STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 2, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Review JoPC

# Use of Composite Materials for Sustainability

Parveen Kumar[1], Chadetrik Rout[2,*]

***Abstract***

*Composite materials have emerged as key components in the quest for sustainability, providing a means to decrease environmental impact while improving performance in several applications. Some of the major benefits of using composites are durability, cut down regular repairs and replacements, preserve natural resources, reduce waste generation, and carbon footprint related to manufacturing processes. Due to renewability of natural fibers, the use of composites boosts sustainability and minimizes the environmental impact as compared to synthetic fibers. This study explores the production, qualities, and uses of sustainable composite materials, with a focus on bio-based, recycled, and natural fiber-reinforced composites. Key production procedures and problems are discussed, as well as the environmental ramifications of employing these materials. It focuses on the mechanical characteristics, life cycle assessment, and end-of-life disposal issues of sustainable composites. Applications in construction, automotive, aerospace, renewable energy, etc. are investigated, demonstrating the adaptability and potential use of these materials. The future prospects of research and development are reviewed and discussed, with an emphasis on increasing recycling technologies and material performance. The study emphasizes the significance of sustainable composite materials in meeting environmental goals and promoting innovation in material science. It also stated research attempts to give a solid grip on the existing situation and future possibilities for sustainable composites.*

**Keywords:** Sustainability, bio-based composites, recycled composites, sustainable composites, environmental impact, LCA, green materials, composite manufacturing

## INTRODUCTION

The term "sustainability" ensures that current requirements are addressed without jeopardizing future generation's capacity to satisfy their own, including environmental conservation, economic prosperity, and social impartiality. Environmental sustainability focuses on lowering resource usage, minimizing waste, and safeguarding natural environments. Sustainable methods provide for the protection of biodiversity, mitigation of climate change impacts, and health of ecosystems that are vital to life on Earth. Implementing sustainable practices permits society to lower its carbon footprint and pollution, ensuring cleaner air, safe drinking water, and productive soil [1]. Economic development boosts the optimal use of resources to maintain long-term economic growth and solidity. It involves building systems that are resistant to environmental and social jolts, boosting innovation, and promoting sustainable initiatives. Economic sustainability refers to setting up a balance between economic growth and resource conservation for future generations [2]. Therefore, sustainable composite materials might have far-reaching economic repercussions for many industries, altering production processes, product lifecycles, and market dynamics. Some of the key economic implications of adopting sustainable composite materials across different industries are stated in Table 1. However, social sustainability endeavours

***Author for Correspondence**
Chadetrik Rout

[1]Assistant Professor, Department of Civil Engineering, Maharishi Markandeshwar Engineering College, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, India
[2]Associate Professor, Department of Civil Engineering, Maharishi Markandeshwar Engineering College, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, India

Received Date: November 27, 2024
Accepted Date: December 26, 2024
Published Date: January 20, 2025

**Citation:** Parveen Kumar, Chadetrik Rout. Use of Composite Materials for Sustainability. Journal of Polymer & Composites. 2025; 13(Special Issue 2): S22–S34p.

 

to improve the quality of life for all people by promoting growth and ensuring equitable prospects. It emphasizes the significance of social responsibility and ethical behaviour in handling challenges such as poverty, education, health, human rights, etc. [3]. Objectively sustainability encourages equality and societal justice, which encourages the development of unified, flexible communities capable of long-term fulfilment.

## Composite Materials for Sustainability

Composite materials are well known for their useful combination of different components to build superior qualities of products and play a key role in enhancing sustainability. These structures are made from numerous components, naturally, a matrix and reinforcement, which work together to enhance their mechanical as well as physical characteristics. Therefore, composite's relevance in sustainability is becoming more widely recognized in industrial sectors, such as aerospace, automotive, construction, and energy sectors [4]. Composite materials consist of a matrix and a reinforcing phase, with the matrix holding the fibers together, protecting them from natural degradation/deterioration. The combination produces lightweight robust materials that are corrosion-resistant and can resist high pressures, making them suitable for various challenging applications [5]. Overall, composite materials contribute to sustainability through resource and energy efficiency, durability, and longevity.

## Advances in Sustainable Composites

To date natural fibers including hemp, flax, jute etc., are being used in composites, providing renewable and biodegradable alternatives to synthetic fibers [6]. Bio-composites reduce the dependency on petroleum-based products and lower the total environmental impact. Developments in composite material recycling methods permit for the recovery and reuse of fibers and resins, which increases the material's sustainability. Sustainable composite materials are more important in industries like wind energy, where enormous composite structures like turbine blades are required for sustainable end-of-life solutions [7]. The main objective of continuing research and development in sustainable composites are improving material physical characteristics, enhancing the use of renewable resources, improving recycling techniques, and boosting lifetime analysis [8]. Therefore, the purpose of this study was to analyze and synthesize available knowledge on the development, application, and benefits of composite materials in terms of sustainability. The study also aimed to highlight innovations in composite materials that contribute sustainability concerning environmental, economic, and social developments, addressing production problems and potential solutions.

