ENGINEERING
FOR A SUSTAINABLE
TOMORROW

INNOVATION
EFFICIENCY
RESILIENCE
CIRCULARITY

Sustainable Engineering Technologies for Industrial Innovation

EDITED VOLUME

EDITOR
Prof. Dr. Mehmet Çevik

2026

PEOPLE
TECHNOLOGY
INDUSTRY
A CLEANER
TOMORROW

DUVAR
Duvar Publications

CLEANER
SMARTER
STRONGER
TOGETHER

Sustainable Engineering Technologies for Industrial Innovation

Prof. Dr. Mehmet Çevik
Editor

September, 2026

Sustainable Engineering Technologies for Industrial Innovation

Editor: Prof. Dr. Mehmet Çevik

General Director: Berkan Balpetek

Cover and Page Design: Duvar Design

Printing : September-2026

Publisher Certificate No: 49837

E-ISBN: 978-625-8936-74-2

853 Sokak No:13 P.10 Kemeraltı-Konak/İzmir

Tel: 0 232 484 88 68

www.duvaryayinlari.com

duvarkitabevi@gmail.com

Preface

The accelerating transformation of industry is increasingly shaped by the need to reconcile technological advancement with environmental responsibility, resource efficiency, resilience, safety, and human-centered design. Sustainable Engineering Technologies for Industrial Innovation brings together a multidisciplinary collection of studies addressing these priorities through advanced materials, manufacturing technologies, digital engineering, biomedical design, food microbiology, and sustainable construction.

The volume opens with an examination of energy-efficient biocomposite manufacturing and its contribution to sustainable industrial development. It then considers ceramic–metal composite armors from the perspectives of ballistic principles, protective mechanisms, and structural design concepts. Biomedical engineering is represented through a patient-specific orthosis design for clubfoot syndrome based on reverse engineering, demonstrating the role of digital design and customized manufacturing in individualized healthcare applications.

Digitalization and lifecycle-oriented engineering are explored through a review of digital twin applications in composite structures, with emphasis on modeling, monitoring, and lifecycle integration. Sustainability in advanced transportation systems is addressed through a comprehensive assessment of composite structures in aviation and space, covering lightweight design, manufacturing, repair, and circular end-of-life strategies. The scope of the book also extends to food microbiology through a chapter examining bacterial identification methods from conventional approaches to modern techniques.

Advanced manufacturing and composite-material applications form another important theme of the volume. The performance of polyamide composite bolts produced by material extrusion-based additive manufacturing is investigated, illustrating the potential of polymer composites in functional engineering components. This is followed by the design and manufacturing of biocomposite cervical orthoses, which combines materials engineering with biomedical application. The impact behavior of hybrid composites is then examined, contributing to the understanding of their mechanical response under dynamic loading.

The final chapter broadens the sustainability perspective to the built environment through a review of bio-based brick technologies. It integrates biological and bio-derived materials, processing routes, engineering performance, durability, thermal behavior, lifecycle considerations, and sustainability, highlighting the potential of emerging brick technologies for lower-impact construction.

These contributions demonstrate that sustainable industrial innovation does not arise from a single material, technology, or discipline. Rather, it develops through the integration of material efficiency, lifecycle thinking, digitalization, advanced manufacturing, safety, biological resources, and application-oriented engineering. This volume is intended to provide researchers, engineers, students, and practitioners with current perspectives and practical insights into these interconnected areas of sustainable engineering.

Prof. Dr. Mehmet Çevik
Editor
September, 2026

Table of Contents

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 1-24.

1

Energy-Efficient Biocomposite Manufacturing for Sustainable Industrial Development

Mehmet Çevik[1]*

İzmir Kâtip Çelebi University, Department of Mechanical Engineering, İzmir, Türkiye

**Corresponding author:* mehmet.cevik@ikcu.edu.tr

Abstract

Energy efficiency has become a critical component of sustainable manufacturing due to its influence on resource utilization, production costs, environmental performance, and climate-change mitigation. Within this context, biocomposites have emerged as promising alternatives to conventional petroleum-based materials because of their renewable origins, reduced environmental impacts, and compatibility with circular economy strategies. This study reviews the role of energy efficiency in biocomposite manufacturing from a life-cycle perspective, encompassing raw material production, manufacturing processes, transportation, end-of-life management, and sustainability assessment. Key indicators, including Specific Energy Consumption, energy intensity, energy productivity, resource efficiency, carbon intensity, and circularity metrics, are discussed as quantitative tools for evaluating manufacturing performance. The study further examines engineering approaches for improving energy efficiency through material design, process optimization, additive manufacturing, recycling, and circular manufacturing practices. In addition, the contributions of advanced digital technologies, including artificial intelligence, machine learning, digital twins, and the Industrial Internet of Things, are reviewed in the context of energy monitoring, prediction, optimization, and intelligent decision-making. Based on the reviewed literature, a quantitative and SDG-oriented integrated framework is proposed that combines manufacturing performance indicators, digital technologies, life-cycle assessment, and circular economy principles within a unified sustainability architecture. The proposed framework provides a practical basis for evaluating and optimizing sustainable biocomposite manufacturing systems while supporting progress toward Sustainable Development Goals 7, 9, 12, and 13.

Keywords: Energy efficiency; Biocomposites; Sustainable manufacturing; Life cycle assessment; Artificial intelligence; Circular economy; Sustainable Development Goals

1. Introduction

Energy is a fundamental driver of economic development, industrial production, and societal well-being. However, rapid industrialization, urbanization, and growing consumption have substantially increased

[1] https://orcid.org/0000-0002-6366-5566

global energy demand, while continued reliance on fossil fuels has intensified concerns related to greenhouse gas emissions, climate change, and resource depletion.

In response, energy efficiency has emerged as a key strategy for sustainable development because it reduces energy consumption, lowers production costs, and mitigates environmental impacts. Consequently, governments, industries, and international organizations increasingly regard energy efficiency as a cornerstone of sustainable energy and climate policies.

Manufacturing is among the largest energy-consuming sectors, requiring significant thermal and electrical energy for material processing and production activities. Thus, improving energy efficiency has become a major objective in the transition toward sustainable manufacturing, which seeks to enhance resource utilization, reduce waste, and minimize environmental impacts throughout the product life cycle.

Within this context, biocomposites have attracted growing attention as sustainable alternatives to conventional petroleum-based materials. Produced from natural fibers, bio-based polymers, or waste-derived resources, biocomposites offer potential benefits including reduced dependence on non-renewable resources, lower carbon footprints, and greater compatibility with circular economy strategies. The integration of energy-efficient manufacturing practices with biocomposite technologies therefore represents a promising pathway toward achieving sustainable industrial development and supporting key Sustainable Development Goals (SDGs) related to clean energy, responsible production, industrial innovation, and climate action.

Growing concerns over fossil resource depletion, greenhouse gas emissions, and plastic waste have accelerated the search for sustainable alternatives to conventional petroleum-based composites. Although synthetic composites offer excellent performance in many industrial applications, their production often relies on non-renewable resources and energy-intensive manufacturing processes. Consequently, biocomposites have emerged as promising materials that combine polymer matrices with natural fibers, agricultural residues, or other renewable resources to reduce environmental impacts while maintaining functional performance (Mann et al., 2020; Naik et al., 2022; Deepthi et al., 2026).

Natural fibers such as hemp, flax, kenaf, sisal, and jute have attracted significant attention due to their low density, renewability, biodegradability, and relatively low embodied energy. Similarly, bio-based polymers such as polylactic acid (PLA) provide renewable alternatives to conventional plastics and have demonstrated suitability for applications ranging from packaging and construction to additive manufacturing. The incorporation of agricultural and industrial by-products into biocomposite systems further enhances resource efficiency by supporting waste valorization and circular economy principles (Elfaleh et al., 2023; Tomec et al., 2024).

Despite their potential advantages, biocomposites are not inherently sustainable. Their overall environmental performance depends on factors such as raw material sourcing, processing requirements, transportation, manufacturing technologies, and end-of-life management. Therefore, comprehensive life-cycle assessments are essential to determine whether the benefits associated with renewable feedstocks outweigh the energy and environmental impacts generated throughout the product life cycle (Ead et al., 2021; Fitzgerald et al., 2021; Pamakštys et al., 2026).

Energy efficiency has evolved from a traditional operational concern into a strategic objective that directly influences economic competitiveness, environmental performance, and industrial sustainability. Rising energy costs, regulatory pressures, and global decarbonization targets have intensified efforts to reduce energy consumption while maintaining productivity and product quality. As a result, energy efficiency is increasingly recognized as a key pathway toward sustainable industrial development and climate-change mitigation (Koçaslan, 2022; Renna & Materi, 2021).

Manufacturing systems represent a major opportunity for energy-efficiency improvements because industrial activities consume substantial amounts of energy throughout material processing, transportation, heating, cooling, and assembly operations. Recent advances associated with Industry 4.0 have expanded traditional energy-management approaches through the adoption of artificial intelligence (AI), machine learning (ML), digital twins (DTs), and intelligent monitoring systems. These technologies enable real-time energy monitoring, predictive analysis, process optimization, and data-driven decision-making, thereby enhancing manufacturing efficiency and sustainability performance (Mao et al., 2021; Zekići-Sušac et al., 2021; Bermeo-Ayerbe et al., 2022).

Within biocomposite manufacturing, energy efficiency is particularly important because the sustainability of bio-based materials depends not only on renewable feedstocks but also on the efficiency of the processes used to produce them. Excessive energy consumption during manufacturing can diminish the environmental advantages of biocomposites, highlighting the need for integrated strategies that combine energy efficiency, renewable energy utilization, and circular manufacturing principles. Consequently, manufacturing systems with improved energy performance play a central role in realizing the full sustainability potential of biocomposite materials and supporting broader sustainable development objectives.

2. Energy Efficiency as a Catalyst for SDGs

The SDGs provide a global framework for addressing challenges related to energy, industrial development, resource utilization, and climate change. Among these goals, SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) are particularly relevant to manufacturing systems. Energy efficiency plays a central role in advancing these objectives because it simultaneously reduces energy demand, improves resource utilization, lowers environmental impacts, and supports sustainable industrial development (Taşkın et al., 2025; Koçaslan, 2022; Zakari et al., 2022).

Recent advances in Industry 4.0 technologies have further strengthened the relationship between energy efficiency and sustainable manufacturing. These technologies enable intelligent monitoring, predictive analysis, and process optimization, thereby improving operational performance while reducing energy consumption and emissions (Abadi et al., 2025; Bermeo-Ayerbe et al., 2022; Yenioğlu & Belge, 2022).

Within this context, biocomposite manufacturing provides a particularly relevant case study because it combines renewable materials, circular economy principles, and opportunities for improving energy and environmental performance throughout the product life cycle. Consequently, understanding the contribution of energy-efficient manufacturing to SDGs 7, 9, 12, and 13 is essential for developing sustainable industrial systems. The following subsections examine these relationships in greater detail.

2.1. SDG 7: Affordable and Clean Energy

SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy while promoting substantial improvements in global energy efficiency. Among its targets, SDG 7.3 specifically emphasizes increasing the global rate of energy-efficiency improvement. Within the manufacturing sector, achieving this objective requires the adoption of technologies and practices capable of reducing energy consumption without compromising productivity and product quality. Sustainable production systems, process optimization strategies, renewable energy integration, and intelligent energy-management technologies are therefore essential contributors to SDG 7. Recent studies have demonstrated that improvements in industrial energy efficiency can significantly reduce energy demand while simultaneously lowering operational costs and environmental impacts (Koçaslan, 2022; Zakari et al., 2022). Furthermore, the integration of renewable energy systems with advanced industrial processes has been identified as a promising pathway toward achieving cleaner and more sustainable production systems (Elbir, 2024; Bespalyy, 2023).

2.2. SDG 9: Industry, Innovation and Infrastructure

SDG 9 promotes sustainable industrialization, technological innovation, and resilient infrastructure development. The ongoing transition toward Industry 4.0 has accelerated the adoption of digital technologies capable of enhancing manufacturing efficiency and sustainability. AI, ML, DTs, and Industrial Internet of Things (IIoT) technologies enable real-time monitoring, predictive analytics, adaptive control, and intelligent decision-making, thereby improving both operational and energy performance. Recent research highlights the growing role of AI-driven manufacturing systems in addressing energy-related challenges through predictive modeling, process optimization, and automated energy management (Küçüktüvek & Altay, 2025; Abadi et al., 2025). Similarly, DT technologies have demonstrated significant potential for improving energy efficiency through virtual simulation, performance monitoring, and process optimization (Bermeo-Ayerbe et al., 2022). Consequently, innovation-driven manufacturing systems contribute directly to the objectives of SDG 9 while simultaneously supporting broader sustainability goals.

2.3. SDG 12: Responsible Consumption and Production

SDG 12 focuses on sustainable resource management, waste reduction, and responsible production and consumption patterns. Energy efficiency plays a central role in achieving these objectives because reduced energy consumption is often accompanied by improved material utilization, lower waste generation, and enhanced process efficiency. The emergence of biocomposites aligns closely with SDG 12 due to their reliance on renewable resources, agricultural residues, natural fibers, and recyclable materials. Numerous studies have emphasized the importance of circular economy strategies, waste valorization, recycling technologies, and sustainable material selection in reducing environmental burdens throughout product life cycles (Gültaş, 2024; Das et al., 2022; Shanmugam et al., 2021). In addition, life cycle assessment studies indicate that responsible material choices and efficient manufacturing practices can significantly improve both resource efficiency and environmental performance (Hermansson et al., 2019; Operato et al., 2023; Chen et al., 2024; Fitzgerald et al., 2021; Çevik & Diambu, 2024). So, the development of sustainable biocomposite production systems represents a practical approach to advancing the objectives of SDG 12.

2.4. SDG 13: Climate Action

Climate change remains one of the most significant global challenges facing modern society. SDG 13 calls for urgent action to combat climate change and mitigate its impacts through reductions in greenhouse gas emissions and the promotion of sustainable technologies. Because industrial energy consumption is a major source of carbon emissions, improving energy efficiency constitutes one of the most effective mechanisms for climate-change mitigation. Research consistently demonstrates that reductions in energy consumption are often accompanied by reductions in carbon footprints, particularly when combined with renewable energy adoption and sustainable manufacturing practices (Tariq et al., 2022; Türköz, 2025). Moreover, life cycle assessment studies increasingly reveal that energy-efficient production systems can generate environmental benefits throughout the entire product life cycle, from raw material extraction to end-of-life management (Pamakštys et al., 2026). Accordingly, energy-efficient biocomposite manufacturing contributes not only to industrial sustainability but also to broader climate-action objectives by supporting the transition toward lower-carbon production systems.

3. Energy Efficiency Metrics for Biocomposite Manufacturing

3.1. Fundamentals of Energy Efficiency in Manufacturing Systems

Energy efficiency is a key performance indicator in modern manufacturing because of its direct influence on economic competitiveness, resource utilization, and environmental sustainability. Manufacturing systems consume energy through material preparation, processing, transportation, heating, cooling, and auxiliary operations, making effective energy management essential for reducing costs and environmental impacts. Energy use may be broadly categorized as direct consumption associated with production processes and indirect consumption related to supporting activities. In biocomposite manufacturing, energy efficiency is particularly important because the sustainability benefits of renewable materials can be diminished by energy-intensive production processes. Consequently, quantitative energy-performance indicators are required to evaluate and optimize manufacturing sustainability (Sapuan et al., 2025; Renna & Materi, 2021; Ohenhen et al., 2024).

3.2. Specific Energy Consumption (SEC)

SEC is one of the most widely used indicators for evaluating energy efficiency in manufacturing systems. It represents the amount of energy required to produce a unit mass, volume, or quantity of product and provides a straightforward measure of manufacturing energy performance. Because SEC normalizes energy consumption with respect to production output, it enables meaningful comparisons among different manufacturing processes, materials, production scales, and technological alternatives.

In manufacturing applications, SEC is generally expressed as

$$\text{SEC} = \frac{\text{Total Energy Consumption}}{\text{Quantity of Product Produced}} = \frac{E_{total}}{Q} \tag{1}$$

where E_{total} denotes the total energy consumed during the manufacturing process and Q represents the amount of product produced. Depending on the application, SEC may be reported in units such as kWh/kg, MJ/kg, kWh/m^3, or $kWh/unit\ product$.

The popularity of SEC stems from its simplicity and practical relevance. Unlike total energy consumption, which depends strongly on production volume, SEC provides a normalized indicator that allows manufacturers to assess process efficiency independently of production scale. Lower SEC values generally indicate more efficient manufacturing systems because less energy is required to produce each unit of output.

From a manufacturing perspective, total energy consumption typically consists of several components:

$$E_{total} = E_{processing} + E_{heating} + E_{cooling} + E_{auxiliary} \tag{2}$$

where:

- $E_{processing}$ represents energy directly used for material processing,
- $E_{heating}$ denotes thermal energy requirements,
- $E_{cooling}$ corresponds to cooling and thermal regulation energy,
- $E_{auxiliary}$ includes supporting energy demands such as compressed air, lighting, ventilation, sensors, and control systems.

The relative contribution of these components varies significantly depending on the manufacturing technology employed. For example, extrusion and injection molding processes often exhibit substantial thermal energy demands due to material melting requirements, whereas mechanical processing operations may be dominated by motor power consumption and machine-tool interactions.

For continuous manufacturing operations, SEC may also be expressed in terms of production rate:

$$\text{SEC} = \frac{P}{\dot{m}} \tag{3}$$

where P is the average power consumption of the manufacturing system and $\dot{m}$ is the material throughput rate. Equation (3) highlights an important characteristic of industrial production: increasing throughput often reduces SEC because fixed energy expenditures are distributed over a larger amount of product. This relationship explains why process optimization strategies frequently aim to increase production efficiency while minimizing energy consumption.

In biocomposite manufacturing, SEC has become particularly important because sustainability assessments increasingly require evaluation of both environmental and energy performance. While biocomposites are frequently promoted as environmentally preferable alternatives to conventional composites, their overall sustainability depends not only on the use of renewable materials but also on the efficiency of the manufacturing processes used to produce them. Energy-intensive processing can significantly influence environmental outcomes and may partially offset the benefits associated with renewable feedstocks (Ghomi et al., 2021).

Several factors influence SEC in biocomposite production systems. Material characteristics such as fiber type, fiber loading, moisture content, particle size distribution, and matrix properties can affect processing energy requirements. Process variables including temperature settings, screw speed, injection pressure, residence time, and production throughput also play important roles in determining overall energy demand. Consequently, SEC is not solely a machine-dependent parameter but rather the result of complex interactions between material properties and process conditions.

Additive manufacturing studies further illustrate the usefulness of SEC as an energy-efficiency indicator. Research has shown that printing parameters such as layer height, infill density, printing speed, and material selection can significantly affect energy consumption per unit product. In some cases, optimized process parameters have reduced specific energy consumption by more than 50%, highlighting the importance of process optimization in sustainable manufacturing systems (Garcia et al., 2018; Fontana et al., 2025; Klejnowska et al., 2026).

Beyond individual processes, SEC is increasingly used within broader sustainability frameworks and life cycle assessment studies. By linking energy consumption directly to product output, SEC provides a bridge between manufacturing performance and environmental indicators such as carbon footprint, greenhouse gas emissions, and resource efficiency. As a result, SEC serves not only as a technical measure of manufacturing efficiency but also as an important indicator for evaluating progress toward sustainable production and energy-related SDGs.

For these reasons, SEC is adopted in this study as one of the primary indicators for assessing and comparing the energy performance of biocomposite manufacturing systems. Subsequent sections further examine how SEC interacts with resource efficiency, carbon intensity, digital optimization technologies, and circular manufacturing strategies to support sustainable industrial development.

3.3. Energy Intensity and Energy Productivity Indicators

While Specific Energy Consumption provides a direct measure of the energy required to manufacture a unit of product, additional indicators are often needed to evaluate manufacturing performance from broader economic and sustainability perspectives. Among the most widely adopted metrics are energy intensity and energy productivity, which provide complementary views of energy utilization within industrial systems.

Energy intensity measures the amount of energy required to generate a unit of economic output. In manufacturing applications, it can be expressed as

$$EI = \frac{E_{total}}{V_{production}} \tag{4}$$

where E_{total} is the total energy consumption and $V_{production}$ denotes the economic value of production. Lower energy-intensity values generally indicate more energy-efficient manufacturing operations.

The inverse concept is energy productivity, which measures the economic output generated per unit of energy consumed:

$$EP = \frac{V_{production}}{E_{total}} \tag{5}$$

Higher energy productivity indicates more effective utilization of energy resources and is often employed in national and industrial energy-efficiency assessments (Zakari et al., 2022).

In addition to economic indicators, manufacturing performance is frequently evaluated using power-based metrics. The average power demand of a production system can be expressed as

$$P_{avg} = \frac{E_{total}}{t_{operation}} \tag{6}$$

where $t_{operation}$ denotes the operating time of the manufacturing process. This indicator is particularly useful for comparing technologies that operate under different production schedules.

For sustainable manufacturing applications, energy indicators should be interpreted together rather than individually. A process may exhibit low specific energy consumption while simultaneously displaying poor energy productivity due to high operating costs or limited production value. Similarly, a highly productive process may still generate substantial environmental impacts if energy sources are carbon intensive. Consequently, contemporary energy-efficiency assessments increasingly combine SEC, energy intensity, and energy productivity within integrated sustainability evaluation frameworks (Renna & Materi, 2021; Tariq et al., 2022).

In biocomposite manufacturing, these indicators provide valuable insights into the trade-offs between material sustainability and manufacturing efficiency. Renewable materials may reduce environmental burdens associated with raw-material extraction, yet their processing requirements can influence energy intensity and overall production performance. Therefore, evaluating biocomposite manufacturing systems requires simultaneous consideration of technical, economic, and environmental dimensions of energy efficiency.

3.4. Resource Efficiency and Material Utilization Metrics

Energy efficiency alone does not provide a complete assessment of manufacturing sustainability. A process may consume relatively little energy while simultaneously generating excessive material waste, low product yields, or inefficient resource utilization. Consequently, resource efficiency has emerged as a complementary performance dimension that evaluates how effectively raw materials are converted into useful products. This perspective is particularly important in biocomposite manufacturing, where renewable feedstocks, natural fibers, and bio-based polymers are often promoted as environmentally preferable alternatives to conventional materials (Das et al., 2022; Lizundia et al., 2022).

One of the most common indicators of resource efficiency is material yield, which quantifies the proportion of input material successfully transformed into final products:

$$MY = \frac{m_{product}}{m_{raw}} \tag{7}$$

where $m_{product}$ represents the mass of the finished product and m_{raw} denotes the total mass of raw materials entering the process. Higher material-yield values indicate more efficient utilization of resources and reduced manufacturing waste.

Closely related to material yield is the material loss ratio:

$$MLR = \frac{m_{waste}}{m_{raw}} \tag{8}$$

where m_{waste} denotes the material discarded during manufacturing. Reducing material losses contributes directly to improved resource efficiency, lower production costs, and reduced environmental impacts.

For sustainable manufacturing systems, resource efficiency is often expressed more generally as

$$RE = \frac{m_{product}}{m_{resource}} \tag{9}$$

where $m_{resource}$ represents the total material resources consumed during production. This indicator provides a broader assessment of how effectively manufacturing systems transform resources into useful outputs and is closely aligned with SDG 12, which emphasizes responsible consumption and production.

$$RR = \frac{m_{recycled}}{m_{waste}} \times 100 \tag{10}$$

where $m_{recycled}$ is the mass of recovered material returned to productive use. High recycling rates reduce demand for virgin raw materials and support circular manufacturing strategies.

These indicators are particularly relevant for biocomposite systems because material selection and end-of-life management significantly influence overall sustainability performance. Numerous studies have demonstrated that agricultural residues, natural fibers, recycled polymers, and bio-based matrices can improve resource utilization while simultaneously reducing environmental burdens (Mojapelo et al., 2025; Shanmugam et al., 2021; Operato et al., 2023; Ortega et al., 2022). Furthermore, waste valorization approaches have shown considerable potential for transforming industrial and agricultural by-products into value-added composite materials, thereby improving both resource efficiency and circularity (Lizundia et al., 2022).

Resource-efficiency indicators become even more meaningful when evaluated together with energy metrics. For example, a manufacturing process may achieve low SEC values yet exhibit poor material yield due to excessive scrap generation. Conversely, a process with slightly higher energy consumption may prove more sustainable if it significantly reduces material losses and increases recyclability. Therefore, comprehensive assessments of biocomposite manufacturing should consider both energy-related and material-related indicators rather than relying on a single performance measure.

As sustainable manufacturing increasingly embraces circular economy principles, resource-efficiency metrics are expected to play an increasingly important role in decision-making. Combined with energy-efficiency indicators, these metrics provide a more complete understanding of manufacturing sustainability and establish a foundation for the integrated assessment frameworks discussed in subsequent sections.

3.5. Carbon Intensity and Environmental Performance Indicators

Although energy efficiency and resource utilization provide valuable insights into manufacturing performance, they do not fully capture the environmental consequences of industrial activities. In recent years, increasing attention has been directed toward carbon intensity and related environmental performance indicators because of their direct connection to climate change, greenhouse gas emissions, and sustainability objectives. As manufacturing industries pursue decarbonization pathways, evaluating environmental performance alongside energy and resource efficiency has become essential for comprehensive sustainability assessment (Tariq et al., 2022; Türköz, 2025).

One of the most widely used indicators is carbon intensity, which measures the amount of carbon dioxide emissions associated with a unit of product output:

$$CI = \frac{CO_2}{Q} \tag{11}$$

where CO_2 denotes total carbon dioxide emissions generated during manufacturing and Q represents the quantity of product produced. Lower carbon-intensity values indicate reduced environmental impacts and improved climate performance.

Because energy consumption is often the primary source of manufacturing emissions, carbon intensity is closely related to energy efficiency. A simplified relationship may be expressed as

$$CO_2 = EF \times E_{total} \tag{12}$$

where EF is the emission factor of the energy source and E_{total} is the total energy consumed. This relationship highlights an important principle: reductions in energy consumption generally contribute to lower emissions, but the magnitude of the reduction also depends on the carbon intensity of the energy supply itself.

To evaluate environmental performance more broadly, manufacturing studies frequently employ indicators derived from Life Cycle Assessment (LCA). Unlike process-level energy metrics, LCA-based indicators consider environmental impacts throughout the entire product life cycle, including raw material extraction, transportation, manufacturing, use, and end-of-life management. Such assessments are particularly important for biocomposites because environmental benefits associated with renewable feedstocks may be influenced by transportation requirements, processing energy demands, and disposal strategies (Walker & Rothman, 2020; Pamakštys et al., 2026).

Among the environmental indicators commonly reported in the literature, Global Warming Potential (GWP) remains one of the most widely used. GWP quantifies the cumulative contribution of greenhouse gases to climate change and is generally expressed in terms of carbon dioxide equivalents. Numerous life-cycle studies have employed GWP to compare conventional composites with bio-based alternatives, often demonstrating that appropriately designed biocomposites can achieve substantial reductions in environmental impacts (Beigbeder et al., 2019; Operato et al., 2023).

Environmental performance can also be expressed through carbon efficiency, which relates useful production output to associated emissions:

$$CE = \frac{Q}{CO_2} \quad (13)$$

Higher carbon-efficiency values indicate that greater amounts of product are generated per unit of carbon emitted and therefore represent improved environmental performance.

For biocomposite manufacturing, environmental assessment is particularly important because sustainability claims are frequently based on the renewable nature of constituent materials. However, f studies have emphasized that renewable feedstocks do not automatically guarantee superior environmental performance. Factors such as agricultural practices, transportation distances, processing conditions, additive usage, and end-of-life scenarios can significantly influence life-cycle impacts (Ead et al., 2021; Chen et al., 2024). Rigorous environmental assessment is necessary to determine whether biocomposite systems deliver genuine sustainability advantages over conventional alternatives.

The integration of carbon-intensity indicators with energy-efficiency and resource-efficiency metrics provides a more comprehensive evaluation of manufacturing sustainability. While energy indicators reveal how efficiently energy is utilized and resource indicators measure material utilization effectiveness, environmental indicators quantify the broader ecological consequences of production activities. These metrics establish multidimensional framework for assessing sustainable manufacturing performance and provide a quantitative basis for linking industrial practices with SDGs 7, 12, and 13.

3.6. Mapping Manufacturing Indicators to SDG Metrics

The manufacturing indicators discussed in the preceding sections can be linked directly to several SDGs, thereby providing a broader sustainability context for evaluating industrial performance. Rather than serving solely as engineering measures, these indicators can also be interpreted as quantitative tools for assessing progress toward sustainable development objectives.

Energy-related indicators such as SEC, energy intensity, and energy productivity are closely associated with SDG 7, particularly Target 7.3, which emphasizes improvements in energy efficiency. Lower SEC and energy-intensity values indicate more efficient utilization of energy resources, while higher energy productivity reflects greater economic value generated per unit of energy consumed (Zakari et al., 2022).

Resource-efficiency indicators, including material yield and recycling rate, contribute directly to SDG 12. These metrics evaluate how effectively raw materials are utilized and how successfully waste streams are reintegrated into production systems. Consequently, they provide practical measures of circularity and sustainable resource management (Das et al., 2022; Lizundia et al., 2022). Carbon intensity and carbon efficiency support SDG 13 by quantifying the environmental consequences of manufacturing activities. Reductions in carbon intensity generally indicate lower greenhouse-gas emissions and improved environmental performance throughout product life cycle (Tariq et al., 2022).

In addition, the adoption of advanced technologies aligns with SDG 9 through enhanced industrial efficiency, technological innovation, and sustainable production practices (Abadi et al., 2025). Table 1 summarizes the relationships between the principal manufacturing indicators and the SDGs considered.

Table 1. Relationship between manufacturing indicators and SDGs

Indicator	Primary SDG
SEC	SDG 7
Energy Intensity	SDG 7
Energy Productivity	SDG 7
Material Yield	SDG 12
Resource Efficiency	SDG 12
Recycling Rate	SDG 12
Carbon Intensity	SDG 13
Carbon Efficiency	SDG 13

4. Energy Consumption across the Biocomposite Life Cycle

4.1. Life Cycle Assessment (LCA) Frameworks

LCA is a widely used methodology for evaluating the environmental performance of products and manufacturing systems throughout their life cycles. In biocomposite manufacturing, LCA is particularly important because sustainability depends not only on renewable feedstocks but also on the energy and environmental impacts associated with material production, transportation, manufacturing, use, and end-of-life management (Walker & Rothman, 2020; Ead et al., 2021). A typical LCA study consists of four stages: goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, and interpretation. Depending on the objectives of the study, different system boundaries may be employed to evaluate energy consumption and environmental performance across the product life cycle (Çevik, 2025; Beigbeder et al., 2019).

4.1.1. Cradle-to-Gate Assessment

Cradle-to-gate assessment evaluates environmental impacts from raw material extraction and acquisition through manufacturing, ending when the finished product leaves the factory gate. This approach is widely used in industrial studies because it focuses on stages directly controlled by manufacturers and requires less data than full life-cycle analyses. In biocomposite research, cradle-to-gate assessments are commonly employed to compare the embodied energy, carbon footprint, and resource requirements of bio-based and conventional materials. Such studies often identify raw material production and manufacturing processes as the dominant contributors to energy consumption and environmental impacts (Beigbeder et al., 2019; Ghomi et al., 2021; Äkräs et al., 2024).

4.1.2. Cradle-to-Grave Assessment

Cradle-to-grave assessment extends the system boundary beyond manufacturing to include product distribution, use, maintenance, and end-of-life treatment. This approach provides a more comprehensive evaluation of sustainability by capturing impacts that occur throughout the entire life cycle of a product. For biocomposites, cradle-to-grave analyses are particularly important because environmental benefits achieved during manufacturing may be enhanced or diminished by transportation requirements, service-life performance, recyclability, and disposal methods. Consequently, this framework is frequently used to evaluate the overall sustainability of bio-based materials relative to conventional alternatives.

4.1.3. Circular Life Cycle Models

Circular life cycle models, often referred to as cradle-to-cradle approaches, incorporate recycling, reuse, remanufacturing, and material recovery into the assessment framework. Unlike linear life-cycle models that terminate at product disposal, circular models view waste streams as potential resources that can be reintroduced into production systems. This perspective aligns closely with circular economy principles and SDG 12, which emphasizes responsible consumption and production. In the context of biocomposite manufacturing, circular life cycle models are increasingly applied to evaluate the benefits of recycled polymers, agricultural residues, waste valorization strategies, and closed-loop material systems, thereby providing a more holistic understanding of long-term sustainability performance (Das et al., 2022).

4.2. Energy Demand during Raw Material Production

Raw material production is the first major stage of the biocomposite life cycle and often accounts for a substantial share of total embodied energy. Energy consumption arises from feedstock cultivation, harvesting, extraction, transportation, and processing. Although biocomposites are generally viewed as environmentally favorable alternatives to conventional composites, their overall sustainability depends strongly on the energy requirements of raw material production. Consequently, evaluating the energy demand associated with natural fibers, bio-based polymers, and waste-derived feedstocks is essential for assessing the life-cycle energy performance of biocomposite systems (Beigbeder et al., 2019).

4.2.1. Natural Fibers

Natural fibers such as hemp, flax, jute, kenaf, sisal, and cellulose-based reinforcements are among the most widely used constituents of biocomposites. Compared with conventional reinforcements such as glass fibers, natural fibers generally require less processing energy because they originate from renewable biological resources and often undergo less energy-intensive extraction and preparation procedures. Nevertheless, energy demand can vary considerably depending on agricultural practices, irrigation requirements, fertilizer use, harvesting methods, fiber extraction technologies, and transportation distances. While numerous studies report lower embodied energy for natural fibers than for synthetic reinforcements, the overall environmental benefits depend on efficient cultivation and processing systems that minimize energy inputs throughout the supply chain (Abdur Rahman et al., 2023; Elfaleh et al., 2023; Naik et al., 2022).

4.2.2. Bio-Based Polymers

Bio-based polymers constitute the matrix phase of many modern biocomposites and are increasingly used as alternatives to petroleum-derived plastics. Among these materials, PLA has attracted particular attention because it is produced from renewable feedstocks and exhibits favorable processing characteristics. Despite their renewable origin, bio-based polymers still require substantial energy inputs during feedstock conversion, polymerization, purification, and material preparation. The energy performance of these materials therefore depends not only on their biological source but also on the efficiency of industrial production processes. Recent studies indicate that bio-based polymers can offer environmental advantages over conventional plastics; however, such benefits are highly sensitive to production technologies, energy sources, and system boundaries considered in life-cycle assessments (Kanematsu et al., 2025; Tomec et al., 2024; Rabbi et al., 2026).

4.2.3. Agricultural and Industrial Waste Feedstocks

Agricultural residues and industrial by-products have emerged as attractive feedstocks for sustainable biocomposite production because they reduce reliance on virgin resources while promoting circular economy principles. Materials such as crop residues, food-processing waste, forestry by-products, and recycled polymers can often be incorporated into composite systems with relatively limited additional resource extraction. Since these materials already exist as waste streams, their embodied energy is frequently lower than that of newly produced raw materials. However, energy requirements associated with collection, sorting, cleaning, transportation, and processing must still be considered. Numerous studies have shown that waste-derived feedstocks can significantly improve both resource efficiency and environmental performance, particularly when integrated into closed-loop manufacturing systems and waste-valorization strategies (Fatchurrohman & Yetrina, 2025).

4.3. Energy Demand during Manufacturing Processes

Manufacturing processes represent one of the most energy-intensive stages of the biocomposite life cycle and strongly influence the overall energy performance of the final product. Energy consumption depends on factors such as process type, operating conditions, material characteristics, production scale, and equipment efficiency. In biocomposite manufacturing, thermal energy is required for material softening, melting, curing, and consolidation, while mechanical energy is consumed by motors, presses, pumps, and auxiliary systems. Because these operations are directly controllable, manufacturing offers significant opportunities for energy optimization and sustainability improvement (Renna & Materi, 2021; Operato et al., 2023). The most widely used biocomposite manufacturing processes include extrusion, injection molding, compression molding, and thermoforming.

4.3.1. Extrusion

Extrusion is widely used for manufacturing biocomposite pellets, profiles, sheets, and precursor materials. In this process, polymer matrices and reinforcements are conveyed, mixed, melted, and homogenized within a heated barrel before being forced through a die. Energy consumption arises primarily from barrel heating and screw rotation, with the relative contributions of thermal and mechanical energy depending on processing temperature, screw speed, throughput rate, material viscosity, and fiber loading. Studies indicate that excessive temperatures and screw speeds can increase energy demand without improving product quality, making process optimization one of the most effective strategies for reducing specific energy consumption in extrusion-based biocomposite manufacturing (Ghomi et al., 2021; Fontana et al., 2025).

4.3.2. Injection Molding

Injection molding is widely used to produce complex biocomposite components with high dimensional accuracy and repeatability. The process involves melting the composite material, injecting it into a mold cavity, and cooling the part prior to ejection. Energy consumption is dominated by material melting, injection pressure generation, mold temperature control, and cooling operations, with heating and cooling often accounting for a substantial share of total demand. Consequently, parameters such as melt temperature, injection pressure, cycle time, and mold design strongly influence energy efficiency. Optimized processing conditions and energy-efficient molding systems can significantly reduce energy consumption while maintaining product performance (Curto et al., 2021).

4.3.3. Compression Molding

Compression molding is frequently used for manufacturing natural-fiber-reinforced composites, particularly in automotive, construction, and structural applications. In this process, composite material is placed within a heated mold and consolidated under pressure until the desired shape is achieved. Compared with some alternative manufacturing techniques, compression molding often requires relatively simple equipment and can process large components efficiently. Nevertheless, significant energy consumption may arise from mold heating, pressure generation, and curing operations. The overall energy demand is strongly influenced by processing temperature, molding pressure, curing duration, and material composition. Several studies have reported that careful optimization of curing cycles and temperature profiles can improve energy efficiency while preserving mechanical properties (Abdur Rahman et al., 2023; Naik et al., 2022).

4.3.4. Thermoforming

Thermoforming is commonly employed for shaping thermoplastic sheets into finished products through controlled heating and forming operations. The process typically involves heating a sheet material above its softening temperature, forming it over a mold, and subsequently cooling it to retain the desired geometry. In biocomposite applications, thermoforming is increasingly used for lightweight panels, packaging materials, and semi-structural components. The primary sources of energy consumption are sheet heating and thermal control systems, while mechanical forming generally requires comparatively lower energy inputs. Process efficiency is therefore strongly dependent on heating strategies, temperature uniformity, cycle times, and material characteristics. Because thermoforming often involves fewer processing steps than some alternative manufacturing methods, it can provide energy-efficiency advantages when properly optimized (Mann et al., 2020; Saharudin et al., 2025).

4.4. Transportation and Supply Chain Energy Consumption

Transportation and supply chain activities contribute to the overall energy demand of biocomposite systems by enabling the movement of raw materials, intermediate products, and finished goods throughout the product life cycle. Although transportation energy is generally lower than the energy associated with raw material production and manufacturing, it can significantly influence overall sustainability performance, particularly when supply chains are geographically dispersed (Walker & Rothman, 2020). Transportation energy demand depends primarily on transported mass, transportation distance, and transport mode, and may be approximated by

$$E_{transport} = mde_t \tag{14}$$

where m is the transported mass, d is the transportation distance, and e_t is the specific transportation energy requirement.

For biocomposites, transportation requirements are particularly important because natural fibers and bio-based feedstocks are frequently sourced from agricultural regions that may be distant from processing and manufacturing facilities. Consequently, long transportation routes can reduce some of the environmental advantages associated with renewable materials (Chen et al., 2024).

Supply chain design therefore plays a critical role in sustainable manufacturing. Local sourcing, efficient logistics, and optimized transportation networks can reduce both energy consumption and emissions, while circular economy strategies can further improve resource utilization despite introducing additional collection and recycling flows (Habineza, 2025). Accordingly, transportation should be considered an important, though often secondary, contributor to the overall energy performance of biocomposite manufacturing systems.

4.5. End-of-Life Energy Considerations

End-of-life management represents the final stage of the biocomposite life cycle and can significantly influence overall energy performance and sustainability outcomes. Traditionally, products reaching the end of their service life are disposed of through landfilling or incineration; however, increasing environmental concerns have encouraged the adoption of recycling, reuse, and material recovery strategies. The selection of an end-of-life pathway affects not only waste generation but also the cumulative energy demand associated with the product life cycle (Walker & Rothman, 2020).

Among available options, recycling is generally regarded as one of the most effective approaches for reducing life-cycle energy consumption because it decreases the demand for virgin raw materials and avoids the energy expenditures associated with primary material production. The potential energy savings achieved through recycling can be expressed as

$$E_{saved} = E_{virgin} - E_{recycling} \tag{15}$$

where E_{virgin} denotes the energy required for producing virgin material and $E_{recycling}$ represents the energy consumed during recycling operations. Larger values of E_{saved} indicate greater energy benefits from material recovery.

End-of-life management in biocomposite systems can be more complex than in conventional materials because products often contain multiple constituents with different degradation and recycling characteristics. Nevertheless, recycling, waste valorization, and circular manufacturing strategies have been shown to improve resource efficiency and reduce environmental impacts (Shanmugam et al., 2021). For materials that are difficult to recycle mechanically, energy recovery through thermal conversion processes may provide an alternative utilization pathway by generating useful energy from waste streams. However, because such approaches also consume energy and generate emissions, their sustainability should be evaluated on a case-by-case basis using life-cycle assessment methodologies (Pamakštys et al., 2026).

4.5.1. Recycling

Recycling is one of the most effective end-of-life strategies for reducing the cumulative energy demand of biocomposite systems. By recovering materials from post-consumer or post-industrial waste streams, recycling decreases the need for virgin raw material production, which is often considerably more energy intensive. In addition to lowering energy consumption, recycling contributes to waste reduction, resource conservation, and circular economy objectives. Although the recyclability of biocomposites may be influenced by fiber degradation, matrix characteristics, and material heterogeneity, numerous studies have demonstrated that appropriate recycling strategies can significantly improve the overall sustainability performance of bio-based materials (Lizundia et al., 2022).

4.5.2. Reuse

Reuse extends the service life of products or components by allowing them to be employed again without substantial reprocessing. Because reuse avoids many of the energy expenditures associated with manufacturing replacement products, it is often regarded as one of the most resource-efficient end-of-life options. In biocomposite applications, reuse may involve the continued utilization of structural components, packaging materials, or semi-finished products in secondary applications. Although reuse opportunities depend on product design, durability, and performance retention, extending product life generally reduces life-cycle energy demand and environmental impacts by delaying the need for new material production (Walker & Rothman, 2020).

4.5.3. Energy Recovery

Energy recovery extracts useful energy from waste materials through thermal conversion processes such as combustion, gasification, and pyrolysis. This approach is particularly relevant for materials that are difficult to recycle and can partially offset energy demand by generating heat, electricity, or fuel products. However, because it does not preserve material value, energy recovery is generally viewed as a complementary strategy within circular economy frameworks rather than a substitute for recycling and reuse (Pamakštys et al., 2026; Shanmugam et al., 2021).

4.6. Relationship between Energy Efficiency and Carbon Footprint

Energy efficiency and carbon footprint are closely linked because energy consumption is a major driver of greenhouse-gas emissions throughout the product life cycle. In general, lower energy demand leads to lower emissions, although the extent of this reduction depends on the carbon intensity of the energy source. For biocomposite systems, this relationship is particularly important because the environmental benefits of renewable materials can be enhanced or diminished by the energy requirements of cultivation, processing, transportation, manufacturing, and end-of-life management. Numerous life-cycle assessment studies have shown that lower energy consumption is often associated with reduced carbon footprints, highlighting the importance of integrating energy-efficiency strategies with broader sustainability objectives and SDGs related to clean energy, responsible production, and climate action.

5. Engineering Strategies for Energy-Efficient Biocomposite Manufacturing

This section examines engineering approaches for reducing energy consumption and improving sustainability performance throughout biocomposite manufacturing processes.

5.1. Material Design Strategies

Material design strategies focus on optimizing feedstock selection, fiber reinforcement, and matrix composition to reduce embodied energy while maintaining the desired mechanical and environmental performance of biocomposite systems.

5.1.1. Low-Energy Feedstocks

The selection of low-energy feedstocks represents one of the most effective strategies for improving the energy performance of biocomposite manufacturing. Feedstocks derived from renewable resources, agricultural residues, forestry by-products, and industrial waste streams generally require less cumulative energy than conventional petroleum-based materials because they reduce the need for energy-intensive extraction and primary processing operations. Furthermore, the utilization of locally available feedstocks can decrease transportation-related energy demand and associated emissions. Consequently, the adoption of low-energy feedstocks not only improves manufacturing energy efficiency but also supports circular economy principles and sustainable resource management objectives (Fatchurrohman & Yetrina, 2025; Lizundia et al., 2022).

5.1.2. Natural Fiber Selection

Natural fiber selection plays a critical role in determining both the mechanical performance and energy efficiency of biocomposite systems. Fibers such as hemp, flax, jute, kenaf, and sisal generally exhibit lower embodied energy than synthetic reinforcements such as glass fibers because their production involves fewer energy-intensive processing steps. However, the energy performance of natural fibers can vary considerably depending on cultivation practices, harvesting methods, fiber extraction technologies, and transportation requirements. Therefore, selecting fibers with favorable mechanical properties, low processing requirements, and sustainable supply chains can significantly reduce the overall energy demand of biocomposite manufacturing while maintaining product performance (Abdur Rahman et al., 2023; Elfaleh et al., 2023; Naik et al., 2022).

5.1.3. Bio-Based Matrix Optimization

The matrix phase often constitutes a substantial portion of a biocomposite and therefore strongly influences manufacturing energy consumption. Optimizing bio-based matrices involves selecting materials that combine desirable mechanical properties with low processing temperatures, efficient manufacturability, and reduced environmental impacts. PLA and other bio-based polymers have attracted considerable attention because they can be processed using conventional manufacturing technologies while reducing dependence on fossil resources. Improvements in polymer formulations and processing characteristics can lower energy requirements during melting, mixing, and shaping operations. Matrix optimization represents an effective strategy for enhancing both manufacturing efficiency and sustainability performance (Tomec et al., 2024; Kanematsu et al., 2025).

5.2. Process Optimization Strategies

Process optimization strategies aim to minimize energy consumption by improving operating conditions, reducing process inefficiencies, and enhancing overall manufacturing performance without compromising product quality.

- Throughput Optimization: Increasing production throughput can reduce specific energy consumption by distributing fixed energy expenditures over a larger quantity of product, thereby improving overall manufacturing efficiency.
- Thermal Profile Optimization: Optimized temperature settings reduce unnecessary heating requirements while maintaining adequate material processing conditions, leading to lower energy demand and improved process stability.
- Moisture Control and Drying Efficiency: Effective moisture management minimizes drying energy requirements, prevents material degradation, and improves processing efficiency, particularly for natural-fiber-reinforced biocomposites.
- Equipment Efficiency Improvements: The adoption of energy-efficient motors, heating systems, control technologies, and modern manufacturing equipment can significantly reduce energy losses and improve overall process performance.

5.3. Energy-Efficient Additive Manufacturing

Additive manufacturing offers opportunities for material-efficient production and reduced waste generation, making it an increasingly attractive approach for sustainable biocomposite manufacturing.

5.3.1. PLA-Based Systems

PLA-based systems are widely used in additive manufacturing due to their renewable origin, favorable processing characteristics, and relatively low environmental impact compared with conventional petroleum-based polymers.

5.3.2. Biocomposite Filaments

Biocomposite filaments incorporating natural fibers or waste-derived reinforcements can improve material sustainability while maintaining the design flexibility offered by additive manufacturing technologies.

5.3.3. Process Parameter Optimization

Optimizing printing parameters such as layer height, infill density, print speed, and nozzle temperature can significantly reduce energy consumption while preserving product quality and mechanical performance.

5.4. Circular Economy Strategies

Circular economy strategies seek to minimize waste generation and resource consumption by extending material lifecycles through reuse, recycling, and recovery practices.

5.4.1. Waste Valorization

Waste valorization transforms agricultural residues, industrial by-products, and other waste into value-added biocomposite materials, thus improving resource efficiency and reducing environmental burdens.

5.4.2. Recycling of Biocomposites

Recycling enables the recovery and reuse of valuable materials from end-of-life biocomposite products, reducing the demand for virgin resources and lowering life-cycle energy consumption.

5.4.3. Closed-Loop Manufacturing

Closed-loop manufacturing reintegrates recovered materials into production processes, creating circular material flows that enhance sustainability while reducing waste and resource depletion.

6. Digital Technologies for Energy Optimization

Digital technologies are transforming manufacturing systems by enabling real-time monitoring, predictive analytics, and intelligent decision-making to improve energy efficiency and sustainability performance.

6.1. AI in Energy-Efficient Manufacturing

AI supports energy-efficient manufacturing through data-driven optimization, adaptive control, and automated decision-making that reduce energy consumption while maintaining productivity. By analyzing large volumes of operational data, AI systems can identify hidden patterns, predict process behavior, and recommend optimal operating conditions that improve manufacturing performance. As a result, AI is increasingly being adopted as a key enabling technology for sustainable manufacturing, energy management, and industrial resource optimization.

6.2. ML for Energy Prediction and Monitoring

ML algorithms can analyze operational data to predict energy demand, identify inefficiencies, and support proactive energy-management strategies in manufacturing environments. By learning patterns from historical production and energy-consumption data, these models can provide accurate forecasts of future energy requirements and detect abnormal operating conditions before they result in excessive energy use. Consequently, ML has emerged as a valuable tool for improving energy efficiency, optimizing production schedules, and supporting data-driven decision-making in sustainable manufacturing systems.

6.3. Deep Learning Applications in Manufacturing Systems

Deep learning techniques enable the analysis of complex and high-dimensional manufacturing data, facilitating more accurate predictions of energy consumption, process behavior, and system performance.

6.4. Reinforcement Learning for Process Optimization

Reinforcement learning allows manufacturing systems to autonomously identify optimal operating conditions through continuous interaction with the production environment, thereby improving energy efficiency and process performance.

6.5. Digital Twin (DT) Technology

DT technology creates a virtual representation of a physical manufacturing system, enabling real-time monitoring, simulation, and optimization of operational performance. By integrating physical assets, sensors, data communication systems, and analytical models, DTs establish a continuous connection between physical and digital environments. In manufacturing applications, energy-oriented DTs support the monitoring, prediction, and optimization of energy consumption, thereby improving process efficiency and reducing energy waste.

6.6. Industrial Internet of Things (IIoT) and Smart Manufacturing

The IIoT enables the collection, exchange, and analysis of real-time data from interconnected machines, sensors, and production systems, thereby enhancing visibility across manufacturing operations. Combined with smart manufacturing technologies, IIoT supports predictive maintenance, process optimization and energy-aware decision-making, contributing to improved efficiency and sustainability.

6.7. Synergistic Integration of AI, DTs, and Energy Management

The integration of AI, DTs, and energy-management systems enables a comprehensive approach to optimizing manufacturing performance and sustainability. DTs provide real-time representations of physical processes, while AI algorithms analyze operational data to predict energy demand, identify inefficiencies, and recommend optimal control actions. Together, these technologies support adaptive and data-driven decision-making that improves energy efficiency without compromising productivity or product quality. Consequently, their combined application is increasingly recognized as a key enabler of smart, sustainable, and energy-efficient manufacturing systems.

7. Quantitative Framework for Energy-Efficient Biocomposite Manufacturing

This section presents a quantitative framework that integrates energy, resource, and environmental performance indicators to support the systematic assessment and optimization of energy-efficient biocomposite manufacturing systems.

7.1. Energy Efficiency Indicators

Energy efficiency indicators evaluate how effectively energy resources are utilized during manufacturing operations. Metrics such as SEC, energy intensity, and energy productivity provide quantitative measures of the relationship between energy consumption and production output. These indicators serve as the primary basis for identifying inefficiencies and assessing opportunities for energy optimization.

7.2. Resource Efficiency Indicators

Resource efficiency indicators assess the effectiveness with which raw materials are converted into useful products while minimizing waste generation. Measures such as material yield, resource utilization efficiency, and recycling rate provide insights into the sustainability of manufacturing processes. Improved resource efficiency contributes directly to reduced material consumption, lower costs, and enhanced environmental performance.

7.3. Carbon Efficiency Indicators

Carbon efficiency indicators quantify the relationship between manufacturing output and associated greenhouse-gas emissions. Metrics such as carbon intensity and carbon efficiency enable the evaluation of climate-related impacts and support the development of low-carbon manufacturing strategies. These indicators are particularly important for assessing progress toward decarbonization and climate-action objectives.

7.4. Circularity Indicators

Circularity indicators measure the extent to which materials are recovered, reused, recycled, or reintegrated into production systems. Such metrics provide a quantitative assessment of circular economy performance and help evaluate the effectiveness of waste-reduction strategies. Higher circularity generally corresponds to improved resource conservation, reduced environmental burdens, and enhanced long-term sustainability.

7.5. SDG-Oriented Manufacturing Performance Matrix

The SDG-Oriented Manufacturing Performance Matrix integrates energy, resource, environmental, and innovation indicators within a unified framework aligned with SDGs 7, 9, 12, and 13. By linking manufacturing metrics to specific sustainability objectives, the matrix enables a more comprehensive assessment of industrial performance beyond conventional productivity measures. Such an approach facilitates benchmarking, decision-making, and the identification of improvement opportunities in sustainable biocomposite manufacturing systems.

7.6. Comparative Evaluation Framework for Sustainable Manufacturing Systems

A comparative evaluation framework is proposed to assess manufacturing systems using four key sustainability dimensions: energy efficiency, resource efficiency, environmental performance, and circularity (See Table 2). Each dimension is represented by a normalized score ranging from 0 to 100, enabling direct comparison among alternative materials, processes, and production strategies.

The overall Sustainable Manufacturing Index (SMI) is defined as

$$\mathrm{SMI} = w_E E_s + w_R R_s + w_C C_s + w_{CI} CI_s \tag{16}$$

where E_s, R_s, C_s, and CI_s denote the energy, resource, carbon, and circularity scores, respectively. For simplicity, equal weighting may be adopted when no specific sustainability priorities are defined.

Table 2. Proposed sustainability evaluation framework

Dimension	**Example Indicator**
Energy Efficiency	SEC, Energy Intensity
Resource Efficiency	Material Yield, RE
Environmental Performance	Carbon Intensity
Circularity	Recycling Rate

This framework provides a practical basis for comparing manufacturing alternatives and supports SDG-oriented sustainability assessment by simultaneously considering energy, resource, environmental, and circularity performance.

8. Proposed Integrated Framework

8.1. Conceptual Architecture

Based on the reviewed literature, an integrated framework is proposed to connect material selection, manufacturing operations, digital technologies, sustainability assessment, and SDGs within a unified decision-support structure. Adopting a life-cycle perspective, the framework tracks biocomposite materials through manufacturing, monitoring, assessment, and optimization stages while continuously evaluating energy, resource, and environmental performance. At the operational level, biocomposite material design and manufacturing processes generate energy-consumption and resource-utilization data. Advanced digital technologies support these activities through real-time monitoring, predictive analysis, and process optimization. The resulting data are assessed using the quantitative indicators presented in Section 7, including energy efficiency, resource efficiency, carbon efficiency, and circularity metrics.

These indicators are subsequently integrated within an SDG-oriented evaluation layer aligned with SDGs 7, 9, 12, and 13. Feedback from this assessment process supports continuous improvement, creating a closed-loop sustainability framework for biocomposite manufacturing. The conceptual architecture of the proposed framework is illustrated in Figure 1.

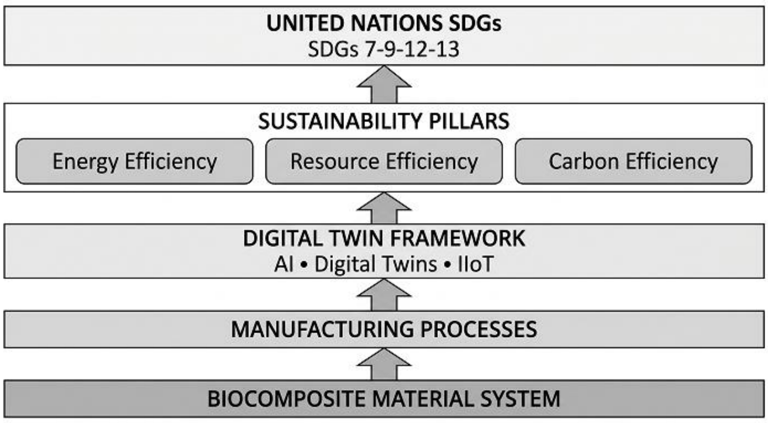

Figure 1. Integrated framework linking biocomposite materials, manufacturing processes, digital technologies, sustainability performance indicators, and SDGs.

This architecture provides a holistic framework for evaluating and improving the sustainability performance of biocomposite manufacturing systems by integrating engineering, environmental, and digital perspectives within a common assessment structure.

8.2. Framework Components and Integration

The proposed framework integrates biocomposite materials, manufacturing processes, digital technologies, life-cycle assessment, and circular economy principles within a unified sustainability architecture. Manufacturing operations generate energy and resource consumption data, while AI, DTs, and IIoT technologies provide monitoring, prediction, and optimization capabilities. LCA supplies a life-cycle perspective for environmental assessment, whereas circular economy principles support resource recovery and closed-loop production. Together, these components enable energy-efficient and sustainable biocomposite manufacturing.

8.3. SDG Evaluation Layer

The SDG Evaluation Layer translates manufacturing performance indicators into sustainability outcomes by linking energy, resource, environmental, and innovation metrics to relevant SDGs. This layer enables the proposed framework to assess manufacturing performance not only from an engineering perspective but also in terms of broader sustainability objectives.

8.3.1. SDG 7 Assessment

The framework supports SDG 7 by promoting improvements in energy efficiency through reduced SEC, optimized manufacturing operations, and data-driven energy management. These improvements contribute directly to more efficient utilization of energy resources across the biocomposite manufacturing lifecycle.

8.3.2. SDG 9 Assessment

The framework contributes to SDG 9 through the integration of advanced digital technologies which enhance industrial innovation, support intelligent manufacturing, and facilitate continuous performance improvement.

8.3.3. SDG 12 Assessment

The framework supports SDG 12 by encouraging efficient resource utilization, waste minimization, recycling, and circular manufacturing practices. The incorporation of renewable feedstocks and circularity indicators further strengthens sustainable production and consumption patterns.

8.3.4. SDG 13 Assessment

The framework contributes to SDG 13 by reducing energy consumption, lowering carbon intensity, and promoting environmentally responsible manufacturing practices. Through the combined application of energy-efficiency strategies and life-cycle thinking, the framework supports the transition toward lower-carbon manufacturing systems.

8.4. Framework Benefits and Industrial Applications

The proposed framework offers several advantages for sustainable biocomposite manufacturing by integrating material design, manufacturing processes, digital technologies, life-cycle assessment, and circular economy principles within a unified structure. Through continuous monitoring and performance evaluation, the framework supports reductions in energy consumption, improvements in resource utilization, lower carbon emissions, and enhanced overall sustainability performance. Furthermore, the incorporation of AI and DT technologies enables data-driven optimization and adaptive decision-making in complex manufacturing environments.

From an industrial perspective, the framework can be applied across a wide range of sectors that utilize biocomposite materials, including automotive, construction, packaging, consumer products, and additive manufacturing. Manufacturers can employ the framework to compare alternative materials and processes, identify energy-saving opportunities, evaluate sustainability performance, and support compliance with environmental regulations and sustainability targets. Consequently, the framework provides a practical foundation for advancing energy-efficient manufacturing while contributing to broader industrial sustainability and SDGs.

9. Future Research Directions

Despite significant advances in sustainable manufacturing, several research gaps remain in the field of energy-efficient biocomposite production. Existing studies often address energy efficiency, material sustainability, digital technologies, life-cycle assessment, and circular economy principles independently, with limited development of integrated assessment frameworks. Furthermore, the combined application of AI, DTs, and LCA for real-time energy optimization remains insufficiently explored, while the lack of standardized sustainability indicators hinders meaningful comparisons among manufacturing systems. Future research should therefore focus on developing data-driven and digitally enabled frameworks that integrate energy, resource, environmental, and circularity considerations to support more intelligent, adaptive, and sustainable biocomposite manufacturing systems.

10. Conclusions

Energy efficiency plays a central role in sustainable manufacturing by influencing resource utilization, production costs, environmental performance, and climate-change mitigation. This study examined energy efficiency in biocomposite manufacturing from a life-cycle perspective, highlighting the roles of raw material production, manufacturing processes, transportation, end-of-life management, and sustainability assessment. Particular attention was given to the relationships among energy consumption, carbon footprint, resource efficiency, circularity, and SDGs 7, 9, 12, and 13.

The review showed that biocomposites offer significant opportunities for sustainable industrial development through the use of renewable feedstocks, natural fibers, bio-based polymers, and waste-derived materials. However, their environmental benefits depend not only on material composition but also on the efficiency of manufacturing processes and supply chains. Consequently, strategies such as process optimization, additive manufacturing, recycling, and circular economy practices are essential for maximizing the sustainability potential of biocomposite systems.

To support this objective, a quantitative and SDG-oriented integrated framework was proposed that combines manufacturing performance indicators, digital technologies, life-cycle assessment, and circular economy principles within a unified sustainability architecture. The framework provides a practical basis for evaluating and optimizing sustainable biocomposite manufacturing systems and supports the transition toward more intelligent, resource-efficient, and low-carbon industrial production.

Conflict of Interest Statement

The author declares that there are no conflicts of interest regarding the publication of this manuscript.

References

Abadi, M. M. K. F., Liu, C., Zhang, M., Hu, Y., & Xu, Y. (2025). Leveraging AI for energy-efficient manufacturing systems: Review and future perspectives. *Journal of Manufacturing Systems, 78*, 153–177. https://doi.org/10.1016/j.jmsy.2024.11.017

Abdur Rahman, M., Haque, S., Athikesavan, M. M., & Kamaludeen, M. B. (2023). A review of environmental friendly green composites: Production methods, current progresses, and challenges. *Environmental Science and Pollution Research, 30*, 16905–16929. https://doi.org/10.1007/s11356-022-24879-5

Äkräs, L., Silvenius, F., Baniasadi, H., Vahvaselkä, M., Ilvesniemi, H., & Seppälä, J. (2024). *A cradle-to-gate life cycle assessment of polyamide-starch biocomposites: Carbon footprint as an indicator of sustainability*. *Clean Technologies and Environmental Policy*, *26*, 3297–3312. https://doi.org/10.1007/s10098-024-02884-1

Beigbeder, J., Soccalingame, L., Perrin, D., Bénézet, J.-C., & Bergeret, A. (2019). How to manage biocomposites wastes end of life? A life cycle assessment approach (LCA) focused on polypropylene (PP)/wood flour and polylactic acid (PLA)/flax fibres biocomposites. *Waste Management*, *83*, 184–193. https://doi.org/10.1016/j.wasman.2018.10.036

Bermeo-Ayerbe, M. A., Ocampo-Martinez, C., & Diaz-Rozo, J. (2022). Data-driven energy prediction modeling for both energy efficiency and maintenance in smart manufacturing systems. *Energy*, *238*(Part B), Article 121691. https://doi.org/10.1016/j.energy.2021.121691

Bespalyy, S. (2023). Green energy efficiency and its impact on sustainable development. IOP Conference Series: Earth and Environmental Science, 1231(1), 012015. https://doi.org/10.1088/1755-1315/1231/1/012015

Çevik, M. (2025). Lifecycle approaches to sustainable materials and green composites in engineering systems. In M. Çevik (Ed.), *Advances in Scientific Research* (pp. 244–255). Duvar Publications.

