolonged moisture exposure or thermal cycling, highlighting the dominance of degradation-driven failure mechanisms over short-term strength enhancement. This constraint-driven behavior explains why NFRC deployment has expanded primarily into semi-structural and functional components, such as automotive interior panels, packaging boards, vibration-damping elements, and thermal–acoustic insulation, rather than fully load-bearing structures.

Hybridization strategies further reinforce this trend. Natural–synthetic hybrids and particle-assisted systems, including SiO_2-filled PALF/sisal composites, typically exhibit tensile strengths of 50–55 MPa, flexural strengths exceeding 60 MPa, wear reductions of approximately 8–12%, and improved dimensional stability. However, these systems remain sensitive to environmental aging, particularly when subjected to combined moisture and thermal stress. These findings confirm that NFRC performance optimization is no longer dictated by strength maximization alone but by a multi-objective trade-off among interfacial bonding, durability, and process scalability.

5. Processing Techniques

5-1. Compression molding

Compression molding (Figure 7) is a widely used method for fabricating NFRCs, known for producing high-strength components with minimal defects. In this process, a measured blend of natural fibers and a polymer matrix is placed into a heated mold cavity. When the mold is closed, heat and pressure are applied, allowing the material to take the desired shape and enabling the polymer to cure, resulting in a consolidated composite part. The quality of NFRCs produced by compression molding is influenced by several key parameters:

(1) Molding temperature: It is critical to optimize the temperature to ensure proper polymer flow and curing without damaging the natural fibers. Studies show that correct temperature settings are vital for achieving the desired mechanical properties in short, natural fiber-reinforced polymer composites [58].

(2) Compression Pressure: Proper pressure is necessary to remove voids and ensure good fiber–matrix bonding. Research indicates that pressure plays a significant role in the composite's performance, with insufficient pressure leading to poor adhesion between fibers and matrix [59].

(3) Holding Time: The duration for which temperature and pressure are maintained affects the curing process and the composite's final properties. Studies emphasize that optimizing holding time is important to balance both production efficiency and material performance [41].

Optimizing these parameters is essential for enhancing the mechanical properties of NFRCs. For example, adjusting compression molding conditions, as shown in Figure 6, has been found to significantly

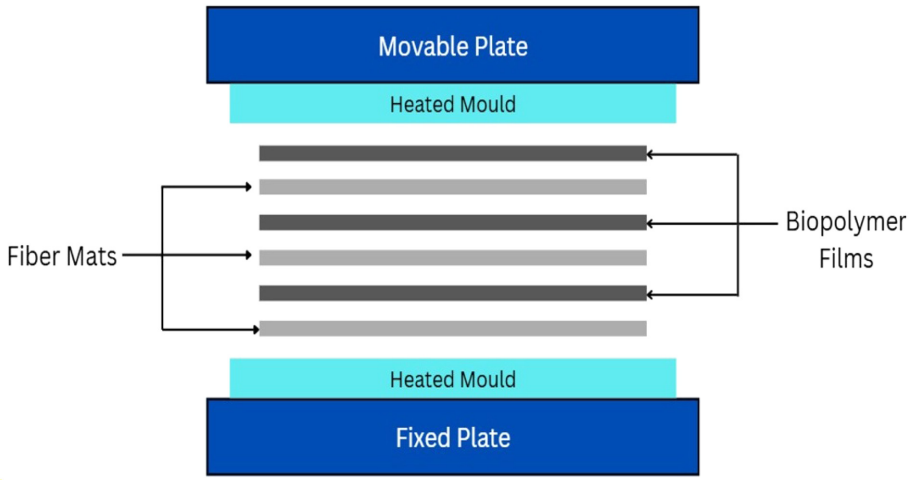

Fig. 7. Schematic representation of compression molding.

improve the tensile properties of natural fiber-reinforced polymer composites [60]. Additionally, the natural variability in fibers, such as differences in moisture content and fiber morphology, requires careful control of processing conditions. Understanding the unique characteristics of each fiber type is crucial for tailoring the compression molding process to achieve optimal composite performance [61,62]. In conclusion, compression molding is an efficient and versatile method for producing NFRCs. By carefully controlling processing parameters and accounting for the natural variability of fibers, manufacturers can create composites that meet high-performance standards for various applications.

