STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Issue 3, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/JOPC/

Review JoPC

Biobased Composite Materials for Sustainability

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Abstract

Due to increasing demand for sustainable materials in various industrial sectors has directed a significant interest in biobased composite materials. Biobased materials, derived from biological resources, offer a promising substitute as compared to conventional composites that rely greatly on fossil fuels. This paper explores the advanced applications of biobased composites across various sectors such as automotive, construction, packaging etc., emphasising their potential to reduce environmental impact while maintaining the standard performance criteria. The incorporation of natural fibers, with biodegradable resins not only enhances mechanical properties but also subsidizes to carbon sequestration, thereby mitigating climate change impacts. Moreover, the lifecycle assessment of biobased composites uncovers less energy consumption and lessened greenhouse gas emissions as compared to traditional composite materials. This study also explores various challenges such as variability in raw material properties and the need for standardized testing methods to confirm reliability and durability in applications. By promoting collaboration between manufacturers, researchers, and policymakers, this study certainly promotes the development of innovative processing techniques and establishment of a circular economy structure. The discussion underscores the importance of biobased composites in achieving sustainability goals, promoting resource efficiency, and enhancing product lifecycle management. The changeover to biobased composite materials represents a significant step towards a more sustainable future, aligning industrial practices with ecological preservation and societal needs. Through continued innovation and investment, biobased composites can play a very important role in reforming the materials landscape, contributing to a greener and more sustainable economy.

Keywords: Sustainability, biobased composites, natural fibers, renewable resources, carbon sequestration, lifecycle assessment, ecological preservation

INTRODUCTION

Biobased composites represent a progressive approach in engineering sciences, integrate the benefits of natural resources with emerging engineering techniques. It can be defined as materials composed of a matrix derived from biological sources, such as plant fibers or biopolymers, biobased composites which offer an eco-friendly alternative to traditional synthetic composites [1]. These biobased materials not only hold the inherent properties of strength, light-weight, biodegradability, etc., but also contribute significantly to reducing environmental impact by promoting sustainability [2]. As industries gradually seek to minimize their carbon footprint, biobased composite materials emerge as a viable option/solution, for addressing both performance and ecological concerns [3]. They find various applications across in different sectors, including automotive, construction, and goods(consumer), showcasing their versatility and adaptability. Furthermore, advances in processing

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Received Date: April 10, 2025
Accepted Date: May 05, 2025
Published Date: May 13, 2025

Citation: Parveen Kumar, Chadetrik Rout. Biobased Composite Materials for Sustainability. Journal of Polymer & Composites. 2025; 13 (3): 163–170p.

and material formulation techniques continue to increase their durability and mechanical capabilities, allowing them to compete with traditional materials [4]. In essence, biobased composites represent a harmonious combination of nature and technology, paving the path for a more sustainable future while pushing the limits of material inventiveness [5]. Their progress/development not only promotes environmental stewardship, but also stimulates economic growth by utilising renewable resources [6]. Table 1 summarises the chronological/historical relevance and development of biobased composites.

THE NEED FOR SUSTAINABLE MATERIALS

Resource depletion, pollution and climate change have all contributed to an increase in the need for sustainable materials [15]. Traditional composite materials ideally cause more carbon emissions and waste [16]. Sustainable materials, particularly biobased composites, provide an environmentally beneficial option using renewable resources and lowering dependency on fossil fuels [13]. They not only reduce environmental effects, but also encourage circular economy concepts because they are biodegradable or recyclable [17]. As companies strive for greener practices, the use of sustainable materials is very important to promoting a healthy world and assuring long-term resource availability. The materials also play an important role in sustainable development because they combine performance with environmental responsibility [18]. Their lightweight and robust characteristics improve energy efficiency in a variety of industries, including transportation and construction, greatly lowering fuel consumption and emissions [19]. In general, biobased composites reduce dependency on fossil fuels and waste by using renewable resources like natural fibres as discussed before. Therefore, their potential for recycling and reusability aligns with circular economy ideas, which promote natural resource conservation [20]. As most of the industries use composite materials, they help to create a more sustainable future by combining economic growth with environmental stewardship through innovative research. Some of the composites (Natural/biobased and synthetic) are illustrated in Figure 1.