Çevik, M., & Diambu, A. N. (2024). Advancing Sustainable Development Goals through the use of biocomposites for a greener future. In M. Çevik (Ed.), *Scientific Research Reports* (pp. 1–13). Duvar Publications.

Chen, L., Zhang, Y., Chen, Z., Dong, Y., Jiang, Y., Hua, J., Liu, Y., Osman, A. I., Farghali, M., Huang, L., Rooney, D. W., & Yap, P.-S. (2024). Biomaterials technology and policies in the building sector: A review. *Environmental Chemistry Letters*, *22*, 715–750. https://doi.org/10.1007/s10311-023-01689-w

Curto, M., Le Gall, M., Catarino, A. I., Niu, Z., Davies, P., Everaert, G., & Dhakal, H. N. (2021). Long-term durability and ecotoxicity of biocomposites in marine environments: A review. *RSC Advances*, *11*(53), 32917–32942. https://doi.org/10.1039/D1RA03023J

Das, O., Babu, K., Shanmugam, V., Sykam, K., Tebyetekerwa, M., Neisiany, R. E., Försth, M., Sas, G., Libres, J. G., Capezza, A. J., Hedenqvist, M. S., Berto, F., & Ramakrishna, S. (2022). Natural and industrial wastes for sustainable and renewable polymer composites. *Renewable and Sustainable Energy Reviews*, *158*, 112054. https://doi.org/10.1016/j.rser.2022.112054

Deepthi, C., Shimi, G. J., Pillai, P. S., Rajasree, G., Thomas, U. C., & Manju, R. V. (2026). Biocomposites: A review of materials, properties and applications for sustainable development. *Asian Research Journal of Agriculture*, *19*(2), 207–219. https://doi.org/10.9734/arja/2026/v19i2843

Ead, A. S., Appel, R., Alex, N., Ayranci, C., & Carey, J. P. (2021). Life cycle analysis for green composites: A review of literature including considerations for local and global agricultural use. *Journal of Engineered Fibers and Fabrics*, *16*, 1–20. https://doi.org/10.1177/15589250211026940

Elbir, A. (2024). Highly efficient energy integration: Thermodynamic analysis of heat recovered from SOFC through S-CO_2 and Kalina cycles. *International Journal of Thermodynamics*, *27*(4), 43–55. https://doi.org/10.5541/ijot.1486368

Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., & Garnier, C. (2023). A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results in Engineering*, *19*, 101271. https://doi.org/10.1016/j.rineng.2023.101271

Fatchurrohman, N., & Yetrina, M. (2025). Comprehensive framework for the application of bio composites materials in sustainable manufacturing. *International Journal of Engineering, Technology and Natural Sciences*, *7*(1). https://doi.org/10.46923/ijets.v7i1.406

Fitzgerald, A., Proud, W., Kandemir, A., Murphy, R. J., Jesson, D. A., Trask, R. S., Hamerton, I., & Longana, M. L. (2021). A life cycle engineering perspective on biocomposites as a solution for a sustainable recovery. *Sustainability*, *13*(3), 1160. https://doi.org/10.3390/su13031160

Fontana, L., Minetola, P., Khandpur, M. S., & Giubilini, A. (2025). Evaluating self-produced PLA filament for sustainable 3D printing: Mechanical properties and energy consumption compared to commercial alternatives. *Journal of Manufacturing and Materials Processing*, *9*(6), 172. https://doi.org/10.3390/jmmp9060172

Garcia, F. L., Moris, V. A. da S., Nunes, A. O., & Silva, D. A. L. (2018). Environmental performance of additive manufacturing process—An overview. *Rapid Prototyping Journal*, *24*(7), 1166–1177. https://doi.org/10.1108/RPJ-05-2017-0108

Ghomi, E. R., Khosravi, F., Ardahaei, A. S., Dai, Y., Neisiany, R. E., Foroughi, F., Wu, M., Das, O., & Ramakrishna, S. (2021). The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material. *Polymers*, *13*(11), 1854. https://doi.org/10.3390/polym13111854

Gültaş, M. P. (2024). Sustainability management practices in the furniture sector: An analytical study. *Furniture and Wooden Material Research Journal*, *7*(2), 250–265. https://doi.org/10.33725/mamad.1568828

Habineza, J. (2025). Evaluating the performance of green logistics vs. traditional logistics in efficiency and sustainability across African countries: An SEM analysis. *PressAcademia Procedia*, *21*(1), 75–81. https://doi.org/10.17261/Pressacademia.2025.1996

Hermansson, F., Janssen, M., & Svanström, M. (2019). Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. *Journal of Cleaner Production*, *223*, 946–956. https://doi.org/10.1016/j.jclepro.2019.03.022

Kanematsu, Y., Noguchi, H., Semba, T., Yano, H., & Kikuchi, Y. (2025). *Life cycle assessment of automobile parts made of cellulose nanofiber-reinforced bio-polyethylene using the pulp direct kneading method* (Preprint). ChemRxiv. https://doi.org/10.26434/chemrxiv-2025-qhs18

Klejnowska, K., Yusufova, N., & Faludi, J. (2026). Sustainability evaluation of ambient-temperature biocomposite additive manufacturing using life cycle assessment. *Sustainability*, *18*(3), Article 1223. https://doi.org/10.3390/su18031223

Koçaslan, G. (2022). Conceptualizing energy efficiency within the scope of energy security and energy sustainability. *Stratejik ve Sosyal Araştırmalar Dergisi*, *6*(3), 581–594. https://doi.org/10.30692/sisad.1175444

Küçüktüvek, M., & Altay, Ç. (2025). Wooden structures in sustainable design: AI-based energy efficiency and environmental impact. *PLANARCH - Design and Planning Research*, *9*(1), 90–98. https://doi.org/10.54864/planarch.1586765

Lizundia, E., Luzi, F., & Puglia, D. (2022). Organic waste valorisation towards circular and sustainable biocomposites. *Green Chemistry*, *24*(14), 5429–5476. https://doi.org/10.1039/D2GC01668K

Mann, G. S., Singh, L. P., Kumar, P., & Singh, S. (2020). Green composites: A review of processing technologies and recent applications. *Journal of Thermoplastic Composite Materials*, *33*(8), 1145–1171. https://doi.org/10.1177/0892705718816354

Mao, W., Zhao, Z., Chang, Z., Min, G., & Gao, W. (2021). Energy-efficient Industrial Internet of Things: Overview and open issues. *IEEE Transactions on Industrial Informatics*, *17*(11), 7225–7237. https://doi.org/10.1109/TII.2021.3067026

Mojapelo, K. S., Kupolati, W. K., Burger, E. A., Ndambuki, J. M., Snyman, J., & Sadiku, E. R. (2025). Recent progress in preparation, improvement and applications of green polymer composites. *Biopolymers*, *116*, Article e70059. https://doi.org/10.1002/bip.70059

Naik, N., Shivamurthy, B., Thimmappa, B. H. S., Gupta, A., Guo, J. Z., & Seok, I. (2022). A review on processing methods and characterization techniques of green composites. *Engineered Science*, *20*, 80–99. https://doi.org/10.30919/es8d713

Ohenhen, P. E., Chidolue, O., Umoh, A. A., Ngozichukwu, B., Fafure, A. V., Ilojianya, V. I., & Ibekwe, K. I. (2024). Sustainable cooling solutions for electronics: A comprehensive review: Investigating the latest techniques and materials, their effectiveness in mechanical applications, and associated environmental benefits. *World Journal of Advanced Research and Reviews*, *21*(1), 957–972. https://doi.org/10.30574/wjarr.2024.21.1.0111

Operato, L., Vitiello, L., Aprea, P., Ambrogi, V., Salzano de Luna, M., & Filippone, G. (2023). Life cycle assessment of poly(lactic acid)-based green composites filled with pine needles or kenaf fibers. *Journal of Cleaner Production*, *387*, Article 135901. https://doi.org/10.1016/j.jclepro.2023.135901

Ortega, F., Versino, F., López, O. V., & García, M. A. (2022). Biobased composites from agro-industrial wastes and by-products. *Emergent Materials*, *5*(4), 873–921. https://doi.org/10.1007/s42247-021-00319-x

Pamakštys, K., Sholokhova, A., Gurauskienė, H., & Varžinskas, V. (2026). Environmental assessment strategies for biodegradable polymer composites: A review of life cycle perspectives on agro-waste reinforced materials. *Polymers*, *18*(6), Article 700. https://doi.org/10.3390/polym18060700

Rabbi, M. F., Sarker, R., Becker, J., Badsha, A. R., Arefin, M., Zahan, I., Arifuzzaman, M., Al Bari, M. A., & Kibria, M. G. (2026). Investigating the shear and thermal behavior of additively manufactured wood-PLA biocomposites including a life cycle assessment. *Journal of Natural Fibers*, *23*(1), Article 2640270. https://doi.org/10.1080/15440478.2026.2640270

Renna, P., & Materi, S. (2021). A literature review of energy efficiency and sustainability in manufacturing systems. *Applied Sciences*, *11*(16), Article 7366. https://doi.org/10.3390/app11167366

Saharudin, M. S., Ullah, A., & Younas, M. (2025). Innovative and sustainable advances in polymer composites for additive manufacturing: Processing, microstructure, and mechanical properties. *Journal of Manufacturing and Materials Processing*, *9*(2), Article 51. https://doi.org/10.3390/jmmp9020051

Sapuan, S. M., Ilyas, R. A., Nugroho, A., & Rajeshkumar, L. (2025). Energy efficiency and sustainability in composites industry. *Physical Sciences Reviews*, *10*(5-6), 525–556. https://doi.org/10.1515/psr-2024-0031

Shanmugam, V., Mensah, R. A., Försth, M., Sas, G., Restás, Á., Addy, C., Xu, Q., Jiang, L., Neisiany, R. E., Singha, S., George, G., Jose E, T., Berto, F., Hedenqvist, M. S., Das, O., & Ramakrishna, S. (2021). Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Composites Part C: Open Access*, *5*, Article 100138. https://doi.org/10.1016/j.jcomc.2021.100138

Tariq, G., Sun, H., Ali, I., Pasha, A. A., Khan, M. S., Rahman, M. M., Mohamed, A., & Shah, Q. (2022). Influence of green technology, green energy consumption, energy efficiency, trade, economic development and FDI on climate change in South Asia. *Scientific Reports*, *12*, Article 16376. https://doi.org/10.1038/s41598-022-20432-z

Taşkın, N., Tombul, E., & Şen, F. M. (2025). Energy efficiency in the context of renewable energy and sustainability: Research trends between 2017-2024. *The Black Sea Journal of Sciences*, *15*(4), 1504–1523. https://doi.org/10.31466/kfbd.1662431

Tomec, D.K., Schöflinger, M., Leßlhumer, J., Gradišar Centa, U., Žigon, J., & Kariž, M. (2024). The effects of microcrystalline cellulose addition on the properties of wood–PLA filaments for 3D printing. *Polymers*, *16*(6), Article 836. https://doi.org/10.3390/polym16060836

Türköz, K. (2025). Green energy efficiency for environmental sustainability: Evidence from BRICS countries. *Istanbul Gelisim University Journal of Social Sciences*, *12*(3, Special Issue on Sustainability), 959–973. https://doi.org/10.17336/igujss.1471015

Walker, S., & Rothman, R. (2020). Life cycle assessment of bio-based and fossil-based plastic: A review. *Journal of Cleaner Production*, *261*, Article 121158. https://doi.org/10.1016/j.jclepro.2020.121158

Yenioğlu, Z. A., & Belge, Z. S. (2022). Benchmarking urban energy efficiency with deterministic and stochastic methods. *International Journal of Advanced Engineering and Pure Sciences*, *34*(1), 107–122. https://doi.org/10.7240/jeps.1002152

Zakari, A., Khan, I., Tan, D., Alvarado, R., & Dagar, V. (2022). Energy efficiency and sustainable development goals (SDGs). *Energy*, *239*, Article 122365. https://doi.org/10.1016/j.energy.2021.122365

Zekići-Sušac, M., Mitrović, S., & Has, A. (2021). Machine learning based system for managing energy efficiency of public sector as an approach towards smart cities. *International Journal of Information Management*, *58*, Article 102074. https://doi.org/10.1016/j.ijinfomgt.2020.102074

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 25-38.

2

Ceramic–Metal Composite Armors: Ballistic Principles, Protective Mechanisms, and Structural Design Concepts

Latif Tibet Aktaş[1]*

İzmir University of Economics, Department of Mechanical Engineering, 35330, Balçova, İzmir, Türkiye

Corresponding author: tibet.aktas@ieu.edu.tr

Abstract

Ceramic-metal composite armors represent one of the most established families of lightweight ballistic protection systems because they combine the high hardness and compressive strength of ceramics with the ductility, structural continuity and fragment-retention capacity of metallic constituents. In a typical design, the ceramic strike face blunts, erodes, fractures or deflects the projectile, whereas the metallic backing supports the ceramic, absorbs residual kinetic energy through plastic deformation and maintains the integrity of the protection package. The ballistic performance of such systems is governed not only by the intrinsic properties of the ceramic and metal, but also by the architecture of the armor, the ceramic-metal interface, the confinement condition, the impact location, the threat type and the damage tolerance required for multi-hit service. This chapter reviews the principles of ceramic-metal composite armors with emphasis on ballistic science, constituent materials, energy absorption mechanisms, projectile deflection, fracture and fragmentation, wave propagation, multi-hit resistance, structural architectures and emerging concepts such as reconfigurable or self-healing armor systems. Particular attention is given to geometric armor concepts, including spherical, prismatic, tile-based and cellular designs, because these approaches can alter local impact mechanics beyond conventional flat ceramic strike-face behavior.

Keywords: Ceramic armor; Metal-ceramic composite; Ballistic impact; Projectile deflection; Fracture; Multi-hit resistance; Lightweight armor

1. Introduction

The historical evolution of armor technologies has been driven by a continuous competition between projectile lethality and protective efficiency. Early armor systems relied primarily on monolithic metallic plates, in which ballistic resistance was obtained by increasing thickness, hardness and mass. This design philosophy remains relevant for some structural and vehicle armor applications; however, modern ballistic

[1] https://orcid.org/0000-0002-0974-1759

threats have imposed severe constraints on mass, mobility, payload capacity and survivability. The contemporary design problem is therefore not merely to stop a projectile, but to do so with a minimum areal density while controlling behind-armor effects, structural damage, fragment dispersion and multi-hit degradation (Hazell, 2022; Crouch, 2017).

Composite armor systems emerged from the need to decouple the functions of projectile defeat and residual energy absorption. Instead of assigning all protective functions to a single material, a composite armor distributes the impact event among constituents with different mechanical roles. A hard strike face breaks or erodes the projectile, a ductile backing dissipates energy and prevents catastrophic separation, and interlayers or adhesives regulate stress-wave transmission and damage spreading. Ceramic-metal armors are among the most important examples of this design philosophy. Their engineering value arises from the coupling of a brittle but hard ceramic component with a ductile metallic component, producing a response that is not attainable by either constituent alone (Crouch et al., 2017; Aguilar-Elguezabal et al. 2026; Dresch et al., 2021).

The importance of ceramic-metal composite armor is particularly evident in vehicle protection. Vehicle armor must resist high-velocity kinetic threats, fragments and, in some cases, repeated or spatially distributed impacts while preserving mobility. The high hardness and relatively low density of alumina, silicon carbide and boron carbide make them attractive for reducing projectile penetration capacity; nevertheless, their brittleness and tendency toward local fragmentation require backing, confinement and architectural optimization (Medvedovski, 2010a; Medvedovski, 2010b; Dresch et al., 2021). For this reason, the protective performance of ceramic-metal armor is strongly dependent on system-level design rather than ceramic selection alone.

Recent studies have also shown that geometric configuration is an active design variable in ceramic-based armors. Curved ceramics, ceramic spheres, ceramic tiles, prismatic cores and modular particle systems can change the local incidence angle, redistribute stress waves, confine fracture and modify the trajectory of the projectile. In previous finite element work on alumina-sphere armor, Aktaş and Çevik (2022) showed that increasing sphere diameter from 12.7 mm to 20 mm and changing the layout from hexagonal to checkerboard arrangement could substantially reduce projectile exit velocity under the modeled conditions. Their subsequent study on checkerboard-formation ceramic spheres further demonstrated that the local impact position has a major influence on residual velocity and kinetic-energy loss, with central sphere impact producing the strongest reduction and interstitial void impact producing the least favorable response (Aktaş & Çevik, 2025a). In a related prismatic-spherical ceramic armor concept, triangular prismatic alumina ceramics and freely positioned alumina spheres were integrated inside an aluminum casing to promote projectile deflection and limited gravity-assisted gap filling after impact (Aktaş & Çevik, 2025b). These studies illustrate why modern ceramic-metal armor design must consider geometry, impact localization and post-impact damage state together.

The objective of this study is to review ceramic-metal composite armors from a principles-and-mechanisms perspective. The discussion begins with the fundamentals of ballistic science and then examines composite armor architecture, material selection, protective mechanisms, structural designs, advanced concepts and unresolved research limitations. The emphasis is on engineering interpretation rather than detailed experimental protocol, so that the study can function as a general reference for the design and evaluation of ceramic-metal composite armor systems.

2. Fundamentals of Ballistic Science

2.1. Internal, External and Terminal Ballistics in Armor Design

Ballistics is commonly divided into internal, external and terminal ballistics. Internal ballistics concerns the processes that accelerate the projectile inside the weapon system, including pressure generation, barrel interaction and muzzle velocity. External ballistics describes projectile motion after leaving the muzzle and before target interaction, including aerodynamic drag, yaw, stability and trajectory. Terminal ballistics addresses the interaction between the projectile and the target. Armor engineering is primarily a terminal-ballistics discipline, but internal and external ballistic parameters determine the initial conditions imposed on the target: projectile mass, velocity, nose shape, spin, yaw, impact angle and material state at impact.

For ceramic-metal armor, projectile velocity and nose shape are critical because they determine strain-rate level, contact pressure and the sequence of damage mechanisms. A blunt projectile, an ogival projectile and an armor-piercing projectile do not produce identical ceramic fracture patterns. Similarly, a normal impact and an oblique impact may lead to different combinations of penetration, ricochet, ceramic cracking, projectile erosion and backing deformation. Therefore, ballistic resistance cannot be represented by a single material parameter. It is a system response to a specific projectile-target interaction.

2.2. Ballistic Impact, Energy Transfer and Backface Deformation

The initial kinetic energy of a projectile is proportional to its mass and the square of its velocity. During impact, this energy is redistributed into projectile deformation and erosion, ceramic fracture and comminution, heat, sound, kinetic energy of fragments, plastic deformation of the backing and residual projectile motion. In ceramic-faced systems, the first milliseconds or microseconds of contact are dominated by high compressive stresses near the strike face. These stresses can exceed the local strength of both projectile and ceramic, leading to projectile blunting or erosion and to the formation of a damaged ceramic zone under the impact point (Medvedovski, 2010a; Medvedovski, 2010b; Dresch et al., 2021).

Backface deformation is a central performance criterion, especially for personal and vehicle armor systems located close to protected structures or occupants. Even when full perforation is prevented, the remaining impulse can produce significant rear-surface bulging, localized indentation or transmitted blunt trauma. The effect of impact geometry on ballistic trauma has been experimentally investigated in multilayered ceramic armor systems, where the shape and incidence of impact affected trauma absorption (Braga et al., 2018). This highlights a key principle of armor design: stopping the projectile is necessary but not sufficient; the armor must also regulate the spatial and temporal distribution of momentum transmitted to the protected side.

3. Ceramic-Metal Composite Armor Systems

3.1. General Structure: Ceramic Strike Face, Metallic Backing and Interface

A ceramic-metal composite armor generally consists of a ceramic strike face bonded, confined or mechanically supported by a metallic backing. The ceramic layer is positioned toward the threat side because its function is to reduce projectile penetration capacity at the earliest stage of impact. The metallic backing is placed behind the ceramic to support it under compressive loading, absorb residual energy, reduce tensile back-face failure and retain fragments. In practical armor packages, polymeric adhesives, elastomeric layers, fiber wraps, spall liners or environmental covers may also be included to improve durability and control fragmentation (Akella, 2020).

The ceramic phase can be treated as a reinforcement or as a functional strike-face phase, whereas the metal behaves as a matrix, support plate, casing or backing depending on the architecture. The interface between ceramic and metal is a critical region because it governs load transfer, confinement, stress-wave reflection and delamination. A perfectly rigid bond may transmit high stresses efficiently, whereas a compliant interlayer may delay or redistribute stress waves. Experimental and numerical work on ceramic/composite armors has shown that interlayer material can strongly affect stress transmission, ceramic damage spread and the load transferred to the backing (Tasdemirci et al., 2012).

3.2. Classification of Ceramic-Metal and Hybrid Armor Systems

Ceramic-metal armor systems can be classified according to architecture, constituent material and threat level. The most common configuration is a ceramic-front/metal-back bilayer. More complex systems include ceramic-metal-polymer hybrid plates, ceramic tiles bonded to metallic substrates, metal-confined ceramic inserts, free-particle ceramic armor, sandwich panels with ceramic or metallic cores, and ceramic-metal structures combined with fiber-reinforced backings. A practical classification is given in Table 1.

Table 1. Representative classification of ceramic-metal and hybrid composite armor systems

Armor class	Typical constituents	Primary function	Design concern
Ceramic-front metallic backing	Alumina, SiC or B_4C with steel, aluminum or titanium backing	Projectile erosion/blunting followed by backing plasticity	Interface failure and backface deformation
Ceramic tile armor	Discrete ceramic tiles on metallic or composite support	Damage localization and replaceability	Tile gaps and edge impacts
Particle or sphere-reinforced armor	Ceramic spheres or particles supported by metal/casing	Deflection, distributed fracture and modularity	Interstitial voids and packing density
Hybrid ceramic-metal-polymer armor	Ceramic strike face, metal support and fiber/polymer backing	Combined hard defeat and tensile energy absorption	Manufacturing complexity and environmental durability
Geometric/cellular armor	Prismatic, corrugated, lattice or cellular ceramic/metal features	Path deviation, confinement and controlled collapse	Repeatability, modeling accuracy and cost

3.3. Reinforcement and Core Architectures in Armor Design

In conventional composite materials, reinforcement architecture is often described in terms of fibers, particles, laminates and cellular cores. The same terminology can be adapted to armor, but the interpretation must remain ballistic. Fiber-reinforced structures, such as aramid or UHMWPE laminates, are efficient in tensile membrane stretching and fragment capture. Particle-reinforced and sphere-based systems introduce many local contact and fracture sites, potentially improving damage localization. Layered and sandwich structures use separation of functions: a hard front surface for projectile defeat and a tougher rear region for energy absorption. Cellular and geometric structures introduce controlled deformation, spatial impedance variation or trajectory modification.

The architectural approach is particularly relevant for ceramic-metal systems because ceramics fail in a brittle and statistically variable manner. A monolithic ceramic plate may offer high initial resistance, but once fractured, its residual capacity near the damaged zone decreases. Modular ceramic arrangements can limit the extent of damage and may preserve unaffected regions for subsequent impacts. However, modularity also introduces gaps, edge effects and local vulnerability. Aktaş and Çevik's impact-location analysis of checkerboard ceramic sphere armor is a clear example: the interstitial void case exhibited a much higher residual velocity than the central sphere impact case, demonstrating that the spatial arrangement of ceramics can create both resistance-enhancing and vulnerability-enhancing regions (Aktaş & Çevik, 2025a).

4. Materials Used in Ceramic-Metal Composite Armors

4.1. Metallic Materials: Armor Steels, Aluminum Alloys and Titanium Alloys

Metallic constituents in ceramic-metal armor provide structural support, energy absorption and fragment containment. Armor steels are widely used because of their high strength, hardness, availability and relatively low cost. High-hardness steels can resist penetration directly and can also serve as backing plates for ceramic strike faces. Their main disadvantage is density, which increases areal mass. Aluminum alloys are attractive where weight reduction and manufacturability are important. Their lower density allows thicker structural sections for a given mass, but their lower hardness and strength compared with armor steel usually require careful integration with ceramics or other reinforcements. Titanium alloys offer high specific strength and corrosion resistance, but cost and processing constraints limit their broad use in many armor systems (Hazell, 2022; Crouch, 2017; Crouch et al., 2017).

The backing metal must be selected by considering its dynamic plasticity, failure strain, strain-rate sensitivity, thermal softening and ability to remain intact after ceramic fragmentation. Metallic backings are often modeled with constitutive laws such as Johnson-Cook plasticity and failure because ballistic impact involves large strains, high strain rates and localized heating. Johnson and Cook's fracture model remains one of the widely cited formulations for describing failure of metals under combined effects of strain, strain rate, temperature and pressure (Johnson & Cook, 1985). In practical design, however, model calibration is as important as model selection; inaccurate failure parameters can lead to misleading predictions of perforation, plug formation or rear-face tearing.

4.2. Ceramic Materials: Alumina, Silicon Carbide, Boron Carbide and Zirconia-Based Ceramics

Ceramics used in armor are selected for high hardness, high compressive strength, high elastic modulus, thermal stability and relatively low density. Alumina is one of the most widely used armor ceramics because it offers a favorable balance of cost, manufacturability and performance. Silicon carbide provides higher hardness and lower density than alumina, which often improves mass efficiency. Boron carbide is even lighter and harder, making it attractive for weight-critical armor, although its ballistic performance can be affected by pressure-induced damage mechanisms, processing route, microstructure and threat condition. Zirconia and zirconia-toughened ceramics can offer improved fracture toughness, but their higher density can reduce their mass-efficiency advantage for some applications (Medvedovski, 2010a; Medvedovski, 2010b; Dresch et al., 2021).

The ballistic effectiveness of a ceramic cannot be inferred only from hardness. Fracture toughness, elastic modulus, acoustic impedance, compressive strength, microstructural defects, grain size and confinement condition all influence performance. Fejdyś et al. (2021) found that the ballistic behavior of hybrid ceramic-UHMWPE armor did not correlate simply with individual properties such as hardness, Young's modulus or brittle fracture behavior; acoustic impedance compatibility and fracture toughness were also important, particularly for multi-hit response. This supports the system-level view that ceramic armor design must consider the interaction among ceramic, backing, interface and threat rather than ranking materials solely by nominal hardness.

4.3. Polymeric Interlayers, Adhesives and Fiber Backings

Although this study focuses on ceramic-metal systems, polymeric and fiber materials frequently appear in ceramic-metal hybrid armor. Adhesives provide bonding, but they also influence stress-wave reflection, delamination and damage-spreading behavior. Elastomeric or polymeric layers may reduce peak stresses transmitted to the backing or change the fracture pattern of the ceramic. Fiber-based backings such as aramid, glass fiber and UHMWPE laminates are efficient in tensile deformation, delamination and fragment capture. In ceramic/UHMWPE armors, residual strength after ballistic impact has been studied to assess the structural capacity remaining after one or more projectile strikes (Chen et al., 2022). Polyurea reinforcement has also been investigated as a means of improving ceramic/metal armor performance by modifying fragmentation and interface response (Si et al., 2022).

A ceramic plate covered with a composite wrap can exhibit a different fracture development from an uncovered ceramic plate. Rahbek et al. (2017) showed experimentally and numerically that composite covering affects ballistic fracture damage development in ceramic plates. This finding is relevant to ceramic-metal armor because the cover or wrap may not be a primary load-carrying layer in static design, but it can play a significant role in dynamic confinement, fragment retention and crack evolution.

4.4. Material Selection Criteria for Ballistic Protection

Material selection for ceramic-metal armor requires simultaneous evaluation of protection level, areal density, cost, manufacturability, environmental durability, multi-hit requirement and structural integration. A simplified summary is presented in Table 2. The optimum design is rarely the one with the highest value of a single property. For example, a very hard ceramic may perform poorly if it is insufficiently supported, while a ductile backing may absorb energy efficiently but fail to reduce projectile penetration if the ceramic strike face is too thin or poorly confined.

Table 2. Engineering criteria for material selection in ceramic-metal composite armor design

Selection criterion	Ceramic-related consideration	Metal/interface-related consideration
Areal density	Low density and high mass efficiency	Backing thickness optimized for support and plastic work
Projectile defeat	Hardness, compressive strength and fracture mode	Confinement and prevention of premature ceramic separation
Damage tolerance	Fracture toughness and modular architecture	Ductility, strain-rate response and fragment retention
Multi-hit performance	Localized damage and tile/particle replacement capacity	Stable support after first impact
Manufacturability	Sintering quality, machining tolerance and cost	Joining, welding, forming and adhesive control
Durability	Moisture, temperature and aging effects on auxiliary layers	Corrosion resistance and interface aging

5. Protective Mechanisms in Ceramic-Metal Armors

5.1. Projectile Erosion, Blunting and Ceramic Dwell

One of the primary functions of the ceramic strike face is to impose very high contact stress on the projectile. When an armor-piercing projectile contacts a hard ceramic, the projectile nose may blunt, mushroom, fracture or erode. This reduces its penetration efficiency before it reaches the backing. Under certain high-velocity conditions, a ceramic may temporarily resist penetration while the projectile material flows or erodes at the interface; this phenomenon is often discussed in connection with dwell behavior. The duration and effectiveness of dwell depend on ceramic strength, confinement, projectile material, impact velocity and interface support (Holmquist & Johnson, 2002; Holmquist & Johnson, 2005).

The high-velocity response of ceramics is frequently represented in numerical simulations using the Johnson-Holmquist family of ceramic constitutive models. Holmquist and Johnson characterized silicon carbide under high-velocity impact and demonstrated the importance of pressure-dependent strength, damage and equation-of-state response for capturing ceramic behavior (Holmquist & Johnson, 2002, 2005). Similar constitutive approaches have been developed for other ceramics, including aluminum nitride (Holmquist et al., 2001). In ceramic-metal armor simulations, such models allow researchers to represent the transition from intact ceramic strength to damaged ceramic resistance, although predictive accuracy depends on calibration against appropriate experiments.

5.2. Ceramic Fracture, Comminution and Fragment Momentum

Ceramic fracture is not merely a failure process; it is also an energy absorption mechanism. Crack initiation, crack branching, pulverization and comminution consume energy and redistribute momentum away from the projectile axis. At the same time, excessive fragmentation can reduce residual protection because the damaged ceramic zone may no longer sustain compressive load effectively. The challenge is therefore to promote beneficial fracture and projectile erosion while preventing catastrophic loss of structural integrity. Medvedovski emphasized that ceramic armor performance is strongly influenced by design and structure, including fragmentation control and support condition (Medvedovski, 2010a; Medvedovski, 2010b).

Fragment momentum must also be managed. After impact, ceramic fragments can be accelerated toward the backing and may damage adhesive layers or rear structures. A ductile metal casing or backing can retain these fragments and convert their kinetic energy into plastic work. In the prismatic-spherical alumina armor system reported by Aktaş and Çevik (2025b), the aluminum casing was used not only as an exterior cover but also as a structural containment component for fragmented ceramics. This illustrates the dual mechanical role of metal in such systems: it supports the ceramic before fracture and controls the consequences of fracture after impact.

5.3. Metallic Backing Plasticity, Membrane Stretching and Spall Control

Once the projectile and ceramic debris reach the backing, the metal dissipates energy mainly through plastic deformation, bending, membrane stretching, local indentation and possible plug formation. The effectiveness of this stage depends on ductility and dynamic strength. A backing that is too brittle may crack or spall; a backing that is too compliant may produce excessive backface deformation. Therefore, the backing is not simply a passive support plate. It is an active energy absorber whose response must be matched to the ceramic strike face.

In vehicle armor, the backing also contributes to structural continuity. Unlike body armor inserts, vehicle armor panels may act as add-on modules, hull components or protective casings. The backing must therefore satisfy both ballistic and structural requirements. This is one reason why ceramic-metal armor development often involves trade-offs among protection, mass, stiffness, manufacturability and repairability.

5.4. Interface Behavior, Delamination and Wave Propagation

Impact generates compressive waves that travel through the ceramic and reflect at material interfaces. When a compressive wave reaches a free surface or a lower-impedance layer, reflected tensile waves can promote ceramic cracking. The interface between ceramic and backing therefore governs not only mechanical attachment but also stress-wave management. Thin, stiff adhesive layers may maintain strong load transfer but can concentrate tensile reflections. More compliant interlayers can spread damage but may reduce ceramic support or allow greater local motion. Tasdemirci et al. (2012) demonstrated that interlayer materials can alter ceramic damage zones and the stress transferred to backing layers in ceramic/composite armors.

Delamination is especially important in hybrid armor packages containing metals, adhesives and fiber-reinforced layers. Delamination may absorb energy but can also reduce load transfer and cause loss of structural integrity. In ceramic-metal systems, debonding may allow ceramic fragments to move independently, which can either reduce or enhance residual protection depending on architecture. For this reason, interface behavior must be considered together with the intended damage mechanism.

5.5. Projectile Deflection and Geometric Effects

Projectile deflection is a distinct protective mechanism in which the projectile trajectory is redirected rather than only slowed. Geometry can promote deflection by altering the local surface normal at impact, imposing asymmetric contact forces or guiding the projectile into neighboring hard features. Curved ceramic surfaces and spherical elements are particularly relevant because the probability of oblique local contact is increased. Shao et al. (2019) experimentally and numerically investigated projectile impact against ultra-high-strength concrete protected with ceramic balls and showed that ceramic spheres could improve penetration resistance and influence trajectory behavior. Liu et al. (2019) numerically analyzed ceramic-ball-protected ultra-high-performance concrete and further demonstrated the role of ceramic spheres in reducing projectile velocity and altering impact response.

The diameter and packing pattern of spherical ceramics determine the size of the local contact region and the distribution of voids. In the Aktaş and Çevik (2022) diameter-pattern study, a finite element model based on a ceramic-ball armor reference configuration was verified and then extended to compare sphere diameter and pattern. The 20 mm checkerboard case produced the lowest modeled exit velocity among the examined cases, whereas smaller-diameter or less favorable layouts allowed higher residual velocities. This result is not a universal design rule; rather, it shows that geometric parameters can be as influential as material parameters within a given armor concept.

Impact location is equally important. If a projectile strikes the center of a ceramic element, the hard phase is fully engaged. If it strikes an edge or a void, the projectile may partially bypass the ceramic or interact with several elements asymmetrically. Aktaş and Çevik's (2025a) checkerboard-formation impact-location study showed that residual velocity varied from 277.7 m/s for central sphere impact to 1075.7 m/s for an interstitial void impact under the simulated conditions. The associated kinetic-energy loss decreased from 98.5% to 77.74%. These values clearly indicate that spatial stochasticity is a core design problem for modular ceramic armor.

5.6. Multi-Hit Resistance and Damage Localization

Multi-hit resistance is one of the most difficult requirements for ceramic armor because the first impact usually damages the ceramic locally. Monolithic ceramic plates may lose effectiveness over a relatively broad damaged region, whereas tile-based or particle-based structures can confine damage to a smaller zone. However, modularity must be balanced against gap vulnerability. The ideal architecture limits crack propagation, prevents fragment loss and preserves adjacent undamaged elements for subsequent impacts.

Free or semi-free ceramic particle systems represent one approach to multi-hit performance. Aydin and Soydemir (2021) experimentally investigated a free ceramic particle armor system and showed that ceramic particles within an aluminum structure can contribute to ballistic protection and post-impact reorganization. Aktaş and Çevik (2025b) extended a related idea by combining fixed triangular prismatic ceramics with freely positioned spherical alumina elements in an aluminum casing, creating a system intended to produce projectile deflection and limited gravity-assisted filling of damaged regions. Such concepts should not be interpreted as full autonomous material self-healing in the chemical sense; rather, they are structural reconfiguration mechanisms that attempt to restore local geometric coverage after impact.

6. Structural Designs of Modern Ceramic-Metal Composite Armors

6.1. Monolithic Ceramic-Faced Metallic Panels

The simplest ceramic-metal armor architecture is a continuous ceramic strike face on a metallic backing. This configuration offers efficient load transfer and relatively straightforward manufacturing. Its primary weakness is the extensive damage that may occur around the first impact, particularly if the ceramic plate is large and insufficiently segmented. Monolithic panels are therefore suitable when single-hit performance is prioritized or when the ceramic layer can be adequately confined and supported.

Numerical simulation has been widely used to evaluate ceramic composite armor under ballistic impact. Krishnan et al. (2010) analyzed ceramic composite armor response numerically, contributing to the understanding of failure progression and residual velocity prediction in ceramic-backed systems. Such studies are essential because full experimental characterization across many thicknesses, materials, impact velocities and angles is expensive and time-consuming. Nevertheless, numerical predictions must be validated because brittle fracture and erosion are sensitive to mesh, contact, damage parameters and failure criteria.

6.2. Layered, Sandwich and Tile-Based Armors

Layered armor systems distribute functions across multiple plates or plies. A ceramic front layer provides hard defeat, a metal or composite backing absorbs residual energy, and additional layers may act as spall liners, covers or environmental barriers. Sandwich structures use separated faces and a lightweight core to improve bending stiffness and impact energy dissipation. Hybrid-cored sandwich plates have been studied experimentally and numerically for ballistic resistance, showing the value of core architecture and material distribution in impact response (Ni et al., 2013). Metallic corrugated cores have also been examined under impact loading, illustrating the potential of structural core geometry to absorb energy through controlled deformation (Wadley et al., 2013).

Tile-based ceramic armors improve damage localization and facilitate replacement of damaged units. The main design challenge is the interface between tiles. Gaps, edges and corners are vulnerable because the projectile may interact with less ceramic mass than during central tile impact. This problem is analogous to the interstitial void issue in sphere-based armor. Consequently, tile geometry, overlap, backing stiffness and adhesive thickness must be optimized together.

6.3. Spherical, Prismatic and Cellular Ceramic Core Concepts

Spherical, prismatic and cellular ceramic cores are increasingly important because they allow armor designers to move beyond flat plate concepts. Spheres can promote oblique local contact and trajectory deviation. Prisms can introduce inclined surfaces, edge interactions and controlled paths for force transfer. Cellular or lattice-like arrangements can combine ceramic hardness with structural voids that reduce mass and influence wave propagation.

The prismatic-spherical armor concept of Aktaş and Çevik is a representative example of geometry-driven armor design. In that system, alumina spheres of 20 mm diameter were positioned in vertical grooves between fixed triangular alumina prisms, all contained within a thin aluminum 5754-H111 casing. The design aimed to combine deflection by spherical and prismatic geometries with structural containment and limited gap filling after impact (Aktaş & Çevik, 2025b). Direct impact on a triangular prismatic ceramic element stopped the bullet core in the reported tests, while several perforating cases still exhibited significant projectile deflection. The study therefore demonstrates how geometry can be used to design for both resistance and trajectory management.

Cellular and geometric armor concepts also have limitations. Manufacturing tolerances, ceramic quality, contact conditions and assembly repeatability become more complex as geometry becomes more elaborate. In addition, local voids may introduce vulnerable impact positions. For this reason, geometric armor should be assessed with probabilistic or spatially resolved impact scenarios rather than only central-hit idealizations.

6.4. Metal-Confined and Repairable Armor Architectures

Confinement improves ceramic performance by suppressing tensile fracture, limiting fragment dispersion and maintaining compressive support around the damaged region. Metal confinement can be provided by a backing plate, side walls, a casing or a pre-stressed frame. A metal casing can also improve repairability by retaining ceramic debris and allowing damaged modules to be replaced. However, confinement increases manufacturing complexity and can add mass if not carefully optimized.

Repairability and residual protection are increasingly relevant for vehicle armor. A system that survives one impact but loses broad-area protection may be unsuitable for operational environments with repeated threats. Modular ceramic-metal structures, replaceable tile panels and reconfigurable particle systems offer potential solutions, but their practical value depends on consistent performance after partial damage, environmental exposure and repeated vibration.

7. Advanced Ceramic-Metal Armor Concepts

7.1. Self-Healing and Reconfigurable Armor Systems

The term self-healing must be used carefully in armor engineering. In polymer science it often refers to chemical or molecular repair mechanisms, whereas in ceramic-metal armor it more commonly describes structural reorganization or damage-tolerant reconfiguration. Free ceramic particles, movable spheres or modular inserts can partly restore geometric coverage after local damage. Aydin and Soydemir's free ceramic particle system and Aktaş and Çevik's prismatic-spherical alumina armor are examples of this structural approach (Aktaş & Çevik, 2025b; Aydın & Soydemir, 2021).

A reconfigurable armor system can be valuable if it limits the formation of persistent gaps after impact. In the prismatic-spherical concept, unbonded spherical ceramics were intended to move under gravity and fill local spaces left by damaged ceramics (Aktaş & Çevik, 2025b). The principal limitation is orientation dependence: gravity-assisted reconfiguration may be less effective when the armor is mounted in non-vertical orientations, subjected to high obliquity impacts or constrained by debris jamming. Future work in this area should distinguish between visually observed gap filling, measurable residual ballistic performance and true restoration of protection level.

7.2. Functionally Graded and Biomimetic Concepts

Functionally graded ceramic-metal armors attempt to reduce abrupt impedance mismatch by gradually varying composition, porosity or mechanical properties through the thickness. Such designs can reduce stress concentration and modify wave reflection, although manufacturing remains challenging. Biomimetic concepts use natural structural principles, such as nacre-like layering, tiled overlap or hierarchical toughening, to improve damage tolerance. The value of these concepts lies not in imitation alone, but in controlled crack deflection, energy dissipation over multiple scales and improved resistance to catastrophic failure.

Recent numerical work on biomimetic ceramic composite armor has examined how structural response and impact dynamics depend on local geometry. Such studies reinforce a broader trend: ballistic protection is moving from material substitution toward architecture-driven performance, where topology, hierarchy and spatial variability are treated as primary design variables (Aktaş & Çevik, 2025a; Pan et al., 2023).

7.3. Additive Manufacturing and Complex Geometry

Additive manufacturing offers potential routes for producing complex metallic backings, graded interlayers, lattice supports and customized confinement frames. For ceramics, additive manufacturing is more challenging because armor-grade ceramics require high density, controlled microstructure and reliable mechanical properties after sintering. Nevertheless, additive methods may become useful for tooling, molds, metallic support structures and hybrid architectures where geometry is too complex for conventional machining.

The greatest opportunity is not necessarily printing the ceramic strike face itself, but integrating complex metal structures around high-quality ceramic inserts. Lattice-supported backings, topology-optimized casings and graded support frames may improve energy absorption and reduce mass while preserving ceramic support.

7.4. Smart, Adaptive and Lightweight Vehicle Armor Technologies

Smart or adaptive armor concepts include embedded sensing, damage monitoring, active response systems and modular replacement strategies. In ceramic-metal armor, sensing may be used to identify damaged zones, estimate residual protection or guide maintenance. Lightweight vehicle armor technologies increasingly require multifunctionality: ballistic protection, structural stiffness, corrosion resistance, thermal stability and maintainability. Advanced composite armor systems for military vehicles have recently been reported with emphasis on design methodology, ballistic testing and comparison of protection systems (Tsirogiannis et al., 2024).

For vehicle applications, the main engineering question is not simply which ceramic is strongest, but which system provides the best protection-to-mass ratio under realistic impact distributions and service conditions. The answer depends on threat spectrum, allowable backface deformation, acceptable cost, repair strategy and integration with vehicle structure.

8. Current Limitations and Research Directions

8.1. Ceramic Brittleness and Scatter in Ballistic Response

Ceramic brittleness remains the central limitation of ceramic-metal armor. Although brittle fracture absorbs energy, it also creates scatter in performance and reduces residual resistance. Microstructural defects, tile edges, surface flaws and support irregularities can produce significant variability in ballistic response. Therefore, armor-grade ceramics require strict quality control and fracture-aware design. Numerical models must also account for damage accumulation and post-failure resistance, not only elastic strength.

8.2. Weight-Protection Trade-Off

Every armor system is constrained by the weight-protection trade-off. Increasing ceramic thickness generally improves projectile defeat, but it also increases cost and may enlarge the fractured region. Increasing backing thickness improves residual energy absorption but increases areal density. The optimum solution often involves a balanced architecture rather than maximum thickness of one constituent. Mass efficiency must be evaluated together with multi-hit performance and structural integration.

8.3. Manufacturing, Joining and Cost

Manufacturing ceramic-metal armor requires control of ceramic sintering, tile machining, backing forming, bonding, curing, assembly tolerance and inspection. Joining is particularly difficult because ceramics and metals have different coefficients of thermal expansion, elastic moduli and fracture behaviors. Adhesive layers must provide durable bonding without creating unfavorable stress-wave reflections or premature delamination. Complex geometric armor concepts add further challenges because local contact, packing and alignment can strongly affect performance.

8.4. Durability and Environmental Effects

Armor systems are exposed to temperature cycles, humidity, vibration, corrosion, ultraviolet radiation and mechanical handling. These environmental factors can degrade adhesives, polymeric covers and fiber-reinforced backing layers. Metallic casings may corrode if not properly protected, while ceramics may be affected by surface damage and mounting stresses. Long-term durability testing should therefore accompany ballistic testing, especially for vehicle-mounted armor expected to remain in service for extended periods.

8.5. Emerging Research Trends

The most important research trends in ceramic-metal armor include architecture optimization, validated numerical simulation, probabilistic impact-location analysis, hybrid ceramic-fiber-metal systems, multi-hit residual performance, modular repairable panels, reconfigurable particle systems and advanced manufacturing of complex support structures. Future studies should report not only whether perforation occurs, but also residual velocity, projectile erosion, backface deformation, damage area, areal density, fragment distribution, impact location sensitivity and residual protection after prior impact.

A critical methodological need is realistic validation. High-fidelity simulations using Johnson-Holmquist ceramic models and Johnson-Cook metal models can be powerful, but they must be calibrated and validated against experiments that capture the relevant failure mechanisms. Mesh dependence, erosion criteria, contact algorithms and material-rate parameters can change predicted residual velocity and damage extent. Transparent reporting of these numerical assumptions is essential for comparing armor concepts across studies.

9. Conclusion

Ceramic-metal composite armors remain a central technology for lightweight ballistic protection because they combine the projectile-defeating capability of hard ceramics with the ductility, support and fragment-retention capacity of metals. Their performance is governed by coupled mechanisms: projectile erosion and blunting, ceramic fracture and comminution, stress-wave propagation, interface behavior, backing plasticity, delamination, fragment containment and, in some designs, projectile deflection. No single material property is sufficient to define ballistic performance; protection emerges from the interaction among material, geometry, interface and threat.

Modern ceramic-metal armor design is increasingly architecture-driven. Tile segmentation, spherical ceramic arrangements, prismatic cores, cellular structures, sandwich panels and modular particle systems can localize damage, alter projectile trajectories and improve mass efficiency. However, geometry also introduces vulnerability through gaps, edges and impact-location sensitivity. Therefore, advanced armor concepts must be evaluated using spatially resolved impact scenarios and multi-hit criteria, not only ideal central impacts.

The literature indicates that future improvements will arise from hybridization, validated computational design, material-interface optimization and multifunctional structural concepts. Reconfigurable or self-healing armor systems are promising when interpreted as structural damage management rather than complete material regeneration. For practical vehicle protection, the next generation of ceramic-metal composite armors must deliver not only high ballistic resistance, but also low areal density, controlled backface response, repeatable manufacturing, environmental durability, inspectability and residual protection after damage.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

References

Aguilar-Elguezabal, A., Reyes-Rojas, A., Esparza-Ponce, H. E., Lardizábal-Gutiérrez, D., & Bocanegra-Bernal, M. H. (2026). Advances in high-performance ceramic materials for aerospace and defence applications: A state-of-the-art review. *Ceramics*, *9*(4), 39. https://doi.org/10.3390/ceramics9040039

Akella, K. (2020). Multilayered ceramic-composites for armour applications. In Y. R. Mahajan & R. Johnson (Eds.), *Handbook of advanced ceramics and composites: Defense, security, aerospace and energy applications* (pp. 403–433). Springer International Publishing. https://doi.org/10.1007/978-3-319-73255-8_11-1

Aktaş, L. T., & Çevik, M. (2022). Diameter and pattern effects of Al_2O_3 balls on ballistic strength of metal-ceramic composites. In *Proceedings of the 6th International Students Science Congress* (pp. 261–263). https://doi.org/10.52460/issc.2022.034

Aktaş, L. T., & Çevik, M. (2025a). Impact location effects on ballistic performance of checkerboard-formation ceramic sphere armor. In *Proceedings of the International Congress on New Trends in Mechanics* (pp. 423–428). Azerbaijan State Pedagogical University.

Aktaş, L. T., & Çevik, M. (2025b). Ballistic impact analysis of composite armors incorporating prismatic and spherical self-healing ceramic structures. *Mechanics of Composite Materials, 61*(4), 739–752. https://doi.org/10.1007/s11029-025-10306-6

Aydin, M., & Soydemir, M. (2021). Ballistic protection performance of a free ceramic particle armor system: An experimental investigation. *Ceramics International, 47*(8), 11628–11636. https://doi.org/10.1016/j.ceramint.2020.12.295

Braga, F. O., Luz, F. S., Monteiro, S. N., & Lima, E. P., Jr. (2018). Effect of the impact geometry in the ballistic trauma absorption of a ceramic multilayered armor system. *Journal of Materials Research and Technology, 7*(4), 554–560. https://doi.org/10.1016/j.jmrt.2018.06.019

Chen, Z., Xu, Y., Li, M., Li, B., Song, W., Xiao, L., Cheng, Y., & Jia, S. (2022). Investigation on residual strength and failure mechanism of the ceramic/UHMWPE armors after ballistic tests. *Materials, 15*(3), 901. https://doi.org/10.3390/ma15030901

Crouch, I. G. (Ed.). (2017). *The science of armour materials*. Woodhead Publishing.

Crouch, I. G., Cimpoeru, S. J., Li, H., & Shanmugam, D. (2017). Armour steels. In I. G. Crouch (Ed.), *The science of armour materials* (pp. 55–115). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100704-4.00002-5

Dresch, A. B., Venturini, J., Arcaro, S., Montedo, O. R. K., & Bergmann, C. P. (2021). Ballistic ceramics and analysis of their mechanical properties for armour applications: A review. *Ceramics International, 47*(7), 8743–8761. https://doi.org/10.1016/j.ceramint.2020.12.095

Fejdyś, M., Kośla, K., Kucharska-Jastrząbek, A., & Łandwijt, M. (2021). Influence of ceramic properties on the ballistic performance of the hybrid ceramic-multi-layered UHMWPE composite armour. *Journal of the Australian Ceramic Society, 57*, 149–161. https://doi.org/10.1007/s41779-020-00516-7

Hazell, P. J. (2022). *Armour: Materials, theory, and design* (2nd ed.). CRC Press/Taylor & Francis. https://doi.org/10.1201/9781003322719

Holmquist, T. J., & Johnson, G. R. (2002). Response of silicon carbide to high velocity impact. *Journal of Applied Physics, 91*(9), 5858–5866. https://doi.org/10.1063/1.1468903

Holmquist, T. J., & Johnson, G. R. (2005). Characterization and evaluation of silicon carbide for high-velocity impact. *Journal of Applied Physics, 97*(9), 093502. https://doi.org/10.1063/1.1881798

Holmquist, T. J., Templeton, D. W., & Bishnoi, K. D. (2001). Constitutive modeling of aluminum nitride for large strain, high-strain rate, and high-pressure applications. *International Journal of Impact Engineering, 25*(3), 211–231. https://doi.org/10.1016/S0734-743X(00)00046-4

Johnson, G. R., & Cook, W. H. (1985). Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. *Engineering Fracture Mechanics, 21*(1), 31–48. https://doi.org/10.1016/0013-7944(85)90052-9

Krishnan, K., Sockalingam, S., Bansal, S., & Rajan, S. D. (2010). Numerical simulation of ceramic composite armor subjected to ballistic impact. *Composites Part B: Engineering, 41*(8), 583–593. https://doi.org/10.1016/j.compositesb.2010.10.001

Liu, J., Wu, C., Li, J., Fang, J., Su, Y., & Shao, R. (2019). Ceramic balls protected ultra-high performance concrete structure against projectile impact—A numerical study. *International Journal of Impact Engineering*, *125*, 143–162. https://doi.org/10.1016/j.ijimpeng.2018.11.006

Medvedovski, E. (2010a). Ballistic performance of armour ceramics: Influence of design and structure. Part 1. *Ceramics International*, *36*(7), 2103–2115. https://doi.org/10.1016/j.ceramint.2010.05.021

Medvedovski, E. (2010b). Ballistic performance of armour ceramics: Influence of design and structure. Part 2. *Ceramics International*, *36*(7), 2117–2127. https://doi.org/10.1016/j.ceramint.2010.05.022

Ni, C. Y., Li, Y. C., Xin, F. X., Jin, F., & Lu, T. J. (2013). Ballistic resistance of hybrid-cored sandwich plates: Numerical and experimental assessment. *Composites Part A: Applied Science and Manufacturing*, *46*(1), 69–79. https://doi.org/10.1016/j.compositesa.2012.07.019

Pan, G., Su, H., Li, X., & Wang, J. (2023). Coupled FEM-SPH simulation of the protective properties for metal/ceramic composite armor. *International Journal of Lightweight Materials and Manufacture*, *6*(4), 543–551. https://doi.org/10.1016/j.ijlmm.2023.05.007

Rahbek, D. B., Simons, J. W., Johnsen, B. B., Kobayashi, T., & Shockey, D. A. (2017). Effect of composite covering on ballistic fracture damage development in ceramic plates. *International Journal of Impact Engineering*, *99*, 58–68. https://doi.org/10.1016/j.ijimpeng.2016.09.010

Shao, R., Wu, C., Su, Y., Liu, Z., Liu, J., Chen, G., & Xu, S. (2019). Experimental and numerical investigations of penetration resistance of ultra-high strength concrete protected with ceramic balls subjected to projectile impact. *Ceramics International*, *45*(6), 7961–7975. https://doi.org/10.1016/j.ceramint.2019.01.110

Si, P., Liu, Y., Yan, J., Bai, F., & Huang, F. (2022). Ballistic performance of polyurea-reinforced ceramic/metal armor subjected to projectile impact. *Materials*, *15*(11), 3918. https://doi.org/10.3390/ma15113918

Tasdemirci, A., Tunusoglu, G., & Guden, M. (2012). The effect of the interlayer on the ballistic performance of ceramic/composite armors: Experimental and numerical study. *International Journal of Impact Engineering*, *44*, 1–9. https://doi.org/10.1016/j.ijimpeng.2011.12.005

Tsirogiannis, E. C., Daskalakis, E., Vogiatzis, C., Psarommatis, F., & Bartolo, P. J. (2024). Advanced composite armor protection systems for military vehicles: Design methodology, ballistic testing, and comparison. *Composites Science and Technology*, *251*, 110486. https://doi.org/10.1016/j.compscitech.2024.110486

Wadley, H. N. G., Dharmasena, K. P., O'Masta, M. R., & Wetzel, J. J. (2013). Impact response of aluminum corrugated core sandwich panels. *International Journal of Impact Engineering*, *62*, 114–128. https://doi.org/10.1016/j.ijimpeng.2013.06.005

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 39-46.

3

A Patient-Specific Orthosis Design for Clubfoot Syndrome Using Reverse Engineering

İrem Arısoy[1]*, Samet Çıklaçandır[2]

İzmir Kâtip Çelebi University, Department of Biomedical Engineering, İzmir, Türkiye

**Corresponding Author*: iremarisoy35@gmail.com

Abstract

Clubfoot (pes equinovarus) is a congenital deformity characterized by an inward and downward positioning of the foot and requires early treatment. By preventing the equinus, varus, and forefoot adduction, orthotics help to keep the foot in the proper alignment. However, these orthotics need to be frequently remanufactured, especially in infants, due to their rapid foot development. Traditional orthotics, relying on plaster casts and manual processes, are time-consuming and costly. Custom-designed orthotics provide more stable support by fitting perfectly to the patient's foot. Nowadays, 3D scanning and 3D printing technologies have become important in the development of personalized medical products for therapeutic purposes. This chapter aims to redesign and print an orthosis used to correct congenital clubfoot in infants using 3D scanning and reverse engineering methods. In this chapter, the geometry of the original orthosis was obtained using a calibrated 3D scanner and Flexscan software. The resulting scan images were edited in mesh format, and irregularities, open areas, and noises on the surface were corrected with appropriate enhancement and smoothing processes in Geomagic Studio. The orthosis's original geometry had to be revised to fit the patient's updated measurements in the subsequent phase. To maintain anatomical proportions, axis-based (X-Y-Z) geometric correction was used. The accuracy of the model's current dimensions was re-measured, checked, and then exported in STL format for 3D printing. The results demonstrate that personalized medical devices can be successfully produced through the systematic application of 3D scanning, controlled scaling, and 3D printing steps. This method offers a significant advantage in terms of cost and time, especially in cases requiring repeated and continuous production.

Keywords: 3D Scanning, 3D Printing, Reverse Engineering, Patient Specific Manufacturing

1. Introduction

One of the most severe congenital orthopedic abnormalities in infants is clubfoot syndrome. According to statistics, there are roughly 1-2 cases for every 1,000 live births, with low- and middle-income nations accounting for 80% of cases (Siapkara & Duncan, 2007). Hindfoot equinus, midfoot cavus, forefoot

[1] https://orcid.org/0009-0005-3105-0363
[2] https://orcid.org/0000-0003-2076-2400

adductus, and hindfoot varus are the four primary components of the deformity (Liu et al., 2014). It is known that the incidence is twice as high in males as in females, with around half of the cases being unilateral.

The Ponseti procedure is the most widely used non-surgical (conservative) technique for treating clubfoot (pes equinovarus). With this approach, lengthy leg casts are used after weekly corrective foot manipulations. To support the correction of the deformity, a percutaneous tenotomy of the Achilles tendon is carried out if required. A foot abduction brace is employed to guarantee long-term protection and ongoing correction throughout treatment (Ponseti et al., 2006; Radler, 2013). Another conventional conservative way for treating clubfoot is the Kite method. Additionally, this approach combines casting, manipulation, and long-term orthotic use.

A labor-intensive technique based on plaster molding, hand shaping, and the use of thermoplastic materials makes up the traditional orthosis production method. This procedure is difficult for the patient, may involve defects in production, is expensive when remanufacturing is necessary, and requires frequent replacements, particularly in newborns during periods of rapid growth. According to the research, traditional customized orthosis production requires several clinical visits and waiting periods of up to six weeks (Hale et al., 2020) Additionally, it has been shown that these procedures raise the incidence of repeated abnormalities and have a negative effect on patient compliance.

Reverse engineering is a technique that enables the modification or customization of an existing physical object's geometry by moving it into a digital environment. In the field of orthotics and prosthetics, computerized processes based on 3D scanning are slowly taking the place of conventional plaster casting techniques. These processes include steps for data gathering (3D scanning), surface processing (CAD/reverse engineering software), and manufacture (3D printing) (Hale et al., 2020; Vivek & Ranganathan, 2019).

The best options for precisely capturing human body anatomy among 3D scanning technologies are structural light scanners and photogrammetry (Silva et al., 2024). Photogrammetry has advantages in terms of affordability, portability, and applicability for therapeutic settings, whereas structural light-based scanners deliver high-resolution point cloud and mesh data. On the other hand, because of their high precision, laser scanning systems are widely used in industrial applications.

Following scanning, the raw data is processed for noise reduction, surface correction, hole sealing, and smoothing. Reverse engineering software like Geomagic Studio, Geomagic Wrap, Rhinoceros, Rapidform, and LeiosMesh are used for this. Because it depends on the operator's software skill, this step is the most important and time-consuming portion of the workflow (Silva et al., 2024) The model developed from CT data for cervical orthosis design was processed using a combination of Mimics, 3-matic, and Geomagic Studio; it was demonstrated that topology optimization reduced the device weight.

The body of research on the use of 3D printing technology in the manufacturing of orthoses is growing quickly. In this case, additive manufacturing technology has been used to create a customized clubfoot orthosis as an alternative to the Ponseti method's limitations. Despite its geometric complexity, it has been demonstrated that this device, which is made using the fused deposition modeling (FDM) approach, is practical (Vivek & Ranganathan, 2019). Similarly, a 3D clubfoot model constructed from computed tomography (CT) images has been used to construct and compare several conceptual orthosis designs. These designs feature spiral wound (Model II), mechanically adjustable (Model III), and deep heel cup (Model I) constructions. The mechanical orthosis showed a maximum displacement of 1.45 mm and a stress of 0.79 N/mm², according to finite element analysis (FEA) data (Vijayaragavan et al., 2017).

Even while clubfoot treatment techniques and digital orthosis manufacturing technologies have advanced significantly, there are still a number of obstacles in clinical practice. Conventional orthosis production techniques are labor-intensive, time-consuming, and heavily reliant on practitioner skill. Furthermore, while additive manufacturing and 3D scanning technologies present viable substitutes, their incorporation into an organized and effective clinical workflow is yet not entirely standardized. Widespread adoption is still limited by data collecting variability, processing complexity, and a lack of effective design methodologies. Thus, a more effective, patient-specific, and repeatable digital methodology for orthosis design and fabrication is obviously needed. This chapter proposes a patient-specific clubfoot orthosis design method based on 3D scanning and reverse engineering. The approach includes digital processing and modeling using reverse engineering tools, manufacture utilizing additive manufacturing techniques, and the collection of anatomical data using 3D scanning. This study aims to assess the viability and efficacy of this digital strategy in terms of clinical applicability, production efficiency, and design accuracy.

2. Materials and Methods

2.1. Data Collection

An existing ankle-foot orthosis (AFO) from a baby with congenital clubfoot served as the reference model. Because the orthosis that is currently made needs to be replaced regularly due to the rapid development of the baby's skeletal and soft tissues over time, the orthosis must be changed regularly. Instead of patients repeatedly coming to the clinic to get 3D scans, a new orthosis design was created based on the patient's existing previous orthosis, meaning a completely new orthosis tailored to the patient was developed without performing a foot scan. The patient's current orthosis was reverse-engineered and moved to a three-dimensional digital environment in order to solve this problem. The patient's existing anatomical measurements were then used to modify the final geometry. This method allowed for patient-specific updates to the current design without requiring the creation of new molds and modeling procedures.