5-2. Injection molding

Injection molding is a widely used technique for large-scale production of NFRCs, favored for its efficiency, repeatability, and ability to produce complex shapes with minimal material waste. In this process, a polymer matrix is melted and combined with natural fibers before being injected into a mold under high pressure. Once the material cools and solidifies, the composite part is ejected from the mold. Injection molding allows for precise control over the dimensions and properties of the composite, making it a popular choice for manufacturing automotive parts, consumer goods, and industrial components [63].

Its ability to ensure uniform fiber dispersion within the polymer matrix results in consistent mechanical properties across the composite. However, the high shear forces and elevated temperatures during processing can lead to fiber degradation, which can impact the final product's mechanical performance. Research has shown that natural fibers, like flax and hemp, can undergo thermal decomposition when exposed to temperatures above 200°C, limiting the selection of polymer matrices to those with lower processing temperatures, such as polypropylene and polyethylene [64]. To reduce fiber degradation, several strategies have been explored, including:

(i) Optimizing Processing Parameters: Adjusting the injection speed, pressure, and temperature can minimize fiber damage while maintaining strong fiber-matrix bonding [65].

(ii) Surface Treatments and Compatibilizers: Adding coupling agents like maleic anhydride grafted polymers enhances adhesion between the fibers and the matrix, improving mechanical properties and reducing thermal degradation [66].

(iii) Hybridization with Synthetic Fibers: Incorporating small amounts of synthetic fibers, such as glass or carbon, can boost the composite's strength and heat resistance without compromising its sustainability [67].

A notable challenge in injection molding NFRCs is moisture absorption by the natural fibers, which can lead to void formation and poor interfacial bonding during processing. Pre-drying the fibers before processing is a common solution to address this issue and enhance composite quality [68]. Additionally, the length of the fibers significantly affects mechanical performance, while shorter fibers improve processability, longer fibers offer better reinforcement and toughness [69]. Recent studies show that properly optimized injection molding conditions can yield NFRCs with mechanical properties comparable to traditional synthetic composites. For instance, research on hemp fiber–reinforced polypropylene composites found that adjusting processing conditions improved tensile strength by up to 25%, while maintaining good thermal stability [70]. In conclusion, injection molding remains a promising method for producing NFRCs, especially for high-volume manufacturing. While challenges like fiber degradation and moisture absorption exist, advancements in processing techniques and material modifications continue to enhance its potential in sustainable composite production.

5-3. Hand-casting method

This method is one among the important techniques with respect to twin-screw extrusion or injection molding. While processing the natural fiber, this method holds better control over mixing and distribution of fibers. It is one of the cost effective methods providing only limited resources for large scale production. It is mainly applicable for small scale production.

5-4. Film Stacking

It is a kind of fabrication technique widely used in the processing of natural fibers, providing specific process parameters which extensively influence the performance of mechanical properties. Parameters like pressure and temperature play a vital role in enhancing the quality of composite material produced from natural fibers. Similarly, other variables like molecular weight of polymer and its structural morphology are also dealt in a controlled manner.

6. Applications of Natural Fiber Composites

6-1. Automotive industry

The NFRCs are becoming increasingly essential in the automotive industry due to their lightweight, sustainable nature, and favorable mechanical properties. These composites are widely used in vehicle interiors, such as door panels, dashboard components, seat backs, and headliners, replacing traditional synthetic materials [71]. The use of NFRCs contributes significantly to vehicle weight reduction, which improves fuel efficiency and reduces emissions. European car manufacturers have adopted these composites for various interior parts, recognizing their advantages in sustainability and weight reduction [72,73]. The polymer composites will be suitable alternatives to other materials used in industries. The different types of polymers are GFRPs – glass fiber-reinforced polymers, CFRPs – carbon fiber-reinforced polymers, hold light weight. The CFRPs possess 1500 MPa as a tensile strength and 1800 MPa as flexural strength.

The global market for natural fiber composites is experiencing strong growth, with estimates predicting it will reach USD 18.65 billion by 2030, growing at a compound annual growth rate of 12.0% from 2025 to 2030. This growth is driven by the automotive sector's increasing demand for eco-friendly, lightweight materials [74]. Fibers

like hemp, flax, jute, and sisal are favored due to their high strength-to-weight ratios and renewability, aligning with the industry's sustainability goals [75].