**Table 1.** Key Economic Implications of Adopting Sustainable Composite Materials Across Different Industries.

| S. N. | Industry | Economic implications |
|---|---|---|
| 1 | Automotive | - Lower material costs over time due to recyclability.<br>- Lighter materials lead to reduced fuel consumption.<br>- Fascinate environmentally conscious consumers. |
| 2 | Construction | - Reduce maintenance costs.<br>- Improve insulation properties to lower energy bills. |
| 3 | Aerospace | - Enhanced fuel efficiency and lower operational costs.<br>- Increased R&D spending on new composite technologies.<br>- Early adoption can lead to market leadership. |
| 4 | Consumer Goods | - Initial investment in new materials may be high.<br>- Can decrease reliance on traditional materials. |
| 5 | Electronics | - Reduces e-waste and associated disposal costs.<br>- Improved flexibility can lead to longer product lifespans. |
| 6 | Textiles | - New segments for sustainable fashion attract consumers.<br>- Initial higher costs may decrease with scale and innovation.<br>- Meeting sustainability standards can avoid penalties. |

 

## TYPES OF SUSTAINABLE COMPOSITE MATERIALS

Mainly three types of composite materials are available such as bio-based, recycled, and natural fiber-reinforced composites, and are discussed subsequently.

### Bio-Based Composites

The bio-based composites are prepared of natural fibers and polymers produced from bio-based natural sources. These composites are more popular because of their environmental benefits, such as degradability and low carbon footprint, making them a more sustainable option than standard composites. These composites are often made from bio-based fibers like flax, hemp, jute, or bamboo, as well as bio-based polymers like polylactic acid (PLA) or polyhydroxyalkanoates (PHA) [8]. These fibers offer reinforcement, improving the mechanical properties of the composites, while the polymers act as a matrix to hold the fibers together. These materials are produced using a variety of manufacturing processes, including as injection moulding, extrusion, compression moulding etc. The benefits of bio-based composites are low density, high specific strength, and stiffness [9]. and are resistant to corrosion and excellent thermal and acoustic insulation qualities. The above qualities make them perfect and sustainable for a variety of applications, such as automobile components, construction materials, packaging, consumer items etc. The primary advantage of bio-based composites is their positive environmental effect i.e., they are biodegradable and recyclable, reducing their impact on landfills and the surrounding environment. Moreover, bio-based composites often consume less energy and produce less greenhouse gas (GHG) emissions than conventional ones [10]. Bio-based composites have several limitations such as fiber characteristics, moisture absorption, and durability [11]. Research work is underway to solve these difficulties and to improve the performance and dependability of bio-based composites. However, recent research is focusing on enhancing manufacturing processes, developing novel bio-based polymers, and increasing applications in other public sectors.

### Recycled Composites

Composite materials help to promote sustainability by reducing waste generation, saving natural resources, and reducing detrimental environmental effects. These composite wastes are processed using recycling e.g., pyrolysis. Recycled composite materials are used in several industries, e.g., construction, aerospace, automotive, automotive etc., and provide significant benefits such as cost savings, waste minimisation, and environmental management [12]. Although, with several problems such as holding material characteristics and confirming quality consistency, constant investigation, and improvement aim to progress in recycling methods and increase the usage of recycled composite materials in various industrial sectors [13].

### Natural Fiber-Reinforced Composites

Natural fiber-reinforced composites are materials made up of mixing natural fibers with a matrix material, usually polymers, to manufacture a composite with better mechanical features [14]. These fibers, originating from plants (e.g., flax, hemp) and animals (e.g., wool, silk), have various benefits, including low density, biodegradability, and renewable properties. The composites have high mechanical qualities, making them appropriate for use in a variety of sectors, including automotive, construction, and packaging. Natural fiber-reinforced composites are environmentally beneficial and may minimize dependency on non-renewable resources, therefore their manufacture corresponds with sustainability goals [15]. However, difficulties such as fiber-matrix compatibility and moisture absorption must be addressed to achieve peak performance.

## MANUFACTURING TECHNIQUES

### Processing Methods

Composite manufacturing uses a variety of processing processes to create composite materials with desired qualities. Table 2 shows the most important approaches employed for manufaturing.

### Challenges in Manufacturing Sustainable Composites

Manufacturing sustainable composites involves some obstacles that the industry must overcome in order to promote environmental responsibility and minimize reliance on non-renewable resources. Table 3 shows some of the significant problems in manufacturing of sustainable composites.

**Table 2.** Process Methods for Composite Materials Manufacturing.

| S N. | Processing method | Elucidation | Source |
|---|---|---|---|
| 1 | Hand layup | It is a manual procedure that involves inserting reinforcing components into a mold and adding resin by hand. | [16] |
| 2 | Automated fiber placement (AFP) | This technology uses robotics to precisely put continuous fibers on a mold. | [17] |
| 3 | Open molding | It is a process in which reinforcing materials are put in an open mold and resin is applied to create a composite. | [18] |
| 4 | Resin infusion | This procedure involves infusing resin into a dry fiber under vacuum, ensuring that the fibers are thoroughly impregnated. | [19] |
| 5 | Compression molding | It uses heat and pressure to consolidate composite materials in a mold cavity, most often for thermosetting composites. | [20] |
| 6 | Filament winding | To construct composite structures, continuous fibers are wound around a revolving mandrel, and resin is applied. | [21] |

** These approaches provide versatility in manufacture of composites for extensive applications.*

**Table 3.** Key Challenges in Manufacturing of Sustainable Composites.

| S N. | Challenges | Elucidation | Source |
|---|---|---|---|
| 1. | Lack of comprehensive assessment | There is a gap in evaluating bio-composites in terms of complete required criteria for a variety of industrial applications. | [8] |
| 2. | Technical problems with natural fiber | Manufacturing composites from natural fibres such as kenaf presents technological obstacles. | [22] |
| 3. | Sustainable manufacturing methods | Developing sustainable production processes for composites is difficult, although progress is being made. | [23] |
| 4. | Supply chain sustainability | Ensuring sustainability across the composites sector supply chain presents difficulties, such as energy savings and waste reduction. | [24] |
| 5. | Management of composite waste | Composite waste management is becoming a more pressing issue as worldwide demand for items built from these materials rises. | [12] |
| 6. | Adapting to climate crisis and regulatory changes | The composites sector is facing hurdles in adjusting to climate crisis concerns and regulatory shifts. | [25] |

**To adopt more sustainable composite manufacturing techniques, industry players must work together, innovate technologically, and get regulatory assistance.*

## PROPERTIES AND PERFORMANCE

Composite materials have various advantages, including more strength and stiffness, low weight, long life, and resistance to erosion and corrosion. The characteristics may be modified during the production process to meet specific application requirements.