Table 1. Evolution of Biobased Composites, Significance and Development.

S no.	Time	Key developments	Significance	Source
1.	Pre-20th Century	Use of natural materials (wood, bamboo) in construction and tools	Established foundational knowledge of natural composites in human culture	[7]
2.	Early 1900s	Introduction of synthetic polymers (e.g., Bakelite)	Marked the shift towards man-made materials, setting the stage for future composite innovations	[8, 9]
3.	1960s-1970s	Emergence of fiberglass and carbon fiber composites	Highlighted the advantages of combining materials for enhanced strength and lightweight properties	[10]
4.	1980s	Initial research into natural fiber composites	Recognized the potential of renewable resources, leading to the exploration of biobased alternatives	[11]
5.	1990s	Development of biopolymers and eco-composites	Focused on sustainability, driving interest in materials derived from renewable sources	[12]
6.	2000s	Increased awareness of environmental issues	Sparked a surge in research and investment in biobased composites across various industries	[13]
7.	2010s-Present	Advancements in processing techniques and material formulations	Enhanced performance and market acceptance, positioning biobased composites as a viable alternative to traditional materials	[14]

Figure 1. Natural and synthetic composites.

TYPES OF BIOBASED COMPOSITE MATERIALS

Biobased composite materials, derived from biobased materials, integrate natural fibers with polymers [21]. These materials offer sustainable substitutes to traditional composites, improving environmental concerns also maintaining their workability and performance [22]. They are ideal for several applications in the construction, automotive, packaging industries etc. [23]. Biobased composites can be classified based on their material and reinforcement factors. Table 2 shows a generalized classification of biobased composites with their applications.

ADVANTAGES AND DISADVANTAGES OF BIOBASED COMPOSITES

Biobased materials offer sustainable alternatives to traditional materials, presenting benefits like reusability, biodegradability and lightweight properties [24]. However, there are some challenges persist, such as moisture sensitivity and variability in performance [25], that necessitate a balanced evaluation for operative application. Table 3 shows a comparative analysis (advantages vs disadvantages) of various aspects of biobased composites. Moreover, the suitability of biobased composites has been investigated by several researchers concerning mechanical properties/characteristics for various applications [26,27,28,29,30], and Table 4 represents a comparative analysis of some important mechanical properties of hemp, jute, and flax fibers.

Table 2. Types of Biobased Composite Materials.

S no.	Type	Sources	Properties	Applications
1.	Natural Fiber	Jute, hemp, flax, sisal	High tensile strength, lightweight, biodegradable	Automotive parts, construction, furniture
2.	Biopolymers	Starch, polylactic acid (PLA), cellulose	Biodegradable, renewable, good mechanical properties	Packaging, disposable items, textiles
3.	Hybrid	Combination of natural fibers and synthetic fibers	Enhanced mechanical properties, improved durability	Aerospace, automotive, sports equipment
4.	Cellulose Nanofibers	Wood, agricultural residues	High aspect ratio, excellent mechanical strength	Reinforcement in plastics, coatings
5.	Bamboo	Bamboo plant	High strength, lightweight, sustainable	Flooring, furniture, construction
6.	Flax Fiber	Flax plants	Good tensile strength, lightweight, eco-friendly	Automotive interiors, insulation
7.	Hemp Fiber	Hemp plants	Strong, durable, resistant to mold	Building materials, textiles

Table 3. Advantages and Disadvantages of Biobased Composites.