Incorporating NFRCs not only helps reduce vehicle weight but also provides cost benefits. These composites can lower production costs due to the reduced need for synthetic materials and the potential for more straightforward manufacturing processes [76]. Additionally, natural fibers offer excellent acoustic and thermal insulation, which enhances passenger comfort [77]. However, issues like moisture absorption and variability in fiber properties require continued research to optimize composite formulations and processing techniques. The automotive industry's ongoing commitment to sustainability and performance continues to drive the use of natural fiber composites in vehicle design, paving the way for greener, more efficient transportation solutions [78].

6-2. Aerospace sector

The aerospace industry is constantly seeking advanced materials to improve fuel efficiency, structural performance, and reduce environmental impact. The NFRCs have emerged as a promising alternative due to their lightweight nature, sustainability, and excellent mechanical properties. These materials are being considered for use in interior cabin components, seat backs, sidewall panels, and other non-load-bearing aircraft structures. The shift toward NFRCs is driven by the need to replace traditional synthetic fiber composites with more eco-friendly, biodegradable alternatives. One of the main advantages of NFRCs in aerospace is their exceptional strength-to-weight ratio, which helps reduce the overall weight of aircraft. Studies have shown that NFRCs offer tensile and flexural properties comparable to traditional fiberglass composites while providing improved damping characteristics that reduce noise and vibrations in the cabin, enhancing passenger comfort [79,80].

Furthermore, NFRCs demonstrate excellent impact resistance, making them suitable for safety-critical applications in aviation. When incorporating NFRCs into aerospace structures, thermal stability and flame resistance must be carefully considered. To meet stringent fire safety regulations, researchers have explored various chemical modifications, such as flame-retardant treatments and hybrid composite approaches [81]. The addition of intumescent flame-retardant coatings and nanoclays has significantly improved the fire performance of NFRCs, making them viable for use in aircraft interiors. NFRCs also exhibit promising behavior under dynamic loading conditions, making them ideal for applications where energy absorption and crashworthiness are important. Studies have shown that flax and hemp fiber-reinforced composites provide excellent energy absorption in simulated impact scenarios, making them potential candidates for aerospace structural reinforcements (Figure 8).

Another important factor for aerospace applications is the resistance of NFRCs to environmental factors like humidity and UV exposure. While natural fibers are prone to moisture absorption, which can lead to degradation, surface treatments such as acetylation and silane coupling have been used to improve their durability [82]. These treatments enhance fiber–matrix adhesion, reduce moisture uptake, and prolong the service life of NFRC-based components. Despite these advancements, challenges remain in integrating NFRCs into primary aerospace structures [83]. Variability in natural

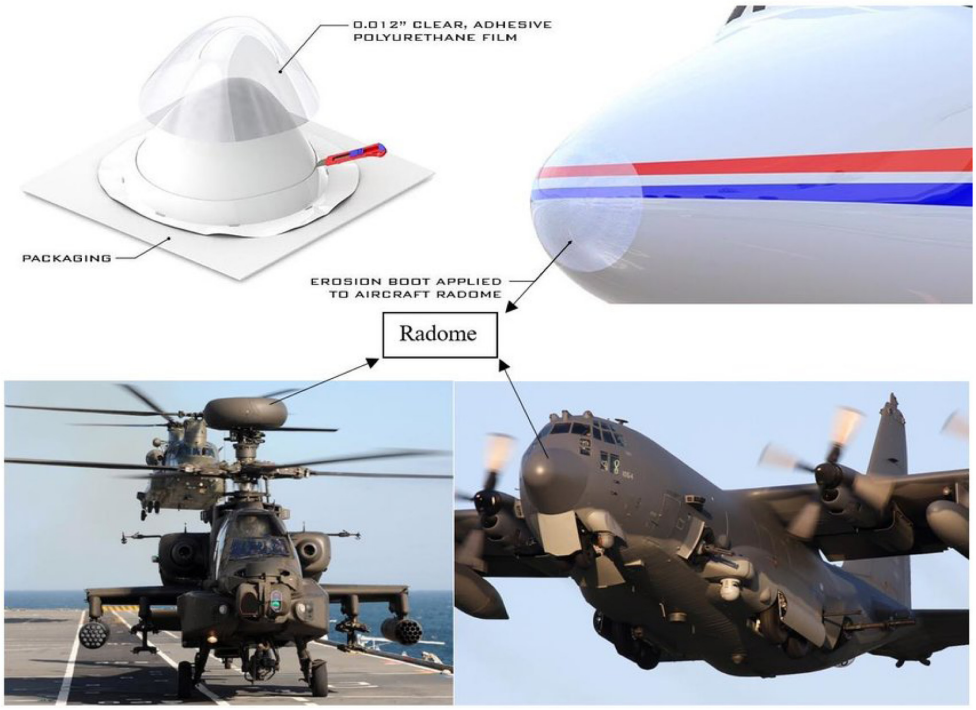

Fig. 8. Natural fiber composite applications in aerospace industries.