### Mechanical Properties

Sustainable composites offer diverse mechanical properties suitable for various industrial and consumer applications, aligning with environmental sustainability goals and offering a viable alternative. Table 4 displays several key mechanical characteristics of composite materials.

### Environmental Impact Assessments (EIA)

Life Cycle Assessment (LCA) is a widely used method for assessing the environmental impact of composite materials, encompassing their entire life cycle from extraction to disposal. Table 5 highlights some of the key aspects of EIA studies of composite materials. According to studies, the environmental effect of composite materials varies greatly depending on the exact materials and production procedures utilized. Some specific case studies related to LCA to evaluate the sustainability of bio-based and recycled composites in various industries are mentioned in Table 6. Composite material's environmental effects may be considerably reduced by recycling and reuse.

**Table 4.** Mechanical Properties of Sustainable Composite Materials [8].

| S N. | Property | Elucidation |
|---|---|---|
| 1 | Strength | Sustainable composites have excellent strength-to-load ratios, making them ideal for a variety of applications requiring strength. |
| 2 | Toughness | These composites frequently have high toughness, allowing them to survive impact and deformation without splitting readily. |
| 3 | Durability | Sustainable composites are highly durable, assuring endurance and resistance to deterioration, making them ideal for long-term usage. |
| 4 | Dimensional stability | They have exceptional stability, and they can retain their shape and size even under dynamic circumstances, which is critical for constant performance. |
| 5 | Biodegradability | Many sustainable composites are biodegradable, which means they degrade spontaneously over time, minimizing environmental impact and increasing eco-friendliness. |
| 6 | Eco-friendliness | These composites are frequently created from renewable resources or recycled materials, which adds to their environmental friendliness and reduces reliance on non-renewable resources. |

**Table 5.** Various Aspects of EIA Studies of Composite Materials.

| S N. | Attribute | Elucidation | Source |
|---|---|---|---|
| 1 | Life cycle assessment (LCA) | Assess the environmental effect of composites across their whole life cycle, from raw material extraction to disposal. | [26] |
| 2 | Environmental impact model development | Models are designed to analyze the effect of composites, taking into account issues such as embedded environmental impact. | [26] |
| 3 | Integration of durability and impact | Durability-based service-life predictions are combined with EIA to assess natural fiber-reinforced composite materials. | [27] |
| 4 | Evaluation of sustainable polymers | Polymers are assessed for their environmental impact, taking into consideration of factors such as energy consumption and economic balance. | [28] |
| 5 | LCA approach | Used to evaluate the environmental consequences of bio-composites | [29] |
| 6 | Resource depletion and global warming | It compares resource depletion and global warming potential for composites made from recycled plastics. | [30] |

**These attributes insights into the EIA of sustainable composites by showing the methodology and variables used to assess their sustainability.*

**Table 6.** Case Studies of LCA to Evaluate the Sustainability of Bio-based and Recycled Composites in Various Industries.

| S N. | Industry | Case study | Materials evaluated | Outcomes | Source |
|---|---|---|---|---|---|
| 1 | Agriculture | LCA of biodegradable mulch films | PLA and other bio-based polymers | Significant reduction in soil pollution compared to traditional plastics | [31] |
| 2 | Aerospace | LCA of bio-based composites | Bio-epoxy resins, natural fibers | Can reduce weight and environmental impact in aircraft. | [26] |
| 3 | Textile | LCA of recycled polyester | Recycled PET vs. virgin PET | Recycled PET significantly lowers greenhouse gas emissions | [32] |
| 4 | Construction | LCA of bio-based insulation materials | Wood fibers, cellulose, and mycelium | Lower carbon footprint and energy consumption than conventional insulations | [33] |
| 5 | Automotive | LCA of natural fiber composites | Hemp and flax fibers, polypropylene | Reduced environmental impact compared to glass fiber composites. | [34] |
| 6 | Packaging | LCA of biodegradable plastics | PLA (Polylactic acid) and starch-based | Biodegradable options showed reduced impacts in waste management | [35] |

## APPLICATIONS OF SUSTAINABLE COMPOSITES

Sustainable composites, manufactured from renewable and biodegradable materials, offer a viable alternative to standard composites in several applications. They have substantial influence in several important fields, including construction, automotive, aerospace, and renewable energy.

### Construction

Table 7 showcases the various applications of sustainable composites in the construction industry, highlighting their durability, strength, eco-friendliness etc.

### Automotive

Sustainable composites are gaining popularity in automobile applications, enhancing environmental sustainability and performance and in certain cases reduces fuel consumption. Table 8 provides a comprehensive overview of their uses and relevant references/sources.