The HDI Advance structured light-based 3D scanner (LMI Technologies) was used to digitize the orthosis's three-dimensional geometry. The HDI Advance is a high-resolution scanning system that uses structured light technology and has two machine imaging cameras. The device can produce 2.6 million points (5.2 million polygons) each scan with dimensional accuracy of up to 45 μm. The scan takes around a second to complete, which is a big benefit, particularly when scanning small objects with complicated surfaces. Export to popular geometric file formats such as PLY, OBJ, STL, ASC, and FBX is supported by the system.

The manufacturer's calibration panel was used to calibrate the HDI Advance equipment prior to starting the scanning process. Correcting camera lens distortion, confirming stereo camera geometry, and aligning the measurement scale with the real dimensions were all part of the calibration process. By projecting known phase-shifted patterns onto the object surface, structured light scanners use cameras to record surface geometry in a high-resolution point cloud format. This technique offers superior accuracy, particularly when scanning small objects with complex geometries (Salvi et al., 2010). Scans were carried out from several perspectives in order to thoroughly capture the surface characteristics of the orthosis (Figure 1).

Figure 1. Positioning of the reference clubfoot orthosis on the scanning platform during the 3D scanning process.

In addition, FlexScan3D software (Polyga) was used for data collection and preliminary scanning (Figure 2). Scanner calibration, data capture, scan alignment, merging, and raw scan cleaning are all provided in a single interface by FlexScan3D, a software program designed specifically for the HDI

Advance scanner. In addition to supporting output in PLY, OBJ, STL, and FBX formats, the program offers capabilities for hole filling and deviation analysis to enhance scan quality. The FlexScan3D software's automatic alignment and merging tools were used to integrate the resulting partial scans into a full 3D model. The scanned model was imported into Geomagic Studio in mesh format after overlapping regions were cleared to create a watertight surface.

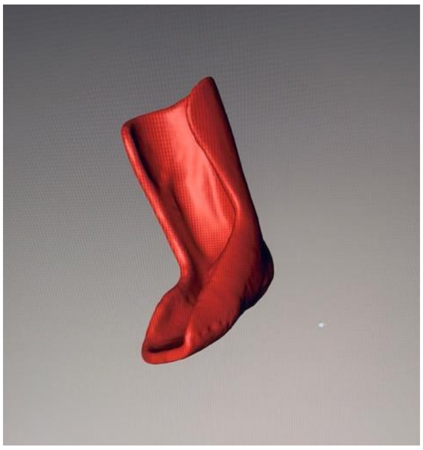

Figure 2. Initial mesh model of the reference orthosis generated in FlexScan3D after scan alignment and merging processes.

Geomagic Studio (3D Systems) software was used to do advanced mesh processing of the scan data (Figure 3). All main 3D scanners are supported by Geomagic Studio, an industry standard reverse engineering software with extensive polygon mesh editing tools and point cloud alignment and merging capabilities. The program provides geometric scaling functions, noise reduction, curvature sensitive smoothing, hole filling, outlier removal, and automatic mesh repair (Mesh Doctor). The Mesh Doctor tool is used to identify and automatically fix mesh flaws such non-manifold edges, self-intersections, and sharp points. Using the Mesh Doctor tool, raw mesh data imported into Geomagic Studio is first put through a systematic quality check. Sharp points, self-intersections, non-manifold edges, high-slope edges, and small component and hole flaws are all automatically identified by Mesh Doctor. The software's one-touch automatic repair feature fixes the great majority of discovered flaws; interactive tools are used to manually fix the remaining complicated flaws.

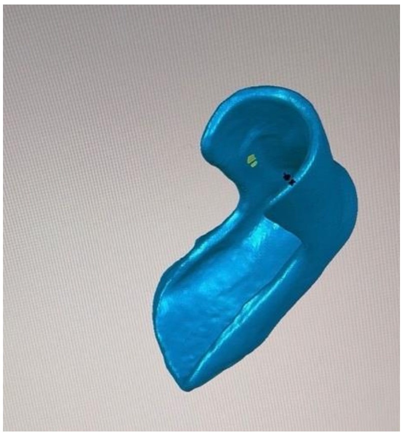

Figure 3. Processed mesh model of the reference clubfoot orthosis in Geomagic Studio after mesh repair, smoothing, and surface correction operations.

A curvature-sensitive smoothing algorithm appropriate for the orthosis's complex surface profile was used during the noise reduction stage. This technique preserves anatomical details in regions with important surface curvature while efficiently reducing scanning noise in flat parts. Bridge and interactive hole filling tools have been used to close open areas created by shadow regions during the scanning process.

In accordance with normal anthropometric protocol, calipers were used to assess the patient's existing anatomy. The model was dimensionally updated while maintaining anatomical proportions using an axis-based (X-Y-Z) geometric scaling technique. The sagittal plane (proximal-distal, Y-axis), coronal plane (mediolateral, X-axis), and transverse plane (superior-inferior, Z-axis) were used as references while creating and transferring the coordinate system to the model. The transformation tools in Geomagic Studio were used to apply the computed scaling factors to the model. Given that newborns' growth rates in several anatomical directions are not identical, independent scaling along each axis is especially crucial (Cha et al., 2017). Measurements of length, width, and height were checked to target values; the model was exported in STL format once dimensional deviations were confirmed to be within allowable tolerance ranges. Because the triangular mesh representation is compatible with printing platforms and can be handled directly by FDM slicing software, the STL format was used.

Digital sculpting, freeform surface modeling, and parametric CAD techniques are all merged into one professional three-dimensional design program called Geomagic Freeform. It performs exceptionally well in medical product design, especially when it comes to modeling complex organic shapes that precisely fit the human body and managing complex surface geometries that are beyond the capabilities of conventional CAD systems. This makes it possible to produce more durable, lighter, better fitting, and patient specific devices. It enables designers and engineers to build complicated forms that are difficult for typical CAD tools to handle by providing voxel based digital sculpting, subdivision surfaces (SubD), and NURBS geometry on a single, integrated platform. With these characteristics, Geomagic Freeform was assessed as an appropriate tool for this research in the digitization and modification of preexisting orthotic geometries.

2.2. Additive Manufacturing

Ultimaker Cura software was used for the slicing procedure (Figure 4). The orthosis model was loaded into software after it had been scaled and exported in STL format. At this point, the printing direction, layer thickness, padding density, and support structure type parameters were modified. The load bearing surfaces of the orthosis were considered while choosing the printing orientation, with the goal being to place the layers perpendicular to the mechanical stress. To make sure the construction has enough rigidity for clinical application, the padding density was changed. The software separated the STL file into layers based on all of these characteristics, transformed it into a G-code file. During the production stage, the Ultimaker 2+ Extended FDM printer was utilised. Using Fused Filament Fabrication (FFF) technology, the printer is a professional-grade desktop 3D printer that is distinguished by its excellent dimensional precision and dependable print quality. The entire process is summarized step-by-step in Figure 5.

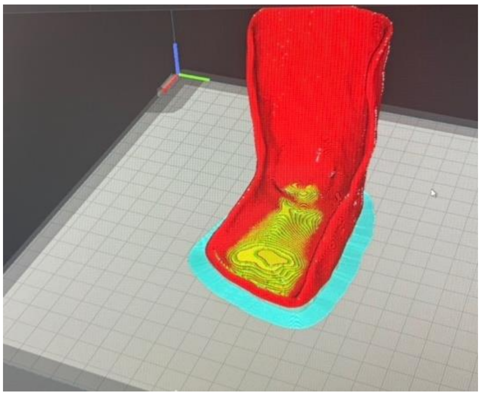

Figure 4. Sliced orthosis model in the Ultimaker Cura with optimized printing orientation and support structures.

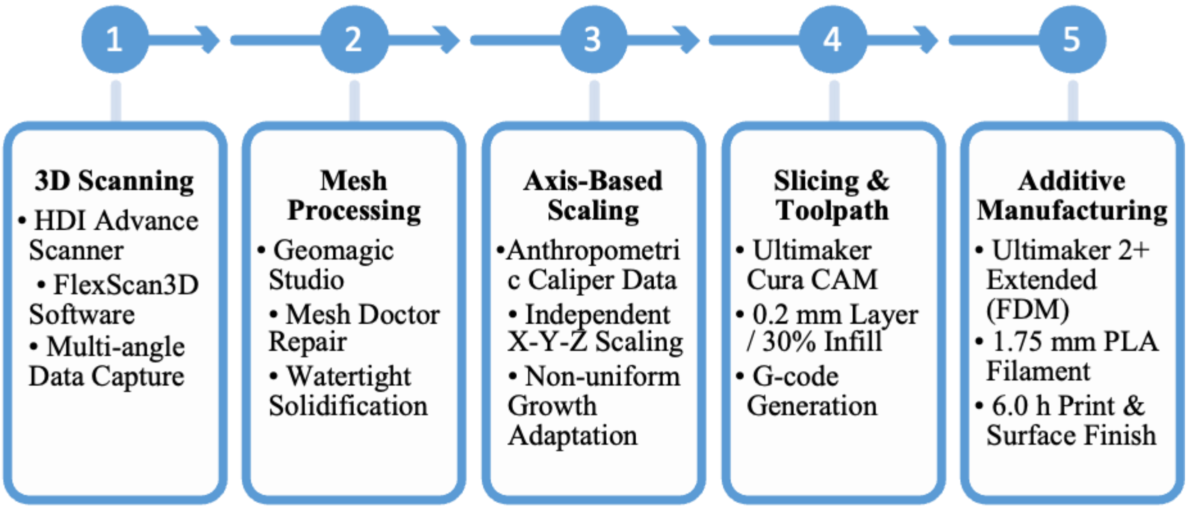

Figure 5. Step-by-step overview of the reverse engineering, parametric scaling, and 3D printing pipeline for patient-specific infant clubfoot orthosis renewal.

The orthosis was made from a polylactic acid (PLA) filament with a diameter of 1.75 mm. PLA is a thermoplastic polymer. It is made from renewable biological resources like sugarcane or maize starch. Its widespread application in the production of medical devices is mostly due to its light weight, low shrinkage, good dimensional stability, and ease of processing in FDM printers (Nouri et al., 2023; Vivek & Ranganathan, 2019). PLA was found to have the highest compressive strength values in a study by (Savonen et al., 2020)that compared various filament materials for newborn clubfoot orthoses.

The Ultimaker 2+ Extended printer received the G-code from the slicing program, and printing was started. Layer adhesion and dimensional consistency were tracked throughout the printing process. 50 grams of PLA filament were used during the 6-hour printing time. The support structures were removed when printing was finished, and a sandpaper was used where surface roughness needed to be reduced. Calliper measurements were used to verify the orthosis's dimensional accuracy.

3. Results and Discussion

The pipeline for digital reverse engineering and additive manufacturing was successfully completed. 50.0 grams of PLA filament (including support material) were used during the exact 6.0-hour FDM production process. The final orthosis had flawless heel shapes, seamless internal surface transitions, and clean layer adhesion. When combined with typical orthotic interface socks, the inside surfaces displayed a non-abrasive finish appropriate for direct soft-tissue contact.

Throughout early childhood, corrective brace usage is necessary for the clinical care of congenital clubfoot. However, because strict orthoses frequently become outdated, pediatric growth rates place significant financial and logistical strain on families and healthcare professionals. Compared to traditional fabrication pipelines requiring manual plaster cast wrapping, curing, plaster positive rectification, and thermoforming which typically demands multiple clinical visits and days to weeks of laboratory turnaround the digital workflow presented here completes physical output within 6 hours from anthropometric input.

Compared to discarded plaster molds and cut thermoplastic sheets, the suggested process significantly decreases raw material waste, using only 50 g of PLA per unit. Additionally, using recyclable, bio-based polymers is consistent with the sustainable healthcare production targets. While the dimensional accuracy and production efficiency are demonstrated, this study has limitations:

- Mechanical and Fatigue Testing: There was no experimental testing of dynamic FEA, cycle fatigue resistance, or long-term creep behavior under physiological newborn kicking loads.
- Clinical Sample Size: Extensive multi-center clinical trials assessing skin pressure distribution and longitudinal correction rates across larger patient cohorts are required, as the framework was tested on a single reference patient model.
- Material Diversity: Advanced medical-grade filaments like PETG, TPU (for flexible corrective hinges), and carbon-fiber-reinforced composites should be benchmarked in future studies.

4. Conclusions

This study demonstrates how custom orthotics for patients with congenital clubfoot syndrome can be made using additive manufacturing, reverse engineering, and 3D scanning. The existing reference orthosis was successfully digitised, mesh defects were corrected, axis-based rescaling based on patient measurements was performed, and it was constructed from PLA using the FDM technique. Therefore, the proposed digital process offers a quicker, more repeatable, and more cost-effective option than traditional manual manufacturing techniques.

This approach is especially appropriate for orthoses that need to be replaced frequently in paediatric patients who are growing quickly because the creation process is quick, requires little materials, and allows for future modification of the digital model. In this way, the research could enhance patient comfort, shorten production times, and make it easier for patients to receive individualised care in clinical settings.

From an engineering standpoint, the chapter offered a comprehensive design process that included the definition of the problem, a review of the literature, contemporary design techniques, an approach to analysis and modelling, the manufacturing process, practical limitations, and sustainability objectives. The application of theoretical and practical knowledge acquired in biomedical engineering education to a clinical problem was made possible by the use of 3D scanning, CAD-based reverse engineering, mesh processing, axis-based scaling, and FDM manufacturing processes. Realistic limitations including economic, environmental, health, safety, ethical, legal, and reproducibility were also taken into consideration when evaluating the study. In this regard, the chapter can be regarded as both a prototype production and a creative and workable engineering solution for creating medical equipment tailored to individual patients.

It is recommended that future research employ FEA and mechanical strength tests, compare various filaments and manufacturing parameters, and do clinical validation with more patients. The clinical dependability of the approach will also be improved by quantitative assessment of factors like long-term use, patient happiness, surface comfort, and biomechanical performance. All things considered, this study offers a solid basis for the use of digital orthotic fabrication techniques in the management of pediatric clubfoot.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

References

Cha, Y. H., Lee, K. H., Ryu, H. J., Joo, I. W., Seo, A., Kim, D. H., & Kim, S. J. (2017). Ankle-foot orthosis made by 3D printing technique and automated design software. *Applied Bionics and Biomechanics, 2017*. https://doi.org/10.1155/2017/9610468

Hale, L., Linley, E., & Kalaskar, D. M. (2020). A digital workflow for design and fabrication of bespoke orthoses using 3D scanning and 3D printing, a patient-based case study. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-63937-1

Liu, X.-C., Tassone, C., Rizza, R., Linford, E., Thometz, J. G., Lyon, R., & Tarima, S. (2014). Newly designed foot orthosis for children with residual clubfoot after Ponseti casting. *Journal of Prosthetics and Orthotics, 26*(1), 38–42. https://doi.org/10.1097/JPO.0000000000000010

Nouri, A., Wang, L., Li, Y., & Wen, C. (2023). Materials and manufacturing for ankle–foot orthoses: A review. *Advanced Engineering Materials, 25*, 2300238. https://doi.org/10.1002/adem.202300238

Ponseti, I. V., Zhivkov, M., Davis, N., Sinclair, M., Dobbs, M. B., & Morcuende, J. A. (2006). Treatment of the complex idiopathic clubfoot. *Clinical Orthopaedics and Related Research, 451*, 171–176. https://doi.org/10.1097/01.blo.0000224062.39990.48

Radler, C. (2013). The Ponseti method for the treatment of congenital clubfoot: Review of the current literature and treatment recommendations. *International Orthopaedics, 37*, 1747–1753. https://doi.org/10.1007/s00264-013-2031-1

Salvi, J., Fernandez, S., Pribanic, T., & Llado, X. (2010). A state of the art in structured light patterns for surface profilometry. *Pattern Recognition, 43*(8), 2666–2680. https://doi.org/10.1016/j.patcog.2010.03.004

Savonen, B., Gershenson, J., Bow, J. K., & Pearce, J. M. (2020). Open-source three-dimensional printable infant clubfoot brace. *Journal of Prosthetics and Orthotics, 32*(2), 149–158. https://doi.org/10.1097/JPO.0000000000000257

Siapkara, A., & Duncan, R. (2007). Congenital talipes equinovarus: A review of current management. *The Journal of Bone and Joint Surgery. British Volume, 89-B*(8), 995–1000. https://doi.org/10.1302/0301-620X.89B8.19008

Silva, R., Silva, B., Fernandes, C., Morouço, P., Alves, N., & Veloso, A. (2024). A review on 3D scanners studies for producing customized orthoses. *Sensors, 24*(5), 1373. https://doi.org/10.3390/s24051373

Vijayaragavan, E., Gopal, T. V., & Viswanath, S. (2017). Conceptual design of orthosis for clubfoot model developed using image reconstruction techniques. In F. Ibrahim, J. Cheong, J. Usman, M. Ahmad, R. Razman, & V. Selvanayagam (Eds.), *3rd International Conference on Movement, Health and Exercise (MoHE 2016)* (*IFMBE Proceedings*, Vol. 58). Springer. https://doi.org/10.1007/978-981-10-3737-5_11

Vivek, C., & Ranganathan, R. (2019). Design and development of orthosis for clubfoot deformity. In L. Kumar, P. Pandey, & D. Wimpenny (Eds.), *3D printing and additive manufacturing technologies*. Springer. https://doi.org/10.1007/978-981-13-0305-0_12

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 47-64.

4

Digital Twin Applications in Composite Structures: A Review of Modeling, Monitoring, and Lifecycle Integration

Merve Yolcu[1], Mehmet Çevik[2]*

İzmir Kâtip Çelebi University, Department of Mechanical Engineering, İzmir, Türkiye

Corresponding author: mehmet.cevik@ikcu.edu.tr

Abstract

Fiber-reinforced polymer (FRP) composites present distinctive challenges for lifecycle management because their structural performance is strongly influenced by manufacturing variability, anisotropic behavior, hidden damage mechanisms, environmental exposure, and evolving service conditions. This review examines recent developments in digital twin technologies for FRP composite structures, with emphasis on manufacturing, advanced modeling, structural health monitoring, environmental degradation, and lifecycle integration. The reviewed literature shows that manufacturing-stage digital twins can reconstruct process conditions, detect anomalies, and incorporate as-built characteristics into virtual models. During operation, physics-based models, reduced-order methods, surrogate models, and machine-learning techniques enable rapid structural prediction, while in situ sensing supports load identification, damage detection, full-field response reconstruction, and fatigue assessment. Emerging approaches also incorporate moisture, temperature, hygrothermal aging, and material-property degradation into continuously updated virtual representations. Despite these advances, current applications remain largely fragmented across individual lifecycle stages. Major barriers include the computational cost of high-fidelity models, long-term sensor reliability, data interoperability, model credibility, uncertainty quantification, and limited generalization beyond validated operating conditions. The review identifies lifecycle integration as the central research need for next-generation composite digital twins. Future frameworks should combine physics-based and data-driven modeling, adaptive multi-fidelity computation, continuous sensing, environmental degradation models, uncertainty-aware updating, and traceable digital threads connecting as-designed, as-manufactured, as-monitored, and as-maintained states. Such integration is essential for developing reliable digital twins capable of supporting predictive maintenance, remaining useful life assessment, and safety-critical engineering decisions.

Keywords: Digital twin; Composite structures; Machine learning; Structural health monitoring; Surrogate modeling

[1] https://orcid.org/0009-0005-0661-4657

[2] https://orcid.org/0000-0002-6366-5566

1. Introduction

Fiber-reinforced polymer (FRP) composites have emerged as indispensable structural materials in modern engineering sectors, particularly in aerospace, automotive, and renewable energy industries, owing to their exceptional strength-to-weight ratios, outstanding fatigue resistance, and tailored directional properties. Unlike conventional isotropic metallic materials, composite structures exhibit highly complex, anisotropic, and heterogeneous characteristics. Under operational environments, they are susceptible to various intricate damage modes—such as matrix cracking, fiber breakage, delamination, and skin-to-stringer debonding—which often initiate at microscopic levels and propagate imperceptibly until catastrophic structural failure occurs. Consequently, ensuring structural integrity and achieving reliable remaining useful life prediction for such complex composite structures remain significant challenges in both academic research and industrial practice (Guo et al., 2022).

Traditional structural-integrity assessment approaches, such as non-destructive evaluation and structural health monitoring (SHM), have been widely implemented to mitigate these risks. However, conventional non-destructive evaluation methods typically operate in a post-mortem or periodic manner, lacking real-time, in situ predictive capabilities during operations (Ghosh et al., 2025). On the other hand, traditional SHM systems provide continuous sensor streams but often struggle to interpret complex multi-site damage states or predict structural responses under unseen future loading conditions. To overcome these limitations, the paradigm of Industry 4.0 has introduced the concept of the digital twin, which ushers in a transformative era for the lifecycle management of advanced composite structures (Milanoski et al., 2021).

To establish a rigorous framework, a crucial distinction must be made between a true digital twin and related virtual modeling concepts. A digital twin is defined as an integrated, multi-physics, multiscale simulation of a physical asset that strictly requires continuous, bidirectional data synchronization between the physical structure and the virtual framework in real-time (Lai et al., 2023; Zuo et al., 2023). This bidirectional linkage clearly differentiates a true digital twin from a *digital shadow*, which features only one-way data flow from the physical object to the digital model without automated reverse communication. Furthermore, both concepts differ fundamentally from a *surrogate model*, which acts as an inexpensive-to-evaluate mathematical approximation of a compute-intensive simulation code, often operating entirely offline without automated real-time physical updates. In the context of composite structures, a robust digital twin framework requires a seamless confluence of three pillars: smart manufacturing/process tracking, real-time advanced modeling, and in situ SHM (Döbrich & Brauner, 2023; Fernández-León et al., 2024).

During the manufacturing phase, a composite's final performance is strongly dictated by process-induced imperfections, such as permeability variations, race-tracking channels in liquid molding, or fiber misalignment (Fernández-León et al., 2024). By establishing a bidirectional digital twin at this early stage, production anomalies can be detected on-the-fly and compensated for prior to assembly. Moving into the operational phase, the digital twin leverages physical sensor networks—such as fiber Bragg grating arrays and machine vision systems—to feed virtual computational models (Alhussein et al., 2025; Döbrich & Brauner, 2023). However, executing high-fidelity, nonlinear finite element (FE) methods or micro-to-macro mechanical transitions in real-time is computationally prohibitive. To bridge this gap, modern composite digital twin architectures heavily rely on artificial intelligence, machine learning, and reduced-order models to act as rapid surrogate platforms capable of instantaneous mechanical interaction and response prediction (Xu et al., 2023). Furthermore, since discrepancies inevitably exist between numerical models and actual physical structures, modern digital twin frameworks incorporate effective error correction strategies and multi-fidelity data fusion algorithms to maintain high fidelity and bound model uncertainties (Zuo et al., 2023).

This study was conducted as a focused narrative review of digital twin applications in FRP composite structures. The literature search emphasized recent work published primarily between 2020 and 2026, while earlier studies were retained where they provided foundational concepts or influential digital twin frameworks. Relevant publications were identified through targeted searches of major multidisciplinary scholarly databases and publisher platforms using combinations of terms such as digital twin, composite structures, FRP, composite manufacturing, SHM, in situ sensing, surrogate modeling, reduced-order modeling, machine learning, remaining useful life, environmental degradation, and lifecycle management. The review was intentionally selective rather than exhaustive and was designed to capture representative developments across manufacturing, computational modeling, operational monitoring, environmental degradation, and lifecycle integration.

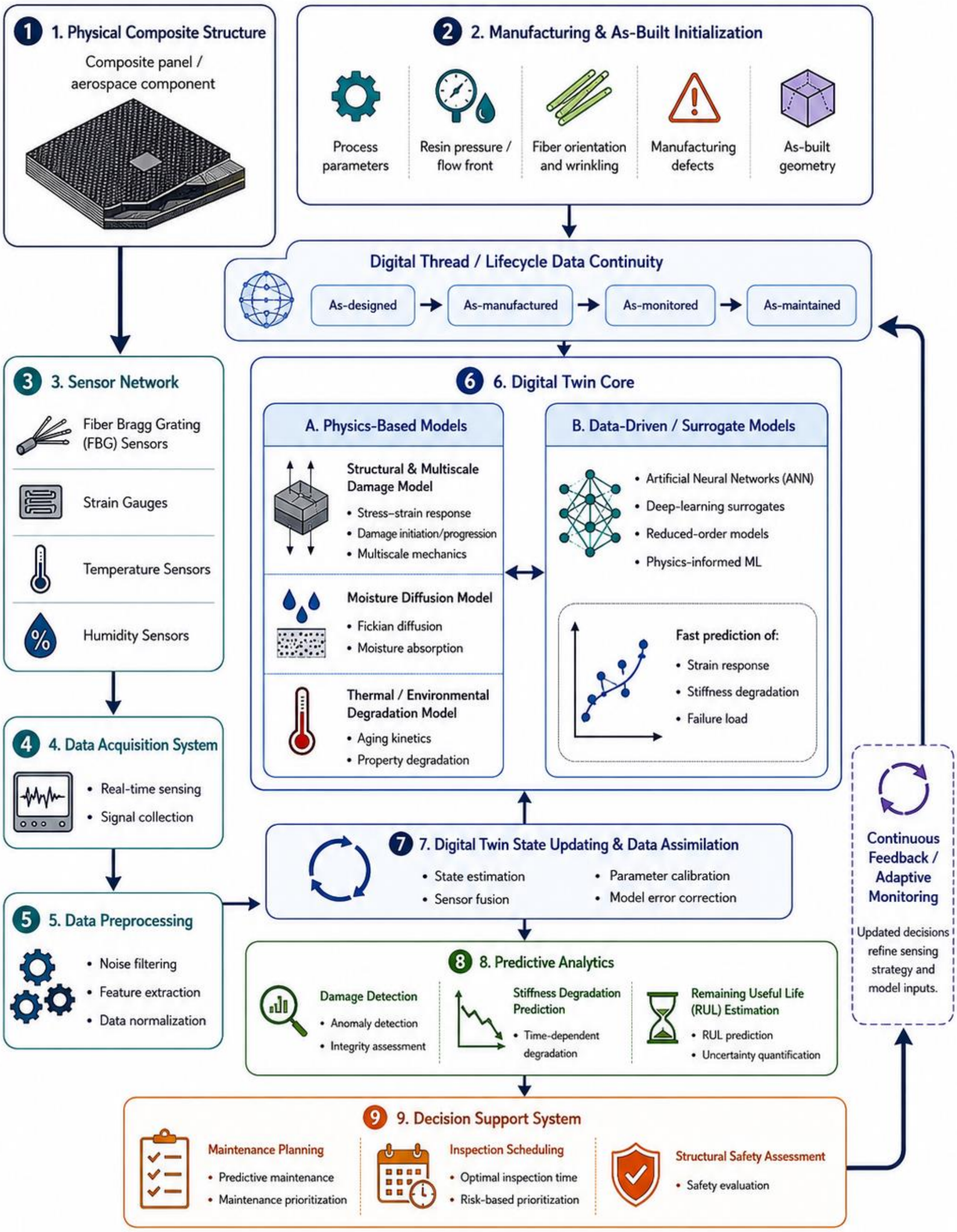

Figure 1. Conceptual architecture of a lifecycle digital twin for composite structures

Figure 1 presents the conceptual architecture adopted to organize the literature reviewed in this chapter. The framework links manufacturing and as-built information with operational sensing, physics-based and data-driven modeling, continuous state updating, predictive analytics, and decision support through a lifecycle digital thread. It therefore illustrates the progression from the as-designed and as-manufactured states to the as-monitored and as-maintained states of a composite structure, while emphasizing continuous feedback between the physical asset and its evolving digital representation.

Priority was given to studies in which digital twin concepts were explicitly linked to FRP or other structurally relevant composite systems and involved some form of physical–virtual interaction, data-driven model updating, monitoring, prediction, or lifecycle decision support. Studies dealing only with conventional FE simulation, static digital models, generic Industry 4.0 architectures, or machine-learning applications without a meaningful connection to digital twinning were generally excluded. Because relatively few studies currently address environmentally driven degradation within fully developed composite digital twins, a limited number of publications from adjacent fields—including environmental digital twins, building monitoring, aircraft degradation, and broader materials engineering—were included where they provided transferable concepts related to real-time environmental sensing, data interoperability, degradation modeling, or lifecycle updating. These studies were used to complement, rather than replace, the composite-specific literature and to identify methodological approaches that may support the development of more comprehensive lifecycle digital twins for composite structures.

2. Digital Twins in Composite Manufacturing

The physical performance and structural reliability of FRP composites are strongly influenced by their processing history. During fabrication, microscopic and macroscopic deviations from nominal process parameters inevitably introduce defects, such as local fiber misalignments, resin-rich zones, and micro-voids (Ashebir et al., 2024; Korkmaz et al., 2022; Kulkarni et al., 2020; Özbek et al., 2020). To minimize scrap rates and guarantee part quality, the establishment of a digital twin framework during the manufacturing phase has emerged as a crucial solution. By establishing real-time feedback loops, virtual models can evaluate manufacturing anomalies as they occur, enabling smart control systems to compensate for these imperfections dynamically (Aniba et al., 2024).

A primary application of manufacturing-stage digital twins is observed in liquid composite molding processes, particularly resin transfer molding. In this method, a dry textile preform is enclosed within a rigid mold and impregnated via polymer resin injection (Uzay & Geren, 2020; Karacor & Özcanlı, 2022). However, a major manufacturing challenge in resin transfer molding is the occurrence of race-tracking, an anomaly where the injected resin flows prematurely along the boundaries or edges of the preform due to poor nesting or cutting tolerances. Race-tracking alters the intended macroscopic flow front, resulting in unimpregnated dry spots and structural macro-defects. To counteract this phenomenon, Fernández-León et al. (2024) developed a robust digital twin framework driven by a deep-learning encoder/decoder surrogate architecture. By utilizing data from a localized network of only five pressure sensors embedded within the mold, their virtual twin acts as an online disturbance detector. It can back-calculate and reconstruct the spatial distribution of the fabric permeability on-the-fly, allowing immediate interrogation of flow front anomalies during the industrial filling cycle.

In parallel with thermal and pressure sensor telemetry, optical data acquisition systems are vital for mirroring physical geometries in virtual spaces. The digital twin must be informed about the precise topological states of dry architectures prior to or during consolidation. In this context, Döbrich and Brauner (2023) introduced an in situ machine vision system tailored for the digital twin modeling of composite structures. Their approach utilizes a specialized industrial camera setup to capture 2D surface features of the textile preform, which are then mapped onto a 3D FE mesh using geometric transformations. This vision-driven digital twin successfully extracts critical structural parameters—such as local fiber orientation angles, shear angles, and surface wrinkling—directly from the production floor. By integrating machine vision into the twin loop, the virtual model shifts from an idealized CAD representation to an "as-built" simulation, ensuring that downstream mechanical analysis accounts for the true, defect-ridden geometry of the manufactured component.

3. Advanced Modeling, Surrogate Platforms, and Error Correction

To establish a high-fidelity digital twin capable of real-time bidirectional interaction, the virtual framework must accurately represent the anisotropic and configuration-dependent mechanical behavior of composite structures. Unlike isotropic materials, the structural response of laminated composites is strongly influenced by constituent properties, stacking sequence, fiber orientation, geometric configuration, boundary conditions, and the development of interacting damage mechanisms. The influence of laminate architecture is particularly important because changes in fiber orientation can substantially alter structural dynamic characteristics. Çevik (2009), for example, demonstrated through FE analysis of angle-ply laminated composite arches that fiber orientation significantly affects both in-plane and out-of-plane natural frequencies, with particularly pronounced effects on in-plane vibration. Such sensitivity highlights the need for digital twin models to retain information on lay-up and fiber orientation when representing the actual structural response of composite components. This requirement becomes even more important when manufacturing-derived information on local fiber orientation, wrinkling, or geometric deviations is incorporated into the as-built twin. While high-fidelity nonlinear FE models can provide detailed stress, deformation, and damage fields, their computational cost generally prevents direct execution within the rapid synchronization loops required for real-time digital twin applications.

Consequently, an important research direction is the coupling of physically detailed computational models with reduced or data-driven representations capable of reproducing their essential behavior at substantially lower computational cost. A notable example is provided by Ghosh et al. (2025) for smart multifunctional composite structures. Focusing on piezoelectric composite laminates used for self-sensing applications, they developed a two-step computational platform incorporating Artificial Neural Networks (ANNs) and a Parametrically Upscaled Coupled Constitutive Damage Mechanics model. Rather than relying solely on idealized macroscopic constitutive assumptions, the framework incorporates Represented Aggregated Microstructural Parameters describing local microstructural morphology and micro-void damage. The ANN provides a computational bridge between these microscale descriptors and macroscopic electromechanical constitutive coefficients, enabling the twin to interpret electrical sensing information and infer otherwise inaccessible subsurface damage evolution in the matrix and fiber–matrix interfaces. This illustrates the particular value of surrogate modeling in composite digital twins: computational acceleration can be achieved without completely abandoning the multiscale physical mechanisms responsible for structural degradation.

A complementary strategy was demonstrated by Milanoski et al. (2023) for stiffened composite panels subjected to compression–compression fatigue. Their approach used a verified three-dimensional FE model of the pristine structure as the digital-twin baseline and employed the detailed FE simulations to train a surrogate model with respect to axial load. Strain measurements obtained from permanently attached fiber Bragg grating sensors were then compared with the surrogate predictions. Measurements remote from the damaged region were used to estimate the applied load, while discrepancies between measured and predicted strain fields provided health indicators for detecting, localizing, and characterizing skin-to-stringer disbonding, impact-damage propagation, and overall stiffness degradation. This approach demonstrates how a computationally expensive FE representation can serve as an offline knowledge generator, while a substantially faster surrogate performs the repeated evaluations required during operational monitoring.

The usefulness of data-driven surrogate models, however, depends strongly on their ability to remain reliable when the monitored structure differs from the configurations represented during training. This is particularly problematic for composites because different lay-ups, material systems, manufacturing variations, and damage states can produce substantial changes in measured responses. Liu et al. (2024) addressed this issue through a structural-digital-twin-assisted domain-generalization framework for fatigue damage detection in carbon fiber reinforced polymer (CFRP) structures. Digital-twin simulations were used to augment limited physical monitoring data, while knowledge distillation and related learning strategies were employed to extract features that remained informative across different composite lay-ups. Their results demonstrated damage-detection accuracies exceeding 80% for target CFRP configurations whose monitoring data were unavailable during training, illustrating the potential of virtual data to improve cross-structure generalization.

The scarcity and imbalance of experimentally measured damage data constitute a related limitation. Acquiring large datasets representing progressive or severe damage in aerospace-grade CFRP components is costly and may require destructive testing. Liu et al. (2025) therefore developed a structural digital twin combined with few-shot meta-transfer learning for CFRP damage detection. The numerical twin generated balanced virtual datasets representing different damage conditions, which were used for pre-training before the model was adapted to the physical domain using only a small number of real observations. The approach substantially improved classification performance under data-scarce conditions and successfully supported damage localization. Such results indicate that simulation-generated data can extend the role of the physics-based twin beyond direct response prediction by providing synthetic training environments for machine-learning models. Nevertheless, the accuracy of such approaches ultimately remains dependent on the representativeness of the underlying numerical twin and the effectiveness of transferring information from simulated to physical domains.

Even with high-fidelity multiscale models and advanced surrogate platforms, discrepancies between idealized virtual twins and their as-built physical counterparts inevitably arise from manufacturing tolerances, uncertain material properties, simplified boundary conditions, sensor errors, and temporal degradation. Zuo et al. (2023) addressed this problem through a digital twin response-prediction framework incorporating three levels of error correction for CFRP configurations. First, macro-geometric correction was used to reconcile the nominal numerical geometry with the actual physical boundaries. Second, adaptive boundary-condition correction adjusted stiffness parameters at loading fixtures using experimental feedback. Finally, an online residual-error correction scheme compensated for remaining nonlinear discrepancies between measured strain responses and virtual predictions. Rather than treating model discrepancy as a fixed calibration error, this approach demonstrates the importance of continuously correcting the numerical representation as new information becomes available.

Recent work further emphasizes that correction should be accompanied by independent validation of the reconstructed structural state. Li et al. (2026), for example, developed a real-time deformation digital twin for composite plates by integrating distributed fiber-optic strain sensing with the inverse FE method and synchronized motion-capture validation. The framework reconstructed full-field dynamic deformation from one-dimensional strain measurements while explicitly addressing time synchronization and environmental and operational variations. Experimental tests under several vibration frequencies and loading positions produced maximum displacement errors below 0.3 mm, while the independent motion-capture system provided a mechanism for dynamic validation and calibration. Together, these developments indicate that advanced composite digital twins increasingly require a hybrid modeling architecture in which high-fidelity physics models establish mechanically meaningful behavior, surrogate and machine-learning models provide computational speed, physical measurements continuously update the virtual state, and error-correction and validation mechanisms prevent progressive divergence between the digital and physical structures.

4. Structural Health Monitoring and In Situ Sensing

Once a composite component transitions from the manufacturing floor to its operational phase, it is subjected to complex cyclic loading profiles, environmental fluctuations, and unexpected impact events. To ensure structural reliability and prevent catastrophic failure, the virtual twin must continuously mirror the live physical state of the asset (Shomran et al., 2023). Modern digital twin architectures achieve this by integrating advanced SHM paradigms with in situ sensing networks, allowing the virtual model to track damage progression, back-calculate operational loads, and predict stiffness degradation in real time.

A critical challenge in the SHM of aerospace composite structures is the detection of subsurface damage, such as skin-to-stringer debonding in stiffened panels under compressive or fatigue loading. Because this damage often propagates internally without visible surface indications, Milanoski et al. (2021) demonstrated a digital twin framework that couples multi-sensor data fusion with fast mathematical surrogates. Their physical testing setup utilizes fiber Bragg grating sensor arrays embedded within the composite structure alongside non-contact digital image correlation systems to capture continuous localized strain fields. By feeding these synchronized experimental telemetry streams into a pre-trained virtual surrogate model, their digital twin successfully interprets changes in the strain signatures and dynamically maps the progression and shape of skin-to-stringer disbond growth during operation.

Aircraft structures are continuously exposed to operational and environmental loads that can induce deformation, damage, and fatigue cracking, making SHM essential for in situ assessment of structural integrity. Kosova et al. (2025) reviewed the current state of SHM in aviation, including civil and military regulations, data-acquisition technologies, and damage detection and identification methods. Their review covers conventional electrical resistance sensors, fiber-optic sensors, piezoelectric sensors, and smart materials, together with knowledge-based, frequency-domain, machine-learning, and deep-learning approaches such as convolutional neural networks and long short-term memory networks. They also highlighted the emerging role of physics-informed neural networks, which integrate physical governing principles with data-driven learning. Despite these advances, directly measuring multiaxial stress states over an entire complex aircraft structure remains impractical because of limitations on the number and placement of physical sensors. To address this constraint, Lai et al. (2023) developed a digital twin framework that combines sparse physical measurements with computational data and demonstrated the approach using an aircraft wing. In the proposed framework, a deep-learning model first uses real-time strain-gauge measurements to solve the inverse load-identification problem and estimate the magnitude and distribution of external loads. These identified loads are then mapped to a high-fidelity computational model database, enabling the digital twin to reconstruct full-field stress distributions from a limited number of sensor measurements. The framework further incorporates rainflow counting to continuously estimate fatigue damage accumulation and structural life consumption, illustrating how digital twins can extend conventional SHM from localized sensing toward comprehensive, real-time assessment of aircraft structures.

5. Environmental Degradation Monitoring in Composite Structures

Beyond mechanical loading, composite structures are also exposed to moisture ingress, humidity fluctuations, thermal cycling, and sudden temperature variations, all of which can alter material properties, accelerate degradation, and reduce long-term durability. Accordingly, recent digital twin research has begun to move beyond purely load-driven structural monitoring toward frameworks that integrate environmental exposure, material degradation, and structural response within the same virtual representation (Karakadakattil, 2026). This transition reflects a broader development in digital twin research. Artioli et al. (2026), reviewing 121 studies across urban environments, agriculture, marine and coastal systems, river and lake networks, forestry, ecology, glaciers, Earth-system science, and building sustainability, showed that environmental digital twins are expanding rapidly but remain technologically immature. Most applications were concentrated at Technology Readiness Levels 2–6, while interoperability, calibration, scaling, deployment, and governance remained recurrent barriers. Their findings are particularly relevant to composite-structure digital twins because they demonstrate that integrating environmental information into a digital twin is not merely a sensing problem but also a problem of data interoperability, model calibration, and lifecycle-scale deployment.

This broader environmental perspective complements the materials-engineering view presented by Tur (2023), who emphasized the ability of digital twins to combine historical information, real-time monitoring, and computational algorithms to predict mechanical properties, failure modes, and phase transformations while simultaneously supporting manufacturing-process optimization. Whereas Tur (2023) considered digital twins primarily as predictive and optimization tools across materials engineering, Alajmi (2024) focused more specifically on FRPs and their sustainability. Alajmi argued that digital twins can improve curing kinetics, mechanical properties, process monitoring, and the sustainable manufacture of both synthetic and natural FRPs, with applications ranging from continuous-carbon-fiber additive manufacturing to recyclable Elium®-based composites. Importantly, this work extends the role of digital twins from improving manufacturing efficiency to balancing structural performance with sustainability objectives. Thus, while Tur (2023) provides a general materials-engineering framework, Alajmi (2024) positions digital twins more explicitly within the lifecycle and sustainability challenges of composite materials.

Studies from the built-environment domain further illustrate how environmental information can be incorporated into operational digital twins. Kang and Mo (2024) identified real-time connectivity and predictability between physical and virtual systems as essential requirements for construction digital twins and demonstrated these principles through environmental-performance monitoring of existing buildings. Abdelfattah and Uzun (2025) adopted a more implementation-oriented approach by integrating Building Information Modeling (BIM) with Internet of Things (IoT) sensors. Their framework continuously synchronized environmental measurements from Arduino-based sensors with a Revit-based BIM model, thereby creating a real-time digital representation of indoor conditions. Although successful at the room scale, the authors identified scalability and response latency as important limitations. In comparison, Kang and Mo (2024) emphasize the conceptual requirements of connectivity and predictability, whereas Abdelfattah and Uzun (2025) demonstrate a concrete sensor-to-model implementation. Both studies nevertheless reinforce an important principle for composite digital twins: environmental sensing becomes useful only when measured data can be reliably transferred to and interpreted by the virtual model in near real time.

A similar progression can be observed in aerospace monitoring. Elizabeth and Barshilia (2024) examined corrosion as a major limitation on aircraft service life and reviewed conventional and advanced nondestructive inspection methods, real-time corrosion sensors, artificial intelligence, machine learning, and digital twin concepts. They proposed that the integration of these approaches could support a virtual replica capable of characterizing the evolving condition of aircraft structures in real time. Their discussion is conceptually related to environmentally driven degradation in polymer composites, although the dominant degradation mechanisms differ.

In metallic aircraft structures, corrosion monitoring is central, whereas in polymer-matrix composites, moisture absorption and hygrothermal aging can alter the matrix, fiber–matrix interface, and overall mechanical response. Experimental studies also demonstrate that environmental exposure can substantially influence the mechanical and thermal behavior of FRP systems. Akderya and Çevik (2018), for example, investigated the effects of thermal-oil environmental aging on E-glass fiber/epoxy composites, highlighting the sensitivity of their mechanical and thermal properties to prolonged environmental exposure. At the structural-joint level, Akderya et al. (2020) further examined the influence of thermal aging on the tensile performance of adhesively bonded E-glass fiber/epoxy joints, demonstrating that environmental degradation may affect not only the composite constituents but also the integrity of bonded interfaces. These findings reinforce the need for environmental digital twins to incorporate material- and connection-specific degradation mechanisms rather than relying on a universal degradation model.

This requirement is addressed more directly by Karakadakattil (2026), who developed a physics-based digital twin framework for coupled hygro–thermo–mechanical degradation in fiber-reinforced polymer composites. The framework combines moisture-diffusion modeling, temperature-dependent aging kinetics, and mechanical-degradation models to estimate the evolution of material properties under coupled environmental conditions. Compared with the more sensor- and data-integration-oriented approaches of Kang and Mo (2024), Abdelfattah and Uzun (2025), and Elizabeth and Barshilia (2024), Karakadakattil (2026) places greater emphasis on embedding degradation physics within the digital twin. This distinction is important because measuring environmental variables alone does not reveal how those variables translate into loss of structural performance. A physically informed digital twin can establish this missing link by converting environmental exposure histories into estimates of moisture uptake, material-property degradation, and structural-condition evolution.

Data-driven approaches provide a complementary route. Aysa and Karimi (2025) investigated CFRP-to-aluminum adhesive joints exposed to natural and accelerated aging under elevated temperature and humidity. Their results showed progressive reductions in mechanical strength together with matrix separation, surface roughening, fiber–matrix debonding, and adhesive degradation. By incorporating newly acquired data into the virtual model, their digital twin approach dynamically updated degradation predictions and improved long-term performance estimation. This differs from the predominantly physics-based approach of Karakadakattil (2026). The latter seeks to represent the governing degradation mechanisms explicitly, whereas Aysa and Karimi (2025) emphasize adaptive prediction through continuous data assimilation and machine learning. Neither approach is necessarily sufficient on its own. Physics-based models provide interpretability and extrapolation grounded in known degradation mechanisms, while machine-learning models can adapt to complex relationships and evolving operational data that may be difficult to capture analytically.

The adaptive capability of machine-learning-enabled digital twins is particularly important when environmental and loading conditions evolve throughout service. Unlike static simulation models, digital twins can be periodically or continuously updated as new measurements become available. Aysa and Karimi (2025), for example, showed how retraining with newly acquired operational data can help maintain predictive accuracy under changing hygrothermal conditions. This capability is especially relevant to aerospace, marine, and renewable-energy structures, where composite components experience simultaneous mechanical loading, moisture exposure, thermal variation, and aging. In such environments, a model calibrated only to initial material properties or laboratory conditions may progressively diverge from the actual structural state.

Taken together, these studies indicate a clear evolution in digital twin research from isolated monitoring and virtual representation toward integrated, adaptive, and lifecycle-oriented systems. Tur (2023) emphasizes prediction and manufacturing optimization, Alajmi (2024) extends this perspective toward sustainable FRP manufacturing, Kang and Mo (2024) and Abdelfattah and Uzun (2025) demonstrate the importance of real-time environmental connectivity, Elizabeth and Barshilia (2024) illustrate the value of combining sensing, nondestructive inspection, AI, and digital twin concepts for aerospace degradation monitoring, while Karakadakattil (2026) and Aysa and Karimi (2025) move further toward explicit prediction of environmentally induced composite degradation. The comparison suggests that the next generation of composite digital twins should not treat structural sensing, environmental monitoring, degradation physics, and machine-learning prediction as separate functions. Instead, these components should be integrated within a unified architecture capable of simultaneously tracking mechanical loading, moisture absorption, thermal aging, and evolving material properties. Such integration would provide a stronger basis for predicting structural integrity, damage progression, and remaining useful life throughout the service lifecycle.

6. Lifecycle Integration and the Digital Thread

A fully functional digital twin for composite structures requires continuity of information across the asset lifecycle rather than isolated virtual models for manufacturing, structural analysis, and service monitoring. The digital thread provides the information backbone linking data generated during design, manufacturing, inspection, operation, maintenance, and retirement. Tao et al. (2018) emphasized the integration of product design, manufacturing, and service data within a digital-twin framework, while Abdel-Aty and Negri (2024) identified traceability and lifecycle-wide data connectivity as central functions of the digital thread. For composite structures, this continuity is particularly important because manufacturing history directly affects structural performance. Process parameters, as-built geometry, fiber orientation, detected defects, and inspection records should therefore become persistent attributes of the operational twin. Zhang et al. (2022) demonstrated this principle in aircraft assembly by integrating digital-twin modules through a digital thread that preserves relationships among product characteristics, process parameters, equipment states, and quality information.

Once the component enters service, the twin must evolve with the physical structure. Tuegel et al. (2011) proposed an aircraft structural digital twin in which an as-built model is periodically updated using actual usage information and probabilistic methods so that accumulated damage and structural life can be reassessed for an individual asset. More recent approaches formalize this process through data assimilation and Bayesian inference. Kapteyn et al. (2022) combined component-based reduced-order models with Bayesian state estimation, allowing sensor observations to identify the model state most consistent with the physical asset while retaining computational efficiency. Similarly, Kapteyn et al. (2021) represented the physical asset and digital twin as coupled dynamical systems whose states evolve through observations and control inputs. Such updating is especially relevant to composites because stiffness loss, delamination growth, environmental degradation, and changing boundary conditions evolve throughout service.

The continuously updated twin can then support predictive maintenance and remaining useful life estimation. Wang et al. (2020) integrated inspection data, finite-element calculations, historical information, a crack-growth model, and Bayesian inference to update aircraft structural life predictions. Chia et al. (2024) likewise identified airframe digital twins as an important route toward structural prognostics and predictive maintenance, while stressing the need to incorporate operational and environmental conditions. More broadly, van Dinter et al. (2022) found remaining useful life estimation to be a principal objective of digital-twin-enabled predictive maintenance. For composite assets, maintenance decisions could therefore be based not only on detected damage but also on its predicted consequences under the recorded loading and environmental history.

Lifecycle integration also increases the importance of model credibility. Validation cannot be treated as a one-time activity at deployment for a twin that continuously evolves through new sensor data, model updates, repairs, and changing operating conditions. Shao et al. (2023) argue that verification, validation, and uncertainty quantification should accompany the digital twin throughout its lifecycle. Composite digital twins should therefore account for uncertainty arising from sensor noise, material variability, model-form error, surrogate approximation, and extrapolation beyond training conditions. Confidence bounds should accompany damage and remaining useful life predictions when these outputs support inspection intervals, repair decisions, or safety-critical operation. The long-term objective is thus a traceable digital thread linking the as-designed, as-manufactured, as-monitored, and as-maintained states of each composite asset, with continuous data assimilation and credibility assessment converting lifecycle information into defensible engineering decisions.

Table 1 summarizes the representative digital twin approaches reviewed in the preceding sections according to their application domain, lifecycle stage, sensing strategy, computational framework, principal function, and remaining limitations. The comparison demonstrates a gradual transition from process-specific manufacturing twins and isolated structural monitoring toward adaptive systems incorporating as-built information, real-time state updating, environmental degradation, and lifecycle-oriented prediction. However, few existing studies integrate all of these functions within a single continuous digital thread.

7. Challenges Toward Lifecycle-Integrated Digital Twins

Despite substantial advances in the application of digital twins to composite manufacturing, multiscale modeling, SHM, environmental degradation assessment, and lifecycle integration, several technical limitations continue to restrict their transition from research demonstrations to reliable industrial implementation. These limitations are particularly pronounced for FRP composites because their structural response is governed by anisotropic and heterogeneous material behavior, manufacturing-induced variability, interacting damage mechanisms, environmental sensitivity, and complex relationships between local damage and global structural response. Furthermore, a lifecycle digital twin must maintain consistency between physical measurements and virtual predictions as the composite structure evolves from its as-manufactured state through operation, degradation, inspection, repair, and continued service. Five research priorities emerge as particularly important: computational efficiency without unacceptable loss of physical fidelity, long-term sensor reliability, interoperable lifecycle data architectures, rigorous verification and uncertainty quantification, and the ability of predictive models to generalize and adapt throughout the structural lifecycle.

7.1. Computational Efficiency and High-Fidelity Modeling

A fundamental challenge for composite digital twins is reconciling the computational cost of detailed structural models with the rapid execution required for real-time state estimation and decision support. FRP structures exhibit material and geometric nonlinearities together with multiple damage mechanisms, including matrix cracking, fiber failure, delamination, interfacial debonding, and local buckling. Accurately representing these phenomena may require nonlinear FE analysis, progressive-damage formulations, or multiscale models linking constituent-level behavior to laminate and structural responses. As discussed earlier in this review, such high-fidelity calculations are generally too computationally demanding for direct execution within continuously synchronized digital twin loops.

The use of deep-learning surrogate architectures in composite manufacturing, such as the framework developed by Fernández-León et al. (2024), illustrates how computationally expensive physical simulations can be replaced by rapidly evaluated representations suitable for near-real-time process monitoring.

Table 1. Synthesis of representative digital twin applications relevant to composite structures across the lifecycle

Study	**Application / Lifecycle Stage**	**Data and DT Approach**	**Main Function**	**Main Limitation / Research Need**
Fernández-León et al. (2024)	Liquid composite molding / Manufacturing	Mold pressure sensors + deep-learning surrogate	Reconstructs permeability and detects race-tracking and flow-front anomalies in real time	Validation under more complex geometries, materials, and process disturbances
Döbrich & Brauner (2023)	Textile composites / Manufacturing	In situ machine vision + 3D FE mapping	Transfers fiber orientation, shear, and wrinkling into an as-built structural model	Primarily surface characterization; internal defects and lifecycle transfer remain limited
Ghosh et al. (2025)	Piezoelectric composites / Modeling and operation	Electrical sensing + ANN-assisted multiscale damage model	Estimates subsurface damage and electromechanical response from limited measurements	Generalization across material variability and interacting damage states
Zuo et al. (2023)	CFRP structures / Model updating	Experimental measurements + geometric, boundary, and residual-error correction	Maintains agreement between physical and virtual structural responses	Further validation under variable loads and progressive multi-mode damage
Milanoski et al. (2021)	Composite aerostructures / SHM	FBGs and DIC + surrogate/data-fusion model	Tracks skin-to-stringer disbond progression during operation	Sensor durability, scalability, and long-term operational validation
Lai et al. (2023)	Aircraft wing / SHM and prognosis	Sparse strain measurements + deep learning and computational database	Identifies loads, reconstructs full-field stress, and estimates fatigue accumulation	Dependent on load-identification accuracy and database representativeness
Karakadakattil (2026)	FRP composites / Environmental degradation	Hygro–thermo–mechanical physics-based model	Converts environmental exposure into evolving material and structural properties	Requires broader experimental and real-time sensing validation
Aysa & Karimi (2025)	CFRP–aluminum joints / Environmental degradation	Hygrothermal test data + machine-learning-enabled updating	Adaptively predicts strength degradation under aging	Extrapolation beyond the available aging and environmental data
Alajmi (2024)	FRP systems / Manufacturing and sustainability	Digital-twin-based process and material optimization	Supports curing, process control, mechanical performance, and sustainability	Lifecycle implementation remains less developed than manufacturing applications
Abdelfattah & Uzun (2025)*	Built environment / Environmental monitoring	IoT environmental sensing + BIM-based virtual model	Demonstrates continuous environmental physical–virtual synchronization	Adjacent-domain application; scalability and latency limitations
Kang & Mo (2024)*	Buildings / Environmental monitoring	Real-time environmental data + DT framework	Demonstrates connectivity and predictive environmental monitoring	Transferable concept rather than a composite-specific implementation
Elizabeth & Barshilia (2024)*	Aircraft degradation / Operation	NDI, sensing, AI/ML, and DT concepts	Supports real-time degradation assessment	Primarily metallic corrosion; FRPs require material-specific degradation models

* Adjacent-domain studies included because they provide transferable concepts relevant to composite digital twins.

This fidelity–efficiency problem extends beyond composite manufacturing. Es-haghi et al. (2024) identified reduced-order modeling, data-driven machine learning, and physics-informed learning as major approaches for enabling real-time digital twin analysis. Drakoulas et al. (2023) similarly demonstrated that machine-learning-assisted reduced-order modeling can reproduce the dominant response of computationally intensive models while substantially reducing evaluation time. However, computational acceleration introduces approximation errors whose importance increases when the structural condition departs from the domain represented during model development. For composites, this problem is particularly relevant when several damage mechanisms interact or when local damage produces abrupt changes in structural response. Future research should therefore emphasize adaptive multi-fidelity architectures rather than relying exclusively on a single surrogate model. Reduced-order or machine-learning models could provide continuous real-time predictions, while higher-fidelity analyses could be selectively activated when abnormal structural states, rapidly evolving damage, or safety-critical conditions are detected. Such architectures could preserve computational efficiency while maintaining sufficient mechanical fidelity for lifecycle decision-making.

7.2. Sensor Reliability and Calibration Stability

The reliability of an operational composite digital twin depends directly on the quality and continuity of the measurements connecting the physical structure to its virtual representation. The frameworks reviewed in this study employ embedded or surface-mounted sensing systems to identify strain fields, infer applied loads, detect damage progression, and update the virtual structural state (Milanoski et al., 2021; Ghosh et al., 2025). Because these measurements provide the evidence by which the virtual model is corrected, sensor degradation can propagate directly into erroneous structural-state estimates.

The problem is particularly significant for composite structures operating under cyclic mechanical loading, thermal variation, humidity, moisture ingress, and other environmental effects. Fiber-optic sensors are attractive for composite SHM because they can be embedded with relatively limited additional mass and can support distributed or multiplexed measurements. Nevertheless, embedding configuration, strain transfer, temperature compensation, sensor placement, signal interpretation, and long-term durability all affect measurement reliability. A recent review by Zhang et al. (2025) emphasizes that sensor embedding methods, monitoring principles, and signal transmission are central determinants of the reliability of SHM results in composite structures and identifies continuing limitations across FBG, piezoelectric, carbon-nanotube, and other emerging sensor technologies. Environmental degradation further complicates this relationship. Aceti et al. (2023) showed that hygrothermal aging can substantially affect composite service performance and highlighted fiber-optic SHM as a means of monitoring moisture-related degradation in service.

Future composite digital twins should therefore treat **sensor health as part of structural health** rather than assuming that incoming measurements remain permanently reliable. Research is needed on redundant sensing, automated drift detection, temperature and moisture compensation, fault-tolerant sensor fusion, self-diagnostics, and periodic or continuous calibration. Algorithms should also distinguish a genuine change in composite behavior from sensor drift, debonding, signal loss, or environmental cross-sensitivity. Without such mechanisms, long-term digital twin updating may diverge from the actual structural condition even when the underlying numerical model remains accurate.

7.3. Data Interoperability and Standardization

Lifecycle implementation introduces another challenge because a composite digital twin must integrate information generated by systems that were not originally designed to operate as a unified digital environment. Relevant data may originate from CAD models, manufacturing simulations, resin-flow monitoring, cure histories, machine-vision inspection, material databases, FE models, nondestructive evaluation, embedded sensors, environmental monitoring, maintenance records, and operational loading histories. The technical challenge therefore extends beyond storing large volumes of heterogeneous information. The relationships, physical meaning, temporal context, and provenance of those data must remain interpretable as information moves between lifecycle stages.

This requirement is particularly important for composites because the as-manufactured state may differ substantially from the nominal design. Local fiber orientation, wrinkles, voids, resin-rich regions, permeability variations, cure history, and other manufacturing features can influence subsequent damage initiation and progression. If such information is lost when the manufacturing twin is transferred into the operational twin, the lifecycle model effectively reverts to an idealized representation and an important purpose of the digital thread is lost. The preceding sections identify the need to progress from idealized CAD representations toward as-built virtual models and to maintain continuous state updating throughout service.

Acharya et al. (2024) demonstrate that digital-twin interoperability encompasses technical, syntactic, semantic, pragmatic, dynamic, and organizational dimensions. Consequently, successful data exchange does not necessarily mean that heterogeneous components interpret and use exchanged information consistently. Standardization efforts provide an important foundation, but domain-specific requirements remain for composite lifecycle applications. Future research should establish common definitions and metadata for material architecture, manufacturing defects, sensor locations, loading histories, degradation states, model versions, inspection findings, uncertainty measures, and repairs. Digital thread architectures should also preserve traceability between individual measurements, model updates, and resulting engineering decisions. Such interoperability would enable the as-designed, as-manufactured, as-monitored, and as-maintained states of a composite component to remain connected rather than becoming isolated digital representations at successive stages of its lifecycle.

7.4. Verification, Validation, and Uncertainty Quantification

As composite digital twins move from monitoring toward prediction and decision support, the credibility of their outputs becomes increasingly important. Agreement between a virtual model and a limited set of sensor measurements does not by itself establish that the twin will remain reliable under different loading conditions, environmental states, or stages of damage evolution. Composite structures contain numerous sources of uncertainty, including constituent and laminate-property variability, fiber-orientation deviations, void content, interfacial properties, manufacturing defects, boundary-condition uncertainty, sensor noise, incomplete load measurements, environmental effects, and model-form assumptions. Surrogate and machine-learning models introduce additional uncertainty associated with training data, approximation error, and extrapolation.

Shao et al. (2023) argue that verification, validation, and uncertainty quantification (VVUQ) should form part of digital twin credibility assessment throughout the twin lifecycle rather than being treated as a one-time activity conducted during initial model development. This principle is particularly relevant to composite digital twins because the physical system itself evolves through fatigue, impact, moisture absorption, thermal aging, inspection, and repair. A twin that was adequately validated in the undamaged state may therefore no longer possess the same predictive credibility after substantial material degradation or structural modification.

Ye et al. (2023) demonstrated a structural digital twin approach in which dynamic sensor information and physics-based models were integrated to reduce uncertainties associated with structural characteristics, loading, fatigue-life prediction, and reliability prognosis. Although that study was not specifically developed for FRP composites, its uncertainty-aware framework is directly relevant to the methodological requirements of composite structural twins. Future research should extend such approaches to composite-specific damage mechanisms and material variability. Digital twins intended to predict delamination growth, stiffness degradation, failure probability, or remaining useful life should provide uncertainty bounds or probabilistic confidence measures rather than deterministic estimates alone. Verification of computational implementation, validation using representative experiments and service data, propagation of sensor and material uncertainties, and quantification of surrogate-model error should accompany significant model updates. These requirements become especially important when twin predictions are used to modify inspection intervals, postpone maintenance, authorize continued operation, or support other safety-critical decisions.

7.5. Model Generalization and Long-Term Adaptability

A final challenge concerns whether a digital twin developed for a particular composite configuration can remain predictive when the physical asset encounters conditions outside those represented during training or calibration. This issue is especially significant for data-driven and hybrid models. Composite structural response depends on numerous interacting variables, including material system, stacking sequence, geometry, manufacturing quality, impact history, load spectrum, temperature, moisture exposure, aging, and existing damage. Experimental datasets cannot realistically cover every combination of these variables, particularly rare but safety-critical damage scenarios.

Nele et al. (2024) identify generalization outside the available data domain and overfitting as important limitations in machine-learning-enabled digital twins. They also note the difficulty of obtaining representative data for extreme or unsafe operating states, for which hybrid combinations of physical simulation and experimental information may help extend the available training domain. For composite applications, this limitation is closely connected to the discrepancy between idealized training conditions and the evolving as-built structure. A surrogate trained using a pristine laminate may remain accurate for ordinary elastic loading but become unreliable after impact damage, moisture-induced property degradation, repair, or interacting delamination and fiber failure.