S no.	Aspect	Advantages	Disadvantages
1.	Sustainability	Derived from renewable resources, promoting eco-friendliness.	Limited availability of some natural fibers.
2.	Biodegradability	Many are biodegradable, reducing environmental impact.	Decomposition can lead to reduced lifespan in some applications.
3.	Weight	Generally lighter than traditional materials, improving energy efficiency.	May not achieve the same strength as some synthetic composites.
4.	Cost	Can be more cost-effective due to the use of agricultural waste.	Initial production costs may be higher for some bio-resins.
5.	Health and Safety	Non-toxic and safer for health compared to synthetic options.	Vulnerable to moisture and pests, affecting durability.
6.	Thermal Properties	Good thermal insulation properties.	May require additional treatments for fire resistance.
7.	Aesthetic Appeal	Unique textures and colors enhance product design.	Limited design options compared to synthetic composites.
8.	Mechanical Properties	High strength-to-weight ratio in some cases.	Variability in quality and performance due to natural sources.
9.	Market Acceptance	Growing consumer preference for sustainable products.	Perception issues regarding performance and durability.

Table 4. Mechanical Properties of Hemp, Jute, and Flax Fibers.

S no.	Property	Hemp fiber	Jute fiber	Flax fiber
1.	Tensile Strength	550 - 900 MPa	300 - 700 MPa	300 - 700 MPa
2.	Elongation at Break	2.5 - 3.5%	1.5 - 2.5%	1.5 - 3.5%
3.	Density	1.48 - 1.5 g/cm³	1.46 - 1.50 g/cm³	1.5 - 1.6 g/cm³
4.	Moisture Absorption	10-12%	12-15%	8-10%
5.	Biodegradability	High	High	High
6.	Thermal Resistance	Moderate	Low	High

APPLICATIONS OF BIOBASED COMPOSITES

Applications of biobased composites are increasingly used across several industries, including automotive, construction, and packaging. Their supportable properties and performance features make them ideal for usages necessitating eco-friendly solutions, contributing to low environmental impact and promoting circular economy [31]. Moreover, factors like fiber orientation and volume fraction dictate the composite's behavior under stress [32], impacting applications across industries, from automotive to aerospace. Fully understanding and manipulating fiber orientation and volume fraction allow scientists/engineers to prepare composites to specific needs [33], enhancing performance while promoting sustainability through innovative material design. This synergy between volume fraction and orientation is vital for advancing composite technology in a competitive market [34]. Table 5 shows applications of biobased composites in various industrial sectors.

CHALLENGES AND LIMITATIONS OF BIOBASED COMPOSITES

Several challenges are faced by biobased composites, such as limited durability, moisture sensitivity, variability in material properties etc. [35]. These constraints hinder their extensive adoption, demanding ongoing research and development to improve performance and address environmental concerns commendably. Table 6 presents challenges and limitations concerning the use of biobased composites.

Table 5. Applications of Biobased Composites in Various Industries.

S no.	Industry	Applications	Examples
1.	Automotive	Interior panels, dashboards, and structural components	Natural fiber-reinforced plastics in car interiors
2.	Construction	Wall panels, insulation, and flooring	Wood-plastic composites for decking and cladding
3.	Packaging	Biodegradable packaging materials	Starch-based films and molded pulp products
4.	Aerospace	Lightweight structural components	Bio-composite parts in aircraft interiors
5.	Textiles	Eco-friendly fabrics and composites	Hemp and flax fibers used in apparel
6.	Furniture	Sustainable furniture designs	Bamboo and reclaimed wood composites
7.	Sports Equipment	Lightweight and durable gear	Bio-composite tennis rackets and bicycles
8.	Consumer Goods	Eco-friendly household items	Biodegradable cutlery and containers
9.	Electronics	Lightweight casings and components	Natural fiber composites in electronic housings
10.	Agriculture	Mulch films and biodegradable plant pots	Compostable seedling trays and agricultural films