fiber properties and limitations in standardization and certification processes have hindered widespread adoption. Ongoing research is focused on optimizing fiber processing, hybridizing NFRCs with synthetic fibers, and developing predictive models to assess long-term performance in aerospace environments. Overall, NFRCs offer a viable and sustainable solution for various non-structural aerospace applications. Their lightweight properties, energy absorption capabilities, and environmental benefits position them as key materials for the next generation of eco-friendly aircraft designs.

6-3. Packaging and construction

Growing environmental concerns about plastic waste and carbon emissions have spurred research into sustainable materials, positioning NFRCs as promising alternatives in industries like packaging and construction. These composites offer an ideal combination of mechanical strength, biodegradability, and sustainability, making them attractive for various applications [84]. Biodegradable and compostable packaging materials made from NFRCs are increasingly being used as eco-friendly substitutes for petroleum-based plastics. Reinforced with fibers like jute, kenaf, and flax, these composites are strong, durable, lightweight, and biodegradable [85]. Research has shown that cellulose-based NFRCs possess excellent barrier properties against oxygen and moisture, making them particularly suitable for food packaging applications.

Hemp fiber–reinforced polylactic acid composites provide superior biodegradability and mechanical performance, making them a viable option for packaging. Additionally, coir and banana fiber composites have demonstrated significant potential due to their antimicrobial properties and ability to withstand various environmental conditions, making them ideal for biodegradable food trays and storage containers. In recent years, the automated processing of NFRC-based packaging materials has also been explored. Techniques such as injection and compression molding have been adapted to manufacture biodegradable films, trays, and containers that maintain high structural integrity while ensuring sustainable end-of-life disposal options.

In the construction sector, NFRCs are being used in structural panels, roofing, wall insulation, and reinforcement materials, reducing the dependence on synthetic fibers and non-renewable resources. Natural fibers like hemp, kenaf, and coir are widely incorporated into cement-based composites, fiberboards, and insulation panels due to their low thermal conductivity, fire resistance, and moisture control properties. One study demonstrated that flax fiber–reinforced composites provide excellent thermal insulation and load-bearing capacity, making them a viable choice for sustainable housing materials [86,87]. Similarly, bamboo fiber composites have been integrated into prefabricated housing panels because of their high flexural strength and eco-friendly nature.

NFRCs also contribute to energy efficiency in buildings. Research has shown that coconut coir and jute fiber composites can effectively reduce heat transfer, lowering energy consumption for heating and cooling. Furthermore, their ability to regulate humidity and moisture absorption makes them valuable materials for green building initiatives [88]. The use of oil palm empty fruit bunch fiber in rigid polyurethane foam composites has also been reported to improve insulation properties by 9.95%, leading to energy cost reductions of up to 0.78 kWh/m^2 and 0.031 kWh/m^2 compared to conventional wall materials made of concrete and wood, respectively [89,90]. With advancements in chemical and physical treatments, the durability and resistance of NFRCs to environmental degradation have significantly improved [91,92]. Hybrid fiber-reinforced composites are now being developed to enhance fire resistance and water repellency, broadening their potential applications in modern construction projects.

7. Conclusion

The research landscape of lignocellulosic, fiber-based polymeric, and hybrid composites has seen remarkable expansion from 2012 to 2024, driven by contributions from multiple disciplines, including materials science, engineering, chemistry, and environmental science. Global research productivity analysis reveals that India, Malaysia, and China are at the forefront of these advancements, with a strong focus on sustainability, improving mechanical performance, and advancing industrial applications. Leading research institutions have played a key role in advancing the field, driving innovation in composite

Table 8. Application sectors, potential benefits, and challenges of lignocellulosic fiber-reinforced polymer composites