Long-term lifecycle twins therefore require more than an initially accurate predictive model. They require mechanisms for identifying when new observations fall outside the domain in which the model has demonstrated credibility. Physics-informed machine learning, transfer learning, active learning, adaptive surrogate models, and controlled continual-learning strategies offer potential routes for maintaining accuracy as the physical asset evolves. However, adaptation should not be equated with unrestricted retraining. Continuous updating can introduce model drift or degrade previously established predictive capability if new data are sparse, noisy, or incorrectly interpreted. Model adaptation must therefore remain traceable and should be accompanied by renewed validation and uncertainty assessment. The ultimate research objective is a composite digital twin that can evolve with changes in manufacturing state, accumulated damage, environmental exposure, maintenance, and repair while retaining demonstrable predictive credibility. Achieving this combination of adaptability, physical consistency, and traceability is likely to be one of the principal requirements for moving composite digital twins from specialized research applications toward dependable lifecycle engineering systems.

8. Conclusion

This review examined the development of digital twin approaches for fiber-reinforced polymer composite structures across manufacturing, structural modeling, operational monitoring, environmental degradation, and lifecycle management. The literature indicates that the principal value of digital twinning for composites lies in its ability to connect information that has traditionally been treated in separate engineering stages. Manufacturing parameters, as-built geometry and defects, structural models, sensor measurements, environmental exposure, damage evolution, and maintenance information can potentially be maintained within a continuously updated representation of the physical asset. This capability is particularly important for composite structures because their structural performance depends strongly on material architecture, processing history, local imperfections, interacting damage mechanisms, and time-dependent environmental effects.

The reviewed studies demonstrate substantial progress within individual parts of this framework. Manufacturing-oriented twins can reconstruct process conditions and transfer measured geometric or material features into as-built models. Physics-based models, reduced-order methods, surrogate models, and machine-learning approaches can substantially accelerate structural prediction while retaining different levels of mechanical information. During operation, SHM integrated with digital twin models enables sparse measurements to be used for load identification, damage localization, full-field response reconstruction, and fatigue assessment. Emerging work on hygrothermal and environmentally induced degradation further expands the digital twin from a predominantly load- and damage-oriented concept toward a representation of the evolving material state. Collectively, these developments show that composite digital twins are moving from static or task-specific virtual representations toward adaptive systems capable of supporting condition assessment, prognosis, and maintenance decisions.

However, the literature also shows that these capabilities remain fragmented. Few existing frameworks maintain continuous information flow from the as-designed and as-manufactured states through monitoring, degradation, maintenance, and subsequent structural updating. Achieving such continuity requires more than increasing computational speed or adding additional sensors. Real-time predictions must remain physically credible as the structure changes, sensor performance itself must be monitored, heterogeneous lifecycle data must remain interoperable and traceable, and model updates must be accompanied by verification, validation, and uncertainty quantification. The ability of data-driven models to recognize extrapolation beyond their validated domains and to adapt without uncontrolled model drift is equally important for long-term deployment.

Future research should therefore focus on lifecycle-integrated composite digital twins rather than increasingly sophisticated isolated applications. A promising direction is a hybrid architecture in which high-fidelity physics models provide mechanistic consistency, reduced-order and machine-learning models provide computational efficiency, sensing and environmental data continuously update the structural state, and adaptive multi-fidelity strategies determine when higher-fidelity analysis or renewed validation is required. These elements should be connected through a traceable digital thread that preserves manufacturing history, structural condition, environmental exposure, model revisions, uncertainty, inspection findings, and maintenance actions throughout the asset lifecycle. Progress toward this architecture would shift composite digital twins from specialized monitoring and simulation tools toward credible lifecycle engineering systems capable of supporting predictive maintenance, remaining useful life assessment, and safety-critical decision-making.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

References

Abdel-Aty, T. A., & Negri, E. (2024). Conceptualizing the digital thread for smart manufacturing: A systematic literature review. *Journal of Intelligent Manufacturing*, *35*(8), 3629–3653. https://doi.org/10.1007/s10845-024-02407-1

Abdelfattah, M., & Uzun, C. (2025). Digital twin prototyping and simulation process proposal in architecture through the integration of BIM and IoT. *Modular Journal*, *8*(2), 427–447. https://doi.org/10.59389/modular.1589036

Aceti, P., Carminati, L., Bettini, P., & Sala, G. (2023). Hygrothermal ageing of composite structures. Part 2: Mitigation techniques, detection and removal. *Composite Structures*, *319*, Article 117105. https://doi.org/10.1016/j.compstruct.2023.117105

Acharya, S., Khan, A. A., & Päivärinta, T. (2024). Interoperability levels and challenges of digital twins in cyber–physical systems. *Journal of Industrial Information Integration*, *42*, Article 100714. https://doi.org/10.1016/j.jii.2024.100714

Akderya, T., & Çevik, M. (2018). Investigation of thermal-oil environmental ageing effect on mechanical and thermal behaviours of E-glass fiber/epoxy composites. *Journal of Polymer Research*, *25*(10), Article 214. https://doi.org/10.1007/s10965-018-1615-2

Akderya, T., Çevik, M., & Sayman, O. (2020). Influence of thermal ageing on tensile performance of E-glass fibre/epoxy composite joints bonded with a diverse set of adhesives. *The Journal of Adhesion*, *96*(6), 539–564. https://doi.org/10.1080/00218464.2018.1480371

Alajmi, A. (2024). Twinning the future: Implementing digital twin technology in the optimisation of fibre-reinforced polymers. *MATEC Web of Conferences*, *401*, Article 11005. https://doi.org/10.1051/matecconf/202440111005

Alhussein, A. N. D., Qaid, M. R. T. M., Agliullin, T., Valeev, B., Morozov, O., & Sakhabutdinov, A. (2025). Fiber Bragg grating sensors: Design, applications, and comparison with other sensing technologies. *Sensors*, *25*(7), 2289. https://doi.org/10.3390/s25072289

Aniba, Y., Bouhedda, M., Bachene, M., Rahim, M., Benyezza, H., & Tobbal, A. (2024). Digital twin-enabled quality control through deep learning in Industry 4.0: A framework for enhancing manufacturing performance. *International Journal of Modelling and Simulation*, 1–21. https://doi.org/10.1080/02286203.2024.2395899

Artioli, L., Borga, G., & Costa, P. (2026). Environmental digital twins: A review of challenges and opportunities. *Human Interaction and Emerging Technologies (IHIET-FS 2026)*, *235*, 177–193. https://doi.org/10.54941/ahfe1007273

Ashebir, D. A., Hendlmeier, A., Dunn, M., Arablouei, R., Lomov, S. V., Di Pietro, A., & Nikzad, M. (2024). Detecting multi-scale defects in material extrusion additive manufacturing of fiber-reinforced thermoplastic composites: A review of challenges and advanced non-destructive testing techniques. *Polymers*, *16*(21), 2986. https://doi.org/10.3390/polym16212986

Aysa, N. H., & Karimi, S. (2025). Integrating machine learning and digital twin for strength prediction of CFRP/aluminum adhesive joints under hygrothermal conditions. *Polymer Composites*, 46(14), 13236–13255. https://doi.org/10.1002/pc.29928

Chia, J. W. Y., Verhagen, W. J. C., Silva, J. M., & Cole, I. S. (2024). A review and outlook of airframe digital twins for structural prognostics and health management in the aviation industry. *Journal of Manufacturing Systems*, *77*, 398–417. https://doi.org/10.1016/j.jmsy.2024.09.024

Çevik, M. (2009). Effects of fiber orientation on out-of-plane and in-plane natural frequencies of angle-ply laminated composite arches. *Journal of Reinforced Plastics and Composites*, *28*(1), 59–71. https://doi.org/10.1177/0731684407083003

Döbrich, O., & Brauner, C. (2023). Machine vision system for digital twin modeling of composite structures. *Frontiers in Materials*, 10, 1154655. https://doi.org/10.3389/fmats.2023.1154655

Drakoulas, G. I., Gortsas, T. V., Bourantas, G. C., Burganos, V. N., & Polyzos, D. (2023). FastSVD-ML–ROM: A reduced-order modeling framework based on machine learning for real-time applications. *Computer Methods in Applied Mechanics and Engineering*, *414*, Article 116155. https://doi.org/10.1016/j.cma.2023.116155

Elizabeth, I., & Barshilia, H. C. (2024). A comprehensive review on corrosion detection methods for aircraft: Moving from offline methodologies to real-time monitoring combined with digital twin technology. *Engineering Science & Technology*, *6*(1), 69–98. https://doi.org/10.37256/est.6120255638

Es-haghi, M. S., Anitescu, C., & Rabczuk, T. (2024). Methods for enabling real-time analysis in digital twins: A literature review. *Computers & Structures*, *297*, Article 107342. https://doi.org/10.1016/j.compstruc.2024.107342

Fernández-León, J., Keramati, K., Baumela, L., & González, C. (2024). A digital twin for smart manufacturing of structural composites by liquid moulding. *The International Journal of Advanced Manufacturing Technology*, 130, 4679–4697. https://doi.org/10.1007/s00170-023-12637-x

Ghosh, S., Dan, S., & Tarafder, P. (2025). Machine learning-enabled multiscale modeling platform for damage sensing digital twin in piezoelectric composite structures. *Scientific Reports*, 15, 6631. https://doi.org/10.1038/s41598-025-91196-5

Guo, J., Zhang, Y., & Wang, J. (2022). Real-time prediction of remaining useful life for composite laminates with unknown inputs and varying threshold. *Machines*, *10*(12), 1185. https://doi.org/10.3390/machines10121185

Kang, T. W., & Mo, Y. (2024). A comprehensive digital twin framework for building environment monitoring with emphasis on real-time data connectivity and predictability. *Developments in the Built Environment*, *17*, Article 100309. https://doi.org/10.1016/j.dibe.2023.100309

Kapteyn, M. G., Pretorius, J. V. R., & Willcox, K. E. (2021). A probabilistic graphical model foundation for enabling predictive digital twins at scale. *Nature Computational Science*, *1*(5), 337–347. https://doi.org/10.1038/s43588-021-00069-0

Kapteyn, M. G., Knezevic, D. J., Huynh, D. B. P., Tran, M., & Willcox, K. E. (2022). Data-driven physics-based digital twins via a library of component-based reduced-order models. *International Journal for Numerical Methods in Engineering*, *123*(13), 2986–3003. https://doi.org/10.1002/nme.6423

Karacor, B., & Özcanlı, M. (2022). Evaluation of mechanical properties of intraply hybrid carbon/aramid composite materials. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi, 27*(2), 537–556. https://doi.org/10.17482/uumfd.978721

Karakadakattil, A. (2026). *A physics-based digital twin framework for hygro–thermo–mechanical degradation in fiber-reinforced polymer composites* [Preprint]. Preprints. https://doi.org/10.20944/preprints202604.0796.v1

Korkmaz, M., Karakuzu, R., & Korkmaz, M. (2022). Mechanical characterization and low-velocity impact behavior of flax woven fabric-reinforced polymer composites. *Journal of Composite Materials*, *56*(20), 3185–3195. https://doi.org/10.1177/00219983221106250

Kosova, F., Altay, Ö., & Ünver, H. Ö. (2025). Structural health monitoring in aviation: A comprehensive review and future directions for machine learning. *Nondestructive Testing and Evaluation*, *40*(1), 1–60. https://doi.org/10.1080/10589759.2024.2350575

Kulkarni, P., Mali, K. D., & Singh, S. (2020). An overview of the formation of fibre waviness and its effect on the mechanical performance of fibre reinforced polymer composites. *Composites Part A: Applied Science and Manufacturing*, *137*, 106013. https://doi.org/10.1016/j.compositesa.2020.106013

Lai, X., Yang, L., He, X., Pang, Y., Song, X., & Sun, W. (2023). Digital twin-based structural health monitoring by combining measurement and computational data: An aircraft wing example. *Journal of Manufacturing Systems*, *69*, 76–90. https://doi.org/10.1016/j.jmsy.2023.06.006

Li, Y., Pan, Y., & Sharif-Khodaei, Z. (2026). Real-time deformation digital twin of composite plates via distributed fiber optic sensing. *Advanced Engineering Informatics*, *69*, Article 103992. https://doi.org/10.1016/j.aei.2025.103992

Liu, C., Chen, Y., Xu, X., & Che, W. (2024). Domain generalization-based damage detection of composite structures powered by structural digital twin. *Composites Science and Technology*, *258*, Article 110908. https://doi.org/10.1016/j.compscitech.2024.110908

Liu, C., Chen, Y., & Xu, X. (2025). Structural digital twin for damage detection of CFRP composites using meta transfer learning-based approach. *Expert Systems with Applications*, *261*, Article 125458. https://doi.org/10.1016/j.eswa.2024.125458

Milanoski, D. P., Galanopoulos, G. K., & Loutas, T. H. (2021). Digital-twins of composite aerostructures towards structural health monitoring. In *2021 IEEE 8th International Workshop on Metrology for AeroSpace (MetroAeroSpace)* (pp. 613–618). IEEE. https://doi.org/10.1109/MetroAeroSpace51421.2021.9511653

Milanoski, D., Galanopoulos, G., Zarouchas, D., & Loutas, T. (2023). Multi-level damage diagnosis on stiffened composite panels based on a damage-uninformative digital twin. *Structural Health Monitoring*, *22*(2), 1437–1459. https://doi.org/10.1177/14759217221108676

Nele, L., Mattera, G., Yap, E. W., Vozza, M., & Vespoli, S. (2024). Towards the application of machine learning in digital twin technology: A multi-scale review. *Discover Applied Sciences*, *6*(10), Article 502. https://doi.org/10.1007/s42452-024-06206-4

Özbek, Ö., Bozkurt, Ö. Y., & Erkliğ, A. (2020). Effect of glass fiber hybridization on low velocity impact behaviors of basalt fiber reinforced composites laminates. *The International Journal of Materials and Engineering Technology*, *3*(1), 21–29. https://izlik.org/JA98XB66YN

Shao, G., Hightower, J., & Schindel, W. (2023). Credibility consideration for digital twins in manufacturing. *Manufacturing Letters*, *35*, 24–28. https://doi.org/10.1016/j.mfglet.2022.11.009

Shomran, A. T., Faisal, B. M., Hussein, E. K., Santos, T., & Fatima, K. (2023). Determination of the fatigue behavior of the composite single-stringer structure based on the quasi-static method. *Eastern-European Journal of Enterprise Technologies, 2*(7(122)), 15–23. https://doi.org/10.15587/1729-4061.2023.277911

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, *94*(9–12), 3563–3576. https://doi.org/10.1007/s00170-017-0233-1

Tuegel, E. J., Ingraffea, A. R., Eason, T. G., & Spottswood, S. M. (2011). Reengineering aircraft structural life prediction using a digital twin. *International Journal of Aerospace Engineering*, *2011*, Article 154798. https://doi.org/10.1155/2011/154798

Tur, E. (2023). Harnessing the power of digital twins for enhanced material behavior prediction and manufacturing process optimization in materials engineering. *Bayburt Üniversitesi Fen Bilimleri Dergisi*, *6*(2), 172–190. https://doi.org/10.55117/bufbd.1303782

Uzay, Ç., & Geren, N. (2020). Advanced technologies for fiber reinforced polymer composite manufacturing. *Kahramanmaraş Sütçü İmam Üniversitesi Mühendislik Bilimleri Dergisi, 23*(4), 245–257. https://doi.org/10.17780/ksujes.809417

van Dinter, R., Tekinerdogan, B., & Catal, C. (2022). Predictive maintenance using digital twins: A systematic literature review. *Information and Software Technology*, *151*, Article 107008. https://doi.org/10.1016/j.infsof.2022.107008

Wang, T., Liu, Z., Liao, M., & Mrad, N. (2020). Life prediction for aircraft structure based on Bayesian inference: Towards a digital twin ecosystem. *Annual Conference of the PHM Society*, *12*(1), Article 8. https://doi.org/10.36001/phmconf.2020.v12i1.1261

Xu, X., Wang, G., Yan, H., Zhang, L., & Yao, X. (2023). Deep-learning-enhanced digital twinning of complex composite structures and real-time mechanical interaction. *Composites Science and Technology, 241*, 110139. https://doi.org/10.1016/j.compscitech.2023.110139

Ye, Y., Yang, Q., Zhang, J., Meng, S., & Wang, J. (2023). A dynamic data driven reliability prognosis method for structural digital twin and experimental validation. *Reliability Engineering & System Safety*, *240*, Article 109543. https://doi.org/10.1016/j.ress.2023.109543

Zhang, Q., Zheng, S., Yu, C., Wang, Q., & Ke, Y. (2022). Digital thread-based modeling of digital twin framework for the aircraft assembly system. *Journal of Manufacturing Systems*, *65*, 406–420. https://doi.org/10.1016/j.jmsy.2022.10.004

Zhang, Y., Wu, X., & Guo, Q. (2025). Advances in sensors technologies for composites structural health monitoring. *Composite Structures*, *370*, Article 119448. https://doi.org/10.1016/j.compstruct.2025.119448

Zuo, J., Zhou, L., Qiao, L., Ding, X., Wu, Q., He, X., & Peng, X. (2023). A new general framework for response prediction of composite structures based on digital twin with three effective error correction strategies. Applied Composite Materials, 30, 449–483. https://doi.org/10.1007/s10443-022-10096-3

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 65-81.

5

Life-Cycle Sustainability of Composite Structures in Aviation and Space Systems: Lightweight Design, Manufacturing, Repair, and Circular End-of-Life Strategies

Latif Tibet Aktaş[1]*

İzmir University of Economics, Department of Mechanical Engineering, 35330, Balçova, İzmir, Türkiye

**Corresponding author:* tibet.aktas@ieu.edu.tr

Abstract

Fiber-reinforced polymer composites are widely used in modern aircraft because their high specific stiffness and strength enable substantial structural weight savings. Their environmental performance, however, cannot be inferred from lightweighting alone. Carbon-fiber production, resin manufacture, composite processing and end-of-life treatment may impose considerable burdens before and after service, whereas lower structural mass can reduce energy use during operation. The overall balance therefore depends on the component, manufacturing route, aircraft mission, service life, maintenance strategy and end-of-life assumptions. The discussion focuses on how structural design and lightweighting interact with environmental burdens across the aircraft life cycle. Particular attention is given to CFRP manufacturing, functional equivalence in material comparisons, operational weight savings, repair and service-life extension, recycling, recycled carbon fibers and emerging thermoplastic and bio-based systems. A separate section addresses satellite and space structures, where lightweighting remains important but life-cycle boundaries differ markedly from those of aircraft. The central premise is that the sustainability of an aerospace composite is determined by the performance of the complete structure over its life cycle rather than by material properties alone.

Keywords: Aerospace composites; Carbon fiber reinforced polymer; Aviation; Space systems; Life cycle assessment; Sustainability; Recycling; Repair.

1. Introduction

Weight is a critical design variable in aerospace engineering because structural mass influences payload, range, fuel demand and, in some cases, the sizing of other aircraft systems. Fiber-reinforced composites are

[1] https://orcid.org/0000-0002-0974-1759

therefore attractive not simply because they are light, but because their high specific stiffness and strength can be tailored through fiber orientation, laminate architecture and local thickness. These characteristics have supported the transition of carbon-fiber-reinforced polymers (CFRPs) from secondary components to major aircraft structures (Soutis, 2005).

The environmental case for lightweight composites is often built around reduced fuel consumption during service. This benefit can be substantial, but it must be weighed against the impacts associated with producing and processing the composite. Life-cycle studies have demonstrated this mechanism. Scelsi et al. (2011) showed that higher production burdens for lightweight composite aircraft structures could be offset by cumulative use-phase savings. At aircraft and fleet scale, Timmis et al. (2015) similarly reported lower lifetime impacts for a composite-intensive aircraft despite higher manufacturing impacts. These findings should not be interpreted as evidence that CFRP is inherently sustainable. Carbon-fiber production and composite processing can be energy intensive, while thermoset CFRP still presents significant end-of-life challenges. The relevant comparison is therefore not simply CFRP versus aluminum per kilogram, but two structures that provide the required aerospace function over an equivalent service period.

More recent assessments have begun to treat the problem at system level. Atescan-Yuksek et al. (2024) compared aluminum and several CFRP alternatives while accounting for manufacturing and operational effects. Under their study assumptions, the higher initial burdens of the composite solutions were recovered during operation, although the reported break-even distance was specific to the materials, structural assumptions and flight scenario considered. Hellmann et al. (2025) extended this type of analysis to aircraft configurations with different CFRP contents, illustrating why component-level mass savings cannot always be scaled directly to aircraft-level environmental performance.

Service life complicates the comparison further. Composite aircraft structures experience inspection, damage, maintenance and repair before reaching end of life. A repair that safely restores structural function can avoid replacement of a much larger component and may therefore contribute to sustainability through service-life extension. End-of-life performance is equally dependent on function: recovered carbon fiber has greater environmental value when it can replace a technically comparable virgin reinforcement than when it is downgraded to a low-performance filler.

Earlier reviews have examined natural fibers, recycled carbon fibers and bio-based matrices as potentially more sustainable aviation materials (Bachmann et al., 2017). The present chapter takes a different approach. Rather than asking which constituent is environmentally preferable in isolation, it follows the composite structure through its life cycle and examines how structural design, manufacturing, operation, repair and end-of-life management interact. A dedicated section also extends this framework to satellite and space structures, where the role of mass and end-of-life management differs substantially from conventional aviation.

2. Composite Structures in Aviation and the Lightweighting Rationale

2.1. Structural Requirements and Specific Performance

The principal advantage of fiber-reinforced composites in aircraft structures lies in their combination of low density and directional mechanical performance. Laminated composites allow stiffness and strength to be distributed according to the load path, provided that off-axis loading, joints, impact damage and interlaminar failure are properly addressed. Soutis (2005) identified high specific stiffness and strength, together with structural tailorability, as central reasons for the increasing use of composites in aircraft.

This also means that substitution cannot be assessed on mass alone. An aluminum and a CFRP component of identical thickness do not necessarily provide equivalent stiffness, strength or damage tolerance. Conversely, replacing a metallic component with an overly conservative composite design may fail to exploit the potential mass advantage. Environmental assessment should therefore follow the final structural solution rather than rely only on material properties. For aerospace applications, functional equivalence is consequently essential. Equal masses of two materials are useful for raw-material comparison, but a structural comparison should, as far as possible, reflect equivalent stiffness, strength, stability, durability or another relevant design requirement.

2.2. From Metallic Structures to CFRP

Aluminum alloys remain important aerospace materials because they combine established design data, mature manufacturing routes and well-developed repair and recycling systems. CFRP therefore represents an alternative structural strategy rather than a universally superior replacement. A useful component-level example is the finite-element study of Kaya and Çevik (2023) on an F-16 main landing-gear structural part. Using the same geometry and boundary conditions, the authors compared an aluminum configuration with a CFRP counterpart under four loading cases. Within their numerical model, component mass decreased from 31.17 to 20.77 kg, corresponding to a reported reduction of 33.37%.

This result demonstrates structural lightweighting potential, but it does not establish environmental superiority. The study was a mechanical finite-element comparison rather than an LCA; carbon-fiber production, composite processing, maintenance and end-of-life treatment were outside its scope. It therefore supports the first step of the sustainability argument—mass reduction—rather than the complete life-cycle conclusion. Wu et al. (2023) examined the same issue at component level through an LCA and life-cycle costing study of an aircraft door. They found that a composite alternative could carry a higher manufacturing burden than the metallic design, while improved structural optimization and reduced material demand could substantially change the outcome. Structural efficiency and environmental performance are therefore closely linked.

2.3. Lightweighting as a Potential Environmental Lever

Aircraft lightweighting has an unusual life-cycle characteristic: production impacts are incurred mainly at the beginning of life, whereas the effect of carrying structural mass recurs throughout service. This explains why a composite can perform poorly in a cradle-to-gate comparison but become favorable when operation is included. Scelsi et al. (2011) demonstrated this behavior at component level, while Timmis et al. (2015) showed that the same mechanism remains relevant at aircraft and fleet scales. Atescan-Yuksek et al. (2024) also reported a break-even behavior between aluminum and the CFRP configurations examined in their study. The precise threshold should not be generalized, because it depends on manufacturing burden, structural weight saving, aircraft efficiency, utilization and service life.

Aircraft-level modeling reinforces this point. Hellmann et al. (2025) evaluated airframe configurations with different CFRP contents rather than assigning a fixed mass reduction to an isolated component. Their approach highlights an important limitation of simplified substitution studies: changing structural material can affect the aircraft as a system. The environmental value of lightweighting therefore depends on the conditions under which the lighter structure is produced and used. The structure must maintain the required performance and durability long enough for operational savings to compensate for its production and end-of-life burdens.

3. Life-Cycle Assessment of Aerospace Composite Structures

3.1. Scope and System Boundaries

ISO 14040 defines the principles and framework of life-cycle assessment, while ISO 14044 specifies the requirements and guidelines for its application (International Organization for Standardization [ISO], 2006a, 2006b). For aerospace composites, however, the most consequential decisions often concern what is being compared and where the system boundary is drawn.

A cradle-to-gate study is appropriate when the purpose is to identify manufacturing hotspots. Witik et al. (2012), for example, compared alternative production routes for composite aircraft components without introducing assumptions about decades of aircraft operation. Wu et al. (2023) similarly used the manufacture of one ATR 72 door as their functional unit.

If lightweighting is part of the claim, the use phase must also be represented. A study cannot demonstrate operational environmental savings if aircraft operation lies outside its boundary. End-of-life treatment introduces further choices concerning recycling credits, material quality and the fate of recovered fibers. Comparative aerospace LCAs should clearly report the life-cycle stages included, the structural function represented, the assumed service life and the treatment of recovered materials.

3.2. Functional Unit and Structural Equivalence

The functional unit should reflect the purpose of the assessment. A mass-based unit such as 1 kg CFRP or aluminum is useful for raw-material comparison but does not represent an aircraft structure. Component-level units—one panel, door or structural member—are more meaningful if the alternatives provide comparable performance. Even then, equivalence may depend on assumptions. In the aircraft-door study of Wu et al. (2023), the metallic and composite doors were treated as functionally equivalent and assumed to have the same service life, although the authors acknowledged uncertainty regarding the composite design.

For structural material selection, comparisons based on equivalent engineering performance—such as equivalent stiffness, strength, buckling resistance or durability—are more defensible than simple mass-based comparisons. Complete equivalence is difficult because metallic and composite structures fail differently, but explicitly stating the design requirement is preferable to comparing equal masses without regard to function.

The same caution applies to the lightweighting result reported by Kaya and Çevik (2023). Their calculated mass reduction can inform an LCA, but an environmental comparison would still require assumptions about structural equivalence, service life, manufacturing and end-of-life treatment. The main functional-unit choices relevant to aerospace composite LCA, and the limitations associated with each level of comparison, are summarized in Table 1.

Table 1. Functional-unit choices in life-cycle assessment of aerospace composite structures

Assessment level	Example functional basis	Suitable use	Main limitation
Material	1 kg CFRP, carbon fiber or aluminum	Raw-material and production hotspot comparison	Does not represent equivalent structural performance
Laminate/ panel	1 m² of panel or laminate	Manufacturing-route comparison when geometry and function are comparable	Equal area does not necessarily imply equal stiffness, strength or service life
Component	One aircraft door, panel or structural part	Product-level material/process comparison	Functional equivalence may still rely on design assumptions
Structural performance	Structure satisfying a prescribed stiffness, strength, stability or durability requirement	Comparative aerospace material selection	Requires detailed structural design and validated performance data
Aircraft/mission	Defined aircraft or transport service over a specified mission or lifetime	Full-system lightweighting assessment	Strongly dependent on mission, utilization and operational assumptions

3.3. Recycling Allocation and Material Quality

End-of-life modeling is particularly challenging for thermoset CFRP because recycling rarely returns the original composite in an equivalent form. Recovered fibers may differ in length, surface condition and mechanical properties, while the matrix may be degraded or lost. Hermansson et al. (2022) examined this issue by treating fiber and matrix as separate material flows in recycling allocation. Their approach allows differences in recovery rate and material quality to be represented more explicitly. Tapper et al. (2020) likewise showed that LCA results for CFRP recycling are sensitive to inventory data and methodological assumptions. Recovery, recycling, reuse and closed-loop substitution represent distinct material outcomes. Recovering carbon fiber does not itself establish closed-loop circularity; the environmental benefit depends on what material the recovered fiber can realistically replace.

3.4. Data Quality and Uncertainty

Composite LCA is sensitive to electricity mix, manufacturing yield, aircraft utilization, service life and recycling assumptions (Wu et al., 2023; Tapper et al., 2020; Gouveia et al., 2022). Additional uncertainty arises because aerospace production data are often proprietary and laboratory-scale studies may not represent mature industrial production (Wu et al., 2023; Gouveia et al., 2022). Structural assumptions are equally important. Predicted mass savings depend on laminate design, geometry, safety factors and optimization level, while operational benefits depend on how those savings affect aircraft performance. Scenario analysis is therefore particularly useful because many uncertain parameters represent plausible alternative systems rather than simple measurement errors. The environmental performance of CFRP therefore depends on the material system, manufacturing route, structural design and service scenario considered in the assessment.

4. Environmental Burdens of Materials and Manufacturing

4.1. Carbon-Fiber Production

Carbon-fiber production is one of the main upstream hotspots in aerospace CFRP. For commonly used PAN-based fibers, precursor manufacture is followed by energy-intensive stabilization and carbonization steps. Prenzel et al. (2024) examined 24 production scenarios and reported climate-change impacts ranging from 13.0 to 34.1 kg CO_2-eq per kilogram of carbon fiber. In their global reference modeling, carbon-fiber manufacturing energy accounted for 59% of the climate-change impact. The spread among scenarios is more informative than any single number because it shows the influence of electricity supply and process efficiency.

Earlier work by Das (2011) had already identified the high energy demand of carbon-fiber production as a major contributor to CFRP life-cycle impacts. Numerical values from older inventories should nevertheless be used carefully because production technology and energy systems continue to change.

4.2. Material Use and Manufacturing Yield

Composite manufacture includes more than fiber and resin. Prepregging, cutting, lay-up, vacuum consumables, curing, trimming and rejected material all contribute to the inventory. For carbon-fiber composites, manufacturing scrap is particularly important because a high upstream burden has already been invested in the material before waste is generated. Witik et al. (2012) showed that material production, particularly carbon fiber, was a major contributor to the environmental burden of the aircraft components they assessed. Manufacturing sustainability should therefore not be reduced to curing energy alone. Material utilization and part yield can be equally important. Structural design also affects the manufacturing inventory. Wu et al. (2023) found that their initial composite aircraft-door design did not realize the mass advantage normally associated with CFRP because of its structural configuration and conservative design assumptions. Improved lightweighting reduced material demand and changed the environmental result.

4.3. Autoclave and Alternative Processing

Autoclave processing remains important in aerospace manufacturing because it provides controlled pressure, temperature and vacuum conditions. Its energy demand has encouraged interest in out-of-autoclave prepregs, resin infusion, hot pressing and alternative curing technologies. These routes should not, however, be placed in a universal environmental hierarchy. Witik et al. (2012) found that some alternative processes reduced energy use or cost, while others gained little advantage because of longer cycles or additional operations. Gouveia et al. (2022) reached an equally instructive result in a laboratory-scale aeronautical sandwich-panel study: within their specific system, autoclave processing performed better than the hot-press alternative in the combined environmental and process assessment. The appropriate conclusion is therefore not that one process is inherently more sustainable. Energy use, cycle time, equipment utilization, consumables, yield and final part quality determine the outcome. A low-energy process that produces greater porosity, higher rejection rates or shorter component life may not provide a lower life-cycle burden.

4.4. Electricity Mix and Production Scale

Electricity supply can strongly influence both carbon-fiber production and component curing, as demonstrated by the scenario differences reported by Prenzel et al. (2024). Production scale also matters because laboratory and prototype manufacturing often use equipment below full capacity, whereas industrial production can distribute some fixed process burdens over a larger output. Laboratory data remain valuable because they provide transparent foreground inventories, but their transfer to industrial aerospace production requires caution. Manufacturing yield, batch utilization and quality-control requirements should therefore be considered whenever process-level LCA results are interpreted. These results point to a coupled design problem: material selection, structural design and production route all contribute to the environmental burden of the final component.

5. Use-Phase Benefits and Service-Life Extension

5.1. Operational Benefits of Structural Lightweighting

The main life-cycle advantage expected from lightweight aircraft structures occurs during operation. Unlike manufacturing impacts, which are largely incurred before entry into service, the effect of structural mass recurs throughout the aircraft lifetime. Even a modest reduction in component mass can therefore accumulate into a substantial operational benefit over repeated flights.

This behavior was demonstrated by Scelsi et al. (2011), who found that the higher initial burdens of lightweight composite structures could be compensated by cumulative fuel and emission savings during use. Timmis et al. (2015) extended the analysis to aircraft and fleet scales and likewise reported lower lifetime impacts for the composite-intensive aircraft considered, despite its higher manufacturing burden. Their fleet-level benefit was smaller than the reduction calculated for an individual aircraft because fleet penetration and traffic growth influenced the system-level result.

The same mechanism appears in more recent studies, although the magnitude of the benefit varies with the assumptions used. Atescan-Yuksek et al. (2024) identified a break-even behavior between aluminum and CFRP alternatives, whereas Hellmann et al. (2025) showed that changing CFRP content at airframe level can influence both aircraft mass and the resulting environmental performance. What changes from one study to another is not the underlying mechanism, but the magnitude of the benefit and the point at which it becomes relevant over the life cycle.

Representative studies illustrating the different scales at which aerospace composite sustainability has been assessed are summarized in Table 2.

Table 2. Representative life-cycle studies relevant to composite structures in aviation

Study	Assessment level	Main focus	Principal contribution	Important limitation
Scelsi et al. (2011)	Material/ component	Aluminum, GLARE and CFRP	Demonstrated cumulative use-phase savings from lightweight structures	Results depend on long-term operational assumptions
Timmis et al. (2015)	Aircraft/ fleet	Composite-intensive aircraft introduction	Connected material substitution with aircraft- and fleet-level emissions	Fleet results depend on penetration and demand scenarios
Atescan-Yuksek et al. (2024)	Structural/ manufacturing	Aluminum versus CFRP alternatives	Demonstrated life-cycle break-even behavior	Break-even distance is scenario-specific
Hellmann et al. (2025)	Aircraft	Different airframe CFRP contents	Linked material selection to preliminary aircraft design and life-cycle impacts	Results remain dependent on aircraft and mission assumptions
Wu et al. (2023)	Component	Aluminum and composite aircraft door	Combined LCA, LCC and lightweight-design scenarios	Functional equivalence and service life contain assumptions
Gouveia et al. (2022)	Manufacturing process	Aeronautical composite sandwich panel	Linked environmental and process efficiency using foreground data	Laboratory-scale production limits direct industrial extrapolation
Monteiro et al. (2026)	Maintenance / repair	Scarf repair versus panel replacement	Quantified repair as a service-life-extension strategy	Outcome depends strongly on damaged-to-total panel area

The studies in Table 2 also show that the apparent benefit of CFRP changes with the scale of analysis. A material-level result cannot be transferred directly to an aircraft, just as the environmental performance of one lightweight component does not by itself establish the response of an entire fleet.

5.2. Damage, Durability and Maintenance

Weight reduction provides little life-cycle benefit if the resulting structure cannot maintain its required performance over the intended service period. Composite aircraft structures may experience impact damage, environmental degradation, delamination and adhesive deterioration, making inspection and maintenance part of their life-cycle performance. This issue is particularly important for bonded repairs. Budhe et al. (2018) reviewed aerospace composite repair with emphasis on environmental durability and identified moisture and temperature as major factors affecting composite laminates, adhesives and bonded joints. Their review also emphasized that the response depends on the adhesive system, composite material, curing conditions and exposure history; there is no single degradation trend that can be transferred to all bonded repairs.

Durability determines how long the environmental burden invested in fiber production and component manufacture continues to provide useful structural service. Premature replacement shortens the period over which operational lightweighting benefits can accumulate and introduces additional material and manufacturing burdens. Service life should therefore be treated as a design variable in comparative LCA rather than assumed to be identical without justification.

5.3. Repair as a Life-Cycle Strategy

Repair offers a different route to reducing life-cycle burdens. Instead of recovering material after a component has been removed from service, repair attempts to preserve the material and structural value already embedded in the aircraft. When technically feasible, this may avoid production and replacement of a substantially larger component.

Monteiro et al. (2026) examined this question directly for an aeronautical composite panel by comparing local scarf repair with complete panel replacement. Using one square meter of intact panel area as the functional unit, the repair scenario produced 6% lower environmental impact and was 29% more eco-efficient than replacement under the conditions analyzed. The study also showed that the damaged-to-total panel area ratio was important: as panel size increased while the damaged area remained fixed, the relative attractiveness of local repair increased.

These results should not be interpreted as evidence that repair is always environmentally preferable. Repair requires inspection, material removal, replacement plies or patches, adhesives, curing energy and quality assurance, and the repaired structure must satisfy the required mechanical performance. For extensive damage, replacement may remain the appropriate technical option. More broadly, the study shows that repairability can be treated as a measurable life-cycle design variable. Repair therefore deserves to be considered alongside manufacturing, operation and end-of-life management. For an aircraft composite structure, retaining a safe component in service through a reliable local repair may preserve more value than recovering its fibers after premature disposal. Design for lightweighting, design for durability and design for repair should therefore be considered together rather than as independent objectives.

The next stage of the life cycle begins when repair is no longer practical or the aircraft reaches retirement. At that point, the environmental outcome depends increasingly on how the composite is dismantled, recovered and returned—or not returned—to productive use.

6. End-of-Life Management and Circularity

6.1. End-of-Life Challenge of Aerospace CFRP

The durability that makes thermoset CFRP attractive in service also complicates its treatment at end of life. Once the matrix has been cross-linked, the composite cannot be remelted in the same manner as a conventional thermoplastic. Aircraft retirement and manufacturing scrap therefore create a material stream in which valuable carbon fibers are embedded in a matrix that must either be fragmented, removed or chemically transformed before further use. CFRP recycling technologies are generally grouped into mechanical, thermal and chemical routes (Pimento & Pinho, 2011; Oliveux et al., 2015). Mechanical recycling reduces composite waste to shorter fibrous or particulate fractions and is comparatively simple, but the original fiber architecture is lost. Thermal processes such as pyrolysis remove the polymer matrix and recover carbon fibers, whereas chemical routes use solvents or reactive media to separate or transform matrix constituents. Each route produces a different recyclate, and these differences are more important than the simple distinction between "recycled" and "not recycled". Pimenta and Pinho (2011) emphasized that the structural value of recycled CFRP depends strongly on fiber reclamation and subsequent remanufacturing. Oliveux et al. (2015) similarly showed that recovered fibers can exhibit different lengths, surface conditions and reinforcement characteristics according to the recycling method. The technical challenge is therefore not only to recover carbon fiber, but to preserve enough of its useful properties to enable a valuable second application.

6.2. Environmental Benefit Depends on Substitution

Recycling does not automatically produce an environmental credit. Witik et al. (2013) compared pyrolysis, incineration with energy recovery and landfill for CFRP waste and demonstrated that the benefit of recycling was strongly influenced by the recovery process and, importantly, by the material displaced by the recycled fiber in its next application. Their analysis used equivalent structural stiffness to account for differences between virgin and recovered materials. Meng et al. (2018) reached a related conclusion when comparing pyrolysis, fluidized-bed and chemical recycling with conventional waste-management options. Recycling scenarios were generally favorable in terms of primary energy demand and global warming potential, but the relative ranking of recycling technologies changed according to the assumed displacement of virgin carbon fiber.

The substitution assumption is therefore critical. A kilogram of recovered carbon fiber does not necessarily replace a kilogram of virgin aerospace-grade carbon fiber. If the recyclate has lower mechanical performance or cannot be processed into equivalent fiber architectures, a larger amount may be required, or the material may move into a less demanding application. The environmental benefit should therefore be related to the function that the recovered material actually performs. End-of-life assessment should distinguish between material recovery and functional value recovery. The first describes the quantity of material diverted from disposal; the second reflects how much technical utility is retained after recycling.

6.3. Closed-Loop and Aviation-to-Aviation Reuse

A strict closed-loop system would return material from an aircraft composite into an equivalent aerospace application. In practice, this is difficult because continuous fibers and carefully controlled laminate architectures are often converted into shorter or less ordered recyclates. Nevertheless, secondary aviation applications can provide a meaningful route for recovered fibers. Meng et al. (2020) examined recycled carbon fiber from aviation waste for use in aircraft interior components as a replacement for virgin glass-fiber composites. Their analysis maintained equivalent stiffness by adjusting component mass according to material properties. Across the manufacturing routes considered, recycled-carbon-fiber composites produced environmental reductions of approximately 4–31% and cost reductions of 5–31% relative to the virgin glass-fiber alternatives.

More importantly, the study demonstrates a practical route for keeping recovered carbon fiber within aviation applications. Carbon fiber originating from high-performance aircraft structures did not need to return to the same primary structural function to retain value within aviation. A lower-demand interior application could provide a technically realistic second use while avoiding production of another reinforcement material. This pathway is better described as aviation-to-aviation circularity than as full restoration of the original CFRP. The fiber remains within the aerospace material system, but its structural role changes.

6.4. Chemical Recycling and Material Redesign

Chemical recycling offers another route because it can potentially recover both fiber and useful matrix-derived products. La Rosa et al. (2021) assessed a chemical recycling route for a recyclable thermoset composite and examined subsequent manufacture of a carbon-fiber thermoplastic composite using recovered short fibers and an epoxy-derived thermoplastic phase. An important aspect of that study was the revision of an earlier, less realistic assumption that long recovered fibers would be immediately available for reuse. The later analysis instead considered shredding before chemical treatment and subsequent remanufacture of short-fiber thermoplastic composites. The example also shows why recycling scenarios need to be consistent with the material form that the selected process can actually deliver.

Circularity can be improved not only by developing better recycling processes for existing composites, but also by designing resin systems and product architectures that make future recovery easier. For aerospace applications, however, recyclability cannot replace structural requirements. Any new matrix or recycling-compatible composite must still satisfy demanding requirements for mechanical performance, durability, thermal stability, fire behavior, processing consistency and certification. Circularity is therefore best treated as an additional design constraint rather than as a reason to compromise the primary engineering function.

6.5. From Recycling Efficiency to Retained Value

The end-of-life performance of aerospace composites is most usefully judged by how much material and functional value remains after service. Landfill retains almost none of that value. Energy recovery retains energy but not reinforcement value. Recycling can preserve part of the carbon fiber value, although the extent depends on fiber quality and the next application. Repair and reuse, discussed in Section 5, may preserve even more value because the original component or structure remains in service.

For the purposes of the present discussion, a qualitative value-retention hierarchy can be expressed as:

$$\text{Continued use and repair} \rightarrow \text{component or material reuse} \rightarrow \text{high-value recycling}$$
$$\rightarrow \text{lower-value recycling} \rightarrow \text{energy recovery} \rightarrow \text{disposal}$$

The exact ranking can vary with the product and process, but the principle is important for aerospace composites: the highest-value strategy is generally the one that preserves the greatest amount of technically useful material with the least additional processing.

7. Emerging Routes toward More Sustainable Aerospace Composites

7.1. Thermoplastic Composite Systems

Thermoplastic composites are receiving increasing attention in aerospace because they offer manufacturing and end-of-life options that differ from conventional thermoset systems. Unlike cross-linked thermosets, thermoplastic matrices can be softened by heating, which enables processes such as press consolidation, thermoforming and welding and can simplify some routes for remanufacturing or recycling. Ozturk et al. (2024) reviewed recent aerospace developments in thermoplastic composites and identified stamp forming, press consolidation, automated fiber placement and welding among the areas receiving substantial research and industrial attention. Shorter processing cycles and the possibility of joining without conventional adhesive bonding are attractive for higher-rate aircraft production. These advantages should not be interpreted as evidence that thermoplastics necessarily have a lower life-cycle impact. High-performance aerospace thermoplastics often require elevated processing temperatures, and the environmental outcome depends on resin production, reinforcement type, processing energy, scrap generation and actual recovery at end of life. Their sustainability must therefore be assessed at component level rather than inferred from recyclability alone.

7.2. Recycled-Carbon-Fiber Composites

Recycled carbon fiber offers a second route by reducing demand for virgin reinforcement while retaining part of the mechanical value originally created during carbon-fiber production. As discussed in Section 6, the environmental benefit depends strongly on fiber quality and the application in which the recyclate is used. The aviation-to-aviation study of Meng et al. (2020) provides a useful example. Recovered carbon fibers were considered for aircraft interior applications in place of virgin glass-fiber composites, with component mass adjusted to maintain equivalent stiffness. This type of secondary application may be more realistic in the near term than attempting to reproduce continuous-fiber primary structures directly from recycled material. The design challenge is therefore to match recovered fiber quality with an appropriate structural function. Recycled carbon fiber should not be regarded simply as a lower-impact substitute for virgin aerospace-grade CFRP; its value depends on retaining sufficient performance to displace another material effectively.

7.3. Bio-Based Matrices and Natural Fibers

Renewable feedstocks offer another possible route to reducing dependence on fossil-derived composite constituents. Dyer and Kumru (2023) reviewed approaches for improving the sustainability of aerospace polymer composites through changes in feedstock, processing chemistry and recycling. These developments are relevant to future matrix systems, but renewable origin alone does not establish lower life-cycle impact or aerospace suitability. Natural-fiber composites illustrate this point particularly well. Bachmann et al. (2017) identified potential applications of natural fibers and bio-based resins primarily in aircraft interiors and secondary structures, where mechanical requirements can be less severe than in primary load-bearing components. Their broader adoption remains constrained by issues including mechanical performance and flammability.

Gomez-Campos et al. (2021) examined this trade-off directly through an LCA of a flax-based aircraft interior panel. Although the bio-based material route provided advantages in parts of the production system, the prototype panel was heavier than the conventional alternative. The study reported that the conventional panel ultimately performed about 14% better in the overall comparison, illustrating how a mass penalty can offset benefits gained from lower-impact material production. For aviation, a lower production impact at the material level does not necessarily translate into a lower-impact component once structural mass is considered.

7.4. Designing Sustainability into the Structure

Emerging materials will have limited effect if sustainability is considered only after the laminate and manufacturing route have already been fixed. A more effective approach is to introduce life-cycle considerations during structural design. For aerospace composites, this can include reducing material scrap, selecting processing routes consistent with production volume, designing joints that permit repair or disassembly, avoiding unnecessary laminate thickness and identifying realistic second-life applications for recovered materials. Dyer and Kumru (2023) similarly frame future aerospace polymer development around the combined roles of feedstock, processing and recycling rather than a single material substitution.

These strategies act at different stages of the life cycle: lightweighting can reduce the operational burden, repair can extend component life, and recycling can retain part of the value embedded in carbon fibers. No single constituent is likely to determine the life-cycle performance of an aerospace composite on its own. Favorable life-cycle performance is more likely to result from a structure designed from the outset to perform efficiently, remain in service for as long as technically justified and retain useful material value when that service ends.

These principles also apply beyond aviation, but the life-cycle context changes substantially once the structure is launched into space. Satellite and launch systems therefore require a separate sustainability framework, which is considered in the following section.

8. Composite Structures in Satellite and Space Systems: Sustainability and Life-Cycle Perspectives

8.1. Lightweight Composite Structures Beyond Aviation

Composite lightweighting remains important once a structure leaves the aviation environment, but its life-cycle meaning changes. In aircraft, mass reduction can generate repeated fuel savings over thousands of flights. For satellites and launch systems, the benefit is instead associated primarily with launch mass, payload capability and the design of the transportation system required to place the spacecraft in its intended orbit. CFRP is used in space structures because its low density and high stiffness support mass-efficient structural design. Stergiou et al. (2022) examined CFRP specifically in the context of space vehicles and the Vega launcher and emphasized the potential benefit of replacing heavier metallic components when reduced mass lowers propulsion requirements. Their LCA also considered alternative end-of-life scenarios for CFRP, demonstrating that the same production and recycling questions encountered in aviation remain relevant to space hardware.

This differs from aviation because the benefit does not accumulate through repeated fuel savings during normal operation. Once a satellite has reached orbit, structural mass does not create a recurring fuel penalty equivalent to carrying mass through repeated atmospheric flights. The mass-related environmental benefit is concentrated more strongly in mission architecture and launch. Aviation and space systems therefore require different interpretations of the same lightweighting principle. The principal differences are summarized in Table 3.

Table 3. Life-cycle implications of composite lightweighting in aviation and satellite/space systems

Life-cycle aspect	Aviation	Satellite/space systems
Main value of lightweighting	Repeated reduction in operational fuel demand	Reduced launch mass and influence on payload/mission architecture
Use phase	Repeated flight cycles over a long service life	Mission-specific orbital or space operation
Maintenance and repair	Inspection and ground-based repair can extend component life	Post-launch physical intervention is generally much more constrained
Conventional end of life	Aircraft recovery, dismantling and material treatment are possible	Depends on mission: re-entry, disposal orbit or continued orbital residence
Circularity opportunity	Repair, component reuse and material recycling	Mainly pre-launch manufacturing loops; post-mission material recovery is presently limited
Additional sustainability concern	Production–operation trade-off	Launch emissions, atmospheric re-entry and use of the orbital environment

8.2. Why Space Systems Require a Different LCA Boundary

Applying conventional LCA to space missions is not straightforward. Maury et al. (2020) reviewed environmental LCA practice in the space sector and found substantial heterogeneity in goal and scope definitions, reflecting the unusual combination of spacecraft production, launch infrastructure, propulsion, ground activities and orbital operation. The space sector also uses specialized materials and processes for which conventional LCA databases may provide limited representation. This has encouraged the development of space-specific approaches. Wilson and Vasile (2023), for example, integrated life-cycle engineering into concurrent mission design and applied it to three SmallSat missions. Their work showed that environmental, economic and social indicators can be introduced during early spacecraft design rather than assessed only after the mission architecture has been fixed.

For composite structures, this is particularly relevant because structural mass interacts with other system choices. Reducing the mass of a satellite panel or launcher component may influence propulsion requirements or available payload, but the environmental consequence depends on the mission and launch architecture. The functional unit for a space composite should therefore be connected to mission function rather than based solely on kilograms of material.

8.3. Launch and Atmospheric Effects

The launch phase introduces environmental mechanisms that have no direct equivalent in conventional aviation LCA. Rocket emissions are released across different atmospheric layers, and their climatic effect can depend on altitude as well as propellant chemistry. Dominguez Calabuig et al. (2024) examined reusable launch-vehicle fleets using a space-specific LCA framework that included high-altitude emissions. Their results showed that climate-impact estimates were highly sensitive to the treatment of rocket exhaust and that propellant choice substantially affected the comparison among the launcher concepts studied. This reinforces an important boundary condition for composite lightweighting: a reduction in spacecraft or launcher structural mass cannot be translated into an environmental benefit without considering the launch system in which that mass reduction occurs.

8.4. End of Mission, Orbital Debris and Design for Demise

End of life is where the difference between aircraft and spacecraft becomes most pronounced. An aircraft can normally be dismantled after service and its materials directed toward reuse, recycling or disposal. A satellite may instead remain in orbit, move to a disposal orbit or re-enter the atmosphere. Conventional terrestrial LCA therefore does not fully represent the consequences of the space-system end-of-mission phase (Maury et al., 2019; Maury et al., 2020). Maury et al. (2019) addressed this problem by proposing a methodology for including orbital-resource use and space-debris effects in life-cycle assessment. Their approach considered both exposure to debris in a given orbit and the potential severity of creating additional debris following spacecraft break-up. Application to alternative post-mission disposal scenarios showed the possibility of burden shifting between terrestrial environmental impacts and protection of the orbital environment.

Composite material selection can also influence re-entry behavior. Design for Demise (D4D) attempts to ensure that spacecraft components break up and degrade sufficiently during atmospheric re-entry to reduce the risk posed by surviving fragments. Recent work by Chen et al. (2026) investigated the thermal degradation and pyrolysis behavior of CFRP specifically for satellite D4D applications. Their modeling and experiments showed that CFRP mass-loss behavior depends on coupled thermal and material processes and on specimen thickness, illustrating that demisability must be engineered rather than assumed from the presence of a polymer matrix. This introduces a trade-off that is specific to space hardware. A material selected for high stiffness and long-term dimensional stability during the mission must also be considered in terms of its behavior after the mission ends. For some spacecraft, the desirable end-of-life response may therefore be controlled degradation rather than material recovery.

8.5. Implications for Sustainable Space-Composite Design

The life-cycle logic developed for aircraft composites remains useful in space systems, but the priority of each stage changes. Manufacturing efficiency and carbon-fiber production remain relevant in both sectors. In aviation, service-life extension and operational fuel savings can dominate the sustainability argument. For satellites, launch architecture, orbital occupation and end-of-mission behavior become comparatively more important. Sustainable space-composite design should therefore link structural optimization with mission-level assessment from the beginning. A lighter component is beneficial only to the extent that it improves the overall mission system, just as a recyclable material is useful only when a realistic recovery pathway exists. Accordingly, composite selection in space systems should be assessed against mission-level mass, launch and end-of-mission consequences.

9. Future Research Perspectives

Despite the growing literature on aerospace composite sustainability, several methodological gaps still limit comparison among materials, manufacturing routes and life-cycle strategies.

9.1. Linking Structural Optimization and LCA

A recurring limitation is the separation of structural design from environmental assessment. Many LCA studies begin with an assumed component mass or weight-saving factor, whereas structural studies often end once mechanical performance has been demonstrated. The studies of Wu et al. (2023) and Hellmann et al. (2025) show the value of connecting these stages more closely. Future assessments should increasingly derive material quantities and mass savings from structurally credible designs rather than from generic substitution ratios. This is particularly important when comparing metals and composites because equal geometry, equal mass and equal structural performance are not interchangeable conditions. Functional equivalence should therefore be demonstrated through appropriate mechanical criteria and carried explicitly into the LCA model.

9.2. Manufacturing Data and Service-Life Uncertainty

Reliable foreground data remain another constraint. Carbon-fiber production, prepreg manufacture and aerospace processing can vary substantially with electricity supply, production scale and technological route (Witik et al., 2012; Prenzel et al., 2024; Gouveia et al., 2022). Greater use of industrial primary data would improve confidence in comparative assessments, particularly for newer thermoplastic and recycling-compatible material systems. Service life is similarly important but often simplified. Composite structures may require inspection, local repair or replacement depending on damage severity and environment. The repair analysis of Monteiro et al. (2026) demonstrates that maintenance decisions can measurably alter life-cycle performance, yet repair is still absent from many aerospace composite LCAs. Future models should treat damage probability, repairability and component life as part of the environmental system rather than assuming an identical lifetime for competing structures.

9.3. Recycling Quality and Circularity

End-of-life assessments need stronger links between recovered material quality and realistic second-life applications. Recycling rates alone provide limited information if fiber length, architecture or surface condition prevent high-value reuse. The allocation issues identified by Hermansson et al. (2022) and Tapper et al. (2020) reinforce the need to distinguish material recovery from functional substitution. Recycling pathways would be more credible if the intended secondary application were identified at the modeling stage. The aviation-to-aviation scenario of Meng et al. (2020) illustrates how recovered carbon fiber can retain value within the sector without necessarily returning to its original primary structural role. Future circularity studies should therefore report not only how much material is recovered, but what it replaces and whether the resulting component satisfies an equivalent engineering function.

9.4. Extending LCA to Space Systems

Space systems introduce additional methodological challenges. Conventional terrestrial LCA does not fully capture orbital occupation, debris generation or some high-altitude launch emissions (Maury et al., 2019; Dominguez Calabuig et al., 2024; Maury et al., 2020). These effects become especially relevant when composite lightweighting is evaluated at mission level. Future space-composite assessments should therefore integrate material production and structural optimization with launch architecture, mission duration and end-of-mission strategy. Design for Demise also introduces a new material-selection problem: a spacecraft component must remain mechanically and dimensionally stable during operation while exhibiting acceptable behavior during atmospheric re-entry (Chen et al., 2026). Across both aviation and space applications, the main research need is therefore greater integration. Structural mechanics, manufacturing, durability, maintenance and end-of-life treatment should be evaluated as parts of the same engineered life cycle rather than as independent optimization problems.

10. Conclusion

The evidence reviewed in this chapter does not support a simple environmental ranking of composites and conventional aerospace materials. CFRP production can carry substantial upstream burdens, and manufacturing efficiency depends on material utilization, processing energy, production scale and part quality. These initial impacts may be recovered during aircraft operation, but the outcome depends on the actual mass reduction, mission profile and service life. A life-cycle perspective also changes the role of durability and repair. Keeping a sound composite component in service can preserve both structural and environmental value, while end-of-life recycling is most beneficial when recovered fibers retain sufficient quality to replace useful virgin materials. Thermoplastic, recycled-carbon-fiber and bio-based systems offer promising routes, but none should be considered inherently sustainable without accounting for structural performance and realistic processing conditions.

For satellite and space systems, the same principles apply within a different life-cycle framework. Lightweighting influences launch and mission architecture rather than recurring aircraft fuel use, while orbital debris, re-entry and end-of-mission management introduce effects that conventional aviation LCA does not encounter. Taken over the full life cycle, no single material or processing choice determines whether an aerospace composite is environmentally preferable. The outcome depends on how structural efficiency, manufacturing, service life, repair and end-of-life management interact in the particular application. Future assessments would therefore benefit from closer coupling between environmental models and the actual mechanical function and service history of the structure.

Conflict of Interest Statement

The author declares that there are no conflicts of interest regarding the publication of this manuscript.

References

Atescan-Yuksek, Y., Mills, A., Ayre, D., Koziol, K., & Salonitis, K. (2024). Comparative life cycle assessment of aluminium and CFRP composites: The case of aerospace manufacturing. *The International Journal of Advanced Manufacturing Technology*, *131*, 4345–4357. https://doi.org/10.1007/s00170-024-13241-3

Bachmann, J., Hidalgo, C., & Bricout, S. (2017). Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review. *Science China Technological Sciences*, *60*, 1301–1317. https://doi.org/10.1007/s11431-016-9094-y

Budhe, S., Banea, M. D., & de Barros, S. (2018). Bonded repair of composite structures in aerospace application: A review on environmental issues. *Applied Adhesion Science*, *6*, 3. https://doi.org/10.1186/s40563-018-0104-5

Chen, W., Shi, J., & Wang, M. (2026). Design-for-demise-oriented modeling and testing of carbon fiber reinforced composites for safe satellite re-entry. *Aerospace Science and Technology*, *168*, 111267. https://doi.org/10.1016/j.ast.2025.111267

Das, S. (2011). Life cycle assessment of carbon fiber-reinforced polymer composites. *The International Journal of Life Cycle Assessment*, *16*, 268–282. https://doi.org/10.1007/s11367-011-0264-z

Dominguez Calabuig, G. J., Wilson, A., Bi, S., Vasile, M., Sippel, M., & Tajmar, M. (2024). Environmental life cycle assessment of reusable launch vehicle fleets: Large climate impact driven by rocket exhaust emissions. *Acta Astronautica*, *221*, 1–11. https://doi.org/10.1016/j.actaastro.2024.05.009

Dyer, W. E., & Kumru, B. (2023). Polymers as aerospace structural components: How to reach sustainability? *Macromolecular Chemistry and Physics*, *224*(24), 2300186. https://doi.org/10.1002/macp.202300186

Gomez-Campos, A., Vialle, C., Rouilly, A., Hamelin, L., Rogeon, A., Hardy, D., & Sablayrolles, C. (2021). Natural fibre polymer composites—A game changer for the aviation sector? *Journal of Cleaner Production*, *286*, 124986. https://doi.org/10.1016/j.jclepro.2020.124986

Gouveia, J. R., Gonçalves, M., Rocha, R., Baptista, A. J., & Monteiro, H. (2022). Efficiency framework to assess aeronautic composite panel production: Tracking environmental and process performance. *Sustainable Production and Consumption*, *31*, 419–431. https://doi.org/10.1016/j.spc.2022.03.007

Hellmann, A. J. G., Barke, A., Heinze, W., Heimbs, S., & Spengler, T. S. (2025). Using lightweight airframe materials in aircraft structures and investigating potential reinforcement effects with sustainable aviation fuels: An analysis of environmental and economic impacts. *Journal of Industrial Ecology, 29*(4), 1135–1150. https://doi.org/10.1111/jiec.70040

Hermansson, F., Ekvall, T., Janssen, M., & Svanström, M. (2022). Allocation in recycling of composites—The case of life cycle assessment of products from carbon fiber composites. *The International Journal of Life Cycle Assessment, 27*, 419–432. https://doi.org/10.1007/s11367-022-02039-8

International Organization for Standardization. (2006a). *Environmental management—Life cycle assessment—Principles and framework (ISO Standard No. 14040:2006).*

International Organization for Standardization. (2006b). *Environmental management—Life cycle assessment—Requirements and guidelines (ISO Standard No. 14044:2006).*

Kaya, İ., & Çevik, M. (2023). Aluminum and carbon fiber reinforced polymer composite material comparative strength analysis of a structural part in F-16 fighter aircraft landing gear. *Savunma Bilimleri Dergisi (The Journal of Defense Sciences), 43*(2), 454–472. https://doi.org/10.17134/khosbd.1243616

La Rosa, A. D., Greco, S., Tosto, C., & Cicala, G. (2021). LCA and LCC of a chemical recycling process of waste CF-thermoset composites for the production of novel CF-thermoplastic composites: Open loop and closed loop scenarios. *Journal of Cleaner Production, 304*, 127158. https://doi.org/10.1016/j.jclepro.2021.127158

Maury, T., Loubet, P., Trisolini, M., Gallice, A., Sonnemann, G., & Colombo, C. (2019). Assessing the impact of space debris on orbital resource in life cycle assessment: A proposed method and case study. *Science of the Total Environment, 667*, 780–791. https://doi.org/10.1016/j.scitotenv.2019.02.438

Maury, T., Loubet, P., Morales Serrano, S., Gallice, A., & Sonnemann, G. (2020). Application of environmental life cycle assessment (LCA) within the space sector: A state of the art. *Acta Astronautica, 170*, 122–135. https://doi.org/10.1016/j.actaastro.2020.01.035

Meng, F., Olivetti, E. A., Zhao, Y., Chang, J. C., Pickering, S. J., & McKechnie, J. (2018). Comparing life cycle energy and global warming potential of carbon fiber composite recycling technologies and waste management options. *ACS Sustainable Chemistry & Engineering, 6*(8), 9854–9865. https://doi.org/10.1021/acssuschemeng.8b01026

Meng, F., Cui, Y., Pickering, S., & McKechnie, J. (2020). From aviation to aviation: Environmental and financial viability of closed-loop recycling of carbon fibre composite. *Composites Part B: Engineering, 200*, 108362. https://doi.org/10.1016/j.compositesb.2020.108362

Monteiro, H., Gouveia, J. R., Gonçalves, M. M., Rocha, R., & Baptista, A. J. (2026). Integrated sustainability assessment of scarf repair for aeronautical composite panels: A total efficiency index approach. *Environmental Impact Assessment Review, 117*, 108217. https://doi.org/10.1016/j.eiar.2025.108217

Oliveux, G., Dandy, L. O., & Leeke, G. A. (2015). Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. *Progress in Materials Science, 72*, 61–99. https://doi.org/10.1016/j.pmatsci.2015.01.004

Ozturk, F., Cobanoglu, M., & Ece, R. E. (2024). Recent advancements in thermoplastic composite materials in aerospace industry. *Journal of Thermoplastic Composite Materials, 37*(9), 3084–3116. https://doi.org/10.1177/08927057231222820

Pimenta, S., & Pinho, S. T. (2011). Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. *Waste Management, 31*(2), 378–392. https://doi.org/10.1016/j.wasman.2010.09.019

Prenzel, T. M., Hohmann, A., Prescher, T., Angerer, K., Wehner, D., Ilg, R., von Reden, T., Drechsler, K., & Albrecht, S. (2024). Bringing light into the dark—Overview of environmental impacts of carbon fiber production and potential levers for reduction. *Polymers*, *16*(1), 12. https://doi.org/10.3390/polym16010012

Scelsi, L., Bonner, M., Hodzic, A., Soutis, C., Wilson, C., Scaife, R., & Ridgway, K. (2011). Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment. *Express Polymer Letters*, *5*(3), 209–217. https://doi.org/10.3144/expresspolymlett.2011.20

Soutis, C. (2005). Fibre reinforced composites in aircraft construction. *Progress in Aerospace Sciences*, *41*(2), 143–151. https://doi.org/10.1016/j.paerosci.2005.02.004

Stergiou, V., Konstantopoulos, G., & Charitidis, C. A. (2022). Carbon fiber reinforced plastics in space: Life cycle assessment towards improved sustainability of space vehicles. *Journal of Composites Science*, *6*(5), 144. https://doi.org/10.3390/jcs6050144

Tapper, R. J., Longana, M. L., Norton, A., Potter, K. D., & Hamerton, I. (2020). An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers. *Composites Part B: Engineering, 184,* 107665. https://doi.org/10.1016/j.compositesb.2019.107665

Timmis, A. J., Hodzic, A., Koh, L., Bonner, M., Soutis, C., Schäfer, A. W., & Dray, L. (2015). Environmental impact assessment of aviation emission reduction through the implementation of composite materials. *The International Journal of Life Cycle Assessment*, *20*(2), 233–243. https://doi.org/10.1007/s11367-014-0824-0

Wilson, A. R., & Vasile, M. (2023). Life cycle engineering of space systems: Preliminary findings. *Advances in Space Research, 72*(7), 2917–2935. https://doi.org/10.1016/j.asr.2023.01.023

Witik, R. A., Gaille, F., Teuscher, R., Ringwald, H., Michaud, V., & Månson, J.-A. E. (2012). Economic and environmental assessment of alternative production methods for composite aircraft components. *Journal of Cleaner Production, 29–30,* 91–102. https://doi.org/10.1016/j.jclepro.2012.02.028

Witik, R. A., Teuscher, R., Michaud, V., Ludwig, C., & Månson, J.-A. E. (2013). Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. *Composites Part A: Applied Science and Manufacturing, 49,* 89–99. https://doi.org/10.1016/j.compositesa.2013.02.009

Wu, M., Sadhukhan, J., Murphy, R., Bharadwaj, U., & Cui, X. (2023). A novel life cycle assessment and life cycle costing framework for carbon fibre-reinforced composite materials in the aviation industry. *The International Journal of Life Cycle Assessment, 28*, 566–589. https://doi.org/10.1007/s11367-023-02164-y

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 82-96.