**Table 7.** Applications of Composite Materials in Construction Sector.

| S N. | Usage | Elucidation | Source |
|---|---|---|---|
| 1 | Structural elements | Sustainable composites are used to build structural parts including beams, columns, and panels because they have good strength-to-weight ratios and are resistant to corrosion. | [36] |
| 2 | Insulation materials | Composites are utilized as insulation materials in buildings to improve energy efficiency and reduce heat transfer, resulting in greater thermal performance and lower energy consumption. | [37] |
| 3 | Cladding systems | Sustainable composites are used as cladding materials on building exteriors, offering weather resistance, durability, and aesthetic appeal while lowering maintenance and lifespan costs. | [38] |
| 4 | Roofing materials | Employed in roofing applications due to their lightweight nature, durability, and weather resistance, which provide long-term protection while also contributing to building sustainability. | [39] |
| 5 | Sustainable wood-plastic composites | Wood-plastic composites (WPCs) made from sustainable materials are used in landscaping and transportation due to their unique mix of wood-like looks and plastic's durability and minimal maintenance requirements. | [40] |

**Table 8.** Applications of Composite Materials in Automotive Sector.

| S N. | Usage | Elucidation | Source |
|---|---|---|---|
| 1. | Vehicle components | Sustainable composites are utilized to make a variety of vehicle components, including body panels, interior trim, and structural parts, because of their lightweight and corrosion resistance. | [41] |
| 2 | Electric and hybrid vehicles | Sustainable composites are essential in electric and hybrid cars for battery enclosures, chassis components, and lightweight body constructions, helping to improve energy and fuel efficiency. | [42] |
| 3 | Bio-composite materials | Bio-composites made from renewable materials are used in automotive applications for lightweight characteristics, acoustic insulation, and emissions reduction in components such as door panels and dashboard trims. | [43] |
| 4 | Structural reinforcements | Sustainable composites give strength and stiffness to automotive structures such as chassis and suspension systems, improving vehicle performance and occupant safety. | [44] |
| 5 | Noise and vibration reduction | Composites with superior acoustic characteristics are used in automotive applications to minimize noise and vibration, hence increasing overall comfort and driving experience. | [45] |

**Aerospace**

Composite materials have been used in aircraft applications e.g., engine blades, brackets, interiors, nacelles, propellers/rotors, single aisle wings, wide-body wings, and so on thereby lessening fuel consumption. Table 9 lists the numerous uses of sustainable composites in the aerospace industry, along with brief explanations and relevant sources.

**Renewable Energy**

The use of composites in renewable energy generation has increased dramatically over the years. Their physical properties allow for design flexibility and good durability, which are ideal for cost savings. Using composite materials in the electric power sector boosts performance and efficiency. Table 10 shows the numerous uses of sustainable composites in the renewable energy industry, along with brief explanations and relevant sources.

**Table 9.** Applications of Composite Materials in Aerospace Sector.

| S N. | Usage | Elucidation | Source |
|---|---|---|---|
| 1 | Aircraft structures | Sustainable composites are widely utilized in construction of aircraft structures, such as fuselages, wings, and empennages, due to their lightweight and high strength qualities. | [9] |
| 2 | Interior components | Composites are used to make aircraft interior components like cabin panels, overhead bins, and seating frames because they are durable, lightweight, and provide design flexibility. | [46] |
| 3 | Engine components | Composites are used in the fabrication of engine components like fan blades, nacelles, and shrouds, helping to improve fuel efficiency and performance. | [47] |
| 4 | Aerospace interiors | Used in aerospace interiors for a range of applications, including flooring, walls, and lavatory components, to provide lightweight solutions while improving passenger comfort. | [48] |
| 5 | Environmental sustainability | Focused on sustainability, which is promoting the usage of eco-friendly composite materials to decrease environmental impact and increase overall sustainability. | [12] |
| 6 | Recyclable materials | Research is continuing to produce recyclable thermoplastic composites for aerospace applications, intending to improve end-of-life recyclability and reduce waste output. | [12] |

**Table 10.** Applications of Composite Materials in Renewable Energy Sector.

| S N. | Usage | Elucidation | Source |
|---|---|---|---|
| 1 | Wind turbine blades | Due to their light weight, durability, and corrosion resistance, they are widely employed in the production of wind turbine blades. | [49] |
| 2 | Solar panel components | Play an important part in the manufacture of various solar panel components, such as frames and supports, by providing lightweight and weather-resistant solutions. | [50] |
| 3 | Hydroelectric turbine components | Used in the manufacture of hydroelectric turbine components due to its corrosion resistance, strength, and longevity. | [51] |
| 4 | Biomass energy equipment | Because of their resilience to chemicals and environmental variables, they may be used to manufacture biomass energy production equipment. | [52] |
| 5 | Geothermal energy systems | They are used in geothermal energy systems because of their resistance to high temperatures, corrosion, and mechanical stress. | [53] |
| 6 | Wave energy converters | Used in the design of wave energy converters, which provide lightweight and robust methods for harvesting wave power. | [54] |
| 7 | Energy storage systems | Find uses in energy storage systems because of their lightweight and durable qualities, which contribute to the efficiency of renewable energy sources. | [23] |
| 8 | Tidal energy infrastructure | Used in the infrastructure of tidal energy projects to provide corrosion resistance and structural integrity in hostile maritime conditions. | [55] |
| 9 | Biofuel production equipment | Because of their resilience to corrosion and chemicals, they are used to fabricate biofuel production equipment. | [56] |

 

## CHALLENGES, EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

Despite their benefits, composites pose several obstacles and constraints in engineering design. One of the most significant obstacles is the complexity and cost of composite manufacture and processing, which sometimes need specialized equipment, methods, and manpower. Table 11 summarises some of the primary problems connected with sustainable composite materials.