Table 6. Challenges and Limitations of Biobased Composites

S no.	Challenge/limitations	Description
1.	Moisture Sensitivity	Natural fibers can absorb moisture, leading to swelling and dimensional instability.
2.	Durability	May have lower resistance to UV light, heat, and chemical exposure compared to synthetic composites.
3.	Variability in Material Properties	Inconsistent quality and performance due to variations in natural fiber sources.
4.	Processing Challenges	Difficulty in processing due to fiber orientation and compatibility with matrix materials.
5.	Limited Mechanical Properties	Some biobased composites may not match the strength and stiffness of traditional composites.
6.	Cost of Biopolymers	Higher production costs for biopolymers compared to conventional plastics.
7.	Market Acceptance	Perception issues regarding performance, leading to hesitance in adoption.
8.	Lifecycle Assessment	Need for comprehensive studies to evaluate the full environmental impact throughout the lifecycle.
9.	Regulatory Standards	Lack of established regulations and standards for biobased composites in some regions.
10.	End-of-Life Options	Limited recycling options compared to synthetic materials, impacting sustainability goals.

INNOVATIONS OF BIOBASED COMPOSITE MATERIALS

Progress in biobased composite materials emphasizes for improving performance and sustainability through cutting-edge processing techniques, unique bio-resins, and hybrid formulations [36]. These advances aim to increase the mechanical properties, reduce environmental impact, and develop applications across several industries. Table 7 represents some innovations in biobased composite materials along with their benefits.

Table 7. Innovations in Biobased Composite Materials for Sustainability.

S no.	Innovation	Description	Benefits
1.	Advanced Natural Fibers	Development of high-performance fibers like hemp, flax, and bamboo.	Improved mechanical properties and reduced carbon footprint.
2.	Biopolymer Integration	Use of renewable biopolymers (e.g., PLA, starch) in composites.	Biodegradable options that minimize environmental impact.
3.	Hybrid Composites	Combining natural fibers with recycled plastics.	Enhanced durability and waste reduction.
4.	3D Printing with Biobased Materials	Customizable designs using bio-composite filaments.	Efficient material use and reduced production waste.
5.	Smart Bio-Composites	Embedding sensors for structural monitoring.	Real-time tracking of integrity in critical applications.
6.	Nanotechnology Applications	Incorporating nanomaterials to improve properties.	Increased strength, thermal stability, and barrier properties.
7.	Eco-Friendly Manufacturing Processes	Adoption of green chemistry in production methods.	Reduced energy consumption and lower emissions.
8.	Lifecycle Assessment Tools	Development of tools to evaluate environmental impacts.	Informed decision-making for sustainable practices.
9.	Consumer Education Initiatives	Programs to raise awareness about sustainable materials.	Increased demand for eco-friendly products.
10.	Recycling and Upcycling Strategies	Innovative methods for recycling biobased composites.	Promotes circular economy and resource efficiency.

CONCLUSION

The use of biobased composite materials is a revolutionary approach towards sustainability, by solving the serious environmental issues associated with conventional materials. As industries recognise the limited resources of fossil fuels and the adverse effects of synthetic materials, biobased composites could provide a viable alternative that is consistent with circular economy concepts. These materials not only minimise dependency on non-renewable resources, but also help to reduce greenhouse gas emissions during their lifetime. biobased composite’s mechanical qualities/properties and adaptability are being improved by innovations such as enhanced natural fibres and integration of biopolymer, making them suitable for a wide range of applications, including automotive, construction, packaging, and other consumer products. The formulation of hybrid composites, which blend natural fibres with recycled materials, demonstrates the potential for waste reduction and resource efficiency. Furthermore, the use of smart technology and eco-friendly production techniques assures that biobased composites can exceed the performance requirements of current applications while minimising environmental impact. As consumer’s knowledge and demand for sustainable goods rise, industries are required to incorporate these biobased materials, resulting in a move towards more sustainable production and consumption practices.