6

Bacterial Identification in Food Microbiology: Methodological Approaches from Conventional to Modern

Şükran Güven[1]*, Özlem Çağındı[2]

Celal Bayar University, Faculty of Engineering and Natural Sciences, Department of Food Engineering, Manisa, Türkiye

Corresponding author: sukranhorasann@gmail.com

Abstract

Different methods for the identification of foodborne microorganisms are comparatively evaluated. Microorganisms are microscopic living organisms that are too small to be observed with the naked eye and can exist either as individual cells or in colonies. The identification and characterization of bacterial species constitute an important area of research, not only for understanding their roles in ecosystems but also for revealing their potential applications in various industrial fields, particularly biotechnology. In the food industry, microorganisms are of considerable importance due to their involvement in food spoilage and their potential to pose risks to food safety. Effective detection and identification of foodborne microorganisms depend on appropriate sampling strategies, which vary according to the characteristics of the food matrix, the target microbial group, and the analytical method employed. Conventional methods for bacterial identification are primarily based on the evaluation of phenotypic characteristics. Gram staining, microscopic cell morphology, colony morphology, and growth characteristics on selective or differential culture media represent the initial stages of bacterial identification. In addition, rapid biochemical tests such as catalase, coagulase, oxidase, indole, and pyrrolidonyl arylamidase tests enable the preliminary identification of certain bacterial pathogens within a short period of time. For example, Escherichia coli can be identified based on characteristic features such as its Gram-negative cell wall structure, indole positivity, and oxidase negativity. While phenotypic characteristics are generally sufficient for classification at the genus level, accurate species-level identification often requires additional biochemical and confirmatory analyses. To address these limitations, multiplex biochemical testing systems, such as the Analytical Profile Index (API), have been developed, providing faster, more standardized, and more reliable identification compared with conventional approaches. In recent years, in addition to culture-based methods, immunological assays and nucleic acid-based molecular techniques have become widely used for the detection and identification of foodborne pathogens. Polymerase Chain Reaction (PCR) and Next-Generation Sequencing (NGS) technologies enable the rapid and accurate identification of microorganisms owing to their high sensitivity and specificity. Furthermore, bacteriophage-based approaches, which are among

[1] https://orcid.org/0009-0002-9295-9042
[2] https://orcid.org/0000-0002-6436-9208

the culture-independent detection methods, have been reported to offer shorter analysis times, high sensitivity, and potential cost advantages compared with conventional culture techniques.

Keywords: Bacterial identification; Biochemical methods; Identification methods; Molecular and genomic techniques; Rapid detection methods

1. Introduction

Microorganisms play a critical role in food production processes and are determining factors in terms of both safety and spoilage. Their interaction with food may render a product unsuitable for human consumption (Saucier, 2016). Accurate identification and systematic classification of microorganisms are possible through the selection of appropriate techniques and an understanding of their mechanisms of action. Microbial identification constitutes an integral component of taxonomy. The hierarchical classification, ranging from the kingdom level to the strain level, demonstrates that the systematics and identification of microorganisms are closely interconnected. Research on microbial identification has evolved through strategies aimed at reducing the time required for routine diagnostics. Today, for a method to be considered successful, results are generally expected to be obtained within 24 hours, while even shorter turnaround times are critically important in emergency situations. The methods used in this field are generally classified as direct and indirect techniques (Franco-Duarte et al., 2019).

The metabolic activity of a bacterium may either lead to food spoilage or be considered beneficial in processing, depending on the desirability of the resulting changes. Bacteria of interest in food microbiology are classified as agents of infection, causes of foodborne intoxication, spoilage microorganisms, and processing aids (Gill, 2017).

2. Traditional Methods

Isolation and culturing, used to determine the phenotypic characteristics of microorganisms, form the basis of traditional methods. These methods are generally based on chemical reactions. A commonly used approach involves monitoring microbial growth, observed by the increase in turbidity of the culture medium (Franco-Duarte et al., 2019). In these traditional methods, which provide the formation of visible colonies, the colonies can then be subjected to various analyses. These methods yield more successful results when the growth requirements of the target microorganisms are known and appropriate culture media are selected. Although they are low-cost and provide both qualitative and quantitative information, they are laborious and time-consuming due to stages such as medium preparation, dilution, plating, incubation, and characterization. Results are obtained after days, and false positives can occur when similar species are involved. They are also insufficient in identifying cells that cannot be cultured (Franco-Duarte et al., 2019). Because many microorganisms cannot grow in culture media during fermentation processes, it is not possible to fully understand the dynamics of microbial ecosystems using culture-based methods alone (Aktepe & Çakır, 2023). Therefore, colony characteristics can be supported by advanced analyses such as Gram staining, biochemical tests, matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS), and PCR sequencing (Aladhadh, 2023). Nevertheless, classical molecular methods still provide important information in the identification and characterization of microorganisms (Aktepe & Çakır, 2023).

2.1. Sampling and Preparation

In food microbiology, prior to analyses such as conventional microbiological culturing, basic sample preparation procedures, including homogenization and dilution, are performed to make the sample suitable for analysis. Initially, solid food samples are transferred into a liquid phase and homogenized to ensure an even distribution of microorganisms and facilitate their transfer to culture media. Subsequently, serial dilution may be applied depending on the sample type and the analytical method used. This step enables the controlled reduction of high microbial loads and promotes the formation of distinguishable and countable colonies on culture media following inoculation. Serial dilutions are generally performed in tenfold increments, allowing for the reliable assessment of microorganisms present in food samples. bels, or data points remain effortlessly legible.

Cultural enrichment is applied to resuscitate and proliferate low levels of pathogenic microorganisms present in food and environmental samples. Enrichment processes are crucial for increasing the detection sensitivity of microorganisms, especially when they are present in low concentrations (Wang & Salazar, 2016). Microbial culture media provide the nutrients necessary for the growth of bacterial populations present within sample matrices. For the detection of foodborne pathogens, cultural enrichment traditionally consists of two stages: primary enrichment using a non-selective medium, followed by secondary enrichment using a selective medium (Dwivedi et al., 2014). Cultural enrichment plays a crucial role in highly sensitive bacterial detection by increasing the concentration of the analytical target and ensuring its homogeneous distribution within the suspension. This approach reduces the probabilistic nature of pathogen detection and facilitates subsequent sample processing. However, a major limitation of this method is that the minimum time required for analysis is largely determined by the duration of the enrichment step itself (Gill, 2017).

2.2. Phenotypic Methods

Phenotypic methods may not always provide accurate and sufficient identification of microorganisms at the species or strain level. Although this classification has long been used as the sole approach, it has led to uncertainties and difficulties in the analysis process. To shorten identification time, molecular biology methods have been developed and supported by various molecular fingerprinting applications.

Initial phenotypic characterization typically begins with Gram staining and includes basic analyses such as catalase and oxidase tests. Carbohydrate metabolism is evaluated through acid production and end products (CO_2, acetate, lactate), while enzyme tests (glucuronidase, glucosidase, galactosidase, fructosidase) are continued. At a more advanced level, tests for indole and H_2S production, gelatine and casein digestion, and amino acid metabolism (e.g., lysine, ornithine, arginine decarboxylation, arginine dihydrolase, phenylalanine deaminase, urease) are used. In addition, lipid metabolism tests (lipase and lecithinase on egg yolk agar, Tween digestion) and cell wall receptor-based assays (optokine, lysozyme sensitivity, bile solubility) are commonly used in the differentiation of Gram-positive cocci (Franco-Duarte et al., 2019).

2.3. Classical Biochemical Tests

Bacteria essentially exist in two different cell types. The Gram staining method used to identify them is based on differences in cell wall structure and chemical composition. In the staining process, bacteria that retain crystal violet stain appear purple and are identified as Gram-positive, while bacteria that retain safranin appear red and are identified as Gram-negative (Beveridge, 2001). However, differences in cell structures are not sufficient for definitive identification at the species level. Various biochemical tests allow for differentiation between species by evaluating the specific metabolic activities of bacteria, such as enzyme activity, carbohydrate fermentation, amino acid decarboxylation, and gas production (Tankeshwar, 2026). Some commonly used classical biochemical tests and their descriptions are given in Table 1. Until the late 1960s, biochemical tests were performed manually in separate tubes, but the development of miniaturized identification systems has brought about a significant transformation in laboratory practices. Multiple biochemical test kits, such as the Analytical Profile Index (API) system, are among the first commercial systems that allow for rapid and standardized bacterial identification (Arbefeville et al., 2024). A typical model is the API (bioMérieux, Craponne, France), where standard methods are integrated into miniaturized reaction pairs, scored as "positive" and "negative," and finally mapped to a scoring system based on "best fit." For many years, researchers used the API 20Eassay device, which consists of a plastic piece containing 20 wells and pH-based substrates (Franco-Duarte et al., 2019).

Table 1. Biochemical tests and their descriptions

Test Name	Purpose / Explanation
Catalase Test	Breaks down hydrogen peroxide into water and oxygen.
Coagulase Test	Indicates the plasma's clotting ability. Bacteria produce the coagulase enzyme, which causes blood plasma to clot, resulting in a positive (+) reaction.
Oxidase Test	Indicates the presence of the cytochrome oxidase enzyme.
Indole Test	Shows the breakdown of tryptophan into indole. E. coli usually gives a positive (+) result.
Sulfur Test	Determines H_2S production. Species such as Salmonella give positive (+) results.
Urease Test	Converts urea to ammonia. Proteus species usually give a positive (+) test result.
Triple Sugar Iron (TSI) Test	Simultaneously demonstrates the fermentation of glucose, lactose, and sucrose, as well as the production of H_2S.
Nitrate Test	Tests the reduction of nitrate to nitrite. Some bacteria give a positive (+) result.
Starch Hydrolysis Test	Indicates the presence of the amylase enzyme. Bacteria that can break down starch give a positive (+) test result.
Carbohydrate Fermentation Test	Demonstrates the ability to ferment certain sugars. Acid and gas formation occurs.
Methyl Red (MR) Test	Identifies the bacteria that carry out mixed acid fermentation. E. coli usually gives a positive (+) result.
Voges–Proskauer (VP) Test	Indicates acetoin production. Enterobacter and Klebsiella usually give a positive (+) result.
Citrate Utilization Test	Identifies bacteria that can utilize citrate as a carbon source.
Bile Esculin Agar Test	Demonstrates the ability to hydrolyze esculin. Enterococcus usually gives a positive (+) test result.
API	Provides rapid and comprehensive identification through the combination of various biochemical tests.

2.4. Identification Methods Using Chromogenic Media

In culture-based methods, the primary goal in identifying microorganisms is to obtain pure cultures. Pure cultures containing a single type of microorganism can be obtained by methods different from enrichment cultures. However, culture-based identification alone is incomplete; because disruptions in the enrichment process can constitute a significant limitation in culture-based biodiversity studies (Franco-Duarte et al., 2019). Although traditional biochemical tests are widely used in the identification of microorganisms, they lead to high labor costs and excessive consumption of reagents and culture media. In contrast, miniaturized biochemical methods make the process more practical by using dried reagents or chromogenic media (Aras, 2011). Chromogenic methods work by utilizing the specific enzymatic activity of microorganisms (Torlak, 2011). Small amounts of samples are cultured in suitable liquid or agar media. Although these substrates are initially colorless or do not exhibit fluorescent properties, they undergo hydrolysis and structural changes under the influence of enzymes specific to the bacteria being studied. As a result of this process, colored or fluorescent markers are released, and the presence of bacteria in the sample can be determined phenotypically. This approach allows for the visual monitoring of phenotypic identifications performed using chromogenic substrates in culture media. A schematic representation of the substrate-based identification process is presented in Figure 1 (Váradi et al., 2017).

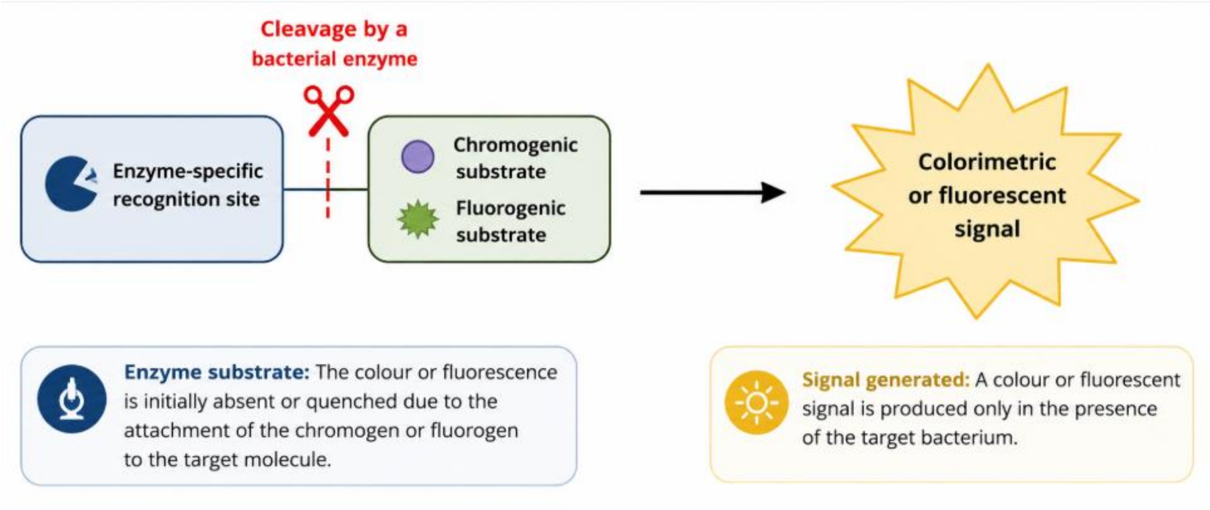

Figure 1. Schematic representation of phenotypic bacterial identification using chromogenic substrates in culture medium (Váradi et al., 2017)

3. Transition from Classical to Modern Methods

The phenotypic characteristics of microorganisms vary depending on their growth conditions. Heat, pH, nutrient requirements, oxidation-reduction potential, environmental and chemical stresses, and toxins are examples of these conditions. In contrast, the genotypic characteristics of bacteria and cells are quite stable; the natural mutation rate in bacterial cultures is approximately one in a hundred million. Recent developments have enabled the use of genetic tests in diagnostic microbiology as both identification and confirmatory tests (Aras, 2011).

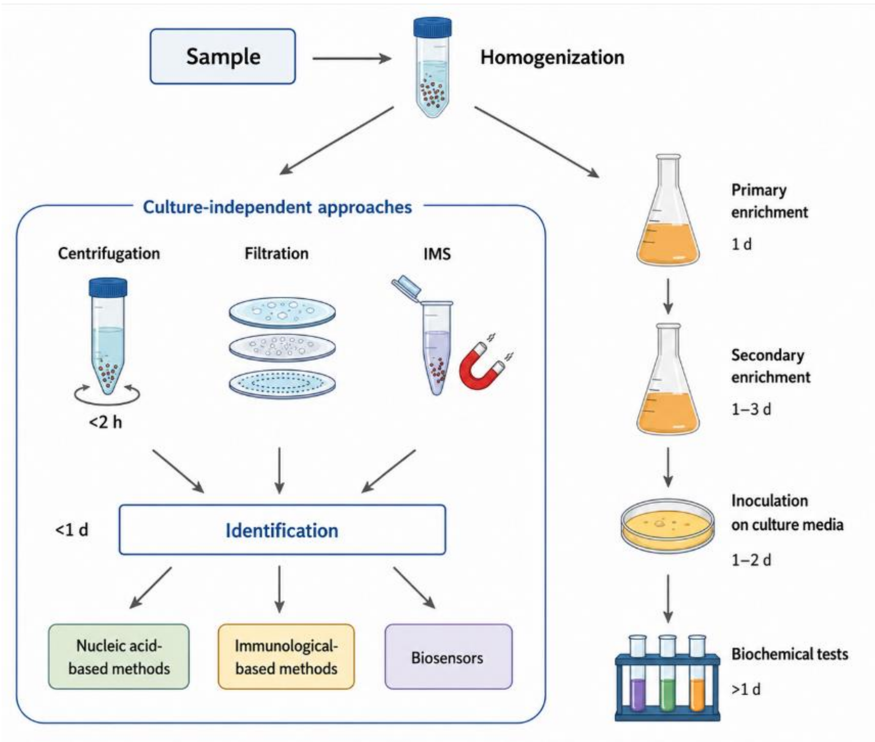

Figure 2. Comparison of culture-independent detection methods with traditional culture-based detection methods, including pretreatment techniques such as centrifugation, filtration, and immunomagnetic separation (IMS) (Wang & Salazar, 2016).

Characterization of bacterial isolates is critically important for identification, establishing relationships between isolates, and understanding phenotypic behavior. Although cultural and molecular methods have long been used for this purpose, genomic analyses are increasingly gaining prominence today. Genomic approaches offer a significant advantage in the identification and subtyping of isolates but have more limited reliability in predicting phenotype (Gill, 2017).

While steps such as pre-enrichment and selective enrichment are commonly applied in classical culture-based methods, the long analysis time has increased interest in faster pre-processing techniques. In this context, physical separation methods, including centrifugation, filtration, and immunomagnetic separation, are widely used to concentrate target microorganisms, especially in culture-independent detection approaches (Figure 2).

For the most accurate identification, classification, and systematics of microorganisms, it is extremely important to select appropriate techniques and thoroughly understand their mechanisms of action (Table 2).

Table 2. Chromogenic media, microscopy, biochemical and molecular techniques used in microorganism identification. (Franco-Duarte et al., 2019)

Chromogenic Culture Media	Biochemical Techniques	Molecular Techniques
Traditional Culture media	Traditional methods Culture medium Wickernham card API BBL Crystal Vitek Biolog System – Omnilog Mass Spectrometry GC LC MALDI-TOF Spectrometry FTIR Raman Spectroscopy Electrokinetic separation Others	PCR Real-time qPCR RAPD-PCR RFLP PFGE Ribotyping WGS MALDI-TOF MS

4. Modern Methods

4.1. Culture-Independent Approaches and Molecular Transformation

Culture-independent methods enable the identification of specific microorganisms in mixed microbial populations. They are also effective in identifying microorganisms that cannot be cultured or are in a viable but nonculturable state. In this context, microscopic techniques are among the powerful tools for identifying these organisms through the visualization of characteristic structures. Various modern identification methods and identifications of some foodborne microorganisms, bacteria, viruses, and fungal species are given in Table 3. The use of genetics as a tool in bacterial identification was a significant turning point with the development of PCR in 1985. Following this development, DNA sequencing, 16S rRNA sequencing, hybridization, and other culture-dependent and culture-independent approaches began to be applied. Thus, speed, accuracy, and specificity in bacterial identification have increased significantly (Franco-Duarte et al., 2019).

Table 3. Methods for detecting foodborne pathogens (Aladhadh, 2023)

Detection Approach	**Typical Methods**	**Target Microorganisms**	**Basic Principle**
Culture-Based Methods	Conventional culturing, selective and differential media	Bacteria, fungi, viruses	Growth of target microorganisms on suitable culture media under controlled conditions
Immunological Methods	ELISA, Lateral Flow Devices (LFD)	Bacteria, fungi, viruses	Detection based on antigen–antibody interactions
DNA-Based Molecular Methods	Conventional PCR, Nested PCR, Multiplex PCR, Touchdown PCR	Bacteria, fungi, viruses	Amplification of specific DNA regions using target-specific primers
Viability Molecular Methods	Viability PCR (vPCR), Viability qPCR (vqPCR)	Mainly bacteria	Selective detection of viable cells by suppressing amplification of DNA from dead cells
RNA-Based Molecular Methods	RT-PCR, RT-qPCR	Bacteria, fungi, viruses	Detection and quantification of RNA transcripts associated with viable microorganisms

4.2. Molecular Methods

Previously, the identification and characterization of bacterial species were largely carried out using phenotypic and biochemical methods based on pre-isolation and culture. While these methods retain their place in certain environments, molecular-based techniques have provided unprecedented information in bacterial identification and typing (Franco-Duarte et al., 2019). Different approaches are used in the detection and identification of foodborne pathogens. These methods include culture-based techniques, immunological assays, and nucleic acid-based methods (e.g., PCR and NGS) (Aladhadh, 2023).

4.2.1. Genomic Methods

Genomic technologies are considered attractive in terms of culture-independent identification because they allow the parallel detection of multiple genes or transcription products. Franco-Duarte et al. (2019) state that, in principle, the complete genome of multiple target organisms can be validated in complex DNA mixtures with whole genome sequencing (WGS) when sufficiently long reads are used. However, researchers emphasize that these rapidly advancing technologies are still insufficient to overcome two fundamental limitations: achieving high sensitivity and reliably determining viability.

4.2.2. PCR and its Variants

PCR is one of the oldest and most widely used molecular methods for identifying microorganisms. In this method, a specific genomic region that is conserved among organisms but may differ at the species or strain level is amplified by PCR, and the resulting sequences are compared with reference databases for identification. While the 16S rRNA gene is most frequently targeted in the analysis of bacterial communities, the 18S rRNA gene and internally transcribed intermediate (ITS) sequences are commonly used in the profiling of eukaryotic microorganisms (National Academies of Sciences, Engineering, and Medicine, 2018). Rapid and highly sensitive molecular techniques based on nucleic acid amplification, including PCR and its derivatives such as Reverse Transcription-Polymerase Chain Reaction (RT-PCR) and Quantitative PCR (qPCR), are widely used for the detection of pathogenic microorganisms. Amplification of genetic material using primers specific to the target microorganism yields results in a shorter time compared to classical culture methods. PCR-based methods offer advantages such as high sensitivity, specificity, reproducibility, and versatility. However, classical DNA-based PCR methods do not always demonstrate the viability of the microorganism (Aladhadh, 2023).

4.2.3. Real-Time PCR (qPCR)

qPCR enables the quantitative determination of the target pathogen load through fluorescent probes or dyes. This method plays a significant role in the rapid assessment of contamination levels, especially in food samples (Aladhadh, 2023). Due to its high sensitivity and specificity, qPCR is widely used in the detection of pathogens such as viruses, bacteria, and some fungal species. Especially in the diagnosis of infectious diseases, qPCR has become one of the routinely preferred molecular methods in clinical laboratories thanks to its ability to provide rapid and reliable results (Günel & Aydınlı, 2009).

4.2.4. Next Generation Sequencing and Whole Genome Sequencing

NGS technologies have brought about a significant transformation in the field of transcriptomics and have enabled the comprehensive examination of the transcriptome, which includes all RNA molecules expressed in an organism or a specific cell population. Offering high-throughput and relatively cost-effective analysis capabilities, NGS platforms are widely used in the profiling and analysis of RNA molecules and contribute to the detailed evaluation of gene expression (Satam et al., 2023).

NGS technologies, when used in conjunction with bioinformatics tools, are utilized not only in transcriptome analyses but also in WGS applications, which allow for the examination of the entire genome of a single isolate, and in metagenomic studies, which enable the evaluation of microbial communities in complex samples. These methods provide high-resolution data, allowing for more comprehensive characterization of microorganisms, particularly in epidemic tracking, phylogenetic analysis, and food safety applications (Aladhadh, 2023).

4.3. Mass Spectrometry-Based Methods

Mass spectrometry-based methods have gained significant importance in modern microbiology. These techniques stand out with advantages such as rapid results, low analysis time, coverage of a wide range of microorganisms, and the ability to generate molecular fingerprints (Franco-Duarte et al., 2019). Separation-based mass spectrometry (MS) techniques combine the advantages of chromatographic separation with mass analysis. In these methods, sample components are first separated in a chromatographic system to reduce sample complexity and then analyzed using MS. Different distributions between mobile and stationary phases, depending on the solubility, polarity, and volatility properties of the substances, enable efficient separation of analytes. Furthermore, the evaluation of characteristic patterns of parent and daughter ions with advanced MS detectors increases the specificity of the analysis while maintaining high sensitivity (Kiseleva et al., 2022).

4.3.1. Gas Chromatography-Mass Spectrometry (GC-MS)

GC-MS is an analytical technique in which compounds are separated according to their volatility properties, and the gas phase is used as the mobile phase. Due to its high separation capacity, sensitivity, and selectivity, it is widely preferred in metabolomic studies. Furthermore, its ability to provide reproducible molecular fragmentation patterns contributes to the reliable identification of metabolites. However, GC-MS applications are generally limited to volatile compounds or compounds that can be volatilized by derivatization processes, and it yields effective results, especially in the analysis of low molecular weight metabolites (Kiseleva et al., 2022). This method is widely used, particularly in the analysis of non-polar compounds and lipid-structured molecules and also allows for the classification of microorganisms through the evaluation of their lipid profiles. Indeed, Curie point pyrolysis-MS (Py-GC-MS) has been successfully applied in separating Gram-positive and Gram-negative bacteria and has been evaluated as an effective tool in bacterial characterization (Basile et al., 1995).

4.3.2. LC-MS Liquid Chromatography

LC-MS is a modern method that offers faster, more sensitive, and comprehensive identification by analyzing the chemical and metabolic components of microorganisms in detail. It provides high sensitivity, especially in metabolomic evaluations (Franco-Duarte et al., 2019). Liquid chromatography-mass spectrometry (LC-MS) is a powerful analytical technique that uses liquids as the mobile phase and separates analytes according to their solubility and affinity to the stationary phase. Mass spectrometric analysis performed after chromatographic separation allows for the sensitive and selective determination of metabolites found in complex biological samples. LC-MS, widely used especially in metabolomics studies, is considered a universal platform that allows the analysis of numerous metabolites found in biological samples such as plasma and serum (Kiseleva et al., 2022).

It stands out with its advantages of being able to perform a wider range of compound analyses, requiring less sample preparation, being less costly, and providing more sensitive identification compared to GC-MS (Franco-Duarte et al., 2019). The characteristics of these two techniques are given in Table 4.

Table 4. Main characteristics of GC-MS and LC-MS techniques (Kiseleva et al., 2022)

Technique	**Major Strengths**	**Major Limitations**	**Major Detectable Compounds**
GC-MS	Efficient and reproducible chromatography separation; Comprehensive mass spectral libraries	Labor-intensive, time-consuming and varying sample preparation procedure; Complicated identification of unknown compounds	Volatile and thermo-stable compounds; Carbohydrates; Esters; Sterols; Steroids; Eicosanoids; Fatty acids; Amino acids; Organic acids
LC-MS	Broad range of compounds (including polar, bulky, and thermo-labile metabolites) can be analyzed without derivatization; High throughput	Possibility of ion aberrations resulting from a sample matrix; Lack of spectral libraries for identification of metabolites	Nucleotides and nucleosides; Lipids; Non-volatile and thermo-labile compounds

4.3.3. Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry

MALDI-TOF MS stands out as one of the fastest and most widely used modern methods for bacterial identification today. It is based on the principle of mixing and crystallizing the sample with a matrix, an energy-absorbing organic compound. During the analysis, the matrix, excited by a laser beam, causes the ionization of analyte molecules, mostly resulting in the formation of single-protonated ions. The resulting ions are then separated and analyzed according to their mass-to-charge (m/z) ratios. MALDI-TOF MS is the most used system in microbiological applications, where m/z ratios are determined by measuring the time it takes for ions to traverse the flight tube. In addition, ion mirrors found in some TOF analyzers correct for energy differences of ions, increasing measurement accuracy and resolution (Singhal et al., 2015).

In practical applications, ribosomal proteins constitute most bacterial molecules obtained with MALDI-TOF MS. The characteristic masses of proteins specific to certain microorganisms enable the formation of spectra called peptide mass fingerprints (PMFs). An example of PMFs from various species is given in Figure 3. These obtained spectra can be compared with existing databases, allowing for the identification of microorganisms at the genus and species level through automated software (Váradi et al., 2017). Therefore, MALDI-TOF MS is widely used in bacterial identification due to its rapid results, high accuracy, and easy integration into routine laboratory practices (Franco-Duarte et al., 2019). It is also important for ensuring water and food safety and quality by rapidly identifying pathogenic species. It has been shown to be useful for the early detection of bacterial hazards that can contaminate drinking water. Donohue et al. (2007) reported that the method is effective in environmental monitoring by quickly and accurately identifying Aeromonas species, which are among waterborne pathogens, using their m/z signature.

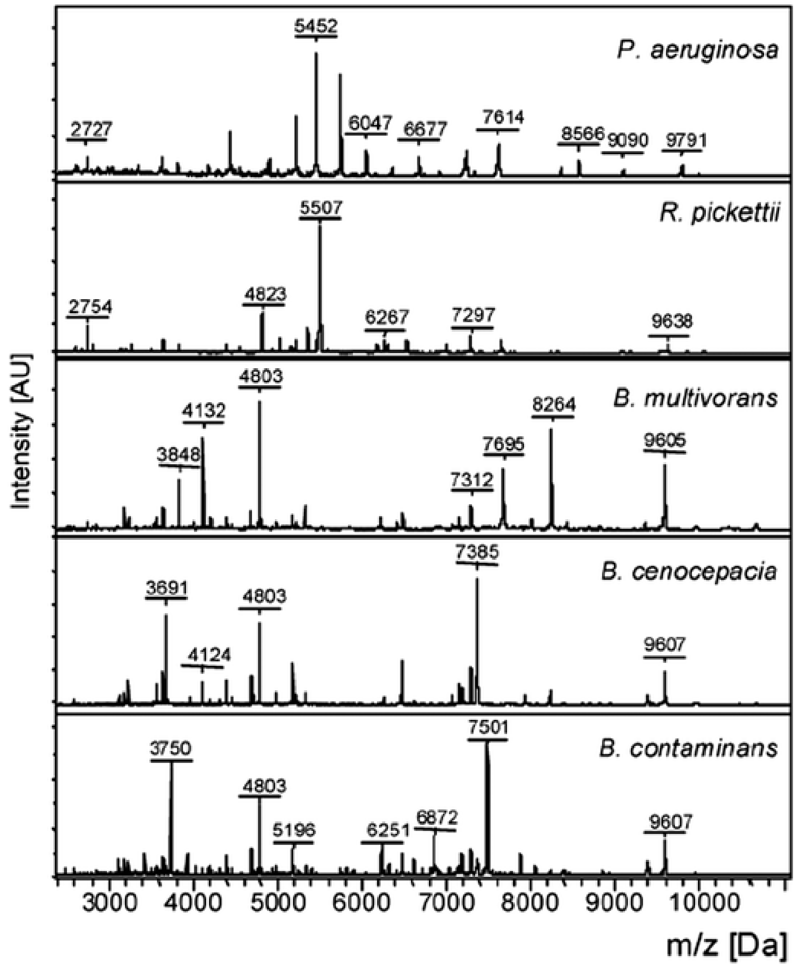

Figure 3. Intact cell MALDI-TOF MS spectra of *Pseudomonas aeruginosa, Ralstonia pickettii, Burkholderia multivorans, Burkholderia cenocepacia,* and *Burkholderia* contaminants

4.4. Spectroscopic Methods

Liquids, cells, or tissues can be examined to determine metabolic fingerprints, and theoretically, any sample can be analyzed using spectroscopy methods. These techniques are of significant value in terms of identifying microorganisms (Franco-Duarte et al., 2019).

4.4.1. Fourier transform infrared spectroscopy (FTIR)

FTIR is a rapid and low-cost analytical method that provides information about the basic molecular structures of microorganisms. Its ability to work with very small sample sizes and its short analysis time offer advantages in microbiological applications. FTIR can be used in determining bacterial composition, examining cellular components, taxonomic classification, microbial load determination, process control, and microbiological quality control studies. However, the performance of the method can be affected by the presence of water in the medium, and overlapping may occur in some spectral regions. Since FTIR only provides information about chemical bonds, it is not suitable for the direct detection of elements or some diatomic molecules. Furthermore, the use of pure culture is necessary to obtain reliable results, and factors such as medium composition, incubation time, and incubation temperature can cause variations in spectral profiles (Kılıç & Karahan, 2010). Franco-Duarte et al. (2019) state that FTIR allows for economical biochemical analysis of cells, tissues, and model organisms thanks to its non-invasive nature and ease of application. Furthermore, the advantages of this technique include the ability to analyze multiple compounds simultaneously, the absence of cell lysis, the avoidance of toxic compounds, and the possibility of real-time process monitoring.

4.4.2. Raman

Raman spectroscopy, a vibrational spectroscopy technique that elucidates the chemical structure of molecules, is based on measuring the light beams that are emitted at a specific angle from a sample excited by a powerful laser source (visible or near-infrared). While a large portion of the light interacting with matter undergoes elastic (Rayleigh) scattering, conserving its energy, the crucial part that provides distinctive information about the molecular structure is inelastic (Raman) scattering, characterized by the energy transfer of photons. The resulting vibrational spectrum is considered a unique "molecular fingerprint" of the molecule in question (Akçe & Kadıoğlu, 2020). Franco-Duarte et al. (2019) emphasize that this method provides complementary information to traditional spectroscopic techniques and allows for the differentiation of microorganisms based on their biochemical composition. Furthermore, it is stated that Raman vibrational spectroscopy is quite useful in identifying subtle differences between the same species.

4.5. Immunological Methods

Immunological methods are based on antigen-antibody interactions specific to microorganisms. These methods utilize polyclonal, monoclonal, or recombinant antibodies to enable rapid and specific detection of pathogens. Latex agglutination tests, manual and automated ELISA (Enzyme-Linked Immunosorbent Assay) methods, lateral flow immunochromatography (lateral flow immunoassay) methods, and immunomagnetic separation (IMS) technology are commonly used immunological methods for bacterial identification (Aras, 2011).

4.6. Advanced Imaging Microscopy Techniques

The microscope is a fundamental tool in the identification of microorganisms found in natural samples. Microscopic images enable the analysis of the shape of biological structures, the tracking of their movements, and their classification. Microscope-based observations are still widely used today to determine morphological differences. However, identifications made solely through microscopy have several limitations: observing small cells is difficult; there are significant size differences among prokaryotes; some cells may be missed because they are close to the resolution limit of the optical microscope; and the abundance of particulate matter or large cells in natural samples can make observation difficult. In addition, separating living cells from dead cells or inert substances is not always easy, and microscopy does not reveal phylogenetic diversity. Beyond these limitations, modern microscopic methods have been developed that offer powerful tools in the identification of microorganisms. These include transmission electron microscopy (TEM), scanning electron microscopy (SEM), confocal laser scanning microscopy (CLSM), and atomic force microscopy (AFM/ATM) (Franco-Duarte et al., 2019). Modern microscopic techniques are often used in conjunction with fluorescent dyes. Since these dyes are specific to nucleic acids, they do not react with inert materials and make visualization more specific and easier. Therefore, they are widely applied in the examination of microorganisms obtained from complex natural environments such as soil and water samples.

The methods discussed here, whether traditional culture-based techniques or modern approaches such as immunological, molecular, or MS, have their own advantages as well as operational and cost limitations (disadvantages). To clarify which method should be preferred in which situations, considering parameters such as speed, cost, sensitivity, and laboratory infrastructure, it is necessary to evaluate the pros and cons of all these basic microbial detection strategies. A general comparison matrix is presented in Table 5.

Table 5. Advantages and disadvantages of detection methods (Singhal et al., 2015)

Detection Method	Advantages	Disadvantages
Conventional methods (culture-based isolation and identification using microbiological media and biochemical tests)	• Sensitive • Cost-effective • Widely accepted as reference methods	• Labor-intensive and time-consuming • May require 24–48 hours or longer to obtain results
Immunological methods	• Faster than conventional methods • Capable of detecting contaminated organisms and their toxins	• Less specific, sensitive, and rapid than nucleic acid-based methods • Require relatively high antigen concentrations • Available for only a limited number of microorganisms
Molecular methods	• Do not necessarily require routine culturing of samples • Highly specific, sensitive, rapid, and accurate • Reduce the risk of contamination during analysis • Enable simultaneous detection of multiple pathogens	• Require high-performance thermal cyclers • Depend on trained laboratory personnel for implementation and interpretation
DNA sequencing	• 16S rRNA and 18S rRNA gene sequencing are considered gold-standard approaches for microbial identification • Capable of identifying fastidious and non-culturable microorganisms	• Require trained personnel and advanced bioinformatics/software infrastructure • Relatively expensive • Not always suitable for routine clinical or food microbiology applications
MALDI-TOF MS	• Rapid and accurate • Lower per-sample cost compared with many molecular and immunological methods • Minimal sample preparation requirements	• High initial instrument acquisition cost • Database quality and coverage may affect identification accuracy

5. Conclusions

This review examines the evolution of bacterial identification in food microbiology from classical methods to modern approaches. In conclusion, bacterial identification methods in food microbiology have undergone a significant transformation, moving from classical culture and microscopy-based approaches to molecular and genomic technologies. Culture, microscopy, and biochemical tests, widely used from the past to the present, maintain their importance due to their ability to isolate live microorganisms, their relatively low cost, and their suitability for routine laboratory applications. However, these methods have limitations such as being time-consuming, the inability to culture some microorganisms, and the susceptibility of phenotypic characteristics to environmental conditions. In contrast, PCR-based methods, real-time PCR, sequencing technologies, and NGS approaches have opened a new era in bacterial identification thanks to their high sensitivity and specificity, rapid results, and the ability to detect even microorganisms that are difficult to culture. Metagenomic approaches contribute to a more comprehensive understanding of the microbial diversity and genetic characteristics of pathogens in food samples.

However, no single method currently in use possesses the ideal characteristics to meet all expectations. Each method has its own advantages and limitations, and the selection of the appropriate method should be made considering many factors such as the purpose of the analysis, sample type, required sensitivity and specificity level, cost, time, and laboratory infrastructure. Therefore, it would be more accurate to consider classical and modern methods not as alternatives to each other, but as complementary approaches. Supporting culture-based methods with molecular techniques will enable both the verification of living agents and the acquisition of more reliable results.

In the future, further improving detection limits, shortening analysis times, and developing integrated systems incorporating different technologies will continue to be among the fundamental goals of food microbiology. Genomic technologies and advancements in this field will enable not only a better understanding of bacteria but also the tracking of pathogens throughout the food chain, the identification of the source of outbreaks, and the more effective management of risks. In conclusion, the correct and conscious use of technological advancements in bacterial identification is of great importance in preventing foodborne illnesses, detecting outbreaks early, and protecting public health. These developments will make significant contributions to the creation of safer food production systems in the future and to strengthening food security on a global scale.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

References

Akçe, M. A., & Kadıoğlu, Y. K. (2020). Raman spektroskopisinin ilkeleri ve mineral tanımlamalarında kullanılması. *Nevşehir Bilim ve Teknoloji Dergisi*, *9*(2), 99–115. https://doi.org/10.17100/nevbiltek.778678

Aktepe, Y., & Çakır, İ. (2023). Gıda mikrobiyolojisinde metagenomik yaklaşımlar. *Gıda*, *48*(6), 1230–1243. https://doi.org/10.15237/gida.GD23101

Aladhadh, M. (2023). A review of modern methods for the detection of foodborne pathogens. *Microorganisms*, *11*(5), 1111. https://doi.org/10.3390/microorganisms11051111

Aras, Z. (2011). *Mikrobiyolojide kullanılan hızlı tanı yöntemleri*. *Türk Hijyen ve Deneysel Biyoloji Dergisi*, *68*(2), 97–104. https://doi.org/10.5505/TurkHijyen.2011.96530

Arbefeville, S. S., Timbrook, T. T., & Garner, C. D. (2024). Evolving strategies in microbe identification—a comprehensive review of biochemical, MALDI-TOF MS and molecular testing methods. *Journal of Antimicrobial Chemotherapy*, *79*(Suppl. 1), i2–i8. https://doi.org/10.1093/jac/dkae275

Basile, F., Voorhees, K. J., & Hadfield, T. L. (1995). Microorganism gram-type differentiation based on pyrolysis-mass spectrometry of bacterial fatty acid methyl ester extracts. *Applied and Environmental Microbiology*, *61*(4), 1534–1539. https://doi.org/10.1128/AEM.61.4.1534-1539.1995

Beveridge, T. J. (2001). Use of the Gram stain in microbiology. *Biotechnic & Histochemistry, 76*(3), 111–118. https://doi.org/10.1080/BIH.76.3.111.118

Donohue, M. J., Best, J. M., Smallwood, A. W., Kostich, M., Rodgers, M., & Shoemaker, J. A. (2007). Differentiation of *Aeromonas* isolated from drinking water distribution systems using matrix-assisted laser desorption/ionization-mass spectrometry. *Analytical Chemistry, 79*(5), 1939–1946. https://doi.org/10.1021/ac0611420

Dwivedi, H. P., Mills, J. C., & Devulder, G. (2014). Enrichment. In C. A. Batt & M. L. Tortorello (Eds.), *Encyclopedia of Food Microbiology* (2nd ed., pp. 637–643). Academic Press. https://doi.org/10.1016/B978-0-12-384730-0.00421-3

Franco-Duarte, R., Černáková, L., Kadam, S., Kaushik, K. S., Salehi, B., Bevilacqua, A., Corbo, M. R., Antolak, H., Dybka-Stępień, K., Leszczewicz, M., Tintino, S. R., de Souza, V. C. A., Sharifi-Rad, J., Coutinho, H. D. M., Martins, N., & Rodrigues, C. F. (2019). Advances in chemical and biological methods to identify microorganisms—From past to present. *Microorganisms, 7*(5), Article 130. https://doi.org/10.3390/microorganisms7050130

Gill, A. (2017). The importance of bacterial culture to food microbiology in the age of genomics. *Frontiers in Microbiology, 8*, Article 777. https://doi.org/10.3389/fmicb.2017.00777

Günel, T., & Aydınlı, K. (2009). Real-time PCR and applications area. *Turkish Journal of Scientific Reviews, 2*(2), 43–45. https://izlik.org/JA88SF26CH

Kılıç, G. B., & Karahan, A. G. (2010). Fourier dönüşümlü kızılötesi (FTIR) spektroskopisi ve laktik asit bakterilerinin tanısında kullanılması. *Gıda, 35*(6), 445–452. https://izlik.org/JA47PD83ZY

Kiseleva, O., Kurbatov, I., Ilgisonis, E., & Poverennaya, E. (2022). Defining blood plasma and serum metabolome by GC-MS. *Metabolites, 12*(1), Article 15. https://doi.org/10.3390/metabo12010015

National Academies of Sciences, Engineering, and Medicine. (2018). *Environmental chemicals, the human microbiome, and health risk: A research strategy*. The National Academies Press. https://doi.org/10.17226/24960

Satam, H., Joshi, K., Mangrolia, U., Waghoo, S., Zaidi, G., Rawool, S., Thakare, R. P., Banday, S., Mishra, A. K., Das, G., & Malonia, S. K. (2023). Next-generation sequencing technology: Current trends and advancements. *Biology, 12*(7), Article 997. https://doi.org/10.3390/biology12070997

Saucier, L. (2016). Microbial spoilage, quality and safety within the context of meat sustainability. *Meat Science, 120*, 78–84. https://doi.org/10.1016/j.meatsci.2016.04.027

Singhal, N., Kumar, M., Kanaujia, P. K., & Virdi, J. S. (2015). MALDI-TOF mass spectrometry: An emerging technology for microbial identification and diagnosis. *Frontiers in Microbiology, 6*, Article 791. https://doi.org/10.3389/fmicb.2015.00791

Tankeshwar, A. (2026, August 6). *Biochemical tests used to identify bacteria in the microbiology laboratory*. Microbe Online. https://microbeonline.com/overview-of-biochemical-tests-used-to-identify-bacteria-in-microbiology-laboratory/

Torlak, E. (2011). Gıda mikrobiyolojisinde *Enterobacteriaceae* üyeleri için kromojenik ve florojenik besiyerleri. *Türk Hijyen ve Deneysel Biyoloji Dergisi, 68*(1), 49–58. https://doi.org/10.5505/TurkHijyen.2011.69077

Váradi, L., Luo, J. L., Hibbs, D. E., Perry, J. D., Anderson, R. J., Orenga, S., & Groundwater, P. W. (2017). Methods for the detection and identification of pathogenic bacteria: Past, present, and future. *Chemical Society Reviews, 46*(16), 4818–4832. https://doi.org/10.1039/C6CS00693K

Wang, Y., & Salazar, J. K. (2016). Culture-independent rapid detection methods for bacterial pathogens and toxins in food matrices. *Comprehensive Reviews in Food Science and Food Safety, 15*(1), 183–205. https://doi.org/10.1111/1541-4337.12175

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 97-105.

7

Strategies for Improving the Stability of Natural Colorants

Emine Erdağ Akca[1]*, Özlem Çağındı[2], Ergun Köse[3]

Manisa Celal Bayar University, Faculty of Engineering and Natural Sciences, Department of Food Engineering, Manisa, Türkiye

**Corresponding author:* emine.erdag@cbu.edu.tr

Abstract

Color is a key quality attribute that strongly influences consumer perception and acceptance of food products. However, natural pigments are highly sensitive to environmental factors such as light, oxygen, temperature, and pH, which can cause color degradation during processing and storage. Although synthetic colorants have traditionally been preferred for their low cost and high stability, growing health and safety concerns have accelerated demand for natural alternatives. Therefore, improving the stability of natural colorants has become a major focus of food research. To enhance the stability of pigments and expand their applications in food systems, various approaches have been developed, including the optimization of processing and storage conditions, the addition of stabilizers, and encapsulation technologies. In this context, this study compiles existing strategies aimed at improving the stability of natural colorants and expanding their applications.

Keywords: Natural colorants; Microencapsulation; Color stability

1. Introduction

The color of a food product has a multifaceted function. It contains many clues about the consumer's perception of taste and freshness, influencing their purchasing and consumption decisions (Khandelwal et al., 2024; Silva et al., 2025). Therefore, maintaining color stability throughout processing, storage, and distribution is essential for ensuring consumer satisfaction and product success in the market. Although many food materials have a natural color, significant changes in that color occur due to the processing and environmental conditions (light, temperature, oxygen, pH, water activity, etc.) before consumption (Molina et al., 2023). The incorporation of various colorants into the food matrix helps maintain the visual appeal that may otherwise be lost during processing and storage, enhances sensory

[1] https://orcid.org/0000-0002-5260-9630
[2] https://orcid.org/0000-0002-6436-9208
[3] https://orcid.org/0000-0002-1893-1984

attributes, and preserves the desired appearance. However, the high cost and relatively low stability of natural colorants make synthetic alternatives economically more attractive (Dey & Nagababu, 2022).

Synthetic colorants have been extensively used for several main reasons, such as compensation of color loss, enhancement of natural color, transformation of color in colorless foods, and product identification, especially for pharmaceuticals. However, many synthetic pigments have been banned or restricted in many countries due to evidence linking them to various diseases from in vivo studies (Mota et al., 2023). Numerous studies have shown that artificial colors used for these purposes are directly linked to various pathological conditions such as cancer, food allergies, and gastrointestinal and respiratory problems. Although a causal relationship cannot be definitively proven, it has been noted that they can lead to an increase in behavioral changes and negative neurological consequences in children and as well as exacerbate symptoms of attention deficit hyperactivity disorder (ADHD) (de Oliveira et al., 2024; Fatima et al., 2025).

In response to these concerns, there has been a surge of interest in the use of natural colorants derived from plant, animal, and mineral sources. This trend is strongly driven by growing demand for clean-label products, perceived health benefits, and sustainability concerns. Despite their advantages, natural colorants are highly sensitive to environmental conditions such as light, oxygen, temperature, and pH, which can lead to degradation and loss of color intensity during processing and storage. Consequently, ensuring the stability of these pigments has become a major challenge for the food industry. To address this issue, various strategies have been developed, including optimization of processing conditions, incorporation of stabilizing agents, advanced packaging systems, and encapsulation technologies, all of which aim to preserve pigment integrity and enhance their applicability in food systems (Zhang et al., 2024; Wijesekara & Xu, 2024).

2. Natural Colorants: Classification and Challenges

Natural colorants could be isolated from mineral ore or from plant/animal sources. Animal-based natural colors are generally known as quinonoid, while mineral ore-based colors are inorganic (metallic). However, plant-based dyes are very diverse and sustainable, including indigoids, terpenoids, and phenolics. Natural food colorants offer several advantages, including low toxicity, biodegradability, sustainability, and renewability. In addition to representing a wide spectrum of color classes, they also possess functional properties that may contribute to the overall quality and potential health benefits of food systems (Jabar, 2023).

Natural colorants used in food systems are primarily classified into several groups based on different characteristics. It is possible to classify them according to their solubility into water-soluble (anthocyanin), lipid-soluble (carotenoid), and ethanol-soluble pigments (alcohol-soluble Monascus). In another type of classification, color pigments are separated according to their chemical structure into subgroups such as carotenoids, iridoids, indoles, and polyphenols. However, several studies about natural color pigments focus on four main color groups: anthocyanins, chlorophylls, carotenoids, and betalains. This is mainly because these four groups are commonly found in the structure of various fruits and vegetables in nature. Anthocyanins are water-soluble flavonoid compounds responsible for red to blue hues, whereas betalains provide red and yellow colors and are mainly found in specific plant sources. Chlorophylls contribute to green coloration, while carotenoids are lipid-soluble pigments associated with yellow, orange, and red tones (Wijesekara & Xu, 2024).

The application of natural colorants in food systems is limited by their low stability under processing and storage conditions. Pigments such as anthocyanins, carotenoids, and chlorophylls are highly sensitive to environmental factors, including light, temperature, pH, and oxygen, leading to degradation, color loss, and reduced shelf life. At the same time, this instability is also negatively affecting consumer acceptance. To address these limitations, various stabilization strategies have been explored, among which encapsulation has emerged as a promising approach. By entrapping pigments within suitable wall materials, encapsulation enhances their stability, enables controlled release, and improves bioavailability, although its effectiveness depends on the physicochemical properties of the pigment and the encapsulation system (Molina et al., 2023; Wijesekara & Xu, 2024).

3. Strategies to Improve Stability

There are several promising strategies to improve the stability of natural colorants and some of these techniques (with their advantages and disadvantages) are summarized in Table 1. The selection and application of the most suitable option among these depends primarily on the structure of the colorant. The effectiveness of stabilization strategies largely depends on the physicochemical properties of individual pigment classes. Optimal stability conditions of major natural colorants are shown in Table 2. Environmental control, including optimization of pH and minimization of exposure to heat, light, and oxygen, remains fundamental. Although pH optimization is recognized as an effective and safe strategy for improving the stability of natural pigments, the development of food systems containing multiple natural pigments requires careful formulation and the application of stabilization strategies, such as encapsulation or copigmentation, to preserve pigment stability and color quality. Because some color pigments remain stable in acidic environments, while others maintain their stability in alcaline conditions (Wijesekara & Xu, 2024). Together with the addition of antioxidants have been found useful for reducing oxidative degradation, although their effectiveness is highly system dependent. The system-dependent effectiveness of antioxidants in stability is well documented; while ascorbic acid can accelerate degradation of anthocyanins, epicatechin gallate and glutathione have been shown to enhance stability. Also, α-Tocopherol shows dual effects both protective and degradative (Xue et al., 2024).

Table 1. Advantages and limitations of stabilization methods used for natural colorants

Stabilization Method	Advantages	Limitations	References
Antioxidant addition	Reduces oxidative degradation	System-dependent effects	Xue et al., 2024
pH optimization	Improves pigment stability	Limited application in some foods	Xue et al., 2024
Vacuum packaging	Reduces oxygen exposure	Additional packaging cost	Yildirim et al., 2023
Spray drying	Economical and scalable	Heat-sensitive compounds may degrade	Ribeiro & Veloso, 2021
Freeze drying	High pigment retention	Expensive and time-consuming	Ribeiro & Veloso, 2021
Co-pigmentation	Enhances color intensity	Stability depends on food matrix	Xue et al., 2024

In addition to formulation and processing approaches, packaging strategies play a crucial role in enhancing the stability of natural colorants throughout storage and distribution. Packaging systems function as a final protective barrier against external environmental factors such as oxygen, light, and moisture, all of which are key drivers of pigment degradation (Zhang et al., 2026). According to the latest findings, the oxygen permeability of packaging materials affects the color stability of foods containing natural pigments. Researchers explain that samples stored in materials with higher oxygen permeability exhibited greater oxidative degradation, leading to accelerated color fading and a loss of natural pigment intensity, while packaging with low oxygen permeability provided better visual quality. These findings demonstrate that reducing oxygen exposure through appropriate packaging selection is necessary to limit oxidative reactions and preserve the stability of natural color compounds (Jiri et al., 2025).

Table 2. Optimal stability conditions of major natural colorants

Pigment Class	Main Color	Optimal pH Range	Temperature Stability	Major Degradation Factors	Reference
Anthocyanins	Red, purple, blue	< 4.0	Sensitive above 60–70°C	High pH, heat, oxygen, light	Xue et al. (2024);
Carotenoids	Yellow, orange, red	Broad pH range (3–8)	Moderate; degradation accelerates at high temperatures	Oxidation, photooxidation, heat	Wijesekara and Xu (2024); Zhang et al. (2024)
Chlorophylls	Green	6.0–8.0	Sensitive to prolonged heating	Acidic conditions, heat, light	Wijesekara and Xu (2024)
Betalains	Red, yellow	4.0–6.0	Sensitive above 50–60°C	Heat, light, oxygen	Wijesekara and Xu (2024); Zhang et al. (2024)

4. Encapsulation Technology for Color Stability

Encapsulation is a technique developed to enhance the stability of natural colorants, which are prone to degradation under environmental stress factors such as oxygen, light, temperature, and pH changes. In this technology, color compounds enclosed within a protective matrix form a physical barrier that limits exposure to environmental conditions. As a result, pigment loss during processing and storage is reduced, and color intensity is preserved (Ijod et al., 2024). There are several advantages for the trend toward researching and applying micro/nano encapsulation; some of these advantages are shown in Figure 1. This technique also minimizes the effects of processing conditions -such as high temperatures- on naturally sensitive color compounds. Encapsulation is a technology based on converting liquid color extracts into solid powders and can reduce water activity (which in turn reduces microbial growth and lowers storage and transportation costs). In addition to this benefit, it facilitates the easier integration of color compounds into foods that would otherwise be incompatible due to pH or solubility conditions (Ribeiro & Veloso, 2021).

Nowadays, many techniques can be used under the headings of physical, chemical, and physicochemical methods to produce micro- and nano-scale capsules (Figure 2). Encapsulation approaches based on different mechanisms for entrapping and protecting bioactive natural color compounds. Physical methods, such as spray drying, freeze drying, and extrusion, primarily rely on mechanical or thermal processes to entrap pigments within protective matrices. Physicochemical methods, including coacervation, liposomes, and nanoemulsions, combine interfacial phenomena with suitable carrier materials to improve pigment stability and dispersibility. Although nanoemulsions are commonly produced using physical processes, such as high-pressure homogenization, microfluidization, or ultrasonication, they are generally classified as physicochemical methods because their formation and long-term stability depend on interfacial phenomena and the action of emulsifying agents. In contrast, chemical methods involve the formation of polymeric shells around the core material through polymerization reactions. Among these, interfacial polymerization occurs at the interface of two phases, whereas in situ polymerization involves polymer formation directly around the core material within the reaction medium. Among the different techniques, the most suitable one is selected depending on the nature of the bioactive and carrier components, considering the desired process conditions such as temperature, pH, concentration, and drying. Nevertheless, spray drying is the most widely used encapsulation technique due to its fast, simple, and relatively cost-effective production. This technique involves rapid solvent evaporation, allowing bioactive compounds to be effectively entrapped within wall materials such as maltodextrin, gum arabic, or protein-based carriers (McClements, 2012; Premjit et al., 2022; Borah et al., 2023; English et al., 2023).

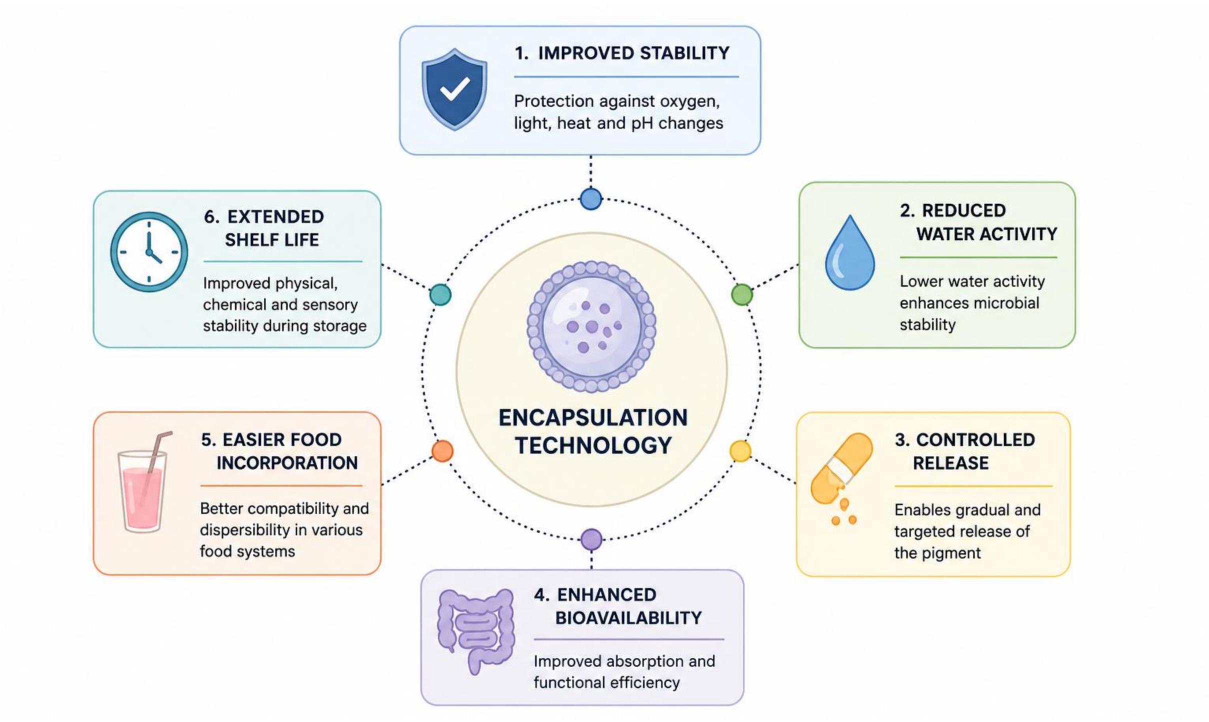

Figure 1. Main advantages of encapsulation technology (Ribeiro & Veloso, 2021)

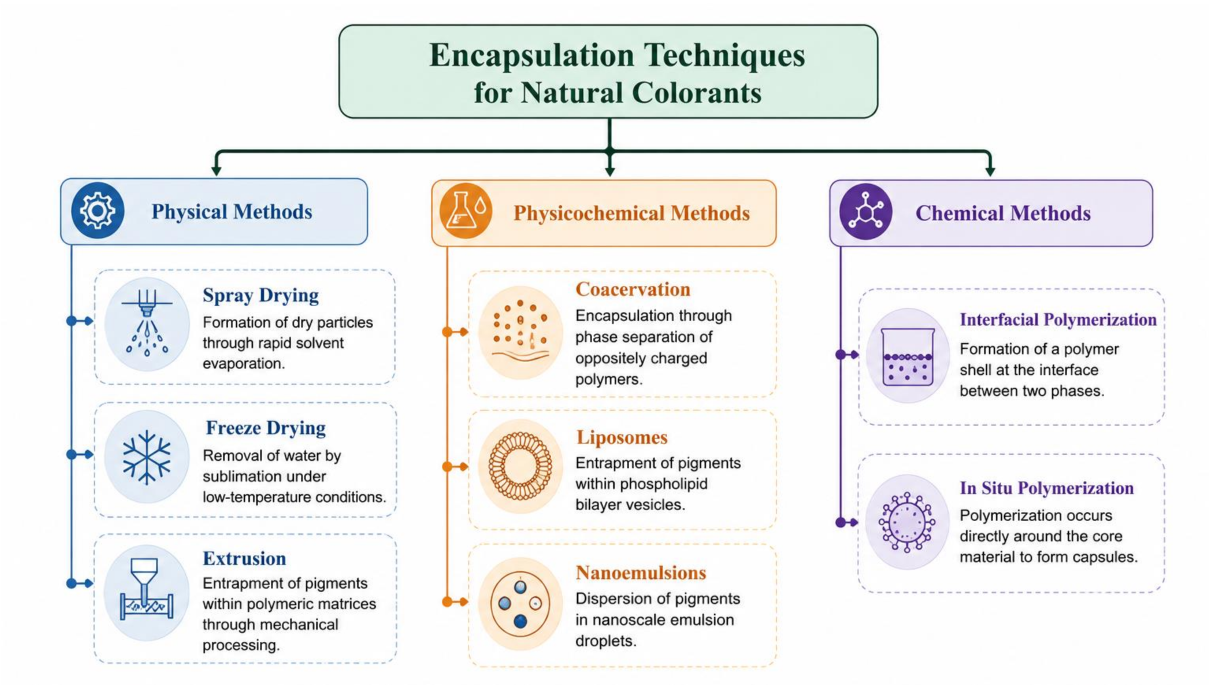

Figure 2. Classification of encapsulation techniques (Premjit et al., 2022; Borah et al., 2023).