### Emerging Technologies in Composite Recycling

To address some challenges in composite recycling techniques concerning quality consistency and waste management certain emerging technologies have evolved such as solvolysis, controlled pyrolysis, cryogenic grinding, hybrid recycling approaches, quality monitoring systems with automated sorting etc. and are discussed below.

#### *Solvolysis*

It is an advanced chemical recycling method that breaks down composites into their original monomers, recovering high-quality fibers and resins [66] while preserving material quality and reduce landfill waste [67].

#### *Controlled pyrolysis*

A new pyrolysis technology optimizes temperature and processing time, preserving fibre integrity and ensuring consistent quality in recycled output [68], effectively manage end-of-life composites [69].

#### *Cryogenic grinding*

It is a low-temperature mechanical recycling technique that separates fibers from matrices, resulting in cleaner, higher-quality, and cost-effective recycled materials [70].

**Table 11.** Challenges Associated with Composite Materials.

| S N. | Challenge | Elucidation | Source |
|---|---|---|---|
| 1 | Recycling and sustainability | Difficult to recycle because of their complicated architectures and a lack of suitable recycling technologies. Composite recycling processes are limited, resulting in lower-quality recycled material. | [57] |
| 2 | Landfill disposal | A significant amount of composite waste still ends up in landfills, contributing to environmental pollution. | [58] |
| 3 | Durability and circularity | Durability and extended lifespan impede recycling and reuse, undermining circular economy attempts. | [12] |
| 4 | Adoption of alternative feedstock | The industry's adoption of sustainable feedstock materials is minimal, limiting the production of eco-friendly composites. | [4] |
| 5 | Environmental impact of production | Synthetic composites are produced with a high energy consumption and generate a lot of trash and byproducts. | [59] |
| 6 | Regulatory and market barriers | Existing regulatory frameworks and commercial needs do not provide adequate support for widespread use of sustainable composites. | [60] |
| 7 | Carbon footprint and life-cycle impacts | To be genuinely successful, they must consider their carbon footprint as well as their full life cycle implications. | [61] |
| 8 | Moisture resistance and fiber/matrix compatibility | Poor moisture resistance and fiber-matrix compatibility are common difficulties with bio-composites. | [62] |
| 9 | High cost | The raw materials and fabrication processes for composites are expensive. | [63] |
| 10 | Technical problems in manufacturing | Damage occurs during production, particularly when natural fibers are used. | [64] |
| 11 | Performance limitations | Composite materials can have transverse characteristics and are susceptible to microcracking, which can result in catastrophic failures. | [65] |
| 12 | Market and adoption barriers | Composite materials are not widely adopted in many sectors due to regulatory and market circumstances. | [57] |

 

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

***Hybrid recycling***

This method combines mechanical and chemical processes to enhance recovery, enabling reliable component extraction from complex composite constructions [71]. thereby reducing waste through precise material usage.

***Quality monitoring systems with automated sorting***

Here AI and machine learning are being used in real-time monitoring systems for recycling processes, enhancing quality control, improving composite material identification [72]. leading to overall waste reduction and promote sustainability.

**Future Directions**

Advancements in several important areas will certainly influence the future of composite materials. Lightweighting is a key focus, seeking to minimize the weight of composite structures while maintaining strength, notably in the automotive and aerospace sectors. The development of nanocomposites and biomaterials promises to improve mechanical characteristics and sustainability. Recycling methods, particularly solvolysis, are being developed to enhance composite material degradation and recovery, therefore addressing environmental issues. Furthermore, composites are rapidly being used in civil engineering, infrastructure, pipe, and tank building, demonstrating their adaptability and durability. Continuous innovation in composite materials assures that they will play an increasingly important role in a wide range of high-performance applications.

However, addressing the problems and future directions of sustainable composites requires overcoming a variety of constraints while progressing towards more ecologically friendly and efficient materials. To address these difficulties, businesses, academics, politicians, and consumers must work together to speed the development and acceptance of sustainable composite materials.

**Research and Development Prospects**

Sustainable composites research investigates natural fibers such as abaca and bamboo as alternatives to conventional materials, intending to solve environmental issues. Processing methods emphasize the use of green composites derived from naturally accessible resources, hence contributing to the creation of sustainable materials. Sophisticated simulations, such as machine learning (ML) assisted molecular dynamics, offer information on material characteristics and performance. Also, there is an increasing importance on absolutely green composites reinforced with natural fibers and recyclable/biodegradable polymers to decrease environmental effects. These works pave the way for composite materials with superior qualities and less negative impact, resulting in a sustainable future.

## CONCLUSION

Comprehensive analysis on composite materials revealed that composite materials signify a feasible path for achieving sustainability goals. These materials often combine natural fibers, resins, and other environmentally components, making them perfect for long-term uses. However, issues in production practices and end-of-life management remain, necessitating innovative solutions to improve their sustainability. The use of natural fibers in construction sector demonstrates their ability to develop sustainable alternatives owing to their availability and lightweight nature. Despite various obstacles, green composites show great potential for a diversified application, providing a poise of environmental advantages and structural integrity. However, upcoming research, must focus on developing sophisticated production techniques and enhancing recycling systems to maximize composite material sustainability. Cooperation among academics, industries, and governments is also required to successfully solve these problems and encourage the broader use of composites. By controlling the potential of composite materials and applying universal approaches, it can pave the path for a more sustainable future in several industrial sectors.