Application sector	Representative applications	Potential benefits	Key challenges	Related references in the manuscript
Automotive	Interior panels, door panels, dashboards, seat backs, headliners, and acoustic/thermal components	Reduced component weight, renewable reinforcement, and potential improvements in fuel efficiency	Moisture sensitivity, long-term durability, variation in fiber properties, and manufacturing consistency	[53, 60, 85, 86]
Aerospace	Cabin interiors, sidewall panels, seat backs, and selected non-load-bearing components	Lightweight design and potential reduction in environmental impact	Fire, smoke and toxicity requirements, environmental ageing, and application-specific certification	[53, 82, 85, 86]
Construction	Building panels, roofing, insulation, fiberboards, and housing components	Renewable reinforcement, reduced material density, and thermal/acoustic insulation potential	Water absorption, dimensional stability, fire resistance, and long-term weathering	[68–73, 76]
Packaging	Bio-based films, trays, containers, and fiber-reinforced packaging composites	Potential reduction in dependence on conventional packaging materials and renewable material content	Moisture and barrier performance, scalability, and end-of-life management	[64–66, 80]

processing, fiber–matrix interactions, and the development of eco-friendly materials. Materials Science remains the dominant research area, underscoring its critical role in the development and characterization of lignocellulosic fiber composites. Engineering disciplines have made significant contributions by optimizing the practical applications of these composites in sectors such as automotive, aerospace, and construction. Chemistry and Chemical Engineering have focused on refining material properties, while Environmental Science has gained increasing attention, reflecting the rising importance of sustainability, biodegradability, and circular economy principles. The growing research interest and industrial demand for LCF–PHC point to a promising future for bio-composites in diverse applications. Nevertheless, challenges related to scalability, recyclability, and cost-efficiency must be addressed to facilitate broader adoption. Future research will likely center on improving mechanical and thermal properties, refining processing techniques, and reinforcing sustainability through advanced life-cycle assessments and eco-friendly manufacturing methods. By promoting global collaborations and leveraging technological innovations, researchers and industries can continue to expand the potential of LCF-PHC. As nations and institutions align their efforts with global sustainability objectives, lignocellulosic fiber composites will play an essential role in reducing environmental impact, fostering green manufacturing, and shaping the future of sustainable materials.

8. Future Research Priorities

Based on the bibliometric trends and qualitative evidence reviewed in this study, three focused priorities are identified for advancing lignocellulosic fiber–reinforced polymer composites from laboratory-scale development toward reliable engineering applications.

8-1. Establish reproducible structure–processing–property relationships

Future studies should systematically investigate how fiber chemistry, surface-treatment conditions, fiber geometry, and processing parameters jointly influence mechanical performance and fiber–matrix interfacial bonding. Consistent reporting of experimental procedures, material variability, and test conditions is essential to enable reliable comparisons between studies and to support evidence-based material selection.

8-2. Demonstrate long-term durability and application-specific performance

Research should move beyond initial mechanical-property measurements toward evaluating moisture resistance, thermal and environmental aging, mechanical-property retention, and fire performance where relevant. Testing under representative service conditions will help determine whether reported laboratory improvements translate into dependable performance in automotive, aerospace, construction, and packaging applications.

8-3. Validate scalability and sustainability across the material life cycle

Promising composite systems should be assessed for manufacturing consistency, processing efficiency, resource consumption, and end-of-life management. Life-cycle assessment and recyclability or biodegradability studies, where applicable, should use transparent assumptions and consistent system boundaries to substantiate environmental claims and identify realistic routes to industrial adoption.

Together, these priorities address the key gap between increasing research activity and demonstrated technological readiness. The fuzzy logic framework presented in this review can support the qualitative interpretation of relationships among fiber characteristics, treatment conditions, and composite performance; however, its decision-support rules require independent experimental validation before they can be used for quantitative prediction or material ranking. Progress in reproducible characterization, service-condition validation, and life-cycle-informed scale-up will provide a stronger basis for assessing the practical maturity of lignocellulosic fiber-reinforced polymer composites.

Declarations:

Ethics Approval

Not applicable

Conflicts of Interest

The author(s) declare(s) no conflicts of interest to report regarding the present study.

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Author Contributions

Baranitharan Paramasivam: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Writing - Original Draft, Writing - Review & Editing, Project administration; Malinee Sriariyanun: Formal analysis, Supervision, Funding acquisition; Deeban Booramurthy: Methodology, Formal analysis, Investigation; Santhosh Kumar Doraichamy: Methodology, Formal analysis, Investigation; Athanasia Amanda Septevani: Formal analysis, Data curation.

Availability of Data and Materials

The data that support the findings of this study are available from the Corresponding Author, upon reasonable request.

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