5. Application in the Food Industry

The use of natural colorants depends largely on their stability during processing, storage, and distribution. Recent studies have shown that encapsulation is an effective method for overcoming the low bioavailability and stability issues associated with natural pigments. Across various food categories, dairy products, beverages, confectionery (jelly candies, gum), baked goods, meat substitutes, and functional foods constitute the primary application areas for natural colorants. With their purple-to-red hues and strong antioxidant capacity, anthocyanins are widely added to beverages, desserts, ice cream, and other dairy products (Magalhães et al., 2024). Similarly, carotenoids such as β-carotene and lycopene are widely used in fat-containing products, including sauces, dairy products, and baked goods, while chlorophyll derivatives are preferred for green coloring in mint-flavored products, beverages, and plant-based foods (Jurić et al., 2022; Wijesekara & Xu, 2024). Recent studies on the use of natural colorants and various stabilization techniques are summarized in Table 3.

Table 3. Studies about stabilization of natural colorants

Natural Colorant	**Food Product**	**Stabilization Technique**	**Main Findings**	**Reference**
Anthocyanins from jabuticaba peel	Yogurt	Spray drying with maltodextrin	Improved color stability and maintained anthocyanin content during refrigerated storage	Machado et al., 2023
Anthocyanins from hibiscus	Yogurt	Freeze drying + ionic gelation encapsulation	Encapsulated pigments showed lower color variation and higher stability under storage conditions	Stella et al., 2023
Anthocyanin extracts from red cabbage, chokeberry, and cornelian cherry	Bread	Microencapsulation with maltodextrin and inulin	Enhanced antioxidant activity and improved anthocyanin retention during digestion	Czubaszek et al., 2023
Red cabbage anthocyanins	-	Encapsulation against oxygen and sunlight exposure	Encapsulation significantly increased thermal and oxidative stability of anthocyanins	Sendri et al., 2023
Curcumin	Smart food packaging films	Sodium alginate–egg white protein film incorporation	Improved pH sensitivity and enhanced curcumin stability in active packaging systems	Li et al., 2024
Natural pigments (red beet, paprika oleoresin, cacao pigments)	Plant-based meat analogs	Pigment combination optimization	Improved cooked meat-like appearance and color stability	Ryu et al., 2023
Betalain-rich beetroot extract	Betalain waste extract powder	Freeze-drying microencapsulation with gum arabic and maltodextrin	Improved stability and antioxidant retention of betalains	Mkhari et al., 2023

6. Conclusions

Natural colorants have attracted considerable attention as promising alternatives to synthetic dyes due to their safety, sustainability, and additional bioactive properties. However, their widespread application in food systems remains challenging because of their susceptibility to environmental factors such as light, oxygen, temperature, and pH variations. These conditions can accelerate pigment degradation, resulting in color loss, reduced functionality, and limited shelf life. Therefore, improving the stability of natural pigments has become a key research priority for both academia and the food industry. Various stabilization strategies have been developed to overcome these limitations, including optimization of processing and storage conditions, incorporation of stabilizing agents, advanced packaging systems, and encapsulation technologies. However, encapsulation technology (spray drying, freeze drying, gelation, etc.) offers significant benefits in the application of these bioactive colorants with potential health effects, providing not only color stability but also controlled release and improved bioactivity. Recent studies have demonstrated the successful application of stabilized natural colorants in a wide range of products, including dairy foods, beverages, confectionery products, bakery goods, plant-based foods, and intelligent packaging systems.

Acknowledgements

This study was supported by Manisa Celal Bayar University Scientific Research Projects Coordination Unit by Project Number 2025-060.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

References

Borah, M. S., Tiwari, A., Sridhar, K., Narsaiah, K., Nayak, P. K., & Stephen Inbaraj, B. (2023). Recent trends in valorization of food industry waste and by-products: Encapsulation and in vitro release of bioactive compounds. *Foods*, *12*(20), Article 3823. https://doi.org/10.3390/foods12203823

Czubaszek, A., Czaja, A., Sokół-Łętowska, A., Kolniak-Ostek, J., & Kucharska, A. Z. (2023). Quality of bread enriched with microencapsulated anthocyanin extracts during in vitro simulated digestion. *Journal of Cereal Science*, *113*, Article 103724. https://doi.org/10.1016/j.jcs.2023.103724

de Oliveira, Z. B., Silva da Costa, D. V., da Silva dos Santos, A. C., da Silva Júnior, A. Q., de Lima Silva, A., de Santana, R. C. F., Santos, S. R. B., & da Silva, S. K. R. (2024). Synthetic colors in food: A warning for children's health. *International Journal of Environmental Research and Public Health*, *21*(6), Article 682. https://doi.org/10.3390/ijerph21060682

Dey, S., & Nagababu, B. H. (2022). Applications of food color and bio-preservatives in the food and its effect on the human health. *Food Chemistry Advances*, *1*, Article 100019. https://doi.org/10.1016/j.focha.2022.100019

English, M., Okagu, O. D., Stephens, K., Goertzen, A., & Udenigwe, C. C. (2023). Flavour encapsulation: A comparative analysis of relevant techniques, physiochemical characterisation, stability, and food applications. *Frontiers in Nutrition*, *10*, Article 1019211. https://doi.org/10.3389/fnut.2023.1019211

Fatima, S., Saifullah, M., Khalid, M., Talha, M., & Waafira, A. (2025). Protecting developing brains: Urgent need to regulate synthetic food dyes in children's diets. *Annals of Medicine and Surgery*, *87*(10), 6918–6919. https://doi.org/10.1097/MS9.0000000000003770

Ijod, G., Nawawi, N. I. M., Anwar, F., Adzahan, N. M., & Azman, E. M. (2024). Recent microencapsulation trends for enhancing the stability and functionality of anthocyanins: A review. *Food Science and Biotechnology*, *33*(12), 2673–2698. https://doi.org/10.1007/s10068-024-01603-2

Jabar, J. M. (2023). Classification of natural dyes for sustainable exploitation. In S. S. Muthu (Ed.), *Natural dyes and sustainability* (pp. 165–182). Springer.

Jiri, M., Kristina, T., Katerina, K., Martin, L., Marketa, P., & Martin, S. (2025). Effect of plastic packaging on lyophilized goulash and eggbarley with different types of meat. *Scientific Reports*, *15*(1), Article 36774. https://doi.org/10.1038/s41598-025-20705-3

Jurić, S., Jurić, M., Król-Kilińska, Ż., Vlahoviček-Kahlina, K., Vinceković, M., Dragović-Uzelac, V., & Donsì, F. (2022). Sources, stability, encapsulation and application of natural pigments in foods. *Food Reviews International*, *38*(8), 1735–1790. https://doi.org/10.1080/87559129.2020.1837862

Khandelwal, A. R., Singh, D., Singh, M., & Sharma, I. (2024). Influence of colour psychology on consumer buying behaviour. *Journal of the KR Cama Oriental Institute*, *78*, 11–20.

Li, H., Liu, M., Ju, X., Zhang, H., Xia, N., Wang, J., Wang, Z., & Rayan, A. M. (2024). Physico-chemical characteristics of pH-driven active film loading with curcumin based on the egg white protein and sodium alginate matrices. *Foods*, *13*(9), Article 1340. https://doi.org/10.3390/foods13091340

Machado, K. R. D., Tulini, F. L., Guimarães, J. D. G. L., Moraes, I. C. F., Ditchfield, C., Lima, C. G. D., Silva, V. M., & Favaro-Trindade, C. S. (2023). Production and evaluation of yogurt colored with anthocyanin-rich pigment prepared from jabuticaba (*Myrciaria cauliflora* Mart.) skin. *Processes*, *11*(2), Article 526. https://doi.org/10.3390/pr11020526

Magalhães, D., Gonçalves, R., Rodrigues, C. V., Rocha, H. R., Pintado, M., & Coelho, M. C. (2024). Natural pigments recovery from food by-products: Health benefits towards the food industry. *Foods*, *13*(14), Article 2276. https://doi.org/10.3390/foods13142276

McClements, D. J. (2012). Nanoemulsions versus microemulsions: Terminology, differences, and similarities. *Soft Matter*, *8*(6), 1719–1729. https://doi.org/10.1039/c2sm06903b

Mkhari, T., Kaseke, T., & Fawole, O. A. (2023). Encapsulation of betalain-rich extract from beetroot postharvest waste using a binary blend of gum Arabic and maltodextrin to promote a food circular bioeconomy. *Frontiers in Nutrition*, *10*, Article 1235372. https://doi.org/10.3389/fnut.2023.1235372

Molina, A. K., Corrêa, R. C., Prieto, M. A., Pereira, C., & Barros, L. (2023). Bioactive natural pigments' extraction, isolation, and stability in food applications. *Molecules*, *28*(3), Article 1200. https://doi.org/10.3390/molecules28031200

Mota, I. G. C., Neves, R. A. M. D., Nascimento, S. S. D. C., Maciel, B. L. L., Morais, A. H. D. A., & Passos, T. S. (2023). Artificial dyes: Health risks and the need for revision of international regulations. *Food Reviews International*, *39*(3), 1578–1593. https://doi.org/10.1080/87559129.2021.1934694

Premjit, Y., Pandhi, S., Kumar, A., Rai, D. C., Duary, R. K., & Mahato, D. K. (2022). Current trends in flavor encapsulation: A comprehensive review of emerging encapsulation techniques, flavour release, and mathematical modelling. *Food Research International*, *151*, Article 110879. https://doi.org/10.1016/j.foodres.2021.110879

Ribeiro, J. S., & Veloso, C. M. (2021). Microencapsulation of natural dyes with biopolymers for application in food: A review. *Food Hydrocolloids*, *112*, Article 106374. https://doi.org/10.1016/j.foodhyd.2020.106374

Ryu, K. K., Kang, Y. K., Jeong, E. W., Baek, Y., Lee, K. Y., & Lee, H. G. (2023). Applications of various natural pigments to a plant-based meat analog. *LWT*, *174*, Article 114431. https://doi.org/10.1016/j.lwt.2023.114431

Sendri, N., Singh, S., Bhatt, S., Gupta, M., & Bhandari, P. (2023). Insight into the influence of oxygen, sunlight and temperature on the stability and color attributes of red cabbage anthocyanins and *in vitro* gastrointestinal behaviour. *Food Chemistry Advances*, *3*, Article 100359. https://doi.org/10.1016/j.focha.2023.100359

Silva, J., Lima, F. E., Souza, C., Moreira-Leite, B., & Sousa, P. (2025). The influence of food colors on emotional perception and consumer acceptance: A sensory and emotional profiling approach in gastronomy. *Foods*, *14*(22), Article 3818. https://doi.org/10.3390/foods14223818

Stella, T. R., Paraíso, C. M., dos Santos Pizzo, J., Visentainer, J. V., Dos Santos, S. S., & Madrona, G. S. (2023). Hibiscus (*Hibiscus sabdariffa* L.) extracts freeze-dried and encapsulated by ionic gelation: An approach for yogurt application. *Journal of Food Measurement and Characterization*, *17*(3), 2630–2638. https://doi.org/10.1007/s11694-023-01818-7

Wijesekara, T., & Xu, B. (2024). A critical review on the stability of natural food pigments and stabilization techniques. *Food Research International*, *179*, Article 114011. https://doi.org/10.1016/j.foodres.2024.114011

Xue, H., Zhao, J., Wang, Y., Shi, Z., Xie, K., Liao, X., & Tan, J. (2024). Factors affecting the stability of anthocyanins and strategies for improving their stability: A review. *Food Chemistry: X*, *24*, Article 101883. https://doi.org/10.1016/j.fochx.2024.101883

Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., Radusin, T., Suminska, P., Marcos, B., & Coma, V. (2018). Active packaging applications for food. *Comprehensive Reviews in Food Science and Food Safety*, *17*(1), 165–199. https://doi.org/10.1111/1541-4337.12322

Zhang, N., Ahmad, B., Xu, F., & Liu, J. (2026). Recent advances in the development of active and intelligent packaging films using fruit peel powders. *Foods*, *15*(1), Article 162. https://doi.org/10.3390/foods15010162

Zhang, Z. H., Chen, J., Huang, X., Aadil, R. M., Li, B., & Gao, X. (2024). Natural pigments in the food industry: Enhancing stability, nutritional benefits, and gut microbiome health. *Food Chemistry*, *460*, Article 140514. https://doi.org/10.1016/j.foodchem.2024.140514

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 106-113.

8

Design and Manufacturing of Biocomposite Cervical Orthoses

Kerem Yıldız[1], Rumeysa İncesu[2]*

İzmir Bakırçay University, Department of Biomedical Engineering, Graduate Education Institute, İzmir, Türkiye

Tarkan Akderya[3]

İzmir Bakırçay University, Department of Biomedical Engineering, Faculty of Engineering and Architecture, İzmir, Türkiye

**Corresponding author:* rumeysa.incesu@bakircay.edu.tr

Abstract

Weakness of the cervical musculature and the inability to maintain an upright head posture are frequently manifested clinical features in various neuromuscular and neurodegenerative disorders, including amyotrophic lateral sclerosis (ALS)/motor neuron disease, myopathy, and Parkinson's disease. Patients, particularly those with myopathies and ALS, commonly present with involuntary cervical flexion or dropped head syndrome (head ptosis) resulting from profound weakness of the neck extensor muscles. Failure to sustain a neutral anatomical posture not only engenders social isolation, but also precipitates dyspnea, severe mechanical neck pain, and visual field restriction. In cases where the underlying aetiology cannot be treated directly, external intervention via customised cervical orthoses is essential to stabilise the cervical spine, maintain horizontal gaze, prevent head drop, and alleviate chronic pain, thereby significantly enhancing patient quality of life. The biomedical sector offers many alternative cervical orthoses with different designs and mechanical properties. In general, some designs cannot provide the necessary support because they are too soft, while others significantly restrict mobility due to their excessively rigid structure. Since orthosis-prosthesis materials cannot provide the desired mechanical performance on their own when used in pure form, composite materials that offer high strength, low weight, and appropriate biomechanical properties are preferred today. By evaluating the mechanical properties of the material to be used, the appropriate production technique is determined, and the design process is shaped accordingly.

Keywords: Cervical orthosis; Biocomposite materials; Manufacturing techniques; Orthosis design

[1] https://orcid.org/0009-0006-3278-8287
[2] https://orcid.org/0000-0002-8781-2428
[3] https://orcid.org/0000-0001-6459-386X

1. Introduction

Cervical orthoses are typically employed to immobilise the neck in patients after cervical spine surgery, preventing secondary injuries by offering support and immobilisation. These orthoses are commercially available in modular designs and various sizes, with adjustable components to fit an individual's neck height, width, and condition. However, during use—especially after neck injuries or surgery—discomfort, moisture buildup, and poor ventilation can reduce patients' willingness to wear a cervical orthosis (Hsiao et al., 2024). The main goals of using cervical orthoses are to rest and support the neck and allow the muscles to relax. They are used as standard treatment in accident and emergency departments for initial immobilisation after numerous soft tissue traumas (Beavis, 1989).

Biocomposites consist of natural fibres embedded in a matrix of biodegradable or non-biodegradable polymers. Polymer matrix biocomposites include natural or bio-based polymers like poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), and polycaprolactone (PCL), as well as synthetic polymers such as thermoplastics and thermosets, combined with reinforcements like carbon fibres, glass fibres, or natural fibres. Fibres improve strength, help maintain rigidity, and guard against moisture. The aspect ratio and fibre size are vital for composite strength. While small particles can be integrated effectively, low aspect ratios may cause stress concentrations, which decrease strength compared to pure polymers. Higher aspect ratios improve mechanical properties by enabling better load transfer and increasing the strength-to-weight ratio. Biocomposites made from biopolymers and natural fibres are preferred for their cost-effectiveness, biodegradability, recyclability, and eco-friendly disposal (Pokharel et al., 2022).

Biocomposites find applications in the automotive, construction, biomedical, and packaging sectors. However, their use is generally limited to non-load-bearing and non-structural roles because of their mechanical property constraints. In the construction sector, biocomposites need high tensile and compressive strength. Natural biocomposites show decent mechanical properties, including stiffness, strength, elasticity, and Young's modulus. Their performance largely depends on factors like fibre type, orientation, microfibril angle, processing method, physical traits, and the bonding between fibre and matrix. The microfibril angle influences fibre stiffness, while natural fibres reinforce the composite and enhance these properties. Among all factors, fibre/matrix adhesion is most critical; improved adhesion facilitates more effective stress and load transfer between the fibre and matrix (Zwawi, 2021). Matrices hold fibres together and transfer applied loads to these fibres. They protect the fibres from mechanical damage and environmental influences. Matrices can be made from polymers sourced from renewable resources like vegetable oils or starches. Alternatively, synthetic, fossil-derived polymers are now more commonly used. These include pure or recycled thermoplastics like polyethylene, polypropylene, polystyrene, and polyvinyl chloride, as well as pure thermosets such as unsaturated polyesters, phenol formaldehyde, isocyanates, and epoxies (Fowler et al., 2006). Classification of biocomposite materials is given in Figure 1.

2. Cervical Orthoses

2.1. Purposes and Types of Cervical Orthoses

Cervical orthoses are designed to immobilise and support the neck. They typically wrap around the neck with fabric, flexible materials, or rigid plastic. Rigid cervical orthoses are recommended in neck trauma cases to reduce neurological disability and maintain spinal stability. Due to potential complications associated with rigid cervical orthoses, soft cervical orthoses are offered as an alternative. Rigid cervical orthoses provide superior stabilisation in terms of range of motion compared to soft cervical orthoses. However, increased orthosis rigidity can reduce user comfort and increase complications, despite more effective restriction of movement. This can negatively impact rehabilitation outcomes by reducing patient compliance with treatment and the recommended duration of orthosis use (Hsiao et al., 2024). Figure 2 illustrates the types of cervical orthoses.

A soft cervical orthosis is made of foam, fabric covering, and a strap (Barati et al., 2017). Usually, the strap is fastened at the back, but it can also be placed at the front based on the user's choice. Patients using a soft cervical orthosis might experience warmth and psychological comfort from the fabric covering (Beavis, 1989). Soft cervical orthoses cannot substantially limit cervical spine movement and, as a result, do not provide sufficient structural support (Barati et al., 2017).

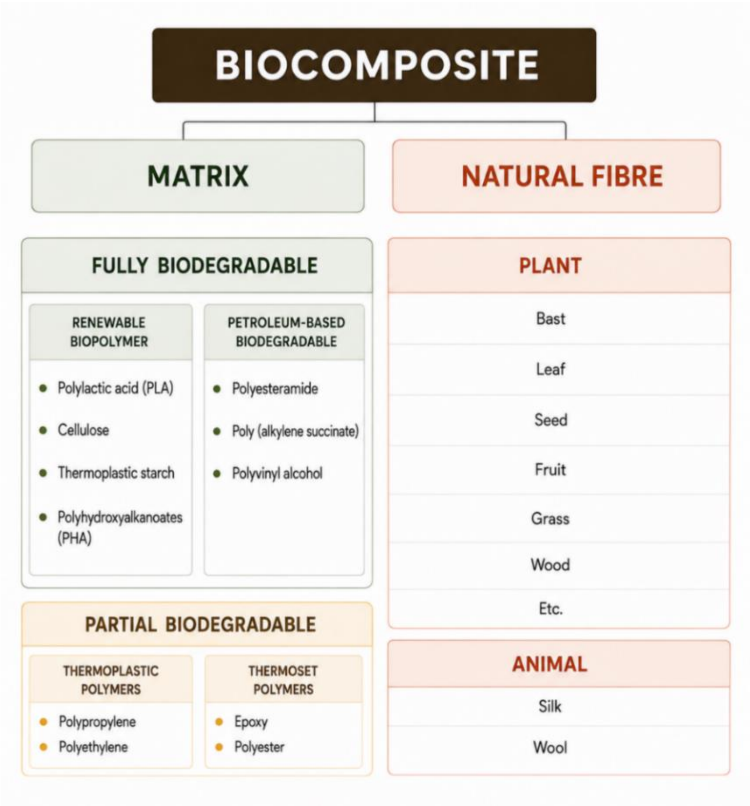

Figure 1. Classification of biocomposites based on matrix and natural fibre

Figure 2. Types of cervical orthosis

The Philadelphia collar, typically constructed from a stiff plastic plate, restricts a wider range of neck movements compared to a soft cervical orthosis (Barati et al., 2017). The collar is vertically reinforced from the chin to the manubrium and shaped to cover the area from the outer projection of the occipital bone to the top of the scapular spine at the back. It includes a front opening for tracheostomy, so the user's chin should be aligned with the centre (Ghorbani et al., 2016).

Some types of orthotics, such as halo vest orthotics, are used especially for C1 and C2 fractures. While these orthotics help stabilise fracture sites, they can cause side effects, including pin loosening, infection at the pin sites, penetration into the skull, and aesthetic issues associated with halo vest orthotics. Other orthotics, such as Minerva and Aspen orthotics, have been designed and used to address problems associated with halo vest orthotics (Karimi et al., 2016).

2.2. Materials Used in 3D-Printed Cervical Orthoses

Thermoplastic materials and photosensitive resins are the most widely used in 3D printing. Thermoplastics are mainly used in Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS), while photosensitive resins are primarily used in PolyJet technologies (Li et al., 2022). Selecting materials for 3D-printed orthoses requires evaluating biocompatibility, mechanical strength, and durability. Alternatives to PLA include polyethylene terephthalate glycol, thermoplastic polyurethane (TPU), thermoplastic elastomers, and medical-grade resins (Narayan et al., 2025). TPU filament is popular for home 3D printing due to its user-friendly nature and wide extrusion temperature range of 180–210 °C (Mwema et al., 2020).

PLA has disadvantages like low impact resistance, limited elongation at break, and higher cost compared to standard plastics. Nonetheless, blending PLA with other polymers or fillers can mitigate these issues. For example, adding natural rubber enhances the durability of PLA-based filaments, making them more suitable for 3D printing (Babu et al., 2022). Compared to Acrylonitrile Butadiene Styrene (ABS), PLA is harder, melts at a lower temperature, and requires less heat during forming. These characteristics also help save energy (Li et al., 2022).

ABS and Polyamide (PA) are the primary thermoplastics used in 3D-printed rehabilitation orthoses. ABS is a non-crystalline thermoplastic known for its high strength, toughness, and ease of processing, making it highly common in everyday applications. It is often used in FDM and SLS printing methods. PA provides excellent mechanical strength, thermal and corrosion resistance, and good airflow in models produced via SLS. It is also the main material for Multi-Jet Fusion (MJF) printing. TPU is a versatile material used in FDM, SLS, and MJF 3D printing. It offers superior resistance to abrasion and tearing, is recyclable, and naturally decomposes. Orthoses made from TPU and PLA are effective and cost-efficient (Li et al., 2022).

2.3. Cervical Orthosis Design

Before obtaining the patient's 3D neck anatomy, each camera position needs to be calibrated to a global coordinate system (Ambu et al., 2024). A 3D surface scan was captured with the 'Artec EVA' handheld scanner and Artec Studio 12 Professional software, which processes 3D surface data, once the patient's head was in the correct position (Hale et al., 2020). During the scan, the patient sits comfortably with eyes closed and chin tucked in, ensuring the ear canals are directly above the shoulders. The scan area includes the upper chest, back, full neck, and part of the head near the neck. A pre-set anatomical neck feature template with a maximum two-part matching algorithm is used to align neck features between the template and the patient (Serratosa, 2014). A Hungarian algorithm is used to find a perfect matching with the least weight after normalising the distances between each pair of features (Jonker & Volgenant, 1986). These features serve as reference points for determining the two centre lines of the orthosis's front and back sections, establishing the anatomical coordinate frame, and ensuring accurate circumferential mating/closure between the shells. The orthosis prototype is made by extending the surface of the neck model to a designated width and thickness (Hsiao et al., 2024).

The user imports a 3D scan mesh into the software and positions a basic guide shape, such as a cylinder, on the scan. The software projects this guide shape onto the 3D mesh, generating 'rays' that extend outward from the guide points along their normal directions. These normals are then flipped and oriented toward the scan mesh. When a 'ray' intersects the scan mesh, the point on the mesh is moved to the intersection point. This process produces a mesh suitable for the 3D scan, which can be easily modified. The software uses a position-based dynamic solver to find the minimum surface. This solver keeps the upper and lower mesh boundaries fixed and iteratively adjusts the other points to minimise edge lengths between neighbouring points. The initial projected mesh shifts toward this minimum surface until it deviates from the original scan (Hale et al., 2020).

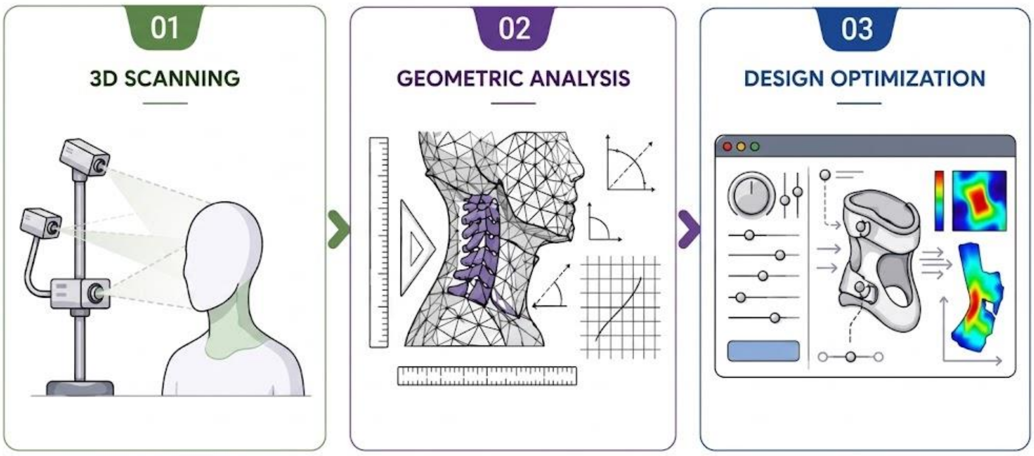

Figure 3. Stages of cervical orthosis design

The goal in orthotic design for myopathy-associated joint instability is to achieve a lightweight structure that simultaneously meets structural requirements. This is typically accomplished by creating a ventilation pattern, preferably using an automated or semi-automated technique, to reduce the risk of irritation caused by sweating and moisture buildup associated with orthosis use. Several methods can achieve this ventilation pattern. Areas lacking a pattern, which are essential for functional purposes and the placement of closure mechanisms, should also be maintained and organised (Ambu et al., 2024). Stages of cervical orthosis design are given in Figure 3.

2.4. 3D Scanning Methods

- **Photogrammetric Scanners:** Photogrammetry is a 3D scanning approach that uses photographs to create detailed three-dimensional models. It involves taking multiple images from various angles and combining them to produce an accurate 3D representation. This technique is valuable in orthotic design because precise replication of body parts is essential. Photogrammetry mitigates problems from patient movement during scanning and does not require markers on the patient (Grazioso et al., 2018).
- **Laser Scanners:** Laser technology is frequently used to scan shapes and surfaces, efficiently collecting anthropometric data and aiding in the development of custom orthotics through digital scans. However, its limited range can be a drawback, especially for larger body parts such as legs and feet (Silva et al., 2024).
- **Optical Scanners (Photogrammetry):** Optical photogrammetric systems rely on ambient illumination to capture multi-angle photographic images of the anatomical surface, mathematically triangulating these coordinates to form a 3D "point cloud" (Wells, 2019). Balancing image acquisition speed with the resolution of optical sensors and electronic hardware is essential for generating a high-quality CAD model (Del Corso et al., 2009). These systems typically provide a more cost-effective and user-friendly solution compared to active 3D scanning methods. However, because they do not emit their own structured light sources and depend largely on ambient illumination, variations in lighting and surface contrast make them more prone to scanning errors and reconstruction artefacts (Silva et al., 2024).

- **Structured Light Scanners:** This technology precisely replicates complex body shapes, capturing intricate features, surface textures, and subtle anatomical differences. This precision is essential for creating effective and comfortable orthotics. However, a major drawback is that patients must remain still during scanning to achieve accurate results (Silva et al., 2024). Since structured lighting involves capturing multiple images from various angles in a continuous sequence, small movements can lead to inaccuracies in the final model (Shamata & Thompson, 2018). Another limitation is the lengthy processing time and high computational resource requirements (Zhang & Yilmaz, 2016). Though this technology gathers highly detailed data, converting it into a usable 3D model can be slow and difficult, particularly for patient groups like children or those with specific disabilities (Silva et al., 2024).

3. Conclusion

Cervical orthoses can help patients perform their daily activities more safely and comfortably by maintaining the head in the correct position and stabilising the neck region in conditions such as neck muscle weakness, cervical trauma, cervical spine surgery, and neuromuscular diseases. Biocomposite materials can combine features such as low weight, mechanical strength, sustainability, biodegradability, and rigidity in a single material. Thanks to these features, it is a frequently preferred material for producing cervical orthoses. By combining 3D scanning, CAD-based design, and additive manufacturing with biocomposite materials, personalised cervical orthoses that adapt to the patient's anatomical features can be produced. Personalised design improves the orthosis fit in the neck region, and a geometric structure that provides ventilation can help reduce issues such as sweating, moisture accumulation, and skin irritation.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

Funding

This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Grant Number 425S480 and İzmir Bakırçay University Research Projects Coordination Office under grant number BBAP.2024.006. The authors thank TÜBİTAK and İzmir Bakırçay University Research Projects Coordination Office for their support.

References

Ambu, R., Oliveri, S. M., & Calì, M. (2024). Neck orthosis design for 3D printing with user enhanced comfort features. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *18*(8), 6055–6068. https://doi.org/10.1007/s12008-023-01507-1

Babu, R. D., Veezhinathan, M., Adithya, S. S., & Jagadeesan, N. (2022). Design and development of a 3D printable neck brace- A finite element approach. *Journal of Clinical and Diagnostic Research, 16*(9), PC10-PC15. https://doi.org/10.7860/JCDR/2022/57066.16975

Barati, K., Arazpour, M., Vameghi, R., Abdoli, A., & Farmani, F. (2017). The effect of soft and rigid cervical collars on head and neck immobilization in healthy subjects. *Asian Spine Journal*, *11*(3), 390–395. https://doi.org/10.4184/asj.2017.11.3.390

Beavis, A. (1989). Cervical orthoses. *Prosthetics and Orthotics International*, *13*(1), 6–13. https://doi.org/10.3109/03093648909079403

Del Corso, M., Abà, G., Vazquez, L., Dargaud, J., & Ehrenfest, D. M. D. (2009). Optical three-dimensional scanning acquisition of the position of osseointegrated implants: An in vitro study to determine method accuracy and operational feasibility. *Clinical Implant Dentistry and Related Research*, *11*(3), 214–221. https://doi.org/10.1111/j.1708-8208.2008.00106.x

Fowler, P. A., Hughes, J. M., & Elias, R. M. (2006). Biocomposites: Technology, environmental credentials and market forces. *Journal of the Science of Food and Agriculture*, *86*(12), 1781–1789. https://doi.org/10.1002/jsfa.2558

Ghorbani, F., Kamyab, M., Azadinia, F., & Hajiaghaei, B. (2016). Open-design collar vs. conventional philadelphia collar regarding user satisfaction and cervical range of motion in asymptomatic adults. *American Journal of Physical Medicine & Rehabilitation*, *95*(4), 291–299. https://doi.org/10.1097/PHM.0000000000000374

Grazioso, S., Selvaggio, M., & Di Gironimo, G. (2018). Design and development of a novel body scanning system for healthcare applications. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *12*(2), 611–620. https://doi.org/10.1007/s12008-017-0425-9

Hale, L., Linley, E., & Kalaskar, D. M. (2020). A digital workflow for design and fabrication of bespoke orthoses using 3D scanning and 3D printing, a patient-based case study. *Scientific Reports*, *10*(1), 7028. https://doi.org/10.1038/s41598-020-63937-1

Hsiao, Y.-C., Chen, C.-D., Wu, Y.-H., & Fang, J.-J. (2024). Anatomical-based customized cervical orthosis design in automation. *Applied Sciences*, *14*(16), 7424. https://doi.org/10.3390/app14167424

Jonker, R., & Volgenant, T. (1986). Improving the Hungarian assignment algorithm. *Operations Research Letters*, *5*(4), 171–175. https://doi.org/10.1016/0167-6377(86)90073-8

Karimi, M., Kamali, M., & Fatoye, F. (2016). Evaluation the efficiency of cervical orthoses on cervical fracture: A review of literature. *Journal of Craniovertebral Junction and Spine*, *7*(1), 13. https://doi.org/10.4103/0974-8237.176611

Li, J., Chen, S., Shang, X., Li, N., Aiyiti, W., & Gao, F. (2022). Research progress of rehabilitation orthoses based on 3D printing technology. *Advances in Materials Science and Engineering*, *2022*, 1–16. https://doi.org/10.1155/2022/5321570

Mwema, F. M., Akinlabi, E. T., & Fatoba, O. S. (2020). Visual assessment of 3D printed elements: A practical quality assessment for home-made FDM products. *Materials Today: Proceedings*, *26*, 1520–1525. https://doi.org/10.1016/j.matpr.2020.02.313

Narayan, Y. S., Prakash, K. J., Sai, M. T., Sridhar Babu, B., & Devana, S. R. (2025). Development of a 3D-printed cervical collar using biocompatible and sustainable polylactic acid. *Journal of the Mechanical Behavior of Materials*, *34*(1), 20250077. https://doi.org/10.1515/jmbm-2025-0077

Pokharel, A., Falua, K. J., Babaei-Ghazvini, A., & Acharya, B. (2022). Biobased polymer composites: A review. *Journal of Composites Science*, *6*(9), 255. https://doi.org/10.3390/jcs6090255

Serratosa, F. (2014). Fast computation of bipartite graph matching. *Pattern Recognition Letters*, *45*, 244–250. https://doi.org/10.1016/j.patrec.2014.04.015

Shamata, A., & Thompson, T. (2018). Using structured light three-dimensional surface scanning on living individuals: Key considerations and best practice for forensic medicine. *Journal of Forensic and Legal Medicine*, *55*, 58–64. https://doi.org/10.1016/j.jflm.2018.02.017

Silva, R., Silva, B., Fernandes, C., Morouço, P., Alves, N., & Veloso, A. (2024). A review on 3D scanners studies for producing customized orthoses. *Sensors*, *24*(5), 1373. https://doi.org/10.3390/s24051373

Wells, J. C. (2019). Three-dimensional optical scanning for clinical body shape assessment comes of age. *The American Journal of Clinical Nutrition*, *110*(6), 1272–1274. https://doi.org/10.1093/ajcn/nqz258

Zhang, Y., & Yilmaz, A. (2016). Structured light based 3D scanning for specular surface by the combination of gray code and phase shifting. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B3*, 137–142. https://doi.org/10.5194/isprsarchives-XLI-B3-137-2016

Zwawi, M. (2021). A review on natural fiber bio-composites, surface modifications and applications. *Molecules*, *26*(2), 404. https://doi.org/10.3390/molecules26020404

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 114-125.

9

Impact Behaviour of Hybrid Composites

Egemen Aksel[1], Rumeysa İncesu[2]*

İzmir Bakırçay University, Department of Biomedical Engineering, Graduate Education Institute, İzmir, Türkiye

Tarkan Akderya[3]

İzmir Bakırçay University, Department of Biomedical Engineering, Faculty of Engineering and Architecture, İzmir, Türkiye

Corresponding author: rumeysa.incesu@bakircay.edu.tr

Abstract

Composite materials are widely used across various industries today because of key attributes such as high strength and rigidity. These materials are an alternative to metals due to their high strength, light weight, and versatile design options. Despite these advancements, research on "hybridisation" has gained momentum due to strong demand for new, lightweight, and cost-effective materials with enhanced strength. Hybrid composites, which include multiple types of fibres in a single structure, have become essential for combining desired properties and achieving a better balance. In engineering, a sudden external load may lead to unforeseen outcomes. In these situations, the material should respond suitably. The way impact loading affects the material varies depending on its use and location. Accordingly, the response of the material to impact loading will also differ. Various test methods exist to assess impact behaviour. Impact tests gather data on the mechanical properties of materials, particularly under conditions prone to brittle fracture, and measure the energy needed for the sample to break under dynamic stress (impact resistance). Engineers investigate materials to determine whether they undergo ductile or brittle fracture at various temperatures, how much energy they can absorb during fracture, and their overall fracture toughness. This study investigates the dynamic behaviour, energy absorption properties, and fracture modes of hybrid composite materials under various impact loading conditions. It also explores how layer arrangement and fibre combinations influence impact resistance, within the context of existing literature. The aim is to develop a framework for selecting and optimising materials that balance high strength and lightness for industrial use.

Keywords: Hybrid composite; Impact behaviour; Charpy impact test; Izod impact test; Low-velocity impact test

[1] https://orcid.org/0009-0008-7658-2779
[2] https://orcid.org/0000-0002-8781-2428
[3] https://orcid.org/0000-0001-6459-386X

1. Introduction

Composites offer numerous advantages such as corrosion resistance, versatile design possibilities, durability, lightweight nature, and high strength. Composites are now integral to many daily products across various sectors, including construction, healthcare, oil and gas transport, sports, aviation, and space exploration (Swolfs et al., 2014).

Hybrid composites are advanced materials formed by combining different fibre types within a single polymer matrix. This design provides greater stiffness and strength than single-reinforced polymer composites. Usually, in hybrid composites, one fibre—such as glass or Kevlar—tends to have a low modulus and is cost-effective, whereas the other fibre—like boron or carbon—exhibits a high modulus and is more expensive. Interest in naturally reinforced hybrid polymer composites is growing across sectors such as automotive, defence, railways, furniture, and civil engineering. These composites are notable for being biodegradable, lightweight, and environmentally safe. The use of natural fibres is increasing because of their lower density, superior strength-to-weight ratio, and sound insulation qualities compared to synthetic fibres (Huang et al., 2025).

Impact resistance is defined in three ways: the amount of energy absorbed during a penetrating impact, the level of damage after a non-penetrating impact, and the residual properties that remain post-impact. In hybrid composites, layer arrangement is closely linked to dispersion and plays a crucial role in determining layer positions; both are significant parameters for impact performance. In the most typical interlayer configuration, dispersion is fully governed by how the layers are arranged (Swolfs et al., 2014). A major drawback of natural fibres is their variability in characteristic properties. Assessing the impact resistance of natural fibre-reinforced composites remains a key challenge. It has been established that the impact properties of natural fibre-reinforced composites are not on par with those of synthetic fibre-reinforced composites. Hybridisation, which involves combining different fibre types within the matrix, offers high impact energy absorption and improved load-carrying capacity. It is also environmentally friendly and helps reduce the vulnerabilities of both natural and synthetic fibres. Impact resistance is a crucial mechanical property of lightweight fibre-reinforced polymer composites (FRPs), directly influencing their suitability for various engineering applications. However, because fibres are inherently brittle, the trade-off between strength and toughness remains one of the main challenges in FRP design (Huang et al., 2025). Fibre metal laminates (FMLs) are created by layer-by-layer stacking of thin metal alloy sheets bonded with fibre-reinforced composite layers. The excellent fatigue and fracture resistance of composites, along with the high toughness, impact resistance, durability, and easy assembly of many metal alloys, allow FMLs—currently in high demand—to outperform other materials (Sharma & Velmurugan, 2026).

2. Composite Materials

A composite material consists of two or more distinct materials combined at a macroscale with a minimal interface between them. One part is the reinforcement (the reinforcing phase), and the other is the matrix phase. The success of combining fibrous reinforcement with matrix materials into a composite mainly depends on choosing the right processing method. Many processing methods exist, each with distinct features. The capacity to tailor composites for particular applications is a major benefit of this material, yet it also presents one of its most complex challenges (Karbhari, 2003).

2.1. Polymer Composites Reinforced with Natural and Synthetic Fibres

Generally, synthetic fibre-reinforced polymer composites outperform monolithic polymer materials in long-term creep resistance, fatigue life, and adherence to expected product functions. Synthetic fibre-reinforced polymer composites can also incorporate fillers to form multifunctional materials with diverse properties. These synthetic composites can also be improved by enhancing corrosion and abrasion resistance, environmental stability, thermal insulation, and conductivity. Recently, synthetic fibre-reinforced polymer composites have found widespread use in various structural engineering applications. These include reinforcement materials for strengthening walls, fibre-reinforced polymer composite structural systems, reinforcement bars and cables, composite bridge decks, and coils used for seismic strengthening of columns (Asyraf et al., 2022; Bank, 2006; Hollaway, 2010).

Natural fibres are biodegradable, unlike synthetic ones, which do not decompose easily. Advances in composite materials are driving the need to use natural fibres to address environmental concerns and promote sustainability. These natural fibres offer many benefits, including being cost-effective, lightweight, widely available, sustainable, and causing minimal abrasive wear on processing equipment. Moreover, natural fibre composites are cost-effective and eco-friendly, making them a popular choice across different industries because of their outstanding mechanical properties. Biopolymers, which are polymer blends reinforced with natural fibres, create excellent low-density, biocompatible, and recyclable composites (Mohanty et al., 2002; Rangappa et al., 2019).

2.2. Particle-Reinforced Polymer Composites

Particle-based composites are less effective at enhancing strength than fibre-based composites. Particle-reinforced composites are used in applications that demand high abrasion resistance, such as road surfaces. Adding gravel as a reinforcement filler significantly increases the hardness of cement. Particle-reinforced composites are beneficial because they are cost-effective and easy to manufacture and shape. Concrete exemplifies this well; it is made up of coarse rock or gravel aggregate embedded in a cement matrix. Here, the aggregate enhances hardness and strength, while the cement acts as a binder to keep the structure intact (Callister Jr, 2000; Fu et al., 2008).

2.3. Application Areas of Composite Materials

Advanced composite materials are increasingly used in producing aerospace components, wind turbines, and marine equipment due to their superior stiffness-to-weight ratio, strength, corrosion resistance, light weight, and improved mechanical properties. Furthermore, significant progress has been made in enhancing the efficiency and cost-effectiveness of advanced composites, while also boosting specific properties such as strength and modulus. Advanced composites are widely used across various industries, such as producing chemical containers, pressure vessels, machine and power transmission shafts, and robot arms (Figure 1) (Cong et al., 2011; Mallick, 2007; Rana & Fangueiro, 2016).

no.	industry	applications
1	space	radar and satellite structures
2	aircraft	primary and secondary parts of structures
3	automobiles	body and other critical parts
4	civil infrastructures	truss-type structures, bricks, columns, and beams
5	wind turbine blades	rotor blades, nose cone, and some other parts
6	sports	table tennis boards, tennis, badminton, golf clubs, baseball bats, hockey sticks and others

Figure 1. Application areas of composite materials

2.4. Hybrid Composites

Hybrid composites reinforced with natural fibres are becoming more popular in automotive, aerospace, marine, construction, and consumer goods sectors because of their lightweight, eco-friendly nature, and excellent performance (Jawaid & Abdul Khalil, 2011; Sanjay et al., 2016). Hybrid composites integrate two or more reinforcement materials within a single polymer matrix. Even at low glass fibre reinforcement rates (petroleum-based synthetic fibres), hybridisation enhances strength, stiffness, impact resistance, and thermal stability, all while decreasing weight and cost. These composites are ideal for automotive interior panels, instrument panels, construction, sports equipment, packaging, and marine uses that demand medium to high performance and sustainability. These composites, formed by blending synthetic and natural fibres to enhance mechanical and thermal properties, offer a sustainable, eco-friendly alternative to conventional materials. In composites, natural fibres are gaining recognition as a more cost-effective, lightweight, and environmentally friendly alternative to glass fibres (Dendriyal et al., 2026). Two fibres can be combined by stacking layers of each fibre or by mixing and weaving them throughout the composite cross-section. The three most common fibre types used in composites are carbon, glass, and aramid (such as Kevlar). Over recent decades, experiments have explored hybrid types with all possible fibre combinations, such as carbon/glass, carbon/Kevlar, and glass/Kevlar. In this case, two or more distinct reinforcement layers are laminated on top of each other. Various other procedures are also feasible, including creating intralayer hybrids (combining two fibre types within the same layer), randomly mixing fibres, selectively placing specific fibres to enhance strength, and developing super hybrids in which each fibre is deliberately oriented (Figure 2) (Santulli, 2019).

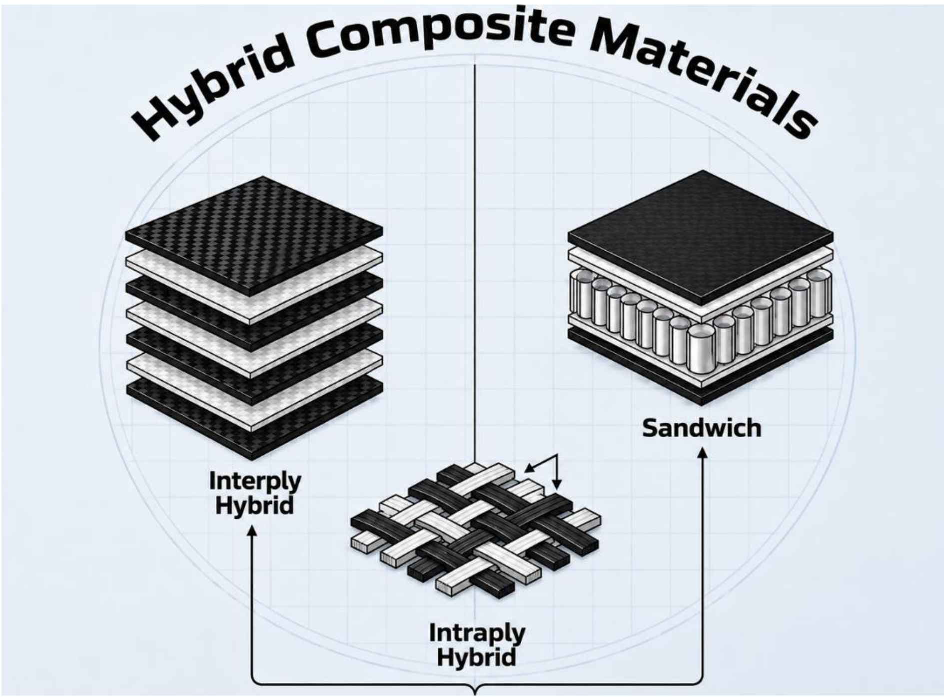

Figure 2. Types of hybrid composites

3. Impact Characteristics of Hybrid Composites

The impact performance of hybrid composites has become increasingly important as lightweight, damage-tolerant structural materials are in greater demand across the aerospace, automotive, marine, and defence sectors. Hybrid composites differ from traditional single-fibre-reinforced composites by integrating various reinforcement materials, creating a synergistic balance of stiffness, strength, toughness, and energy absorption. Integrating fibres with varying mechanical properties helps disperse impact stresses, thereby minimising localised damage and enhancing the overall impact resistance of the composite structure (Swolfs et al., 2014).

3.1. Impact Test Methods

Impact testing assesses how specific materials like polymers, ceramics, and composites react to sudden stress. Impact testing evaluates how engineering materials endure high-speed loads, emphasising toughness, brittleness, notch susceptibility, and impact strength. Quantitatively measuring impact characteristics provides significant advantages for product liability and safety. Impact test specimens feature various notch configurations, including V-notch, U-notch, and keyhole notch (Saba et al., 2019).

3.1.1. Charpy Impact Test

Originally developed for testing metals, the Charpy impact test has also been widely applied in initial impact research on FRP composites. It evaluates both the impact energy absorption and distribution, along with the fracture pattern. The specimen is a thick beam that may or may not have notches and is freely supported at both ends. The testing device primarily includes a recording scale and a pendulum hammer. During the impact test, the pendulum hammer is raised to an appropriate height according to the kinetic energy shown on the recording scale. It is then released to swing in a circular motion and hit the centre of the target specimen. The energy lost from specimen fracture is determined by subtracting the final height of the pendulum from its initial height (Wang & Xian, 2023). The Charpy impact test setup is shown in Figure 3.

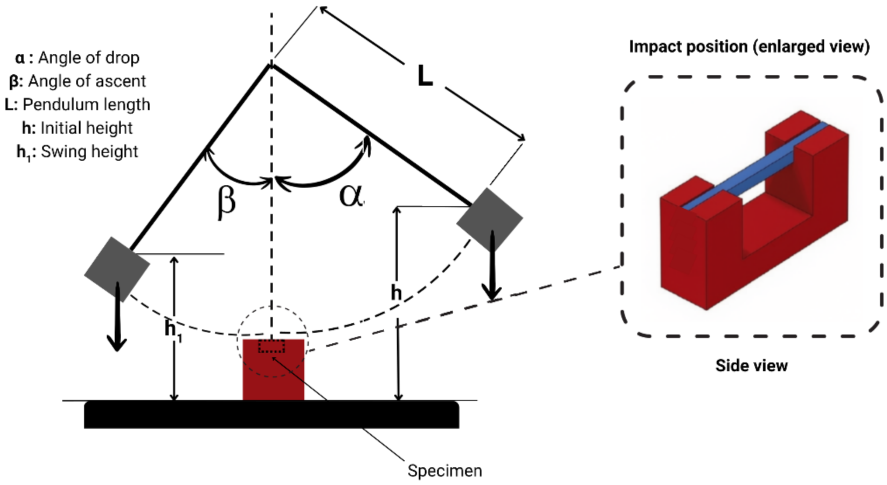

Figure 3. Charpy impact test setup.

3.1.2. Izod Impact Test

The Izod impact test evaluates the amount of energy needed to break a specimen by striking it with a weighted pendulum hammer released from a calibrated height. Typically, 'Izod' refers to impact testing on a notched specimen, though unnotched specimens are sometimes tested as well, indicated in the technical data sheet as 'unnotched rod' or 'unnotched Izod.' The notch, which must be machined rather than moulded, serves as a stress concentrator, prompting the rod to fracture at a designated point. A notch of a specified size, as defined in ASTM D-256 and ISO 180:1993 test standards, is machined onto one side of the test rod at a designated distance from one end. The notch is positioned in the clamp, and a pendulum is released to strike the rod, measuring the energy needed to fracture the specimen. Results can be influenced by how securely the specimen is clamped in the holder, as well as by any burrs or defects in the injection-moulded specimen (Wagner et al., 2014). The Izod impact test setup is shown in Figure 4.

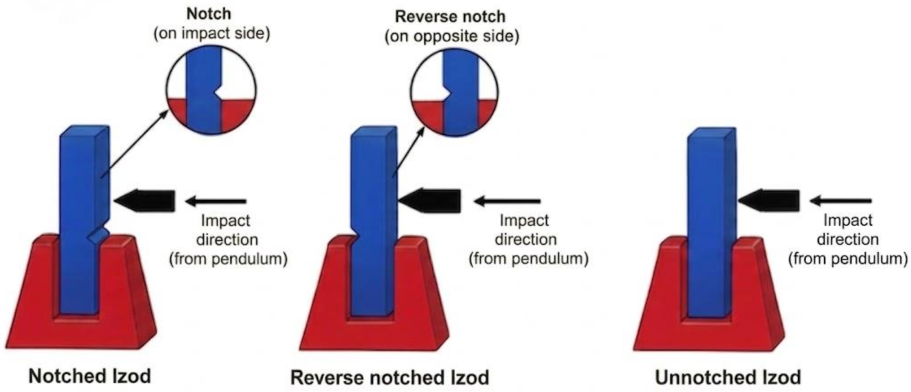

Figure 4. Izod impact test setup

3.1.3. Drop Weight Impact Test

The drop weight test is likely the most common, practical, and economical method among various testing options. It offers a qualitative measure of the energy the specimen absorbs, determined by counting impacts until a certain damage level is achieved. The impact count varies based on factors such as the impactor size, drop height, specimen thickness, and boundary conditions. These machines deliver impact forces by repeatedly dropping impactors of different weights from different heights (Murali et al., 2024). The drop-weight impact test setup is shown in Figure 5.

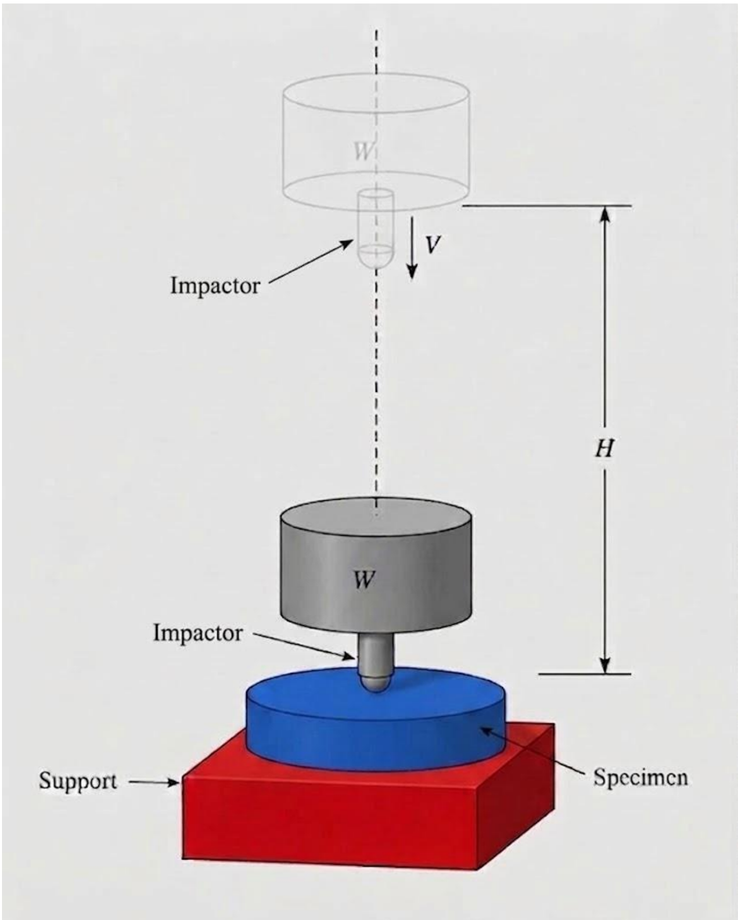

Figure 5. Drop-weight impact test setup

3.2. Studies on the Impact Characteristics of Hybrid Composites

Various studies have shown that combining carbon and glass fibres increases low-velocity impact resistance by delaying destructive damage and reducing interlayer separation damage. Similarly, natural-synthetic fibre hybrid composites have exhibited superior specific energy absorption compared to composites reinforced with only natural fibres, thanks to the complementary mechanical behaviour of the component reinforcements (Jawaid & Abdul Khalil, 2011).

In one study, a glass/hemp hybrid composite material with higher impact resistance and toughness was obtained by reinforcing the outer surface of a hemp fibre-reinforced composite with 11% by volume of glass fibre, exhibiting excellent stiffness and flexural strength (Shahzad, 2011).

The impact behaviour of hybrid composites is generally evaluated using parameters such as peak impact force, absorbed energy, penetration threshold, damage area, and residual mechanical properties. Among these parameters, absorbed energy and post-impact compressive strength are considered key indicators of structural integrity and damage tolerance. Recent research shows that properly designed hybrid architectures can significantly improve post-impact performance by reducing damage accumulation and preserving load-transfer capacity within the composite laminate (Fiore et al., 2015).

In another study, adding 8.6% by weight of glass fibre to a hybrid composite material containing sisal fibre and pineapple leaf fibre improved the impact strength and toughness of the composite material by 87% (Mishra et al., 2003).

Tensile, bending, and impact analyses were performed on hybrid composite materials prepared using banana, sisal, and glass fibres. The impact strength was found to be 7.6 and 8.4 J for banana and sisal composites, 7.4 J for the (Banana + Sisal) hybrid composite, and 13.3 J for the (Banana + Sisal + Glass) hybrid composite. In conclusion, hybridisation increases the strength of the biocomposite (Arthanarieswaran et al., 2014).

Short banana fibres (B) and woven coconut sheath (C) fibres were placed in a polyester matrix in specific weight percentages and layer arrangements, and tensile, bending, and impact tests were performed. The best results in tensile, bending, and impact strength values were obtained in samples where banana fibre was present at 66% by weight, and the fibres were arranged in CCB and BBC layer arrangements (Senthil Kumar et al., 2016).

In another study, the mechanical properties such as tensile, bending, and impact strength were analysed on a layered hybrid biocomposite material with natural sisal and banana fibres and a sisal/banana/banana/sisal layer arrangement. In order to make a comparison, the mechanical properties of sisal/epoxy and banana/epoxy composites were also included to determine which composite had the highest mechanical strength. It was observed that the composite with the highest mechanical strength was the sisal/epoxy composite, and its tensile, bending, and impact strengths were measured as 24.5 MPa, 80.45 MPa, and 1.76 J, respectively (Siva et al., 2021).

Another study examined the impact of low-speed impacts on fibre-reinforced polymer composites, detailing the factors influencing these properties. The findings are summarised as follows:

- Thermoplastic resins demonstrate excellent impact resistance, damage tolerance, and outperform thermoset resins.
- Few studies exist on thermoplastic resins in 3D composites, mainly due to poor interface strength and manufacturing challenges.
- The damage area grows with higher impact energy, which also significantly affects absorbed energy and peak force.
- Thin-layer composites can absorb more impact energy than thick-layer ones. The matrix type greatly influences damage resistance and energy absorption. Additionally, fibre orientation and the number of fibre layers impact absorbed energy, which increases notably with higher fibre volume fractions (Pai et al., 2021).

In the study conducted by Guida et al. (2019), an experimental-numerical study aimed to determine the mechanical properties of a composite laminate consisting of thermoplastic resin reinforced with layers of carbon sheets and a fabric combined with a shape memory alloy. To evaluate the effect of the hybrid fabric on impact behaviour, experimental impact tests were performed on both carbon fibre reinforced polymer (CFRP) composites and hybrid samples. Low-speed impact tests revealed that samples containing hybrid layers had a higher energy absorption capacity during impact. These tests demonstrated that both material systems absorbed different energy levels, amounting to 12.28 J and 18.42 J, during low-velocity impacts. However, the delamination area of CFRP samples is much larger compared to hybrid samples. Therefore, the hybridisation process alters the energy absorption mechanisms of the structure, changing the response of the reinforced material to low-speed impacts.

Carbon fibre plate moulding compounds demonstrated the highest in-plane tensile and compressive stiffness and strength, thanks to the superior performance of their fibres compared to glass fibre alternatives. This resulted in higher peak forces by increasing flexural stiffness during impact. However, as the energy level rose, the structural integrity of carbon plate moulding compounds declined, and their post-impact compressive strength dropped notably. Conversely, glass plate moulding compounds showed better impact tolerance; ductile glass fibres allowed for larger deflections and helped maintain in-plane stiffness and strength after impact. Micro-CT results confirmed that carbon plate moulding compounds had more extensive damage surface expansion and severe localised microcracks in both in-plane and out-of-plane directions, unlike the lower crack density seen in glass plate moulding compounds. Energy dissipation correlated with crack density, with carbon sheet moulding compounds displaying the highest energy dissipation capacity (Pheysey et al., 2025).

From repeated impact tests, it was found that glass fibre-reinforced polymer composites had the highest impact resistance, while carbon fibre-reinforced polymer composites had the lowest. These results were attributed to the higher tensile capacity of glass fibres compared to carbon fibres, and it was interpreted that glass fibre-reinforced polymer composites absorbed impact energy by exhibiting more deformation than carbon fibre-reinforced polymers. In addition, hybrid composites exhibited the properties of both carbon fibre-reinforced polymer and glass fibre-reinforced polymer composites. On the other hand, the average penetration threshold values for glass fibre-reinforced polymer, hybrid, and carbon fibre-reinforced polymer composites were measured as 43, 13, and 9, respectively. This shows that glass fibre-reinforced polymer composites exhibit approximately five times higher penetration threshold values than carbon fibre-reinforced polymer composites, leading to the conclusion that glass fibre-reinforced polymer composites are more suitable for impact-resistant applications. Additionally, the low-velocity impact responses of glass fibre-reinforced polymer composites remained largely unchanged up to the 35th impact, maintaining structural integrity without significant damage. Conversely, repeated impacts on carbon fibre-reinforced polymer composites led to a gradual decline in their dynamic responses, with more severe damage appearing at fewer impacts because of their limited deformation ability (Coskun et al., 2025).

4. Future Perspectives

Although hybrid composite technology has advanced significantly, several technical and methodological challenges remain to be addressed in future research:

- **AI-Driven Multi-Scale Modelling and Optimisation:** Future work should increasingly focus on integrating machine learning algorithms and multi-scale finite element analysis to predict the dynamic impact responses and failure modes of complex hybrid architectures. Algorithmic prediction of optimal layer stacking sequences and fibre volume ratios will replace time-consuming trial-and-error experimental campaigns.
- **Advanced Eco-Hybrids and Circular Economy:** As environmental regulations tighten, the development of fully bio-based or recyclable hybrid composites—utilising biopolymers (e.g., PLA, PHA) combined with surface-modified natural fibres and recyclable synthetic reinforcements—warrants deeper investigation. Improving the interfacial shear strength (IFSS) between hydrophilic natural fibres and hydrophobic matrices remains a primary goal.