## REFERENCES

1. Goodland R, Daly H. Environmental sustainability: universal and non-negotiable. *Ecol. Appl.* 1996;6(4):1002-17. https://doi.org/10.2307/2269583

2. Xue M. Natural resource performance for a green economic growth: From short-term to long-term quality. *Resour. Policy.* 2024;91:104654. https://doi.org/10.1016/j.resourpol.2024.104654
3. Santos E. From neglect to progress: Assessing social sustainability and decent work in the tourism sector. *Sustainability.* 2023;15(13):10329. https://doi.org/10.3390/su151310329
4. Maiti S, Islam MR, Uddin MA, et al. Sustainable fiber-reinforced composites: A Review. *Adv. Sustain. Syst.* 2022;6(11):2200258. https://doi.org/10.1002/adsu.202200258
5. Campbell FC, editor. Lightweight materials: understanding the basics. ASM international; 2012.
6. 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
7. Majewski P, Florin N, Jit J, et al. End-of-life policy considerations for wind turbine blades. *Renew. Sustain. Energy Rev.* 2022;164:112538. https://doi.org/10.1016/j.rser.2022.112538
8. Andrew JJ, Dhakal HN. Sustainable biobased composites for advanced applications: recent trends and future opportunities-A critical review. *Compos. C: Open Access.* 2022;7:100220. https://doi.org/10.1016/j.jcomc.2021.100220
9. AL-Oqla FM, Hayajneh MT, Nawafleh N. Advanced synthetic and biobased composite materials in sustainable applications: a comprehensive review. *Emergent Mater.* 2023;6(3):809-26. https://doi.org/10.1007/s42247-023-00478-z
10. Dornburg V, Lewandowski I, Patel M. Comparing the land requirements, energy savings, and greenhouse gas emissions reduction of biobased polymers and bioenergy: An analysis and system extension of life-cycle assessment studies. *J. Ind. Ecol.* 2003;7(3-4):93-116. https://doi.org/10.1162/108819803323059424
11. Ramesh M, Palanikumar K, Reddy KH. Plant fibre based bio-composites: Sustainable and renewable green materials. *Renew. Sustain. Energy Rev.* 2017;79:558-84. https://doi.org/10.1016/j.rser.2017.05.094
12. 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
13. Hagnell MK, Åkermo M. The economic and mechanical potential of closed loop material usage and recycling of fibre-reinforced composite materials. *J. Clean. Prod.* 2019;223:957-68. https://doi.org/10.1016/j.jclepro.2019.03.156
14. Ramachandran A, Mavinkere Rangappa S, Kushvaha V, et al. Modification of fibers and matrices in natural fiber reinforced polymer composites: A comprehensive review. *Macromol. Rapid Commun.* 2022;43(17):2100862. https://doi.org/10.1002/marc.202100862
15. Skosana SJ, Khoathane C, Malwela T. Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting. *J. Thermoplast. Compos. Mater.* 2024:08927057241254324. https://doi.org/10.1177/08927057241254324
16. Elkington M, Bloom D, Ward C, et al. Hand layup: understanding the manual process. *Adv. Manuf.: Polym. Compos. Sci.* 2015;1(3):138-51. https://doi.org/10.1080/20550340.2015.1114801
17. Raspall F, Velu R, Vaheed NM. Fabrication of complex 3D composites by fusing automated fiber placement (AFP) and additive manufacturing (AM) technologies. *Adv. Manuf.: Polym. Compos. Sci.* 2019;5(1):6-16. https://doi.org/10.1080/20550340.2018.1557397
18. Rajak DK, Pagar DD, Kumar R, et al. Recent progress of reinforcement materials: a comprehensive overview of composite materials. *J. Mater. Res. Technol.* 2019;8(6):6354-74. https://doi.org/10.1016/j.jmrt.2019.09.068
19. Van Oosterom S, Allen T, Battley M, et al. An objective comparison of common vacuum assisted resin infusion processes. *Compos. - A: Appl. Sci. Manuf.* 2019;125:105528. https://doi.org/10.1016/j.compositesa.2019.105528
20. Tatara RA. Compression molding. InApplied plastics engineering handbook 2024 Jan 1 (pp. 389-424). William Andrew Publishing. https://doi.org/10.1016/B978-0-323-88667-3.00011-4
21. Peters ST, Tarnopol'skii YM. Filament winding. InComposites Engineering Handbook 1997 Mar 19 (pp. 527-560). CRC Press.


 