REFERENCES

1. TG YG, Nagaraju SB, Puttegowda M, et al. Biopolymer-based composites: an eco-friendly alternative from agricultural waste biomass. J. Compos. Sci. 2023;7(6): 242. https://doi.org/10.3390/jcs7060242
2. Carvalho D, Ferreira N, França B, et al. Advancing sustainability in the automotive industry: Bioprepregs and fully biobased composites. Compos. C: Open Access. 2024;14:100459. https://doi.org/10.1016/j.jcomc.2024.100459
3. Selvaraj VK, Subramanian J, Suyambulingam I, et al. Influence of biobased kenaf polymer composites on mechanical and acoustic properties for futuristic applications: An initiative towards net-zero carbon emissions. Polym. Test. 2024;134:108409. https://doi.org/10.1016/j.polymertesting.2024.108409

4. Chang BP, Mohanty AK, Misra M. Studies on durability of sustainable biobased composites: A review. RSC Adv. 2020;10(31):17955-99. https://doi.org/10.1039/C9RA09554C
5. Bühler M, Hollenbach P, Köhler L, et al. Unlocking resilience and sustainability with earth-based materials: a principled framework for urban transformation. Front. Built Environ. 2024;10:1385116. https://doi.org/10.3389/fbuil.2024.1385116
6. Olaniyan AR, Ogunlade CA, Babalola RT, et al. Biobased Industries and Their Products in the Global South. InSustainable Bioeconomy Development in the Global South: Volume II Bioeconomy Techniques 2025(pp. 159-184). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-96-0305-3_6
7. Marin E, Boschetto F, Pezzotti G. Biomaterials and biocompatibility: An historical overview. J. Biomed. Mater. Res. A. 2020;108(8):1617-33. https://doi.org/10.1002/jbm.a.36930
8. Baekeland LH. The synthesis, constitution, and uses of Bakelite. Ind. Eng. Chem. Res. 1909;1(3):149-61. https://doi.org/10.1021/ie50003a004
9. Sperling LH. History of interpenetrating polymer networks starting with bakelite-based compositions. In100+ Years of Plastics. Leo Baekeland and Beyond 2011(pp. 69-82). American Chemical Society. https://doi.org/10.1021/bk-2011-1080.ch005
10. Vergara W. Materials Revolution, What Does It Mean for Developing Countries? World Bank-Technical Papers; 1993.
11. Faruk O, Bledzki AK, Fink HP, et al. Progress report on natural fiber reinforced composites. Macromol. Mater. Eng. 2014;299(1):9-26. https://doi.org/10.1002/mame.201300008
12. Bismarck A, Baltazar-Y-Jimenez A, Sarikakis K. Green composites as panacea? Socio-economic aspects of green materials. Environ. Dev. Sustain. 2006;8:445-63. https://doi.org/10.1007/s10668-005-8506-5
13. Mohanty AK, Misra M, Drzal LT. Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. J. Polym. Environ. 2002;10:19-26. https://doi.org/10.1023/A:1021013921916
14. Nagaraja S, Anand PB, Ammarullah MI. Synergistic advances in natural fibre composites: a comprehensive review of the eco-friendly bio-composite development, its characterization and diverse applications. RSC Adv. 2024;14(25):17594-611. https://doi.org/10.1039/D4RA00149D
15. Yang M, Chen L, Wang J, et al. Circular economy strategies for combating climate change and other environmental issues. Environ. Chem. Lett. 2023;21(1):55-80. https://doi.org/10.1007/s10311-022-01499-6
16. Chen G, Li J, Sun Y, et al. Replacing traditional plastics with biodegradable plastics: impact on carbon emissions. Engineering. 2024;32:152-62. https://doi.org/10.1016/j.eng.2023.10.002
17. Zaborowska M, Bernat K. The development of recycling methods for biobased materials–A challenge in the implementation of a circular economy: A review. Waste Manag. Res. 2023;41(1):68-80. https://doi.org/10.1177/0734242X221105432
18. Krauklis AE, Karl CW, Gagani AI, et al. Composite material recycling technology-state-of-the-art and sustainable development for the 2020s. J. Compos. Sci. 2021;5(1):28. https://doi.org/10.3390/jcs5010028
19. Raja P, Murugan V, Ravichandran S, et al. A review of sustainable bio-based insulation materials for energy-efficient buildings. Macromol. Mater. Eng. 2023;308(10):2300086. https://doi.org/10.1002/mame.202300086
20. Dahiya S, Katakojwala R, Ramakrishna S, et al. biobased products and life cycle assessment in the context of circular economy and sustainability. Mater. Circ. Econ. 2020;2:1-28. https://doi.org/10.1007/s42824-020-00007-x
21. Suárez L, Castellano J, Díaz S, et al. Are natural-based composites sustainable?. Polymers. 2021;13(14):2326. https://doi.org/10.3390/polym13142326
22. Cywar RM, Rorrer NA, Hoyt CB, et al. Biobased polymers with performance-advantaged properties. Nat. Rev. Mater. 2022;7(2):83-103. https://doi.org/10.1038/s41578-021-00363-3
23. Johansson C, Bras J, Mondragon I, et al. Renewable fibers and biobased materials for packaging applications-a review of recent developments. BioRes. 2012;7(2):2506-52. https://doi.org/10.15376/biores.7.2.2506-2552