- **Smart and Self-Healing Hybrid Interfaces:** Incorporating self-healing microcapsules, vascular networks, or novel shape memory alloys (SMAs) into hybrid laminates can enable autonomous repair of internal delaminations and matrix microcracks following non-penetrating impact events.
- **Extreme Environmental and Multiphysical Testing:** Future experimental studies should expand beyond room-temperature impact characterisation. Investigating the impact, puncture, and fatigue resistance of hybrid structures under extreme thermal fluctuations, hygrothermal ageing, UV exposure, and high-velocity/ballistic conditions will be vital for next-generation aerospace, defence, and marine deployment.

5. Conclusion

This review explores the mechanical, structural, and dynamic response mechanisms of hybrid composite materials under different impact loading conditions. Conventional single-fibre-reinforced polymer composites typically present a trade-off between stiffness and damage tolerance: high-modulus synthetic fibres such as carbon tend to fail in a brittle, catastrophic manner under impact, whereas natural fibres are limited by property variability and lower overall mechanical strength. The literature synthesised in this study shows that hybridisation—achieved through the strategic integration of synthetic-synthetic, natural-synthetic, or fibre-metal laminates (FMLs)—effectively mitigates these drawbacks through synergistic energy dissipation.

Key findings highlighted in this study include:

- **Damage Tolerance and Energy Absorption:** The incorporation of ductile, low-cost, or high-strain fibres (e.g., glass, Kevlar, or natural fibres) alongside high-stiffness reinforcements (e.g., carbon, boron) redistributes localised impact stresses. This configuration delays delamination, restricts the propagation of microcracks, and maintains higher residual compressive strength after impact.
- **Architectural and Stacking Optimisation:** Impact properties—specifically peak force, damage area, and penetration threshold—are heavily governed by layer arrangement, fibre volume fraction, and dispersion within the polymer matrix. Interlayer and hybrid architectures allow tailored stress transfer, preventing catastrophic structural collapse.
- **Functional Hybridisation:** Advanced hybrid configurations, including shape-memory-alloy-integrated composites and thermoplastic-matrix hybrids, exhibit superior superelasticity and hysteresis under low-velocity impact, thereby transforming the energy absorption profile and drastically reducing internal delamination zones.
- **Testing and Characterisation:** Standardised test protocols (Charpy, Izod, and drop-weight impact) provide crucial quantitative metrics—such as notch sensitivity, ductile-to-brittle transition, and multi-impact endurance—which are essential for designing crashworthy structures.

In conclusion, hybrid composites present an exceptionally adaptable material platform, enabling engineers to balance high specific strength, lightness, damage tolerance, and environmental sustainability for critical structural applications.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

Funding

This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Grant Number 223M016. The authors thank TÜBİTAK for their support.

References

Arthanarieswaran, V. P., Kumaravel, A., & Kathirselvam, M. (2014). Evaluation of mechanical properties of banana and sisal fiber reinforced epoxy composites: Influence of glass fiber hybridization. *Materials & Design*, *64*, 194–202. https://doi.org/10.1016/j.matdes.2014.07.058

Asyraf, M. R. M., Khan, T., Syamsir, A., & Supian, A. B. M. (2022). Synthetic and Natural Fiber-Reinforced Polymer Matrix Composites for Advanced Applications. *Materials*, *15*(17), 6030. https://doi.org/10.3390/ma15176030

Bank, L. C. (2006). *Composites for Construction: Structural Design with FRP Materials*. John Wiley & Sons.

Callister Jr, W. D. (2000). Materials Science and Engineering—An Introduction (5th ed.). *Anti-Corrosion Methods and Materials*, *47*(1). https://doi.org/10.1108/acmm.2000.12847aae.001

Cong, W. L., Pei, Z. J., Deines, T. W., & Treadwell, C. (2011). Rotary ultrasonic machining of CFRP using cold air as coolant: Feasible regions. *Journal of Reinforced Plastics and Composites*, *30*(10), 899–906. https://doi.org/10.1177/0731684411416266

Coskun, B. S., Coskun, T., Kapıcı, S., Tarih, Y. S., & Şahin, Ö. (2025). The modal characteristics of the CFRP, GFRP and hybrid composites exposed to HCI environment and impact loadings. *Journal of Advances in Manufacturing Engineering*, *6*(2), 68–76.

Dendriyal, A., Ram, S. C., Kumar, R., & Jain, A. (2026). Fabrication of eco-friendly hybrid composites using natural fibers (flax/bamboo) and effect of chemical treatment on the water absorption, mechanical, and thermal properties. *Progress in Engineering Science*, *3*(2), 100277. https://doi.org/10.1016/j.pes.2026.100277

Fiore, V., Scalici, T., Di Bella, G., & Valenza, A. (2015). A review on basalt fibre and its composites. *Composites Part B: Engineering*, *74*, 74–94. https://doi.org/10.1016/j.compositesb.2014.12.034

Fu, S.-Y., Feng, X.-Q., Lauke, B., & Mai, Y.-W. (2008). Effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate–polymer composites. *Composites Part B: Engineering*, *39*(6), 933–961. https://doi.org/10.1016/j.compositesb.2008.01.002

Guida, M., Sellitto, A., Marulo, F., & Riccio, A. (2019). Analysis of the Impact Dynamics of Shape Memory Alloy Hybrid Composites for Advanced Applications. *Materials*, *12*(1), 153. https://doi.org/10.3390/ma12010153

Hollaway, L. C. (2010). A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. *Construction and Building Materials, Special Issue on Fracture, Acoustic Emission and NDE in Concrete (KIFA-5)*, *24*(12), 2419–2445. https://doi.org/10.1016/j.conbuildmat.2010.04.062

Huang, Y., Liu, Y., Liu, H., Zhang, S., Hu, J., & Zhao, J. (2025). Low-velocity impact and compression-after-impact behaviors of carbon/glass fiber hybrid composite laminates based on thin-ply carbon fiber prepreg and unidirectionally arrayed chopped strand. *Thin-Walled Structures*, *211*, 113075. https://doi.org/10.1016/j.tws.2025.113075

Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, *86*(1), 1–18. https://doi.org/10.1016/j.carbpol.2011.04.043

Karbhari, V. M. (2003). Durability of FRP Composites for Civil Infrastructure—Myth, Mystery or Reality. *Advances in Structural Engineering*, *6*(3), 243–255. https://doi.org/10.1260/136943303322419250

Mallick, P. K. (2007). *Fiber-Reinforced Composites: Materials, Manufacturing, and Design, Third Edition*. CRC Press.

Mishra, S., Mohanty, A. K., Drzal, L. T., Misra, M., Parija, S., Nayak, S. K., & Tripathy, S. S. (2003). Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Composites Science and Technology*, *63*(10), 1377–1385. https://doi.org/10.1016/S0266-3538(03)00084-8

Mohanty, A. K., Misra, M., & Drzal, L. T. (2002). Sustainable Bio-Composites from Renewable Resources: Opportunities and Challenges in the Green Materials World. *Journal of Polymers and the Environment*, *10*(1), 19–26. https://doi.org/10.1023/A:1021013921916

Murali, G., Wong, L. S., & Abid, S. R. (2024). A comprehensive review of drop weight impact testing: Evaluating the Pros and Cons in fiber-reinforced concrete performance assessment. *Journal of Building Engineering*, *94*, 109934. https://doi.org/10.1016/j.jobe.2024.109934

Pai, Y., Pai, K. D., & Kini, M. V. (2021). A review on low velocity impact study of hybrid polymer composites. *Materials Today: Proceedings, First International Conference on Advanced Trends in Mechanical and Aerospace Engineering*, *46*, 9073–9078. https://doi.org/10.1016/j.matpr.2021.05.390

Pheysey, J., Del Cuvillo, R., Naya, F., Pernas-Sanchez, J., De Cola, F., & Martinez-Hergueta, F. (2025). Low-velocity impact response of hybrid sheet moulding compound composite laminates. *Composites Part A: Applied Science and Manufacturing*, *188*, 108527. https://doi.org/10.1016/j.compositesa.2024.108527

Rana, S., & Fangueiro, R. (2016). Advanced Composites In Aerospace Engineering. In *Advanced Composite Materials for Aerospace Engineering: Processing, Properties and Applications* (pp. 1–15). Woodhead Publishing.

Rangappa, S. M., Siengchin, S., Parameswaranpillai, J., Jawaid, M., Pruncu, C. I., & Khan, A. (2019). A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization. *Carbohydrate Polymers*, *207*, 108–121. https://doi.org/10.1016/j.carbpol.2018.11.083

Saba, N., Jawaid, M., & Sultan, M. T. H. (2019). 1—An overview of mechanical and physical testing of composite materials. In M. Jawaid, M. Thariq, & N. Saba (Eds), *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites* (pp. 1–12). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102292-4.00001-1

Sanjay, M. R., Arpitha, G. R., Naik, L. L., Gopalakrishna, K., & Yogesha, B. (2016). Applications of Natural Fibers and Its Composites: An Overview. *Natural Resources*, *07*(03), 108–114. https://doi.org/10.4236/nr.2016.73011

Santulli, C. (2019). Mechanical and Impact Damage Analysis on Carbon/Natural Fibers Hybrid Composites: A Review. *Materials*, *12*(3), 517. https://doi.org/10.3390/ma12030517

Senthil Kumar, K., Siva, I., Rajini, N., Winowlin Jappes, J. T., & Amico, S. C. (2016). Layering pattern effects on vibrational behavior of coconut sheath/banana fiber hybrid composites. *Materials & Design*, *90*, 795–803. https://doi.org/10.1016/j.matdes.2015.11.051

Shahzad, A. (2011). Impact and fatigue properties of hemp–glass fiber hybrid biocomposites. *Journal of Reinforced Plastics and Composites*, *30*(16), 1389–1398. https://doi.org/10.1177/0731684411425975

Sharma, A. P., & Velmurugan, R. (2026). High-velocity impact behavior and energy absorption characteristics of hybrid titanium composite laminates. *International Journal of Impact Engineering*, *208*, 105551. https://doi.org/10.1016/j.ijimpeng.2025.105551

Siva, R., Kesavaram, B., Jones Martin, J., Mathiselvan, G., Navas, K. B., & Sangeetha, M. (2021). Mechanical behavior of sisal and banana fiber reinforced hybrid epoxy composites. *Materials Today: Proceedings, 3rd International Conference on Frontiers in Automobile & Mechanical Engineering*, *44*, 3692–3696. https://doi.org/10.1016/j.matpr.2020.10.805

Swolfs, Y., Gorbatikh, L., & Verpoest, I. (2014). Fibre hybridisation in polymer composites: A review. *Composites Part A: Applied Science and Manufacturing*, *67*, 181–200. https://doi.org/10.1016/j.compositesa.2014.08.027

Wagner, J. R., Mount, E. M., & Giles, H. F. (2014). 21—Testing Properties. In *Extrusion (Second Edition)* (pp. 241–253). William Andrew Publishing. https://doi.org/10.1016/B978-1-4377-3481-2.00021-1

Wang, Z., & Xian, G. (2023). Impact performances of fiber reinforced polymer composites and cables: A review. *Composite Structures*, *319*, 117128. https://doi.org/10.1016/j.compstruct.2023.117128

This chapter is part of the book: **Sustainable Engineering Technologies for Industrial Innovation**, Editor: Mehmet Çevik, Duvar Publications, 2026, pp. 126-162.

10

Bio-Based Brick Technologies for Sustainable Construction Integrating Materials, Performance and Sustainability

Ebubekir Atan[1]*, Mustafa Öncül[2] and Mehmet Çevik[3]

İzmir Kâtip Çelebi University, Department of Mechanical Engineering, İzmir, Türkiye

Corresponding author: ebubekir.atan@ikcu.edu.tr

Abstract

Growing interest in low-carbon and circular construction has accelerated the development of bricks incorporating renewable biological resources, agricultural residues, bio-derived materials, and biologically mediated binding processes. This review critically examines 81 publications published between 2005 and 2026 and proposes an integrated framework for bio-based, bio-derived, and biologically fabricated brick technologies. The systems are classified into seven families covering natural-fiber and lignocellulosic composites, agricultural-, food-, and animal-waste composites, pore-engineered fired bricks, biopolymer- and bio-binder-modified bricks, mycelium-based materials, biomineralized bricks, and multifunctional bio-derived systems. The review focuses on relationships among feedstock origin, matrix type, processing route, microstructure, mechanical properties, thermal performance, durability, environmental impacts, and scalability. Processing emerges as a key determinant of performance because compaction, firing, pyrolysis, fiber treatment, fungal growth, and microbial or enzymatic mineralization govern pore structure and bonding. Porosity is identified as the central microstructural mediator, frequently linking lower density and thermal conductivity with reduced strength and increased moisture uptake. Consequently, higher bio-content does not necessarily yield better overall performance. Many systems appear more suitable for non-load-bearing masonry, insulation, partitions, and multifunctional envelopes than for primary structural applications. Mycelium and biomineralization offer novel fabrication routes, but durability, process control, production time, and scalability remain major constraints. Evidence is also limited for fire resistance, long-term aging, building-scale behavior, life-cycle impacts, and economic feasibility. Future research should move from single-property waste substitution toward standardized, performance-balanced masonry systems supported by multi-objective optimization, pilot-scale production, and life-cycle assessment.

Keywords: Bio-based bricks; Sustainable masonry; Life cycle assessment; Mycelium composites; Biomineralization; Circular economy; Sustainability

[1] https://orcid.org/0000-0001-7422-3416
[2] https://orcid.org/0000-0002-4441-6353
[3] https://orcid.org/0000-0002-6366-5566

1. Introduction

1.1. Environmental Burden of Conventional Brick Production

Conventional brick production imposes environmental burdens through both raw-material extraction and manufacturing. Clay-based bricks require large quantities of natural mineral resources, while extraction of suitable clay can contribute to land degradation and depletion of locally available raw-material reserves. Their manufacture is also energy intensive because conventional ceramic bricks are typically fired at high temperatures to achieve the required mechanical strength and durability. The associated fuel and electricity consumption contributes to greenhouse-gas emissions and increases the embodied energy of masonry products (Demir, 2008; Görhan & Şimşek, 2013; Bories et al., 2015; Lewo Nkondi et al., 2025). These impacts become increasingly important in the context of continued growth in construction activity and the corresponding demand for masonry materials, particularly in rapidly urbanizing regions (Ahmad et al., 2025; Jwaida & Di Sarno, 2026).

At the same time, agriculture, forestry, and food-processing activities generate substantial quantities of lignocellulosic residues and other biological wastes, including straw, rice husk, sawdust, bagasse, nutshells, coffee residues, and animal-derived wastes. Disposal or uncontrolled treatment of these materials can itself create environmental problems, whereas their incorporation into construction materials offers a potential route for waste valorization and partial substitution of virgin resources (Ganasen et al., 2023; Le et al., 2023; Şahin, 2026). Consequently, the development of bricks incorporating bio-based and bio-derived constituents addresses two interconnected challenges: reducing the resource and energy intensity of conventional masonry production and creating higher-value applications for renewable or residual biological materials. This dual motivation has driven increasing research on bio-based, bio-derived, and biologically fabricated brick systems.

1.2. Biological Resources as Alternative Brick Constituents

A wide range of biological resources has been investigated as alternative constituents in brick production. Natural fibers and lignocellulosic residues such as hemp, kenaf, sisal, date-palm fibers, straw, rice husk, corn residues, sawdust, sugarcane bagasse, and other crop by-products have been incorporated into clay, earth, cementitious, and alkali-activated matrices as reinforcement, lightweight aggregate, filler, or pore-forming material (Binici et al., 2005; Laborel-Préneron et al., 2017; Khoudja et al., 2021; Biswas et al., 2024). Agricultural and food-processing wastes further extend this resource base to materials such as coffee husks and grounds, citrus residues, beet pulp, nut shells, and paddy-stubble-derived products, while animal- and marine-derived wastes, including bovine excreta, eggshells, and seashells, have also been explored as partial constituents of masonry materials (Moussa et al., 2022; Abdallah & Estévez, 2023; Jaramillo et al., 2025a, 2025b).

Biological resources may also enter brick systems after transformation or through their functional role in material formation. Biomass-derived products such as biochar and biomass ash have been used to modify density, pore structure, thermal performance, and resource efficiency (Boussaa et al., 2023; Paul et al., 2026), while biopolymers including starch, lignin, chitosan, sodium alginate, and other bio-derived binders have been investigated as matrix modifiers or binding agents (Arab et al., 2021; Harb et al., 2023; Shahat & Soliman, 2025). A distinct class of materials relies directly on biological activity: fungal mycelium can bind particulate substrates into cohesive composites, while microbially induced calcite precipitation (MICP) and enzyme-induced carbonate precipitation (EICP) can cement granular materials through biomineralization (Bernardi et al., 2014; Ongpeng et al., 2020; Cheng et al., 2020; Zhang et al., 2022). These diverse routes demonstrate that biological resources can function not only as substitutes for conventional raw materials but also as active structural, binding, and functional components in emerging brick technologies.

1.3. Evolution from Waste Incorporation to Engineered Bio-Based Masonry

Research on bio-based masonry has progressively moved beyond the simple substitution of conventional raw materials with agricultural or biological wastes. Early approaches largely treated biomass residues as alternative fillers, aggregates, or pore-forming agents intended to reduce virgin-material consumption and divert wastes from disposal. Subsequent studies increasingly exploited the intrinsic properties of biological constituents, particularly natural fibers, to reinforce earthen, clay, and cementitious matrices and modify crack propagation, density, and thermal behavior (Binici et al., 2005; Görhan & Şimşek, 2013; Laborel-Préneron et al., 2017).

More recent developments represent a transition from passive incorporation toward biologically mediated material formation and engineered functionality. Biopolymers and mycelium can act as binding phases, while microbial and EICP enable the fabrication of bricks through biomineralization rather than conventional firing or cement hydration (Bernardi et al., 2014; Arab et al., 2021; Ongpeng et al., 2020). The field is now extending further toward multifunctional masonry, in which bio-derived constituents provide functions beyond material substitution, including thermal energy storage, photocatalytic self-cleaning, acoustic performance, and moisture regulation (Bordoloi et al., 2025; Yavaş et al., 2023). This evolution can therefore be summarized as waste substitution → bio-reinforcement → bio-binding → biofabrication → multifunctionality, reflecting a shift from waste utilization toward deliberately engineered bio-based masonry systems.

1.4. Problem of Terminology

The literature lacks a consistent terminology for bricks incorporating biological materials or biological processes. Terms such as *bio-brick*, *biocomposite brick*, *eco-brick*, *bio-based brick*, *biomass brick*, *bio-cemented brick*, and *sustainable brick* are often used for materially different systems. For example, *bio-brick* may refer to bricks produced by MICP or EICP (Bernardi et al., 2014; Cheng et al., 2020; Arab et al., 2021), whereas *biocomposite brick* is also used for units containing retained biological constituents such as mycelium, fibers, starch-based matrices, or biochar-derived functional materials (Ongpeng et al., 2020; Harb et al., 2023; Waskar & Anadinni, 2026).

Other labels are even broader. *Eco-brick* and *sustainable brick* may describe products containing natural fibers, agricultural residues, biomass ash, industrial wastes, or combinations of these materials, irrespective of whether a biological phase remains in the finished unit (Abdullah & Jamaai, 2016; Boussaa et al., 2023; Sutcu et al., 2019). Such terminological overlap complicates comparison among studies and may obscure fundamental differences in composition, processing, and binding mechanisms. Accordingly, Table 1 summarizes the terminology adopted in this review, which distinguishes bio-based, bio-derived, and biologically fabricated bricks according to the origin, transformation state, and functional role of the biological constituent rather than relying solely on the terminology used by individual authors.

In this review, bio-based, bio-derived, and biologically fabricated are used as the primary classification terms, while *bio-brick*, *eco-brick*, *biomass brick*, and *sustainable brick* are treated as broader or author-specific labels rather than technically equivalent material categories.

1.5. Research Gap, Aim, and Novelty of the Present Review

Existing reviews provide substantial coverage of individual segments of the bio-based construction-material literature, but their scopes are generally confined to specific material families or processing routes. Broad reviews have examined construction biocomposites and circular bio-based building materials (Ahmad et al., 2025; Le et al., 2023, 2024), while others have focused on mycelium composites (Alaneme et al., 2023; Jones et al., 2020; Jin et al., 2026), unfired waste-derived bricks (Lachheb et al., 2023; Wang & Abuel-Naga, 2025), natural-fiber-reinforced earth blocks (Riffi et al., 2026), or fired clay bricks containing lignocellulosic biomass, biomass ash, and other organic additives (Labaied et al., 2022; Lewo Nkondi et al., 2025). As a result, retained biological constituents, thermally transformed biomass, bio-derived binders, fungal composites, biomineralized bricks, and multifunctional systems are often discussed in separate research domains.

The present review addresses this fragmentation by integrating the main routes through which biological and bio-derived resources enter masonry technology. It examines how material origin and processing affect microstructure, engineering performance, durability, building-scale behavior, and sustainability. Its main contribution is a cross-technology framework linking biological origin → processing → structure → properties → application → life-cycle performance. This framework enables comparison across bio-based, bio-derived, and biologically fabricated bricks while identifying key trade-offs and barriers to scalable masonry applications.

Table 1. Proposed terminology and operational classification of bio-based, bio-derived, and biologically fabricated brick systems used in this review

Term	Operational definition used in this review	Typical constituents / mechanism	Representative studies
Bio-based brick	Brick in which a biological constituent remains physically present in the final material.	Natural fibers, straw, hemp, kenaf, sawdust, palm residues, coffee husk, paper/pulp.	Binici et al. (2005); Laborel-Préneron et al. (2017); Khoudja et al. (2021); Biswas et al. (2024)
Biocomposite brick	Brick composed of a matrix and one or more biological or bio-derived phases that contribute to structure or functional performance.	Earth/fiber, clay/fiber, cement/agro-waste, starch/biomass, mycelium composites.	Ashour et al. (2015); Harb et al. (2023); Ongpeng et al. (2020); Waskar and Anadinni (2026)
Bio-derived brick	Brick containing a material originating from biomass but chemically or thermally transformed before or during production.	Biochar, biomass ash, calcined shells, biomass used as burnout pore former.	Boussaa et al. (2023); Paul et al. (2026); Aouba et al. (2016); Sakhare and Ralegaonkar (2016)
Biomass-modified / biomass brick	Brick in which biomass or biomass residue is directly incorporated, often as filler, aggregate, reinforcement, or pore former.	Rice husk, sawdust, wheat straw, hazelnut shell, bagasse.	Görhan and Şimşek (2013); Bories et al. (2015); Atan et al. (2021); Moussa (2024)
Bio-cemented brick	Brick formed or strengthened through biologically or enzymatically induced mineral precipitation.	MICP, EICP, calcium carbonate precipitation.	Bernardi et al. (2014); Cheng et al. (2020); Arab et al. (2021); Gandhi (2025)
Biologically fabricated brick	Brick whose formation, binding, or consolidation relies directly on biological activity.	Mycelium binding, microbial mineralization, biowelding.	Abdallah and Estévez (2023); Ongpeng et al. (2020); Zhang et al. (2022)
Eco-brick	Broad environmental label used for bricks intended to reduce resource consumption, waste, energy use, or emissions; not necessarily bio-based.	Natural fibers, industrial wastes, biomass residues, recycled mineral wastes.	Abdullah and Jamaai (2016); Sutcu et al. (2019)
Sustainable brick	Umbrella term referring to bricks developed to improve environmental performance across production, use, or end-of-life stages.	Bio-based, bio-derived, recycled-waste, unfired, low-carbon, multifunctional systems.	Wang and Abuel-Naga (2025); Jwaida and Di Sarno (2026)

2. Review Methodology and Scope

2.1. Literature Identification

The literature search was developed iteratively. An initial pool of studies was identified using combinations of terms related to biocomposite bricks, bio-bricks, bio-based bricks, natural-fiber bricks, agricultural-waste bricks, and related masonry materials. This initial set was subsequently expanded through targeted keyword searches covering specific material and processing classes, including mycelium bricks, MICP/EICP bricks, biopolymer bricks, biochar bricks, biomass-modified fired bricks, natural-fiber earth blocks, and bio-based phase-change materials (PCMs). Backward and forward citation tracking of relevant primary studies and review articles was also used to identify additional publications outside the initial terminology.

The search covered multidisciplinary bibliographic databases, scholarly search engines, publisher platforms, and DOI-based retrieval sources in order to capture literature spanning materials science, civil engineering, building physics, biotechnology, and sustainability. After screening for relevance and removing clearly unrelated studies, the final working corpus comprised 81 publications published between 2005 and 2026. The iterative expansion of the search was necessary because the relevant literature is distributed across several research domains and employs inconsistent terminology for closely related brick technologies.

2.2. Search Terminology

The literature search employed a broad set of keywords to capture the different technological routes represented in the field. Core search terms included biocomposite brick, bio-brick, bio-based brick, natural fiber brick, agricultural waste brick, and biomass brick. These were supplemented with more specific terms such as mycelium brick, biochar brick, MICP brick, EICP brick, biopolymer clay brick, and fired biomass brick. Related combinations involving earth blocks, lignocellulosic residues, biomass ash, natural fibers, biopolymers, biomineralization, and multifunctional bio-based masonry were also used where necessary.

The use of multiple overlapping search terms was required because no single terminology encompasses the full range of materials considered in this review. In particular, similar technologies are variously described as bio-based, biocomposite, eco-friendly, biomass-modified, bio-cemented, or sustainable bricks, while some studies are indexed primarily under the name of the biological constituent or processing mechanism rather than under a generic brick-related term.

2.3. Inclusion Criteria

Studies were included when they investigated masonry bricks or blocks containing biological or bio-derived constituents, or when biological processes contributed directly to material formation or binding. This scope covered natural-fiber and lignocellulosic composites, agricultural and food-processing residues, biomass-derived products, biopolymers, mycelium-based materials, and microbially or enzymatically mineralized bricks. Studies incorporating bio-derived functional additions, such as biochar or phase-change systems, were also retained. Closely related building-envelope biocomposites were included selectively when their findings provided transferable evidence on properties relevant to masonry applications, such as thermal conductivity, moisture buffering, durability, or environmental performance. Major review articles were retained to establish the state of the art and identify previously defined material classes and research gaps.

2.4. Exclusion Criteria

Studies were excluded when they were unrelated to construction masonry or when the term brick referred only to geometric form, material architecture, or a non-building application. General building-energy studies without direct relevance to bio-based masonry materials were likewise excluded. These criteria led to the removal of initially identified studies whose use of the term brick did not correspond to a masonry unit or whose research focus fell outside the material scope of the review.

2.5. Evidence Classification

The final corpus was classified by evidence type. Primary experimental studies formed the basis for comparing composition, processing, microstructure, and engineering properties. Numerical and building-performance studies extended material-scale findings to wall and building behavior, while life-cycle and economic studies addressed environmental impacts, resource efficiency, cost, and scalability. Review articles were used to establish terminology, the state of the art, and research gaps, but not as independent quantitative evidence. Supporting and comparator studies were retained where they provided relevant benchmarks for conventional or non-bio-based masonry systems.

3. Conceptual Definition and Taxonomy

3.1. What Constitutes a Bio-Based Brick?

For the purposes of this review, a bio-based brick is defined as a masonry unit in which at least one constituent originates from renewable biological resources and remains materially present in the final product, contributing to its structure, binding, reinforcement, density, thermal behavior, moisture response, or other functional properties. Typical constituents include natural fibers, lignocellulosic residues, agricultural by-products, food-processing wastes, bio-based binders, and other biomass-derived organic phases retained within earth, clay, cementitious, lime, polymeric, or related matrices.

This operational definition intentionally distinguishes bio-based bricks from systems in which the biological feedstock is substantially transformed before or during manufacture, such as biomass ash, biochar, or combustible pore-forming additives, and from bricks whose formation depends primarily on biological activity, such as mycelium growth or microbial mineralization. Those materials are classified in this review as bio-derived and biologically fabricated bricks, respectively, as summarized in Table 1. The distinction is based on the state and role of the biological constituent in the finished masonry unit rather than on the terminology adopted by individual authors.

3.2. Bio-Based, Bio-Derived, and Biologically Fabricated Bricks

3.2.1. Bio-Based Bricks

In bio-based bricks, the biological phase remains physically present in the finished masonry unit and contributes directly to its structure or performance. Typical constituents include straw, hemp, kenaf, sawdust, palm fibers, coffee husk, and other lignocellulosic residues incorporated as fibers, aggregates, fillers, or reinforcing phases. Representative systems include fiber-reinforced earth bricks, date-palm-waste bricks, kenaf-containing bricks, and coffee-husk alkali-activated bricks (Abdullah & Jamaai, 2016; Laborel-Préneron et al., 2017; Khoudja et al., 2021; Biswas et al., 2024).

3.2.2. Bio-Derived Bricks

In bio-derived bricks, the original biological feedstock undergoes substantial thermal, chemical, or mineral transformation before or during brick production. This category includes biochar, biomass ash, eggshell or seashell powders, and biomass introduced into fired clay as a combustible pore-forming additive. Although the original organic structure may be altered or destroyed, its biological origin remains relevant to resource recovery and material functionality (Aouba et al., 2016; Boussaa et al., 2023; Ibrahim et al., 2022; Paul et al., 2026). Fired bricks containing agricultural residues therefore differ fundamentally from retained-fiber biocomposites because the biomass may primarily influence the final material through burnout-induced pore formation.

3.2.3. Biologically Fabricated Bricks

In biologically fabricated bricks, biological activity participates directly in the formation or consolidation of the masonry unit. Mycelium-based systems employ fungal hyphae to bind particulate substrates into cohesive composites, whereas MICP and EICP generate mineral bonds through biologically mediated carbonate precipitation (Bernardi et al., 2014; Cheng et al., 2020; Ongpeng et al., 2020; Arab et al., 2021). In these systems, biology functions as part of the manufacturing or binding mechanism rather than merely as a feedstock source. This distinction provides the basis for comparing the three material families according to their processing routes, structure–property relationships, and potential construction applications.

3.3. Proposed Classification of Brick Systems

Based on the origin, transformation state, binding mechanism, and functional role of the biological constituent, the reviewed brick systems are grouped into seven principal families, as illustrated in Figure 1. (A) Natural-fiber and lignocellulosic composite bricks contain retained plant-derived fibers or particles, such as straw, hemp, kenaf, palm fibers, sawdust, and similar residues, within earth, clay, cementitious, or polymeric matrices (Binici et al., 2005; Khoudja et al., 2021). (B) Agricultural-, food-, and animal-waste composite bricks incorporate residues such as coffee waste, bagasse, paper/pulp waste, eggshells, seashells, and other biological by-products as fillers, aggregates, or partial raw-material substitutes (Muñoz et al., 2020; Ibrahim et al., 2022; Biswas et al., 2024). (C) Bio-derived pore-engineered fired bricks use biomass or biomass-derived constituents to modify the pore structure during firing, typically through combustion or thermal transformation of rice husk, straw, sawdust, nutshells, or related residues (Aouba et al., 2016; Atan et al., 2021). (D) Biopolymer- and bio-binder-modified bricks employ starch, lignin, chitosan, sodium alginate, bio-adhesives, or related materials to modify binding or interfacial behavior (Arab et al., 2021; Harb et al., 2023; Shahat & Soliman, 2025). (E) Mycelium-based biofabricated bricks rely on fungal growth to bind particulate substrates (Ongpeng et al., 2020; Abdallah & Estévez, 2023), whereas (F) bio-cemented and biomineralized bricks are consolidated through MICP, EICP, or related carbonate-precipitation mechanisms (Bernardi et al., 2014;

Cheng et al., 2020). Finally, (G) bio-derived multifunctional bricks incorporate biological or bio-derived constituents to provide additional functions beyond conventional mechanical and thermal performance, including thermal-energy storage, self-cleaning, photocatalytic, acoustic, or moisture-regulating behavior (Bordoloi et al., 2025; Yavaş et al., 2023). This seven-family taxonomy provides the organizational framework used throughout the remainder of the review.

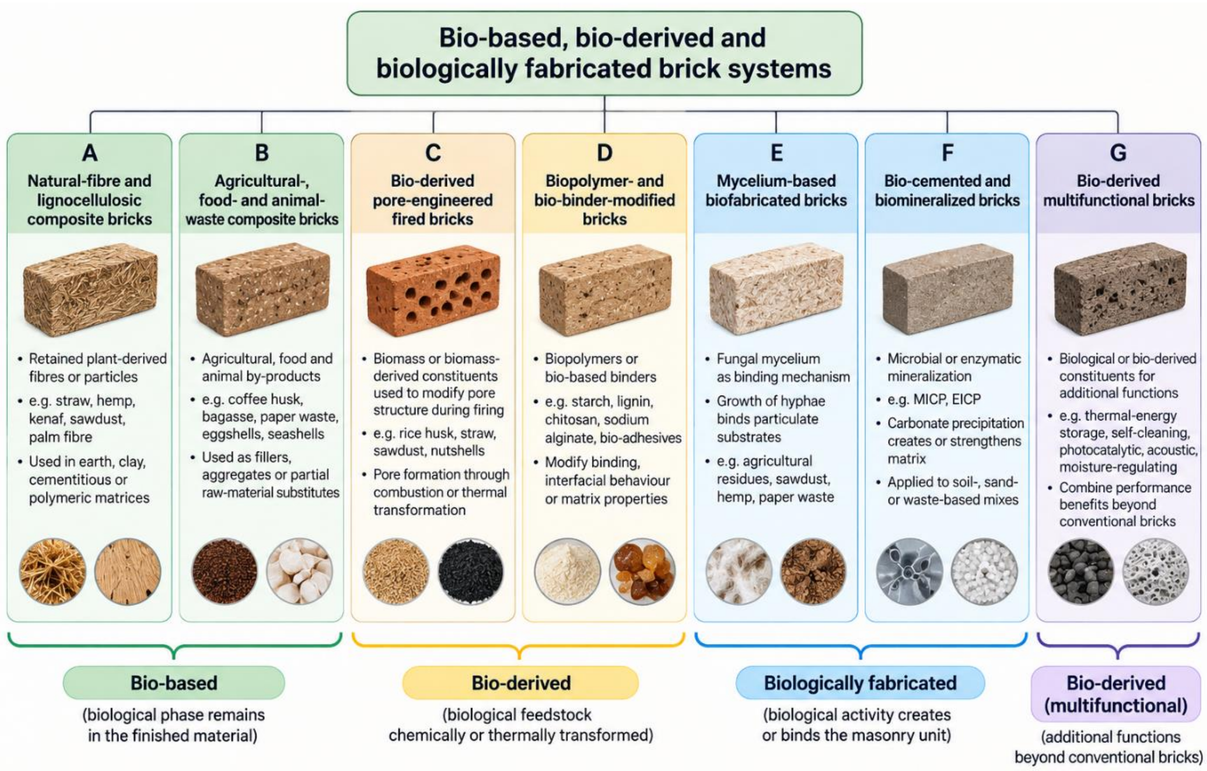

Figure 1. Proposed classification of bio-based, bio-derived, and biologically fabricated brick systems into seven principal technological families

4. Biological and Bio-Derived Feedstocks

4.1. Cereal and Crop Residues

Cereal and crop residues constitute one of the most extensively investigated feedstock groups for bio-based brick production because they are widely available, renewable, and often generated in large quantities as agricultural by-products. Wheat and barley straw have been incorporated mainly as fibrous or particulate bioaggregates in earth and clay matrices, where they influence density, pore structure, mechanical behavior, and hygrothermal performance (Aouba et al., 2016; Giroudon et al., 2019; Laborel-Préneron et al., 2018). Rice husk has been used both as a retained biomass constituent and as a combustible pore-forming additive in fired clay bricks, while paddy stubble has also been converted to biochar for incorporation into masonry units (Görhan & Şimşek, 2013; Paul et al., 2026; Demirel, 2026).

Other crop residues include corn-derived lignocellulosic waste, sugarcane bagasse, and groundnut shell. Corn residues have been employed to modify the porosity, density, and compressive strength of fired clay bricks, whereas sugarcane bagasse has been investigated for improving thermal performance and reducing building-envelope energy demand (Utami et al., 2021; Moussa, 2024). Groundnut shell and related nutshell residues have similarly been considered as lightweight fillers or pore-forming biomass within the broader agricultural-waste masonry literature (Ganasen et al., 2023; Jwaida & Di Sarno, 2026). Across these feedstocks, the principal material functions are reinforcement, lightweight aggregate substitution, pore generation, and thermal-property modification, with the dominant mechanism depending on whether the biomass remains in the final brick or is thermally transformed during processing.

4.2. Wood, Forestry, and Processed Cellulosic Residues

Wood, forestry, and processed cellulosic residues constitute an important feedstock group for bio-based and bio-derived brick systems. Wood chips and sawdust can be incorporated as lightweight lignocellulosic fillers or pore-forming constituents, depending on the matrix and processing route. In unfired systems, these materials may remain within the composite and contribute to lightweighting and thermal insulation, whereas in fired clay bricks sawdust largely combusts during firing and generates additional porosity. This mechanism can reduce density and thermal conductivity, although excessive incorporation may increase water absorption and reduce mechanical strength (Alabduljabbar et al., 2021; Lewo Nkondi et al., 2025).

Processed cellulosic wastes, particularly paper and pulp residues, have also been used as fibrous reinforcement or lightweight additions in masonry materials. Their cellulose-rich structure can improve thermal performance and contribute to waste valorization, although the effects on strength and moisture sensitivity depend strongly on dosage and matrix compatibility (Muñoz et al., 2020). Wood-derived biomass may also be converted into ash, representing a bio-derived rather than retained bio-based constituent. Wood biomass ash has been used as a stabilizing or mineral addition in compressed earth bricks, where it can modify mechanical, thermal, and durability properties (Boussaa et al., 2023). Thus, this feedstock group spans retained lignocellulosic materials, recycled cellulosic fibers, and thermally transformed mineral residues.

4.3. Palm and Fibrous Plant Residues

Palm-derived and other fibrous plant residues are widely used as reinforcing or lightweight constituents because of their low density, elongated morphology, and lignocellulosic structure. Date-palm fibers and wastes have been incorporated into raw-earth and insulating brick systems, where they can reduce density and thermal conductivity while modifying strength and moisture response (Khoudja et al., 2021; Rima & Nadir, 2024). Palm-shell-derived particles have likewise been investigated as lignocellulosic fillers in unfired clay bricks, with performance governed strongly by filler content and the resulting increase in porosity (Claudel et al., 2025).

Other plant fibers investigated in brick and related masonry systems include hemp, kenaf, sisal, abaca, *Stipa ichu*, and seagrass. Hemp and kenaf have been used as reinforcing or lightweight bioaggregates in cementitious, lime, and brick matrices (Abdullah & Jamaai, 2016; Abdellatef et al., 2020), while sisal and other natural fibers have been incorporated to improve crack resistance and mechanical behavior in recycled or hybrid brick systems (Kumar et al., 2024; Zhang et al., 2024). *Stipa ichu* and seagrass have been studied in adobe-type composites for their influence on mechanical and thermal properties (Piñas et al., 2020; Olacia et al., 2020). Across this group, fiber geometry, surface condition, dosage, and interfacial bonding are key parameters controlling whether the primary benefit is reinforcement, lightweighting, or improved thermal performance.

4.4. Food-Processing Wastes

Food-processing activities generate organic residues that can serve as lightweight fillers, bioaggregates, binding constituents, or feedstocks for biologically fabricated materials. Coffee-derived wastes have received particular attention. Coffee husk has been used as a partial aggregate replacement in alkali-activated bricks, while spent coffee grounds have been incorporated into lightweight non-load-bearing composites, exploiting their low density and lignocellulosic character (Biswas et al., 2024; Moussa et al., 2022). Beet pulp has similarly been combined with starch to produce insulating composite bricks, demonstrating the potential of carbohydrate-rich processing residues as constituents of low-density building-envelope materials (Harb et al., 2023).

Other food-processing residues include citrus peel and related fruit wastes. Citrus peel has been investigated as a substrate in mycelium-based composites, where the residue contributes both as a biomass feedstock and as part of the resulting composite structure (Fernández et al., 2025). Across this category, composition, moisture content, particle size, and pretreatment strongly affect compatibility with the matrix or biological binder. Their utilization therefore combines waste valorization with the potential to tailor density, thermal behavior, and other functional properties of masonry-related composites.

4.5. Animal- and Shell-Derived Residues

Animal- and shell-derived residues represent a smaller but distinct feedstock group in bio-based and bio-derived masonry. Bovine excreta have been incorporated with other agricultural residues in composite bricks, where their organic and fibrous fractions contribute to matrix modification and waste valorization (Jaramillo et al., 2025a, 2025b). Eggshell waste, which is predominantly calcium-carbonate-based, has been used as a mineral-rich bio-derived constituent in ceramic brick production and can partially replace conventional raw materials while influencing density, strength, and thermal behavior (Ibrahim et al., 2022).

Seashell waste provides a similarly calcium-carbonate-rich biogenic resource and has been incorporated either as a mineral constituent or as part of hybrid biologically fabricated systems. Seashell-derived powders have been used in low-carbon composite bricks, while shell-based materials have also been combined with mycelium-mediated biowelding (Rao et al., 2024; Abdallah & Estévez, 2023). Because eggshell and seashell constituents are largely mineral in nature after processing, these systems are generally more appropriately classified as bio-derived rather than retained bio-based materials.

4.6. Bio-Derived Functional Materials

The term bio-derived functional materials is used here for constituents obtained from biological resources through extraction, conversion, or other processing and incorporated primarily to impart a specific material function. This group is therefore broader than the strictly bio-derived brick category defined in Section 3.2.2. It includes both substantially transformed biomass products and processed bio-based binders or modifiers that remain materially present in the finished brick.

Among the substantially transformed constituents, biochar is produced by thermochemical conversion of biomass and can modify pore structure, density, thermal conductivity, moisture interaction, and carbon-storage potential, whereas biomass ash is the mineral-rich residue of combustion and may act as a stabilizing, filler, or reactive mineral addition (Boussaa et al., 2023; Paul et al., 2026). By contrast, lignin, starch, chitosan, sodium alginate, and bio-adhesives are processed biological materials used mainly as binders, interfacial modifiers, or matrix-forming agents. Their incorporation can affect cohesion, porosity, mechanical behavior, and thermal response (Arab et al., 2021; Harb et al., 2023; Jaramillo et al., 2025a, 2025b; Kamar et al., 2025; Shahat & Soliman, 2025). Thus, while all materials in this subsection originate from biological resources, their classification within the final brick depends on both their degree of transformation and their functional role.

4.7. Biological Agents

Biological agents should be distinguished from conventional bio-based material constituents. Material constituents such as fibers, bioaggregates, biochar, ash, or biopolymers are introduced primarily because they remain as part of the brick matrix and directly contribute to its physical or functional properties. By contrast, biological agents are included mainly because they actively drive material formation, binding, or mineralization during fabrication. Their classification is therefore based on function rather than solely on whether biological matter remains in the finished product.

Fungal mycelium develops a hyphal network that grows through particulate substrates and binds them into a cohesive composite (Ongpeng et al., 2020; Abdallah & Estévez, 2023; Zhang et al., 2022). Although mycelium remains materially present after drying or deactivation, its defining role is as an active biofabrication and binding agent. Ureolytic bacteria promote calcium carbonate precipitation in MICP, thereby cementing granular particles into brick-like units (Bernardi et al., 2014; Kumar et al., 2019; Cheng et al., 2020; Gandhi et al., 2025). Enzymes perform a similar catalytic role in EICP without requiring living microbial cells (Arab et al., 2021). Thus, biological agents are differentiated from passive bio-based constituents by their active participation in the manufacturing mechanism.

5. Matrix Systems and Material Architecture

The behavior of a biological constituent depends strongly on the matrix in which it is embedded. The same fiber or residue may act as reinforcement, lightweight aggregate, pore former, binder modifier, or biological substrate depending on matrix chemistry, interfacial bonding, and processing. The reviewed systems can therefore be classified according to eight principal matrix architectures.

5.1. Earth and Adobe Matrices

Earth and adobe matrices are among the most established hosts for lignocellulosic fibers and bioaggregates. Straw, hemp shiv, palm residues, seagrass, *Stipa ichu*, and other plant materials are incorporated into soil-based matrices to control cracking, reduce density, and modify thermal and moisture behavior (Binici et al., 2005; Laborel-Préneron et al., 2018; Olacia et al., 2020; Khoudja et al., 2021). Because these systems are generally unfired, the biological phase remains within the finished brick and its interaction with clay minerals and moisture becomes particularly important.

5.2. Clay Matrices

Clay matrices accommodate both retained and thermally transformed biological constituents. In unfired clay systems, fibers and biopolymers remain part of the composite, whereas in fired bricks biomass such as rice husk, straw, sawdust, and nutshells may combust and generate pores during firing (Demir, 2008; Aouba et al., 2016; Alabduljabbar et al., 2021; Atan et al., 2021). Consequently, clay-based systems exhibit a strong dependence on firing temperature, biomass content, and burnout behavior.

5.3. Cementitious Matrices

Cementitious matrices provide greater initial strength and moisture resistance than many earth-based systems, while allowing agricultural residues, fibers, and bio-derived additives to substitute part of the conventional aggregate or binder system. Kenaf, quarry-dust/kenaf combinations, and mixed agricultural wastes have been investigated in cement-based bricks and related composites (Abdullah & Jamaai, 2016; Kamar et al., 2025; Nakkeeran et al., 2024). Their performance is governed largely by fiber–cement adhesion, water demand, and the influence of organic constituents on hydration.

5.4. Lime-Based Matrices

Lime-based matrices provide a lower-temperature mineral binder environment compatible with many lignocellulosic materials. Hemp-lime composites are the most established example, combining plant-derived aggregates with lime-rich binders to achieve low density, moisture buffering, and thermal insulation (Abdellatef et al., 2020; Formisano et al., 2017). Their relatively low mechanical strength generally favors non-load-bearing and envelope applications.

5.5. Alkali-Activated Systems

Alkali-activated matrices offer an alternative to conventional Portland-cement systems and can accommodate both mineral wastes and biological residues. Coffee husk, for example, has been investigated as a partial replacement for sand in alkali-activated bricks (Biswas et al., 2024). In such systems, compatibility between the organic phase and the alkaline binder, as well as its influence on pore development and reaction products, is critical to final performance.

5.6. Polymer Matrices

Polymer matrices allow natural fibers to function primarily as reinforcing phases within relatively continuous and moisture-resistant binders. Wheat- and rice-fiber-reinforced polymer hybrid bricks illustrate this architecture, in which fiber content, orientation, interfacial adhesion, and thermal stability govern mechanical behavior (Pandey et al., 2026). These systems differ from mineral-matrix bio-bricks because the polymer phase controls much of the load transfer and environmental resistance.

5.7. Biological/Mycelial Matrices

In mycelium-based systems, the matrix is generated partly or predominantly through fungal growth. Hyphae colonize and bind particulate biomass substrates, producing a continuous biological network that functions simultaneously as binder and structural phase (Ongpeng et al., 2020; Zhang et al., 2022;

Abdallah & Estévez, 2023). The resulting architecture depends on fungal species, substrate characteristics, growth conditions, pressing, and post-growth treatment.

5.8. Granular Biomineralized Matrices

Granular biomineralized systems consist of sand, soil, or other particulate media consolidated through biologically or enzymatically induced mineral precipitation. In MICP and EICP systems, calcium carbonate precipitates within particle contacts and pore spaces, forming cementing bridges without conventional firing (Bernardi et al., 2014; Lambert & Randall, 2019; Cheng et al., 2020; Arab et al., 2021). Mechanical performance therefore depends on particle packing, carbonate distribution, treatment cycles, saturation conditions, and the efficiency of the mineralization process.

Across these matrix systems, bio-component content alone is insufficient to explain performance because the same biological feedstock can produce markedly different outcomes depending on matrix type, interfacial interactions, and processing conditions. Material performance should therefore be interpreted as a function of the combined effects of the bio-component, matrix, interface, and processing route. This matrix–interface perspective provides the basis for the processing–structure–property relationships discussed in the following sections.

6. Manufacturing and Processing Routes

6.1. Unfired Molding and Compaction

Unfired molding and compaction are widely used for adobe, compressed-earth, cementitious, and lime-based bio-bricks because they avoid the high-temperature firing stage associated with conventional ceramic masonry. In these systems, the biological constituent generally remains within the finished material, making moisture content, particle grading, compaction pressure, fiber dispersion, and curing conditions particularly important. Adobe and earth-based bricks are commonly produced by mixing soil with fibers or bioaggregates, followed by molding and ambient or controlled drying, while compressed-earth units employ greater compaction to improve density and particle contact (Binici et al., 2005; Ashour et al., 2015; Khoudja et al., 2021).

Cementitious and lime-based bio-bricks similarly rely on molding or compaction followed by binder hydration, carbonation, or drying rather than firing. In these systems, the processing route must balance adequate consolidation with preservation of the lightweight and porous character introduced by the biological phase. Excessive water or insufficient compaction can increase shrinkage and porosity, whereas excessive compaction may reduce the thermal benefits associated with low-density bioaggregates. Consequently, unfired processing is governed by the interaction between mixture consistency, compaction level, curing regime, and the moisture sensitivity of the biological constituent.

The principal unfired processing routes and their controlling parameters are summarized in Table 2, highlighting the trade-off between consolidation, dimensional stability, retained porosity, and moisture sensitivity.

6.2. Fiber Preparation and Treatment

The performance of fiber-reinforced bio-bricks depends strongly on how the biological reinforcement is prepared before mixing. Cutting and grinding are commonly used to obtain fibers or particles of manageable size and to improve dispersion within the matrix, while particle-size control helps regulate packing, porosity, and fiber–matrix contact. Excessively long fibers may promote clustering and poor workability, whereas overly fine particles can reduce the reinforcing effect and behave primarily as fillers (Laborel-Préneron et al., 2017; Kumar et al., 2024).

Drying is generally required to reduce moisture variability, limit biological degradation during storage, and improve control over the effective water content of the mixture. Surface treatments may also be applied to enhance compatibility between hydrophilic lignocellulosic fibers and the surrounding matrix. Alkaline treatment, for example, can remove surface impurities and portions of hemicellulose or lignin, increase surface roughness, and improve interfacial bonding, although excessive treatment may damage the fiber structure. Such modification has been investigated in banana-fiber paperbricks and related natural-fiber systems (Akinwande et al., 2021). Other surface treatments or bio-based coatings may likewise be used to control water uptake, adhesion, and durability. Fiber preparation should be regarded as a key processing variable because fiber geometry, moisture condition, and surface chemistry directly influence dispersion, bonding, and the resulting mechanical and hygrothermal properties.

Table 2. Comparison of principal unfired manufacturing routes for bio-based brick systems

Processing route	**Typical matrix/ system**	**Main processing steps**	**Key control parameters**	**Main advantages**	**Main limitations**
Hand or low-pressure molding	Adobe, raw-earth bio-bricks	Mixing, mold filling, demolding, air drying	Water content, fiber dispersion, drying rate	Simple, low-energy, minimal equipment	Greater dimensional variability, shrinkage, moisture sensitivity
Mechanical compaction	Compressed-earth bricks/blocks	Mixing, placement, static or dynamic compaction, curing/drying	Compaction pressure, moisture content, particle grading	Higher density and dimensional stability than adobe	Excessive compaction may reduce insulating porosity
Cementitious molding/ pressing	Cement-based bio-bricks	Mixing, molding/pressing, moist curing	Water-to-binder ratio, bioaggregate dosage, curing regime	Improved early strength and moisture resistance	Binder-related embodied carbon, possible incompatibility with organics
Lime-based molding	Hemp-lime and related bio-composites	Mixing, light compaction/molding, carbonation/drying	Binder-to-bioaggregate ratio, compaction, drying conditions	Low density, moisture buffer, thermal insulation	Slow curing, relatively low structural strength
Binder-stabilized earth compaction	Earth bricks with cement, lime, gypsum, or bio-binders	Soil blending, stabilizer addition, compaction, curing	Stabilizer content, moisture, compaction energy	Improved strength and erosion resistance	Added binder may increase cost and embodied impact

6.3. Fired Production

Firing distinguishes a major class of bio-derived bricks in which biological additives are thermally transformed during ceramic processing. Unlike unfired biocomposites, these systems derive much of their final performance from biomass burnout, pore generation, and subsequent sintering of the clay matrix.

6.3.1. Biomass as a Pore-Forming Additive

Agricultural and lignocellulosic residues such as rice husk, wheat straw, sawdust, nutshells, and other biomass fractions have been widely incorporated into clay before firing (Demir, 2008; Görhan & Şimşek, 2013; Bories et al., 2015; Aouba et al., 2016; Kizinievič et al., 2018; Alabduljabbar et al., 2021; Atan et al., 2021; Utami et al., 2021; Demirel, 2026; Moussa, 2024). During heating, the organic fraction decomposes and combusts, leaving voids within the ceramic body. The principal role of the biomass is therefore often pore generation rather than reinforcement. Increased pore volume generally reduces bulk density and thermal conductivity, but can also increase water absorption and reduce load-bearing capacity when the additive content becomes excessive. Thus, these materials are more appropriately described as bio-derived pore-engineered fired bricks than as conventional retained-fiber biocomposites.

6.3.2. Effect of Firing Temperature

Firing temperature governs the balance between biomass burnout and ceramic densification. At lower temperatures, incomplete sintering can leave a relatively porous and mechanically weak structure, whereas increasing temperature promotes particle bonding, vitrification, and densification of the clay matrix. These changes generally increase strength and reduce open porosity, although the magnitude of the effect depends on clay mineralogy, biomass dosage, and ash-forming constituents (Aouba et al., 2016; Kizinievič et al., 2018; Alabduljabbar et al., 2021; Atan et al., 2021).

The thermal implications are similarly coupled. Greater porosity produced by biomass burnout tends to lower thermal conductivity, while stronger sintering at higher temperatures may partially counter this effect by densifying the ceramic skeleton. Higher firing temperatures can therefore improve mechanical performance but may diminish some thermal-insulation benefits and increase production energy demand. Selection of the firing regime is consequently a multi-objective problem involving sintering, porosity, density, strength, thermal conductivity, and manufacturing energy, rather than a simple maximization of firing temperature.

6.4. Biochar Production and Incorporation

Biochar production and use in brick manufacture generally involve a sequential process of biomass selection → drying and size reduction → pyrolysis → biochar grinding/sieving → blending with the host matrix → molding or compaction → curing or drying. The initial biomass feedstock is first dried and, where necessary, reduced in size to improve thermal conversion. It is then pyrolyzed under oxygen-limited conditions, producing a carbon-rich and porous solid whose structure depends strongly on feedstock type and pyrolysis temperature. After cooling, the biochar is commonly ground and sieved to obtain a controlled particle-size range before incorporation into the brick mixture.

During brick preparation, processed biochar is blended with soil, clay, cementitious, or other binder systems at a selected dosage, followed by molding or compaction and curing or drying. In the reviewed literature, biochar primarily functions as a lightweight porous additive capable of modifying density, pore structure, thermal conductivity, moisture interaction, and potentially carbon storage (Paul et al., 2026). Its effect is nevertheless highly process-dependent: particle size, pyrolysis conditions, dosage, dispersion, matrix compatibility, and compaction level determine whether thermal and lightweighting benefits can be achieved without excessive loss of mechanical strength.

6.5. Mycelium Cultivation

Mycelium-based brick production follows a biologically driven sequence of substrate preparation → sterilization → inoculation → fungal growth → pressing or shaping → drying/deactivation. Agricultural or lignocellulosic substrates are first cleaned, size-adjusted, and conditioned to provide suitable moisture and nutrients for fungal colonization. Sterilization or pasteurization is then used to suppress competing microorganisms before inoculation with the selected fungal culture, commonly species of *Pleurotus* or related fungi (Ongpeng et al., 2020; Zhang et al., 2022; Abdallah & Estévez, 2023).

During incubation, fungal hyphae spread through the substrate and form an interconnected network that binds the particles into a cohesive composite. The colonized material may then be molded or pressed to increase density and improve dimensional stability. A final drying or heat-treatment stage reduces moisture content and deactivates further fungal growth, thereby stabilizing the product for use. The resulting properties depend strongly on substrate composition, fungal species, growth time, moisture conditions, degree of compaction, and post-growth treatment, making cultivation parameters central to the reproducibility and performance of mycelium-based bricks.

6.6. Microbial and Enzymatic Mineralization

Biomineralized bricks are produced by inducing calcium carbonate precipitation within a granular matrix, creating mineral bridges between particles without conventional firing. The two principal routes are MICP and EICP. Both rely on urea hydrolysis to promote carbonate formation in the presence of calcium ions, but differ in whether living microorganisms or isolated enzymes provide catalytic activity.

6.6.1. Microbially Induced Calcite Precipitation

MICP typically follows the sequence granular substrate preparation → bacterial introduction → nutrient/urea–calcium treatment → carbonate precipitation → repeated treatment or curing → drying. Ureolytic bacteria hydrolyze urea, increasing local alkalinity and promoting precipitation of calcium carbonate at particle contacts. The resulting mineral bridges progressively consolidate sand or soil into a brick-like material. Early work demonstrated the feasibility of biologically cemented sandstone bricks (Bernardi et al., 2014), followed by studies using marine ureolytic bacteria, urine-derived treatment media, controlled saturation, and repeated MICP cycles to improve consolidation and erosion resistance (Kumar et al., 2019; Lambert & Randall, 2019; Cheng et al., 2020; Li et al., 2020; Liu et al., 2021).

More recent work has extended the approach to alternative bacterial sources and carbon-sequestration-oriented bio-brick production (Gandhi et al., 2025).

6.6.2. Enzyme-Induced Carbonate Precipitation (EICP)

EICP replaces living bacterial cells with urease enzymes that catalyze urea hydrolysis and induce calcium carbonate precipitation. A typical sequence involves substrate preparation → preparation of enzyme and cementation solutions → mixing or injection → carbonate precipitation → curing → drying. Because no microbial growth is required, EICP can simplify process control and reduce sensitivity to environmental conditions that affect bacterial activity. However, precipitation distribution, enzyme stability, reagent consumption, and bonding uniformity remain important processing variables. Hybrid approaches combining EICP with biopolymers such as sodium alginate have been investigated to improve particle bonding and brick integrity (Arab et al., 2021). MICP and EICP therefore represent related but distinct biocementation routes, with their effectiveness governed by treatment chemistry, delivery method, precipitation uniformity, and the number of treatment cycles.

6.7. Additive Manufacturing and Biowelding

Additive manufacturing represents an emerging processing route for bio-based masonry, enabling controlled geometry, material placement, and integration of biological binding mechanisms. In contrast to conventional molding, three-dimensional printing can produce customized porous architectures and complex brick geometries while reducing dependence on formwork. Within the reviewed literature, this approach is represented most clearly by the fabrication of a seashell-based biodigital brick subsequently consolidated through fungal growth (Abdallah & Estévez, 2023).

The process combines digital design → material preparation → layer-by-layer printing → inoculation → mycelial colonization → biowelding → drying/deactivation. The biowelding mechanism occurs when fungal hyphae grow across adjacent printed layers or contact surfaces, penetrate local pores and surface irregularities, and form an interconnecting biological network that bridges previously separate material regions. These hyphal bridges increase interfacial continuity and help transfer stresses across layer boundaries, functioning as a biologically generated joining phase rather than as a conventional adhesive. After sufficient colonization, drying or thermal deactivation arrests further fungal growth and stabilizes the bonded structure. Although this hybrid route offers substantial geometric flexibility, its practical application remains limited by printability, interlayer contact quality, growth uniformity, processing time, dimensional stability, and scale-up.

6.8. PCM Incorporation and Encapsulation

PCMs are incorporated into bio-based brick systems to provide latent heat storage and improve thermal regulation. The processing sequence generally involves PCM selection → stabilization or encapsulation → preparation of the bio-based carrier or matrix → PCM incorporation → brick filling or integration → sealing and curing/drying. In the reviewed studies, bio-derived porous materials such as biochar can act as carriers for PCMs, allowing the PCM to be retained within their pore structure and reducing leakage during melting (Bordoloi et al., 2025; Bordoloi & Kalita, 2026).

PCM integration may be achieved by direct filling of brick cavities, impregnation into porous carriers, or incorporation of a stabilized biocomposite PCM into the masonry unit. Encapsulation or shape stabilization is particularly important because repeated solid–liquid phase transitions can otherwise lead to leakage and loss of thermal-storage capacity. The effectiveness of these systems depends on PCM loading, phase-transition temperature, carrier porosity, thermal compatibility with the brick matrix, and long-term cycling stability. Related work has also extended biocomposite PCM integration to autoclaved aerated concrete bricks, demonstrating the broader applicability of this processing route for passive thermal-energy storage (Das et al., 2026).

7. Microstructure and Structure–Property Relationships

7.1. Fiber–Matrix Interface

The fiber–matrix interface is a critical microstructural region in bio-based bricks because it governs stress transfer, crack bridging, moisture transport, and the development of interfacial voids. Effective bonding allows natural fibers to redistribute stresses and delay crack propagation, whereas weak adhesion can promote fiber pull-out, debonding, and localized porosity. Interfacial quality is influenced by fiber morphology, surface roughness, chemical composition, moisture condition, and compatibility with the surrounding earth, clay, cementitious, lime, or polymer matrix (Laborel-Préneron et al., 2017; Kumar et al., 2024).

Natural fibers are hydrophilic and may absorb mixing water, swell, or create weak interfacial zones if poorly dispersed. Surface treatment can improve bonding by increasing roughness or modifying the outer lignocellulosic layers, as demonstrated for alkaline-treated banana-fiber paperbricks (Akinwande et al., 2021). Conversely, excessive fiber content or inadequate pretreatment may increase void formation and reduce matrix continuity. The interface therefore mediates a central trade-off in fiber-reinforced bio-bricks: stronger interfacial bonding generally benefits mechanical performance, while a more porous fiber–matrix architecture may contribute to lower density and thermal conductivity. Understanding this balance is essential for interpreting the apparently contradictory effects of fiber addition reported across different brick systems.

7.2. Pore Formation and Pore Connectivity

Pore structure is one of the principal microstructural features controlling the performance of bio-based and bio-derived bricks. Pores can form through several distinct mechanisms. In unfired fiber- and bioaggregate-containing systems, irregular particle geometry and incomplete packing create interparticle voids, while poor fiber dispersion can generate local cavities and weak interfacial zones. Moisture removal during drying produces additional shrinkage-related pores, particularly where hydrophilic fibers release absorbed water or where differential drying occurs between the biological phase and the surrounding matrix. In cementitious and lime-based systems, entrapped air, bioaggregate water absorption, and incomplete binder penetration into porous plant particles may further increase local porosity.