22. Leão A, Sartor SM, Caraschi JC. Natural fibers based composites–technical and social issues. *Mol. Cryst. Liq. Cryst*. 2006;448(1):161-763. https://doi.org/10.1080/15421400500388088
23. Mohanty AK, Vivekanandhan S, Pin JM, et al. Composites from renewable and sustainable resources: Challenges and innovations. *Science*. 2018;362(6414):536-42. https://doi.org/10.1126/science.aat907
24. Ford S, Despeisse M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *J. Clean. Prod.* 2016;137:1573-87. https://doi.org/10.1016/j.jclepro.2016.04.150
25. Berkhout F, Hertin J, Gann DM. Learning to adapt: organisational adaptation to climate change impacts. *Clim. Change.* 2006;78(1):135-56. https://doi.org/10.1007/s10584-006-9089-3
26. Bachmann J, Hidalgo C, Bricout S. Environmental analysis of innovative sustainable composites with potential use in aviation sector-A life cycle assessment review. *Sci. China Technol. Sci.* 2017;60:1301-17. https://doi.org/10.1007/s11431-016-9094-y
27. Miller SA, Srubar III WV, Billington SL, et al. Integrating durability-based service-life predictions with environmental impact assessments of natural fiber–reinforced composite materials. *Resour. Conserv. Recycl.* 2015;99:72-83. https://doi.org/10.1016/j.resconrec.2015.04.004
28. Wu N, Demchuk Z, Voronov A, et al. Sustainable manufacturing of polymeric materials: A techno-economic analysis of soybean oil-based acrylic monomers production. *J. Clean. Prod.* 2021;286:124939. https://doi.org/10.1016/j.jclepro.2020.124939
29. Chen W, Oldfield TL, Cinelli P, et al. Hybrid life cycle assessment of potato pulp valorisation in biocomposite production. *J. Clean. Prod.* 2020;269:122366. https://doi.org/10.1016/j.jclepro.2020.122366
30. Vidal R, Martínez P, Garraín D. Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters. *Int. J. Life Cycle Assess.* 2009;14:73-82. https://doi.org/10.1007/s11367-008-0043-7
31. de Sadeleer I, Woodhouse A. Environmental impact of biodegradable and non-biodegradable agricultural mulch film: A case study for Nordic conditions. *Int. J. Life Cycle Assess*. 2024;29(2):275-90. https://doi.org/10.1007/s11367-023-02253-y
32. Periyasamy AP, Militky J. LCA (life cycle assessment) on recycled polyester. Environmental Footprints of Recycled Polyester. 2020:1-30. https://doi.org/10.1007/978-981-13-9578-9_1
33. 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
34. Seile A, Spurina E, Sinka M. Reducing global warming potential impact of bio-based composites based of LCA. *Fibers*. 2022;10(9):79. https://doi.org/10.3390/fib10090079
35. Mahalle L, Alemdar A, Mihai M, et al. A cradle-to-gate life cycle assessment of wood fibre-reinforced polylactic acid (PLA) and polylactic acid/thermoplastic starch (PLA/TPS) biocomposites. *Int. J. Life Cycle Assess*. 2014;19:1305-15.
36. Sbahieh S, Rabie M, Ebead U, et al. The mechanical and environmental performance of fiber-reinforced polymers in concrete structures: Opportunities, challenges and future directions. *Buildings*. 2022;12(9):1417. https://doi.org/10.3390/buildings12091417
37. Ramakrishnan S, Wang X, Sanjayan J, et al. Thermal performance assessment of phase change material integrated cementitious composites in buildings: Experimental and numerical approach. *Appl. Energy*. 2017;207:654-64. https://doi.org/10.1016/j.apenergy.2017.05.144
38. Dabous SA, Ibrahim T, Shareef S, et al. Sustainable façade cladding selection for buildings in hot climates based on thermal performance and energy consumption. *Results Eng.* 2022;16:100643. https://doi.org/10.1016/j.rineng.2022.100643
39. Abu-Jdayil B, Mourad AH, Hittini W, et al. Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Constr. Build. Mater.* 2019 Jul 30;214:709-35. https://doi.org/10.1016/j.conbuildmat.2019.04.102
40. Schwarzkopf MJ, Burnard MD. Wood-Plastic Composites-Performance and Environmental Impacts. In: Kutnar, A., Muthu, S. (eds) Environmental Impacts of Traditional and Innovative Forest-based Bioproducts. Environmental Footprints and Eco-design of Products and Processes. Springer, Singapore. 2016:19-43. https://doi.org/10.1007/978-981-10-0655-5_2

 