24. AL-Oqla FM, Hayajneh MT, Nawafleh N. Advanced synthetic and biobased composite materials in sustainable applications: a comprehensive review. Emerg. Mater. 2023;6(3):809-26. https://doi.org/10.1007/s42247-023-00478-z
25. Murawski A, Diaz R, Inglesby S, et al. Synthesis of biobased polymer composites: fabrication, fillers, properties, and challenges. Polymer Nanocomposites in Biomedical Engineering. 2019:29-55. https://doi.org/10.1007/978-3-030-04741-2_2
26. Palanisamy S, Mayandi K, Palaniappan M, et al. Mechanical properties of phormium tenax reinforced natural rubber composites. Fibers. 2021;9(2):11.https://doi.org/10.3390/fib9020011
27. Palanisamy S, Kalimuthu M, Santulli C, et al. Tailoring epoxy composites with Acacia caesia bark fibers: Evaluating the effects of fiber amount and length on material characteristics. Fibers. 2023;11(7):63.https://doi.org/doi:10.3390/fib11070063
28. Sumesh KR, Palanisamy S, Khan T, et al. Mechanical, morphological and wear resistance of natural fiber/glass fiber-based polymer composites. Bioresour. 2024;19(2):3271-89. https://doi.org/doi:10.15376/biores.19.2.3271-3289
29. Palaniappan M, Palanisamy S, Khan R, H. et al. Synthesis and suitability characterization of microcrystalline cellulose from Citrus x sinensis sweet orange peel fruit waste-based biomass for polymer composite applications. J. Polym. Res. 2024;31(4):105. https://doi.org/10.1007/s10965-024-03946-0
30. Karthik A, Bhuvaneshwaran M, Senthil Kumar MS, et al. A review on surface modification of plant fibers for enhancing properties of biocomposites. ChemSelect. 2024;9(21):e202400650. https://doi.org/10.1002/slct.202400650
31. Antov P, Savov V, Neykov N. Sustainable biobased adhesives for eco-friendly wood composites. A review. Wood Res. 2020;65(1):51-62.
32. Ghayoor H, Hoa SV, Marsden CC. A micromechanical study of stress concentrations in composites. Compos. C: Engineering. 2018;132:115-24. https://doi.org/10.1016/j.compositesb.2017.09.009
33. Shah DU. Developing plant fibre composites for structural applications by optimising composite parameters: a critical review. J. Mater. Sci. 2013;48(18):6083-107. https://doi.org/10.1007/s10853-013-7458-7
34. Lei C, Xie Z, Wu K, et al. Controlled vertically aligned structures in polymer composites: natural inspiration, structural processing, and functional application. Adv. Mater. 2021; 33(49):2103495. https://doi.org/10.1002/adma.202103495
35. Winandy JE, Morrell JJ. Improving the utility, performance, and durability of wood-and biobased composites. Ann. For. Sci. 2017;74:1-1. https://doi.org/10.1007/s13595-017-0625-2
36. Pawłosik D, Cebrat K, Brzezicki M. Exploring advancements in biobased composites for thermal insulation: A systematic review. Sustainability. 2025;17(3):1-43. https://doi.org/doi:10.20944/preprints202412.2035.v1