41. Zhang W, Xu J. Advanced lightweight materials for Automobiles: A review. *Mater. Des.* 2022;221:110994. https://doi.org/10.1016/j.matdes.2022.110994
42. Mohanty AK, Vivekanandhan S, Tripathi N, et al. Sustainable composites for lightweight and flame retardant parts for electric vehicles to boost climate benefits: A perspective. *Compos. C: Open Access.* 2023;12:100380. https://doi.org/10.1016/j.jcomc.2023.100380
43. Agarwal J, Sahoo S, Mohanty S, et al. Progress of novel techniques for lightweight automobile applications through innovative eco-friendly composite materials: A review. *J. Thermoplast. Compos. Mater.* 2020;33(7):978-1013. https://doi.org/10.1177/0892705718815530
44. Rajak DK, Pagar DD, Behera A, et al. Role of composite materials in automotive sector: potential applications. *Adv. Eng. Tribol.* 2022:193-217. https://doi.org/10.1007/978-981-16-8337-4_10
45. Căşeriu B, Blaga P. Automotive comfort: State of the art and challenges. InInternational Conference Interdisciplinarity in Engineering 2022 Oct 6 (pp. 375-387). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-22375-4_30
46. Nguyen SN, Millereux A, Pouyat A, et al. Conceptual multifunctional design, feasibility and requirements for structural power in aircraft cabins. *J. Aircr.* 2021;58(3):677-87. https://doi.org/10.2514/1.C036205
47. Ranasinghe K, Guan K, Gardi A, et al. Review of advanced low-emission technologies for sustainable aviation. *Energy*. 2019;188:115945. https://doi.org/10.1016/j.energy.2019.115945
48. Uddin F. Flame-retardant fibrous materials in an aircraft. *J. Ind. Text.* 2016;45(5):1128-69. https://doi.org/10.1177/1528083714540700
49. Karthikeyan N, Anand RB, Suthakar T, et al. Materials, innovations and future research opportunities on wind turbine blades-insight review. *Environ. Prog. Sustain. Energy.* 2019;38(3):e13046. https://doi.org/10.1002/ep.13046
50. Tong, C. (2019). Materials-Based Solutions to Solar Energy System. In: Introduction to Materials for Advanced Energy Systems. Springer, Cham. https://doi.org/10.1007/978-3-319-98002-7_4
51. Quaranta E, Davies P. Emerging and innovative materials for hydropower engineering applications: Turbines, bearings, sealing, dams and waterways, and ocean power. *Engineering*. 2022;8:148-58. https://doi.org/10.1016/j.eng.2021.06.025
52. Okolie JA, Nanda S, Dalai AK, et al. Chemistry and specialty industrial applications of lignocellulosic biomass. *Waste Biomass Valor.* 2021;12:2145-69. https://doi.org/10.1007/s12649-020-01123-0
53. Tong, C. (2019). Advanced materials enable renewable geothermal energy capture and generation. In: Introduction to Materials for Advanced Energy Systems. Springer, Cham. 2019:321-77. https://doi.org/10.1007/978-3-319-98002-7_5
54. Renzi E, Michele S, Zheng S, et al. Niche applications and flexible devices for wave energy conversion: A review. *Energies*. 2021 Oct 12;14(20):6537. https://doi.org/10.3390/en14206537
55. Fang H, Bai Y, Liu W, et al. Connections and structural applications of fibre reinforced polymer composites for civil infrastructure in aggressive environments. *Compos. B: Eng.* 2019;164:129-43. https://doi.org/10.1016/j.compositesb.2018.11.047
56. Marques AC, Mocanu A, Tomić NZ, et al. Review on adhesives and surface treatments for structural applications: Recent developments on sustainability and implementation for metal and composite substrates. *Materials*. 2020;13(24):5590. https://doi.org/10.3390/ma13245590
57. Yang Y, Boom R, Irion B, et al. Recycling of composite materials. *Chem. Eng. Process.: Process Intensif.* 2012;51:53-68. https://doi.org/10.1016/j.compositesa.2013.02.009
58. Witik RA, Teuscher R, Michaud V, et al. Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. *Compos. - A: Appl. Sci. Manuf.* 2013;49:89-99. https://doi.org/10.1016/j.compositesa.2013.02.009
59. Das O, Babu K, Shanmugam V, et al. Natural and industrial wastes for sustainable and renewable polymer composites. *Renew. Sustain. Energy Rev.* 2022;158:112054. https://doi.org/10.1016/j.rser.2021.112054
60. Dewick P, Miozzo M. Sustainable technologies and the innovation-regulation paradox. *Futures*. 2002;34(9-10):823-40. https://doi.org/10.1016/S0016-3287(02)00029-0

 

61. Meng F, Olivetti EA, Zhao Y, et al. Comparing life cycle energy and global warming potential of carbon fiber composite recycling technologies and waste management options. *ACS Sustain. Chem. Eng*. 2018;6(8):9854-65. https://doi.org/10.1021/acssuschemeng.8b01026
62. Sahu P, Gupta MK. A review on the properties of natural fibres and its bio-composites: Effect of alkali treatment. *Proc. Inst. Mech. Eng. Pt. L J. Mater. Des. Appl*. 2020;234(1):198-217. https://doi.org/10.1177/1464420719875163
63. Balasubramanian M. Composite materials and processing. Boca Raton: CRC press; 2014.
64. Lotfi A, Li H, Dao DV, et al. Natural fiber–reinforced composites: A review on material, manufacturing, and machinability. *J. Thermoplast. Compos. Mater.* 2021;34(2):238-84. https://doi.org/10.1177/0892705719844546
65. Wan L, Ismail Y, Sheng Y, et al. A review on micromechanical modelling of progressive failure in unidirectional fibre-reinforced composites. *Compos. C: Open Access.* 2023;10:100348. https://doi.org/10.1016/j.jcomc.2023.100348
66. Branfoot C, Folkvord H, Keith M, et al. Recovery of chemical recyclates from fibre-reinforced composites: A review of progress. *Polym. Degrad. Stab.* 2023:110447. https://doi.org/10.1016/j.polymdegradstab.2023.110447
67. Vogiantzi C, Tserpes K. A preliminary investigation on a water and acetone based solvolysis recycling process for CFRPs. *Materials*. 2024;17(5):1102. https://doi.org/10.3390/ma17051102
68. Qazi H, Lin R, Jayaraman K. Fibre structure preservation in composite recycling using thermolysis process. *Resour. Conserv. Recycl.* 2021;169:105482. https://doi.org/10.1016/j.resconrec.2021.105482
69. Xu M, Yang J, Ji H, et al. Recovering high-quality glass fibers from end-of-life wind turbine blades through swelling-assisted low-temperature pyrolysis. *Waste Manag.* 2024;187:179-87. https://doi.org/10.1016/j.wasman.2024.07.020
70. Wiśniewska P, Haponiuk JT, Colom X, et al. Green approaches in rubber recycling technologies: present status and future perspective. *ACS Sustain. Chem. Eng.* 2023;11(24):8706-26. https://doi.org/10.1021/acssuschemeng.3c01314
71. Wei Y, Hadigheh SA. Development of an innovative hybrid thermo-chemical recycling method for CFRP waste recovery. *Compos. B Eng.* 2023;260:110786. https://doi.org/10.1016/j.compositesb.2023.110786
72. Araujo-Andrade C, Bugnicourt E, Philippet L, et al. Review on the photonic techniques suitable for automatic monitoring of the composition of multi-materials wastes in view of their posterior recycling. *Waste Manag. Res*. 2021;39(5):631-51.

 