A different mechanism dominates in fired clay bricks containing biomass. During heating, lignocellulosic additives undergo thermal decomposition and combustion, leaving behind voids that reflect the size, shape, and distribution of the original particles. At the same time, ceramic sintering tends to densify the clay skeleton, so the final pore structure results from competition between biomass burnout and matrix vitrification (Aouba et al., 2016; Alabduljabbar et al., 2021; Atan et al., 2021). Biochar-containing systems introduce pre-existing internal porosity, whereas biomineralized bricks can experience partial pore filling as calcium carbonate precipitates at particle contacts and within pore spaces. Mycelium-based materials exhibit yet another architecture, in which voids are defined by substrate packing and the extent to which fungal hyphae bridge or occupy interparticle spaces.

The distinction between isolated and interconnected pores is particularly important. Isolated pores can reduce density and heat transfer with relatively limited effects on liquid-water transport, while connected pore networks facilitate capillary absorption and may accelerate moisture ingress and weathering. Increasing bio-content therefore does not merely increase total porosity; it can alter pore size distribution, connectivity, and tortuosity, which helps explain why similar reductions in density or thermal conductivity may be accompanied by markedly different water-absorption and durability responses. Pore architecture thus provides a central link between feedstock morphology, processing route, and the competing thermal, mechanical, and moisture-related properties discussed later.

7.3. Biomass Burnout during Firing

In fired clay bricks containing agricultural or lignocellulosic residues, biomass burnout is a primary mechanism by which the biological additive alters the final microstructure. During heating, moisture is first removed, followed by thermal decomposition of hemicellulose, cellulose, and lignin and subsequent oxidation of the resulting volatile and carbonaceous fractions. As the organic phase is consumed, voids remain within the clay body, and their morphology is influenced by the original size, shape, distribution, and content of the biomass particles. Rice husk, straw, sawdust, and nutshell-derived additives therefore act predominantly as sacrificial pore formers rather than as retained reinforcement in the fired product (Demir, 2008; Görhan & Şimşek, 2013; Bories et al., 2015; Aouba et al., 2016; Alabduljabbar et al., 2021).

The final microstructure reflects a competition between organic burnout and ceramic sintering. Biomass decomposition increases pore volume, whereas increasing firing temperature promotes particle bonding, vitrification, and partial pore closure within the clay matrix. The balance between these mechanisms determines whether the resulting brick exhibits a fine and relatively closed pore structure or a highly connected network of larger voids. Ash-forming components of the biomass may also remain within the ceramic body and participate in mineral reactions during firing, further modifying the matrix depending on feedstock composition (Kizinievič et al., 2018; Atan et al., 2021; Utami et al., 2021).

This burnout–sintering balance is central to the characteristic trade-off observed in biomass-modified fired bricks: increased pore formation can reduce density and thermal conductivity, but excessive or poorly controlled burnout may disrupt matrix continuity and impair strength and moisture resistance. Biomass particle characteristics, additive dosage, heating rate, peak temperature, and soaking time therefore jointly control the resulting pore architecture and engineering performance.

7.4. Mycelial Hyphal Networks

In mycelium-based bricks, bonding develops through several complementary mechanisms associated with fungal hyphae. As the mycelium colonizes the substrate, hyphae grow around and between particles, forming an interconnected network that produces mechanical interlocking and physical entanglement. Hyphae can also penetrate pores, cracks, and surface irregularities of lignocellulosic particles, creating localized anchorage and increasing the effective contact area between adjacent constituents (Ongpeng et al., 2020; Zhang et al., 2022; Abdallah & Estévez, 2023).

A second contribution arises from interfacial adhesion between the fungal cell-wall components and the substrate surface. This adhesion, together with hyphal bridging across particle contacts, creates a continuous biological phase capable of transferring stresses between otherwise discrete particles. The resulting bond quality depends on fungal species, substrate chemistry, particle size, moisture availability, growth time, and degree of colonization. Pressing can further increase interparticle contact and densify the hyphal network, whereas drying or thermal deactivation stabilizes the formed structure.

The mechanical integrity of mycelium composites therefore results from the combined action of hyphal entanglement, pore penetration, surface adhesion, and particle-to-particle bridging, rather than from a conventional hardened binder. Variations in the density and continuity of this network help explain differences in strength, porosity, and thermal performance among mycelium-based brick systems.

7.5. Calcium Carbonate Precipitation in Bio-Cemented Bricks

In bio-cemented bricks, calcium carbonate precipitation provides the principal mineral bonding mechanism between initially loose granular particles. During MICP or EICP treatment, urea hydrolysis generates carbonate species that react with dissolved calcium ions, leading to precipitation of calcium carbonate within pore spaces and, most importantly, at particle contacts (Bernardi et al., 2014; Cheng et al., 2020; Arab et al., 2021). The resulting crystals form mineral bridges between adjacent grains, increasing interparticle cohesion and transforming the granular assembly into a consolidated masonry unit.

Bond effectiveness depends not only on the total quantity of precipitated calcium carbonate but also on its location, morphology, and spatial uniformity. Precipitation concentrated at particle contacts contributes more effectively to load transfer than carbonate deposited as isolated crystals within larger pores. Repeated treatment cycles can increase cementation and improve resistance to compression and erosion, although non-uniform reagent distribution may produce heterogeneous bonding and preferential weak zones (Li et al., 2020; Liu et al., 2021). Excessive pore filling may also reduce permeability and restrict subsequent transport of treatment solutions.

The resulting microstructure is therefore governed by the interaction between particle packing and carbonate distribution. Contact-scale mineral bridging, partial pore filling, and progressive densification of the granular skeleton collectively determine the strength and durability of bio-cemented bricks, while treatment chemistry, saturation state, and delivery conditions control the efficiency and uniformity of these mechanisms.

7.6. Biochar Pore Structure

Biochar introduces a distinct porous phase into brick matrices because its thermochemical production preserves and transforms parts of the original biomass cellular structure into a carbon-rich pore network. Depending on feedstock and pyrolysis conditions, this structure may contain interconnected macro-, meso-, and micropores that increase internal surface area and reduce the apparent density of the biochar-containing composite. When dispersed within a brick matrix, these pores contribute to lightweighting and can interrupt solid-phase heat-transfer pathways, thereby reducing thermal conductivity (Paul et al., 2026).

The influence of biochar is governed not only by its total porosity but also by pore size distribution, connectivity, particle size, and accessibility to the surrounding matrix. Highly porous particles may absorb water or binder into their internal pore system, altering local hydration, interfacial bonding, and effective matrix continuity. At moderate contents, this porous architecture can enhance thermal performance while maintaining adequate structural integrity, whereas excessive incorporation may increase void content and weaken particle-to-matrix bonding. Biochar porosity can also provide storage space for functional substances such as PCMs, allowing the pore network to act as a carrier that limits leakage during melting (Bordoloi et al., 2025). Thus, biochar contributes to brick performance through both its intrinsic internal porosity and the secondary pore structure created at the biochar–matrix interface.

7.7. Microstructural Characterization

Microstructural characterization is essential for linking processing routes to the resulting pore architecture, interfacial bonding, mineral phases, and thermal transformations of bio-based and bio-derived bricks. Scanning electron microscopy (SEM) is widely used to visualize fiber–matrix interfaces, pore morphology, particle bonding, biomass-burnout cavities, mycelial networks, and calcium-carbonate bridges. When coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), local elemental composition can be examined to distinguish mineral phases, ash-derived constituents, or precipitated calcium-rich regions.

X-ray diffraction (XRD) is used to identify crystalline phases and track mineralogical changes associated with firing, stabilization, ash incorporation, or biomineralization. Fourier-transform infrared spectroscopy (FTIR) provides complementary information on chemical functional groups, including changes in lignocellulosic constituents, biopolymers, fungal materials, and mineral–organic interactions. Thermal-analysis techniques further clarify transformation mechanisms: thermogravimetric analysis (TGA) quantifies mass losses associated with moisture removal and thermal decomposition, while differential scanning calorimetry (DSC) and differential thermal analysis (DTA) identify endothermic and exothermic transitions related to biomass degradation, mineral reactions, and phase-change behavior.

The principal microstructural characterization techniques and the information provided by each are summarized in Figure 2. The principal microstructural characterization techniques and the information provided by each are summarized in Figure 2. Together, these techniques link manufacturing conditions to material architecture. This relationship is synthesized in Section 7.8 through the processing–microstructure–property–application framework.

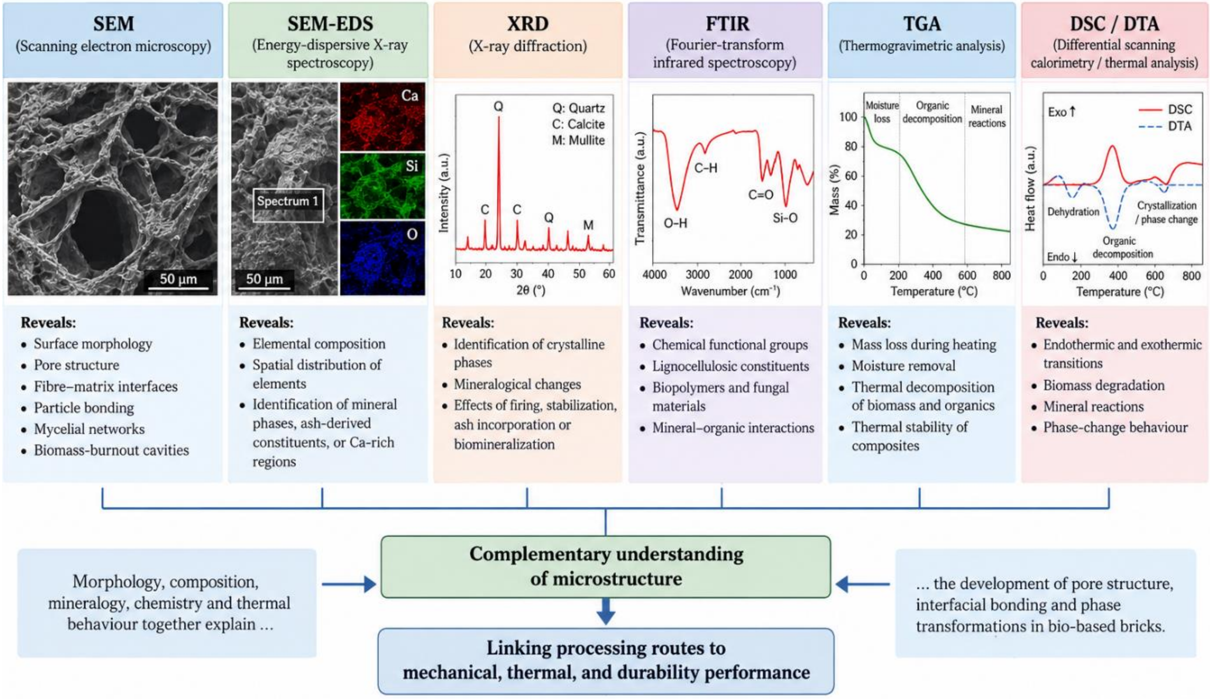

Figure 2. Overview of microstructural characterization techniques used for bio-based and bio-derived bricks, showing the type of information provided by each method and example outputs.

7.8. Fundamental Processing–Structure Relationships

The reviewed systems can be interpreted through the general sequence processing → microstructure → properties → application. Manufacturing conditions determine how the biological or bio-derived constituent is incorporated, transformed, or activated within the brick. Compaction influences particle packing and interfacial contact, firing controls biomass burnout and ceramic sintering, pyrolysis determines biochar pore architecture, fungal cultivation establishes hyphal connectivity, and MICP/EICP governs the distribution of carbonate bonds. These processing routes therefore generate distinct microstructures characterized by variations in porosity, pore connectivity, interfacial adhesion, matrix continuity, mineral bridging, and biological network formation.

The resulting microstructure governs macroscopic behavior. Increased porosity generally favors lightweighting and lower thermal conductivity but may reduce strength and increase moisture uptake, whereas improved fiber–matrix bonding, ceramic densification, hyphal bridging, or calcium-carbonate cementation can enhance mechanical integrity. These property combinations ultimately determine whether a material is suitable for load-bearing masonry, non-load-bearing walls, thermal insulation, acoustic applications, or multifunctional building-envelope systems.

8. Physical Properties

Physical properties provide the first macroscopic indication of how biological constituents alter brick architecture. Across the reviewed systems, the most recurrent changes involve density, porosity, and moisture uptake, although the magnitude and direction of these effects depend strongly on whether the biological phase is retained, combusted during firing, converted to a porous derivative such as biochar, or involved in biological mineralization.

8.1. Bulk Density and Apparent Porosity

A recurring trend across natural-fiber, bioaggregate, mycelium, biochar, and biomass-modified fired bricks is a reduction in bulk density with increasing incorporation of low-density biological constituents. This effect results from both the lower intrinsic density of biomass relative to mineral matrices and the additional voids introduced by irregular particle packing, fiber–matrix interfaces, or biomass burnout. Earth bricks containing plant aggregates and fired clay bricks containing straw, rice husk, sawdust, or other agricultural residues therefore commonly exhibit increasing porosity and decreasing density as bio-content rises (Aouba et al., 2016; Laborel-Préneron et al., 2017; Alabduljabbar et al., 2021; Atan et al., 2021). Similar lightweighting is observed in palm-shell, biochar, and mycelium-based systems (Claudel et al., 2025; Paul et al., 2026; Waskar & Anadinni, 2026).

The density–porosity relationship is nevertheless processing-dependent. In fired systems, organic burnout generates pores while sintering tends to close or refine them, making firing temperature a major control variable. In unfired composites, compaction pressure, particle size, and fiber dispersion determine whether the biological phase produces uniformly distributed pores or larger interfacial defects. Biomineralized systems behave differently because calcium carbonate precipitation can partially fill pore spaces and increase contact density between particles. Thus, bio-content alone cannot predict density or porosity without considering the corresponding matrix and processing route.

8.2. Water Absorption, Sorptivity, and Capillary Uptake

Moisture-related physical properties are particularly important because many biological constituents are hydrophilic and because increased porosity frequently accompanies biomass incorporation. Higher bio-content often increases water absorption by introducing additional open pores, interfacial voids, and lignocellulosic surfaces capable of retaining water. This tendency has been reported in fiber-reinforced earth bricks, biomass-containing fired bricks, and lightweight biocomposites, although the extent varies considerably with pore connectivity and matrix densification (Khoudja et al., 2021; Alabduljabbar et al., 2021; Boussaa et al., 2023).

Total water absorption, however, does not fully describe moisture transport. Sorptivity and capillary absorption depend primarily on the connectivity, size distribution, and tortuosity of the open pore network. A highly porous brick may exhibit relatively moderate capillary transport if much of its pore volume is isolated, whereas a lower-porosity material with interconnected capillaries may absorb water rapidly. Surface treatment, stabilization, increased compaction, ceramic sintering, or carbonate precipitation can reduce effective pore connectivity and thereby limit moisture ingress. This distinction is important when comparing thermal-insulating bio-bricks, since the pore structure responsible for low density and thermal conductivity may simultaneously increase susceptibility to liquid-water penetration.

8.3. Dimensional Stability, Efflorescence, and Overall Biomass-Content Effects

Shrinkage and dimensional stability are influenced by the moisture sensitivity of both the matrix and the biological constituent. In unfired earth-based systems, drying shrinkage arises primarily from water loss and clay contraction, while fibers and bioaggregates can either restrain cracking or increase dimensional instability depending on their dosage, dispersion, and water demand (Wang & Abuel-Naga, 2025). In fired clay systems, dimensional changes occur during both drying and firing. Organic additives may increase the water required for shaping and subsequently increase drying shrinkage, while burnout and ceramic sintering further modify the final dimensions (Demir, 2008; Lewo Nkondi et al., 2025). Demir (2008), for example, found increasing drying and total shrinkage with increasing organic-residue content.

Efflorescence is associated with the transport of soluble salts to the brick surface and their crystallization during moisture evaporation. Its occurrence therefore depends on raw-material chemistry, pore connectivity, moisture movement, and drying conditions rather than on biological content alone. Reviews of fired brick production indicate that inadequate drying conditions and soluble salts can contribute to surface efflorescence, while water absorption and pore structure remain closely related to susceptibility to moisture-driven deterioration (Lewo Nkondi et al., 2025). However, efflorescence is reported much less systematically than density, porosity, water absorption, or strength across the bio-based brick literature, which limits robust cross-study comparison.

Increasing biomass content most commonly produces the coupled trend of lower density and higher porosity, often accompanied by greater water absorption and, in some systems, increased shrinkage (Demir, 2008; Aouba et al., 2016; Alabduljabbar et al., 2021; Lewo Nkondi et al., 2025). These relationships are not universally monotonic because particle grading, fiber treatment, compaction, firing temperature, binder chemistry, and biomineralization can substantially modify pore connectivity and matrix continuity. The resulting physical-property changes form the basis for the mechanical, thermal, and hygrothermal trade-offs examined in the following sections.

9. Mechanical Performance

Mechanical performance determines whether bio-based and bio-derived bricks can function as structural masonry units, non-load-bearing elements, or primarily as insulating components. Reported strengths vary widely because the reviewed materials encompass fundamentally different matrices and bonding mechanisms, ranging from porous mycelium composites to fired ceramics and biomineralized sand. Consequently, comparisons based solely on biomass content are insufficient; matrix continuity, porosity, interfacial bonding, compaction, firing or curing conditions, and biological cementation must also be considered.

9.1. Compressive Strength

Compressive strength is the most frequently reported mechanical property and exhibits the clearest trade-off with lightweighting and pore development. In many lignocellulosic systems, increasing biomass content reduces strength because low-density particles replace stronger mineral phases and introduce additional pores or weak interfaces. For example, increasing palm-shell content in unfired clay bricks reduced compressive strength from 4.64 to 0.12 MPa, while increasing paddy-stubble biochar similarly reduced strength as the material became lighter and more porous (Claudel et al., 2025; Paul et al., 2026). Mycelium-based materials generally occupy the lower-strength range, although optimization of substrate grading, fungal growth, and pressing can substantially improve their resistance (Waskar & Anadinni, 2026).

This relationship is not universal. Appropriate constituent dosage, interfacial modification, mineral reactions, or thermal processing can partly compensate for biomass-induced porosity. Corn-residue-modified fired clay bricks, for example, achieved 6.81 MPa compared with 4.15 MPa for the corresponding clay control (Utami et al., 2021), while chitosan modification increased the reported compressive strength of fired clay compositions despite the development of a more porous microstructure (Shahat & Soliman, 2025). Mineral-rich bio-derived systems can reach still higher strengths: eggshell-containing ceramic bricks achieved 10.5 MPa (Ibrahim et al., 2022), and biomass–seashell alkali-activated bricks reached approximately 10–11.2 MPa under the reported curing conditions (Rao et al., 2024).

Biological cementation provides a different strengthening mechanism. MICP-treated sandstone-like bricks reached approximately 9 MPa through calcium-carbonate bridging between granular particles (Cheng et al., 2020), demonstrating that substantial masonry-scale strength can be obtained without conventional ceramic firing. Conversely, highly porous biochar and mycelium systems remain more appropriate for non-structural or insulating applications. As summarized in Table 3, compressive strength therefore spans more than an order of magnitude across the reviewed technologies, emphasizing that application suitability should be evaluated according to the complete material architecture and processing route rather than under a single generic bio-brick classification.

9.2. Flexural Strength

Flexural strength is reported less frequently than compressive strength but is particularly informative for fiber-reinforced and biomineralized bricks because it reflects crack initiation and post-cracking load transfer. Natural fibers can improve bending resistance even when increasing porosity reduces compressive strength. In recycled-aggregate bricks, for example, increasing sisal-fiber content from 0 to 2% increased flexural strength from 2.8 to 5.2 MPa, an 85.7% improvement attributed to fiber bridging and stress redistribution across developing cracks (Zhang et al., 2024). In fired clay systems, however, the benefit depends strongly on biomass dosage and the resulting pore structure. Aouba et al. (2016) observed slight increases in bending strength at low additions of wheat straw or olive stone flour, whereas higher biomass contents progressively reduced bending resistance as porosity increased.

Biologically cemented systems show a similar dependence on the continuity of the reinforcing or binding network. EICP–alginate bio-bricks exhibited flexural strengths of approximately 1–2.5 MPa (Arab et al., 2021), while fiber reinforcement of MICP-treated bricks improved both flexural response and deformation capacity (Liu et al., 2021). Flexural performance is governed less by bio-content alone than by the ability of fibers, polymeric binders, or mineral bridges to maintain stress transfer after matrix cracking.

Table 3. Representative compressive-strength performance of bio-based, bio-derived, and biologically fabricated brick systems

Study	Bio-source and matrix	Processing	Representative bio-content	Density (kg/m³)	Compressive strength (MPa)
Aouba et al. (2016)	Wheat straw / fired clay	920 °C, 1 h	5 wt% WS	1660	21.4
Aouba et al. (2016)	Olive stone flour / fired clay	920 °C, 1 h	5 wt% OSF	1730	30.5
Atan et al. (2021)	Hazelnut shell + red mud / clay	900 °C, 2 h	10% HS + 30% RM	1420	9.12
Ibrahim et al. (2022)	Eggshell / ceramic matrix	950 °C	20 wt%	1400	10.5
Zhang et al. (2024)	Sisal fiber / cementitious recycled aggregate	28 d curing	1 vol% fiber	NR	36.2
Kamar et al. (2025)	Kenaf core + bio-adhesive / cement	28 d air curing	25% KC + 12% BD	1555	10.22
Pandey et al. (2026)	Wheat fiber + rice husk / epoxy	24 h curing	70 wt% biomass	NR	21.5
Paul et al. (2026)	Paddy-stubble biochar + powder / lime	Unfired	35% BC + 35% PSP	750	0.60
Waskar & Anadinni (2026)	Bagasse + mycelium	Cultivation + pressing	70 vol% bagasse	475–490†	1.85
Cheng et al. (2020)	Microbial cementation / sand	MICP	Treatment-based	NR	≈9

*Measured value; corrected value reported by the authors is approximately 6.64 MPa.
†Density range reported for the high-performing M10–M12 formulations.
NR = not reported for the selected formulation.

9.3. Tensile and Splitting Strength

Direct tensile and splitting-tensile strength are much less systematically reported than compressive or flexural strength in the reviewed bio-brick literature. Consequently, a robust quantitative comparison across technological families is not presently possible. This is an important limitation because tensile resistance governs crack initiation, fracture propagation, and the capacity of masonry units to tolerate handling, restraint, and local stress concentrations.

Where fibrous biological constituents are used, the principal tensile-strengthening mechanisms are fiber bridging, crack deflection, mechanical interlocking, and fiber pull-out. These mechanisms can delay unstable crack propagation even when the fibers do not increase compressive strength. The strong flexural improvement reported for sisal-reinforced recycled bricks is consistent with this mechanism (Zhang et al., 2024). In polymer-based wheat–rice-fiber bricks, compression tests also revealed vertical splitting and wedge-splitting failure, with increasing interfacial debonding and fiber pull-out under thermal exposure (Pandey et al., 2026). These observations demonstrate the importance of tensile-related failure mechanisms, but they should not be interpreted as direct splitting-tensile strength measurements. More standardized direct and indirect tensile testing is therefore required to establish reliable design values for bio-based masonry units.

9.4. Stress–Strain Behavior

Stress–strain behavior provides information that strength values alone cannot capture, particularly stiffness, deformability, post-peak response, and failure mode. Conventional mineral bricks generally exhibit relatively stiff and brittle behavior, whereas incorporation of fibrous or polymeric biological phases can increase deformation capacity through crack bridging and progressive interfacial debonding. Zhang et al. (2024) reported that sisal reinforcement transformed the response of recycled-aggregate bricks from a comparatively brittle post-peak drop toward a more nonlinear and deformable response. At the same time, the elastic modulus decreased from 18.5 to 14.2 GPa as fiber content increased to 2%, illustrating the common trade-off between stiffness and toughness.

The effect of matrix condition is particularly evident in polymer-based bricks. Pandey et al. (2026) observed an approximately linear compressive response at room temperature, followed by increasing nonlinearity, stress fluctuations, and earlier failure as exposure temperature increased from 40 to 60 °C. These changes coincided with epoxy softening, microcracking, fiber–matrix debonding, and fiber pull-out, while average compressive strength decreased from 21.5 MPa at room temperature to 10.8 MPa at 60 °C. Fiber reinforcement can also increase strain capacity in biomineralized bricks: Liu et al. (2021) reported an increase in flexural strain from approximately 1.0% to 2.3% following fiber reinforcement.

Taken together, the available evidence indicates that biological reinforcement may reduce stiffness while increasing deformability and resistance to abrupt cracking. However, full stress–strain curves, elastic modulus, peak strain, and post-peak energy absorption remain inconsistently reported. This limits quantitative comparison of toughness and ductility across bio-based, bio-derived, and biologically fabricated brick systems.

9.5. Failure Mechanisms

Failure mechanisms differ markedly among the reviewed brick families because load transfer is controlled by different microstructural features. Fired clay and other mineral-dominated bricks generally exhibit brittle fracture, with limited deformation after peak load. Increasing biomass-derived porosity can intensify this behavior by reducing the effective load-bearing area and introducing stress concentrations around pores. In fired biomass-modified bricks, strength loss is therefore commonly associated with pore growth, reduced ceramic continuity, and local defects generated during burnout (Aouba et al., 2016; Alabduljabbar et al., 2021; Atan et al., 2021). In the sawdust-containing fired bricks of Alabduljabbar et al. (2021), higher sawdust contents reduced the number of effective clay–clay contacts and produced larger voids, resulting in a more easily crumbled matrix.

Fiber-reinforced systems exhibit more progressive failure. Before matrix cracking, fibers participate in stress transfer through the interface. Once cracks initiate, fiber bridging can restrain crack opening and redistribute tensile stresses, thereby increasing flexural resistance and deformation capacity. Zhang et al. (2024) showed that sisal fibers changed the response of recycled bricks from a brittle post-peak drop toward a more ductile and nonlinear behavior, consistent with crack bridging and stress redistribution. As loading progresses, however, failure may shift to interface debonding and fiber pull-out when interfacial shear stresses exceed the fiber–matrix bond strength. Pandey et al. (2026) observed vertical splitting and wedge-splitting together with increasing fiber pull-out and interfacial debonding, particularly after thermal exposure weakened the epoxy matrix. Thus, fiber reinforcement does not necessarily prevent fracture but can transform it from sudden brittle failure into a more energy-dissipative process.

Biologically fabricated bricks involve different bonding mechanisms. In mycelium-based composites, fungal hyphae grow around and between substrate particles, forming an interconnected biological network that provides particle bridging, surface adhesion, and mechanical interlocking (Ongpeng et al., 2020; Zhang et al., 2022). Failure therefore occurs through progressive rupture of the hyphal network, separation at hypha–substrate interfaces, and local substrate pull-out rather than through fracture of a continuous mineral matrix. Higher colonization and post-growth pressing can increase the number of effective contacts and delay this failure process, although direct fracture-mechanism characterization remains limited in the current literature.

In MICP- and EICP-based bricks, load transfer is provided primarily by calcium-carbonate precipitates that form mineral bridges at particle contacts. Failure initiates when these contact-scale bonds fracture or detach from the granular substrate, after which cracks propagate through weakly cemented regions or along non-uniformly mineralized interfaces (Bernardi et al., 2014; Cheng et al., 2020; Arab et al., 2021). Fiber reinforcement can further modify this mechanism by bridging cracks between mineralized particles and increasing strain capacity, as demonstrated for fiber-reinforced MICP bio-bricks (Liu et al., 2021). Failure behavior can therefore be interpreted as a progression from brittle matrix fracture → fiber-mediated crack bridging and pull-out → biological-network rupture → mineral-bond fracture, depending on the dominant material architecture and binding mechanism.

9.6. Influence of Bio-Content

The influence of bio-content on mechanical performance is strongly dependent on the role of the biological constituent. In fired clay systems, increasing biomass content generally reduces compressive strength because the organic phase burns out and leaves additional pores within the ceramic matrix. This trend is evident for wheat straw and olive stone flour, where increasing biomass content progressively reduced compressive strength as porosity increased (Aouba et al., 2016), and for sawdust-modified bricks, where 4 and 8 wt% additions reduced compressive strength by approximately 22% and 48%, respectively (Alabduljabbar et al., 2021). Similar behavior was observed for hazelnut-shell/red-mud bricks, although higher firing temperature partly compensated for the loss through enhanced densification and vitrification (Atan et al., 2021).

In fiber-reinforced and binder-modified systems, the relationship may be non-monotonic. Low-to-moderate fiber contents can improve crack bridging, flexural resistance, and post-cracking behavior, whereas excessive fiber addition increases porosity, promotes agglomeration, and weakens matrix continuity. Zhang et al. (2024), for example, obtained maximum compressive strength at 1 vol% sisal fiber, while higher contents reduced strength despite continued gains in flexural performance. A similar balance is evident in kenaf-core cement bricks: increasing kenaf content reduced strength markedly, but the addition of cellulose-based bio-adhesive partly restored interfacial bonding and compressive resistance (Kamar et al., 2025).

For mycelium and biomineralized bricks, "bio-content" cannot be interpreted simply as a mass or volume fraction. In mycelium composites, strength depends on the combined effects of substrate fraction, spawn content, growth duration, particle-size distribution, and post-growth pressing. Waskar and Anadinni (2026), for instance, obtained their highest compressive strength with the lower end of the tested bagasse range combined with higher spawn content and stronger pressing, indicating that greater biological feedstock content does not necessarily produce greater mechanical performance. In MICP/EICP systems, mechanical development is governed more directly by treatment intensity and the amount and distribution of carbonate precipitation than by conventional bio-content. The recurring trend is that increasing biological content enhances lightweighting and, in many cases, thermal performance, but mechanical performance reaches an optimum only when pore formation, interfacial bonding, and matrix continuity remain adequately balanced.

9.7. Structural and Non-Structural Suitability

A central finding of the reviewed literature is that "bio-brick" does not describe a mechanically uniform class of masonry units. As shown in Table 3, reported compressive strengths span from well below 1 MPa in highly porous lightweight systems to more than 30 MPa in fiber-reinforced cementitious or fired ceramic bricks. This wide range arises because the term encompasses fundamentally different material architectures, including unfired lignocellulosic composites, fired pore-engineered ceramics, polymer biocomposites, mycelium-bound units, and biomineralized granular materials. Direct classification based solely on biological origin is therefore inappropriate.

Some systems attain strength levels compatible with conventional masonry applications. Sisal-reinforced recycled-aggregate bricks reached 36.2 MPa, while fired olive-stone-flour bricks achieved 30.5 MPa and wheat–rice fiber epoxy bricks 21.5 MPa (Aouba et al., 2016; Zhang et al., 2024; Pandey et al., 2026). Other materials occupy an intermediate range. Kenaf-core cement bricks with bio-adhesive reached 10.22 MPa, while hazelnut-shell/red-mud fired bricks achieved approximately 9.12 MPa measured strength for the high-waste formulation (Kamar et al., 2025; Atan et al., 2021). These materials may be suitable for masonry applications depending on the applicable standard, unit geometry, durability, and loading conditions.

At the lower-strength end, highly porous mycelium, biochar, and some high-biomass unfired systems are more appropriately regarded as non-load-bearing, partition, infill, or insulation materials. Mycelium-bound bagasse bricks, for example, reached a maximum compressive strength of 1.85 MPa and were explicitly positioned for non-structural insulation, partition walls, and filler applications (Waskar & Anadinni, 2026). Their lower strength is accompanied by very low density and thermal conductivity, illustrating that mechanical performance is often intentionally traded for lightweighting and insulation.

Accordingly, compressive strength alone should not be used to label a bio-brick as structural. Structural suitability also requires consideration of specimen size and test method, flexural and tensile behavior, moisture sensitivity, durability, dimensional stability, fire performance, and compliance with masonry standards. The very large variation in Table 3 therefore supports treating bio-based, bio-derived, and biologically fabricated bricks as distinct engineering material classes with different application envelopes, rather than as interchangeable sustainable substitutes for conventional masonry.

10. Thermal and Thermophysical Performance

Thermal performance is one of the principal motivations for incorporating biological and bio-derived constituents into masonry units. Across the reviewed literature, the most consistent effect is a reduction in thermal conductivity associated with lightweighting and increased pore volume. In its simplest form, the recurring relationship can be expressed as

$$\rho \downarrow \Rightarrow k \downarrow$$

where ρ is bulk density and k is thermal conductivity. As shown in Table 4, this trend is evident across fired biomass-modified ceramics, unfired biocomposites, biochar-containing bricks, and mycelium-bound materials. However, density alone does not determine heat transfer. Pore size, connectivity, moisture content, mineral composition, interfacial structure, firing-induced vitrification, and the intrinsic conductivity of the constituent phases can produce substantial variation between materials of similar density.

Thermal conductivity is by far the most frequently reported thermophysical parameter. In fired clay bricks, biomass generally functions as a pore-forming agent after combustion. Aouba et al. (2016) showed that 5 wt% wheat straw reduced density to 1660 kg/m³ and thermal conductivity to 0.36 W/(m·K), compared with approximately 1977 kg/m³ and 0.52 W/(m·K) for the reference clay. Olive stone flour produced a smaller conductivity reduction at comparable biomass content, demonstrating that feedstock morphology and resulting pore-size distribution are important in addition to total porosity. Similarly, Atan et al. (2021) reduced conductivity from 0.76 to 0.45 W/(m·K) by incorporating 10 wt% hazelnut shell and 30 wt% red mud, while density fell from approximately 1770 to 1420 kg/m³.

The range in Table 4 is very wide, from approximately 0.45 W/(m·K) for a porous fired ceramic containing hazelnut-shell/red-mud waste to only 0.026 W/(m·K) for the optimized mycelium–bagasse composite. The latter combines extremely low density with a highly porous lignocellulosic structure and closed-cell refinement induced by biological growth and pressing. The eggshell-based ceramic system also achieved a relatively low conductivity of 0.27 W/(m·K) at a density of 1.4 g/cm³, illustrating that thermally favorable performance can also arise from mineral transformation rather than retained lignocellulosic porosity. Mushroom-waste clay bricks provide another clear density–conductivity relationship: at 15% waste content, density decreased from 1922 to 1419 kg/m³ while conductivity decreased from 0.77 to 0.293 W/(m·K).

Thermal diffusivity, α, describes the rate at which a temperature disturbance propagates through a material and depends jointly on thermal conductivity, density, and specific heat capacity. It is considerably less frequently reported than conductivity. This gap is important because two materials with similar k values may respond differently under transient thermal loading. Chitosan-modified fired bricks illustrate this distinction: increasing porosity and reducing density lowered both conductivity and diffusivity, with reported diffusivity values decreasing approximately from 0.314 to 0.213 mm²/s across the studied compositions (Shahat & Soliman, 2025). Measurements on adobe and related natural-fiber composites similarly demonstrate that conductivity and heat capacity must be considered together when estimating diffusivity and thermal response.

Table 4. Representative thermal-conductivity performance of bio-based, bio-derived, and biologically fabricated brick systems

Study	**Bio-source**	**Matrix**	**Density (kg/m³)**	**Bio-content**	**k (W/m·K)**	**Test method**
Aouba et al. (2016)	Wheat straw	Fired clay	1660	5 wt%	0.36	Asymmetric hot-plate / effusivity
Atan et al. (2021)	Hazelnut shell + red mud	Fired clay	1420	10% HS + 30% RM	0.45	Modified transient plane source
Ibrahim et al. (2022)	Eggshell	Zeolite-poor ceramic	1400	20 wt%	0.27	NR
Elhady et al. (2025)	Mushroom waste	Clay brick	1419	15%	0.293	NR
Shahat & Soliman (2025)	Chitosan	Fired clay	1840→ 1290	0–8%	0.342→ 0.233	NR
Jaramillo et al. (2025b)	Coffee-husk lignin + bovine excreta	Cementitious	NR	225 g lignin + 315 g excreta	≈0.19	NR
Paul et al. (2026)	Paddy-stubble biochar/powder	Lime-based	750→ 500	PSB 35–55%	0.181→ 0.172	NR
Waskar & Anadinni (2026)	Bagasse + mycelium	Mycelium composite	475–490*	70 vol% bagasse + 10 wt% spawn	0.026	Steady-state heat-flow method

*Density range reported for the high-performing M10–M12 formulations; an individual M12 density was not isolated. NR = not reported in the available source information.

Specific heat capacity is even less systematically characterized. Nevertheless, it is critical for assessing heat-storage capacity and therefore thermal inertia. Bioaggregates can exhibit relatively high specific heat compared with many dense mineral phases, although their lower density may offset this benefit when heat storage is expressed volumetrically. For example, hemp–lime composites have been reported with specific heat capacities of approximately 1250–1557 J/(kg·K) and conductivities of 0.087–0.10 W/(m·K). Et-Tanteny et al. (2025) also explicitly evaluated specific heat capacity in biopolymer-modified unfired clay bricks, highlighting the need to assess heat-storage properties together with conductivity rather than treating k as the sole thermal-performance indicator.

At component and wall scales, thermal resistance integrates material conductivity with thickness and geometry. Consequently, low-conductivity biocomposites can provide substantial resistance when incorporated into sufficiently thick or hollow masonry systems. Harb et al. (2023), for example, combined numerical analysis with a 1 × 1 m experimental wall built from starch/beet-pulp composite bricks. Equivalent thermal resistances of approximately 1.10–1.22 m²·K/W were obtained, and a 23 °C temperature difference applied for 7 h produced only about a 3 °C variation at the opposite wall surface. These results also demonstrate why material-scale conductivity values cannot be directly equated with wall-scale thermal performance, which additionally depends on brick geometry, cavities, joints, wall thickness, and surface heat-transfer conditions.

Thermal inertia describes the ability of the wall system to absorb, store, and subsequently release heat. It therefore depends on the combined effects of density, specific heat, conductivity, and wall thickness. Lightweighting usually decreases volumetric heat capacity because the amount of solid matter per unit volume is reduced. Thus, a very low-density brick may provide excellent insulation but lower sensible heat-storage capacity than a dense ceramic unit. This distinction becomes especially important in climates with large diurnal temperature fluctuations. Bio-derived PCMs provide an alternative mechanism by adding latent rather than solely sensible heat storage. Biochar-supported PCM incorporated into masonry has been shown to delay heat transmission and reduce indoor temperatures, while PCM-filled AAC bricks produced reductions in inner-surface temperature of approximately 3 °C in transient analyses. Biochar-supported PCM walls have likewise produced indoor-temperature reductions of up to 5.8 °C and substantial simulated cooling-energy savings.

Dynamic thermal behavior is more directly represented by time lag and decrement factor. Time lag measures the delay between an exterior temperature fluctuation and the corresponding interior response, whereas the decrement factor describes attenuation of the temperature-wave amplitude through the wall. These parameters remain uncommon in the bio-brick literature, but available studies indicate that biological modification can improve both. Et-Tanteny et al. (2025), for example, reported through TRNSYS simulations a 9.74% increase in time lag and a 16% reduction in decrement factor for biopolymer-modified unfired clay bricks. Such dynamic indicators are particularly valuable because they connect material properties to actual building-envelope performance more directly than steady-state conductivity alone.

Across all systems, pore architecture provides the principal link between bio-content, density, and thermal transport. Air-filled pores interrupt solid conduction paths, so increased porosity generally lowers both density and conductivity. This explains the recurring trend $\rho\downarrow \Rightarrow k\downarrow$. Nevertheless, the relationship is not universal or uniquely defined. Aouba et al. (2016) demonstrated that wheat-straw and olive-stone-flour bricks with similar densities could exhibit different conductivities because their pore-size distributions differed. Atan et al. (2021) similarly showed that higher firing temperature partly closed pores through densification, producing simultaneous increases in density, conductivity, and mechanical strength. More broadly, mineral phases such as quartz and Ca-rich silicates, pore connectivity, specific surface area, retained moisture, and the distinction between open and closed porosity can all shift thermal conductivity independently of bulk density.

Accordingly, thermal performance should be interpreted through the same processing–microstructure–property–application framework used for mechanical behavior. Biological additions can improve insulation through lightweighting and pore formation, but an optimum building material must balance conductivity with heat capacity, moisture response, mechanical integrity, and dynamic thermal performance. The available literature is already comparatively mature with respect to thermal conductivity, whereas thermal diffusivity, specific heat capacity, thermal inertia, time lag, and decrement factor remain much less consistently reported, representing an important gap for future comparative evaluation of bio-based masonry systems.

11. Durability and Service-Life Performance

Durability remains one of the least consistently characterized aspects of bio-based brick research. Moisture-related deterioration is particularly important because lignocellulosic constituents, open pore networks, and weakly stabilized matrices can promote water ingress, swelling, interface degradation, and surface erosion. This limitation is especially evident in biomineralized systems. MICP bio-bricks have been reported to exhibit relatively low water resistance, while fiber reinforcement and repeated MICP treatment substantially improved resistance to accelerated water erosion by strengthening the cemented particle network and bridging developing cracks (Liu et al., 2021). In compressed-earth systems, water durability also depends strongly on stabilizer chemistry and pore structure. Boussaa et al. (2023), for example, found different capillary-water responses for bricks containing two wood-biomass ashes, demonstrating that nominally similar bio-derived additives can produce different moisture resistance because of their mineralogical composition and resulting microstructure.

Wet–dry cycling and freeze–thaw resistance are much less frequently investigated than initial water absorption. These mechanisms are nevertheless critical because repeated moisture expansion, drying shrinkage, and ice formation can progressively enlarge pores and interfacial cracks. Reviews of unfired bricks identify wet–dry and freeze–thaw resistance as key durability indicators, but reporting remains inconsistent across bio-based formulations. The problem is particularly pronounced for highly porous mycelium composites. Recent masonry-scale mycelium studies still characterize mainly short-term mechanical, moisture, and thermal properties, while cyclic wetting–drying, freeze–thaw resistance, biodegradation, and environmental weathering remain untested.

Salt crystallization and efflorescence provide additional indicators of moisture-mediated durability. MICP-produced bricks tested by Cheng et al. (2020) exhibited approximately 10% water absorption and only about 0.5 g mass loss under salt attack, indicating that sufficiently developed carbonate cementation can provide reasonable resistance to saline exposure. Efflorescence is reported more sporadically. Bio-briquette-ash bricks have been evaluated against Indian Standard requirements for efflorescence and general durability (Sakhare & Ralegaonkar, 2016), while paddy-stubble-biochar bricks showed no visible salt deposits in the reported efflorescence test. These observations are useful, but they remain insufficient to establish long-term salt-crystallization resistance under repeated exposure.

Biological deterioration is more specific to systems in which organic matter remains in the final product. Retained fibers, starches, lignocellulosic aggregates, and fungal matrices can be susceptible to moisture-assisted decay, microbial colonization, or loss of interfacial integrity. Mycelium composites present a particular paradox because biodegradability is environmentally attractive at end of life but potentially problematic during service. Existing reviews therefore identify high water absorption, weathering susceptibility, and uncertain long-term durability as major barriers to wider construction use. Evidence for resistance to unwanted biological attack is still limited. Fernández et al. (2025) reported a citrus-peel/mycelium composite with added resistance to biodeterioration and insect-repellent activity associated with residual limonene, but such results should not be interpreted as establishing general fungal or mold resistance for mycelium-based bricks.

Environmental safety is particularly important when biological materials are combined with industrial residues containing potentially hazardous elements. Atan et al. (2021) evaluated this issue by subjecting both the reference and highest-waste brick formulations to TCLP leaching tests followed by ICP-MS analysis. For bricks containing 10% hazelnut shell and 30% red mud, the measured concentrations of Cr, Ni, Cu, Zn, As, Cd, Ba, Hg, and Pb remained below the relevant regulatory limits, indicating effective immobilization of potentially hazardous constituents during firing. These results suggest that the ceramic matrix can retain red-mud-associated heavy metals, allowing firing to contribute simultaneously to waste valorization and reduced leaching risk.

The durability evidence is substantially weaker than the mechanical and thermal evidence. Most studies rely on short-duration water absorption, capillary uptake, isolated salt or efflorescence tests, or laboratory-scale accelerated exposure. Long-term outdoor weathering, repeated wet–dry and freeze–thaw cycling, biological degradation, fungal or mold resistance, sustained salt crystallization, and aging-related strength retention are rarely investigated systematically. The service-life performance of many bio-based bricks therefore remains uncertain even when initial strength and thermal properties are promising. Future work should move from short-term property screening toward multi-cycle accelerated aging, outdoor exposure, residual-property testing, and leaching assessment before and after aging, allowing durability to be evaluated as part of the full processing–microstructure–property–service-life relationship.

12. Fire and High-Temperature Performance

Fire performance varies fundamentally with whether the biological constituent remains in the finished brick or is eliminated during processing. In fired clay systems, lignocellulosic additives are largely decomposed and combusted during firing, leaving a porous mineral skeleton. Their principal influence on subsequent fire behavior is therefore indirect, through the pore structure and ceramic matrix. In unfired lignocellulosic, polymeric, biochar, and mycelium systems, however, combustible organic phases remain and may contribute to ignition, flame spread, charring, and loss of mechanical integrity. Direct standardized measurements of ignition time, flame spread, heat-release rate, and smoke production are nevertheless uncommon in the reviewed brick literature.

Thermal decomposition follows the chemistry of the retained bio-component. Lignocellulosic materials undergo moisture release followed by degradation of hemicellulose, cellulose, and lignin over progressively higher temperature ranges. In palm-shell/clay composites, thermal analysis identified moisture loss near 188 °C, major cellulose degradation around 314 °C, and subsequent mineral transformations above 500 °C (Claudel et al., 2025). Such transformations can increase porosity, disrupt interfaces, and reduce load transfer when the organic phase remains important to the material architecture.

Available high-temperature mechanical evidence confirms this sensitivity. Pandey et al. (2026) reported a decrease in compressive strength of wheat–rice fiber/epoxy bricks from 21.5 MPa at room temperature to approximately half that value at 60 °C, associated with polymer softening, interface degradation, and fiber pull-out. Mineral matrices can provide substantially greater thermal protection by isolating or encapsulating biological constituents. Similarly, surface protection can improve performance: plastered paddy-stubble-biochar bricks showed better fire resistance than unprotected specimens, indicating that mineral coatings can act as thermal barriers and delay direct exposure of combustible phases (Paul et al., 2026).

The largest uncertainty concerns highly organic and biologically fabricated materials. Mycelium and lignocellulosic bricks possess low density and favorable insulation properties, but their retained organic content makes fire safety a critical design constraint. Recent mycelium-brick studies explicitly acknowledge that fire resistance has not been adequately evaluated alongside mechanical and thermal performance. Consequently, low thermal conductivity should not be interpreted as evidence of adequate fire resistance. Wider construction use will require standardized assessment of ignitability, flame spread, heat and smoke release, char formation, residual strength after heating, and the effectiveness of mineral binders, coatings, or other fire-protection strategies.

13. Environmental Sustainability and Circularity

The environmental case for bio-based bricks rests primarily on waste valorization, substitution of virgin mineral resources, and avoidance or reduction of energy-intensive processing, but these benefits are highly route-dependent. Agricultural residues, food-processing wastes, biomass ash, biochar, and other secondary resources can displace clay, sand, aggregates, or conventional binders and divert wastes from disposal (Türkan et al., 2026; Öncül et al., 2025; Çevik & Diambu, 2024; Diambu & Çevik, 2024). However, waste incorporation alone does not establish environmental superiority. Fired bio-derived bricks still require kiln energy, cementitious systems retain impacts associated with clinker production, and polymer-bound composites may introduce substantial embodied impacts despite high agricultural-waste contents. Consequently, environmental performance should be assessed independently from the mechanical datasets discussed earlier.

The strongest advantage generally occurs where biological feedstocks are combined with low-temperature or unfired production. Mycelium-based and other biologically fabricated systems avoid conventional ceramic firing and cement clinker production, but their environmental burdens are not negligible. Stelzer et al. (2021) showed that electricity for sterilization, incubation, and drying accounted for 81.4% of the climate-change impact of fungal composite bricks, demonstrating that low processing temperature does not automatically imply low energy demand. Waskar and Anadinni (2026) reported a cradle-to-gate GWP of approximately 32 kg CO_2-eq/m^3, compared with about 180 kg CO_2-eq/m^3 for fired clay bricks, largely because kiln firing and clinker production were avoided. These results are promising but remain sensitive to electricity source, drying strategy, transport distances, and production scale.

Life-cycle comparisons require particular caution regarding functional units and system boundaries. Many studies are cradle-to-gate and therefore omit service life, maintenance, replacement, demolition, and end-of-life treatment. Waskar and Anadinni (2026), for example, used a functional unit of 1 m^3 and included raw-material collection, substrate processing, inoculation, incubation, drying, and pressing, while comparison data for conventional materials came from secondary databases. The authors also acknowledge that their LCA relies on laboratory-scale assumptions that may differ under industrial production. Comparisons based only on mass or volume can therefore favor very lightweight materials even when their load-bearing capacity, durability, or replacement frequency differs. Performance-equivalent functional units are preferable where possible.

Biogenic carbon introduces another methodological issue. Carbon incorporated in retained biomass, mycelium, or biochar may remain temporarily stored within the building, whereas biomass used as a pore former in fired bricks is largely oxidized during manufacture and should not be treated as long-term carbon storage. Likewise, biodegradation or combustion at end of life can return stored biogenic carbon to the atmosphere. Carbon-storage claims therefore depend on service life, end-of-life scenario, and accounting method and should not be presented as an intrinsic property of all bio-based bricks.

Circularity is similarly matrix-dependent. Unfired lignocellulosic and mycelium materials may offer potential for reuse or biodegradation, provided mineral coatings, synthetic resins, or chemical treatments do not prevent biological recovery. Fired clay and hybrid mineral bricks are more realistically reused as units or recycled as crushed ceramic/mineral material, while cementitious composites may be downcycled as aggregate. Separation and recovery become more difficult in polymer-bound and highly hybridized systems. Thus, greater bio-content does not necessarily mean greater circularity. The most credible circular-economy pathways combine secondary-feedstock use, minimal virgin-resource demand, low-impact processing, adequate service life, and a defined end-of-life route. Dedicated LCA studies and broader circular-material reviews should therefore be used to evaluate these claims separately from laboratory strength or thermal-performance studies, rather than assuming environmental benefit from material origin alone.

14. Economic Feasibility and Scalability

Economic feasibility depends less on the nominal price of the bio-feedstock than on the complete processing chain required to convert it into a consistent masonry material. Agricultural and industrial residues may be inexpensive or locally available, reducing transport and virgin-material demand. Locally sourced clay, biomass, rice husk, sawdust, and similar residues are therefore attractive where stable regional supplies exist. However, collection, sorting, washing, drying, grinding, fiber treatment, sterilization, and storage can offset the apparent raw-material advantage. Agricultural-waste reviews consequently identify feedstock variability, moisture sensitivity, preprocessing, and scalability as persistent barriers to industrial application.

Production energy is similarly route-dependent. Unfired systems can avoid kiln firing, but biological processing may introduce other energy-intensive stages. For mycelium composites, sterilization, incubation, and drying were identified as major environmental and energy burdens, while laboratory-to-industrial scale-up substantially reduced impacts through improved process efficiency (Stelzer et al., 2021). Mycelium manufacture also requires controlled growth periods, moisture regulation, and post-growth densification, introducing longer production cycles and biological variability than conventional brick forming. Fired bio-derived bricks face a different constraint: biomass burnout must be accommodated within industrial kiln schedules without incomplete combustion, cracking, or unacceptable production delays. Experimental sawdust bricks, for example, required specific staged drying and firing programs up to 850 °C, illustrating that waste incorporation may require modification of established ceramic-processing conditions. Industrial adoption of such waste additions nevertheless remains limited in some existing brick-production contexts.

Economic benefits can also arise during building operation when lower thermal conductivity reduces heating or cooling demand. Elhady et al. (2025) reported that walls incorporating 15% mushroom-waste bricks reduced annual cooling demand by 12.4%. A roughly 2% increase in initial cost was offset by estimated annual energy savings of 15.3–17.2%, with projected 10-year cost reductions of 12.5–15.6%. In a different multifunctional approach, biocomposite PCM walls reduced annual cooling demand by 31.4% and produced an estimated dynamic payback period of approximately 9 years. Such results are strongly climate-, energy-price-, wall-design-, and service-life-dependent and therefore should not be generalized to bio-bricks as a whole.

Scale-up barriers differ by technology. Mycelium systems require sterile or controlled cultivation, incubation space, drying, and management of biological variability. Natural-fiber bricks require reproducible fiber size, moisture content, treatment, and dispersion. MICP/EICP systems face reagent, delivery, and processing-time requirements, particularly because repeated mineralization treatments generally increase strength and durability, implying additional material and operational demand. Long curing periods can similarly reduce production throughput in cementitious and unfired systems. Ultimately, commercialization requires consistent feedstock quality, year-round supply, standardized preprocessing, compatibility with existing production lines, predictable curing or growth times, and demonstrable cost advantage at industrial rather than laboratory scales. Economic assessments remain much less common than mechanical or thermal studies, so current claims of low cost and scalability should generally be regarded as preliminary until validated through pilot-scale production and full techno-economic analysis.

15. Optimization, Numerical Modeling and Machine Learning

Optimization and predictive modeling are becoming increasingly important because bio-based brick performance is governed by interacting variables rather than bio-content alone. Feedstock fraction, particle size, fiber treatment, binder content, moisture, compaction, curing, firing temperature, biological-growth conditions, and treatment cycles can simultaneously affect strength, density, water absorption, and thermal performance. Accordingly, design of experiments (DoE) and mixture-design approaches provide a more efficient alternative to one-factor-at-a-time testing. Jaramillo et al. (2025a, 2025b), for example, used mixture design and Response Surface Methodology (RSM) to optimize cement–lignin–bovine-excreta formulations across multiple performance responses. Ganasen et al. (2024) similarly applied RSM-based machine-learning optimization to bio-sandcrete brick modeling.

RSM is particularly useful for identifying factor interactions, constructing response surfaces, and locating optimum compositions within a defined experimental domain. Artificial Neural Networks (ANNs) can represent more nonlinear relationships without prescribing a polynomial response form. Nakkeeran et al. (2024), using groundnut-shell contents between 20 and 60%, applied both approaches to predict compressive strength, density, and water absorption. Reported R^2 values exceeded 0.88 for RSM and 0.99 for ANN. These high values demonstrate fitting capability within the investigated dataset, but they should not automatically be interpreted as evidence of general predictive performance.

Waskar and Anadinni (2026) provide an especially instructive comparison. Their mycelium–bagasse brick study incorporated bagasse content, particle-size distribution, spawn content, moisture, cultivation duration, pressing pressure, and density into the modeling framework. Quadratic RSM models produced R^2 values of 0.997–1.000 for compressive strength, water absorption, sorptivity, and thermal conductivity, whereas the ANN produced only R^2=0.327. Importantly, the authors themselves noted that the near-perfect RSM values may indicate overfitting associated with limited dataset variability. The ANN results likewise illustrate that model convergence does not guarantee strong predictive ability when experimental data are noisy or insufficient.

Numerical modeling also extends experimental material properties to component and building scales. Atan et al. (2021) incorporated experimentally measured thermal conductivities into an ANSYS Fluent model of a perforated brick, thereby accounting for both material conductivity and brick geometry rather than relying on solid-specimen measurements alone. At the building scale, Elhady et al. (2025) used Grasshopper/Ladybug simulations to translate mushroom-waste-induced changes in density and conductivity into cooling-energy performance, predicting a 12.4% reduction in annual cooling demand for the selected wall configuration. Et-Tanteny et al. (2025) used TRNSYS to evaluate time lag and decrement factor, while biocomposite PCM brick studies have used EnergyPlus to estimate whole-building cooling-energy reductions.

Despite this progress, the present modeling literature is constrained by small experimental datasets, unusually high in-sample R^2 values, limited external validation, inconsistent input variables, and strong material specificity. Models trained on one biomass, matrix, curing regime, or geographical feedstock cannot be assumed transferable to another because particle morphology, chemistry, moisture sensitivity, and interface behavior differ substantially. Random train–test splitting of specimens derived from the same experimental campaign may also overestimate generalization compared with validation using independent batches, laboratories, or feedstocks. Predictive accuracy should therefore be demonstrated through cross-validation and external experimental datasets rather than goodness-of-fit statistics alone.

Future optimization should consequently move beyond maximizing a single response. The principal design problem is inherently multi-objective, requiring simultaneous balancing of compressive strength, thermal conductivity, density, moisture resistance, durability, bio-content, production energy, cost, and environmental impact. Coupling experimentally validated surrogate or machine-learning models with multi-objective optimization could therefore identify Pareto-optimal formulations rather than a single nominal "optimum." Such frameworks would be particularly valuable for resolving the recurring trade-off between lightweighting and insulation on one side and mechanical and durability performance on the other.

16. Conclusions

This review shows that bio-based bricks cannot be interpreted as a single material class or through a simple waste-substitution perspective. The principal conclusions are as follows:

1. Bio-based, bio-derived, and biologically fabricated bricks represent fundamentally different technological families. Fiber-reinforced earth bricks, agricultural-waste composites, pore-engineered fired ceramics, biopolymer-modified bricks, mycelium composites, biomineralized units, and multifunctional systems rely on different matrices, bonding mechanisms, and manufacturing routes. Their performance should therefore be assessed within clearly defined material architectures rather than under the generic label of "bio-brick."
2. Processing route is as important as biological feedstock. Biomass may remain as reinforcement, burn out as a pore former, be converted into biochar, or serve as a substrate for biological growth. Compaction, fiber treatment, firing, pyrolysis, fungal cultivation, and MICP/EICP treatment therefore strongly govern final performance. The most useful interpretive framework is processing → microstructure → properties → application.
3. Porosity is the central microstructural mediator linking bio-content with physical, thermal, mechanical, and moisture-related behavior. Increasing bio-content often lowers density and increases porosity through retained low-density biomass, interfacial voids, or biomass burnout. This generally reduces thermal conductivity but may also weaken matrix continuity and increase water uptake. Pore size, connectivity, and morphology are therefore as important as total porosity.
4. Thermal improvement frequently involves mechanical or moisture-related trade-offs. Lower density and thermal conductivity are often accompanied by reduced compressive strength, stiffness, or water resistance. Optimized interfaces, controlled fiber contents, ceramic densification, mineral precipitation, and hybrid binders can partly mitigate these penalties. The key design objective is therefore not maximum bio-content, but an appropriate balance among insulation, strength, moisture resistance, and durability.
5. Many current bio-based bricks are better suited to non-load-bearing and envelope applications than to primary structural masonry. Reported compressive strengths range from below 1 MPa to above 30 MPa, confirming that these materials are not mechanically equivalent. Lightweight partitions, infill walls, thermal and acoustic insulation, and multifunctional envelopes therefore represent the most immediate applications for many systems.
6. Mycelium and biomineralization introduce genuinely new manufacturing paradigms. Mycelium provides cohesion through hyphal growth, whereas MICP and EICP form mineral bonds through carbonate precipitation. These routes offer low-temperature or cement-reduced alternatives but remain constrained by biological variability, processing time, reagent demand, moisture sensitivity, treatment uniformity, and uncertain long-term durability.
7. Evidence becomes substantially weaker beyond laboratory-scale material characterization. Strength, density, water absorption, and thermal conductivity are widely reported, whereas long-term durability, fire behavior, wall-scale performance, building-energy response, life-cycle impacts, economics, and end-of-life remain much less studied. Sustainability claims should

therefore be treated cautiously unless supported by appropriate functional units, service-life assumptions, and scale-relevant data.

8. Future research should move from single-property waste substitution toward performance-balanced and standardized masonry systems. Mechanical, thermal, hygrothermal, durability, fire, environmental, and economic performance should be evaluated within integrated frameworks. Multi-objective optimization, larger datasets, external validation, standardized testing, pilot-scale production, and building-scale demonstrations will be essential for converting biological resources into predictable masonry systems with clearly defined application envelopes.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. All authors have read and approved the final version of the manuscript for submission.

References

Abdallah, Y. K., & Estévez, A. T. (2023). Biowelding 3D-printed biodigital brick of seashell-based biocomposite by *Pleurotus ostreatus* mycelium. *Biomimetics*, *8*(6), Article 504. https://doi.org/10.3390/biomimetics8060504

Abdellatef, Y., Khan, M. A., Khan, A., Alam, M. I., & Kavgic, M. (2020). Mechanical, thermal, and moisture buffering properties of novel insulating hemp-lime composite building materials. *Materials*, *13*(21), Article 5000. https://doi.org/10.3390/ma13215000

Abdullah, H., & Jamaai, A. K. (2016). Properties of eco-brick manufactured using kenaf fiber as matrix. *Journal of Applied and Physical Sciences*, *2*(1), 20–24.

Ahmad, W., McCormack, S. J., & Byrne, A. (2025). Biocomposites for sustainable construction: A review of material properties, applications, research gaps, and contribution to circular economy. *Journal of Building Engineering*, *105*, Article 112525. https://doi.org/10.1016/j.jobe.2025.112525

Akinwande, A. A., Adediran, A. A., Balogun, O. A., Olusoju, O. S., & Adesina, O. S. (2021). Influence of alkaline modification on selected properties of banana fiber paperbricks. *Scientific Reports*, *11*, Article 5793. https://doi.org/10.1038/s41598-021-85106-8

Alabduljabbar, H., Benjeddou, O., Elbechir Soussi, C., Khadimallah, M. A., & Alyousef, R. (2021). Effects of incorporating wood sawdust on the firing program and the physical and mechanical properties of fired clay bricks. *Journal of Building Engineering*, *35*, Article 102106. https://doi.org/10.1016/j.jobe.2020.102106

Alaneme, K. K., Anaele, J. U., Oke, T. M., Kareem, S. A., Adediran, M., Ajibuwa, O. A., & Anabaranze, Y. O. (2023). Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications. *Alexandria Engineering Journal*, *83*, 234–250. https://doi.org/10.1016/j.aej.2023.10.012

Aouba, L., Bories, C., Coutand, M., Perrin, B., & Lemercier, H. (2016). Properties of fired clay bricks with incorporated biomasses: Cases of olive stone flour and wheat straw residues. *Construction and Building Materials, 102*, 7–13. https://doi.org/10.1016/j.conbuildmat.2015.10.040

Arab, M. G., Omar, M., Almajed, A., Elbaz, Y., & Ahmed, A. H. (2021). Hybrid technique to produce bio-bricks using enzyme-induced carbonate precipitation (EICP) and sodium alginate biopolymer. *Construction and Building Materials*, *284*, Article 122846. https://doi.org/10.1016/j.conbuildmat.2021.122846

Ashour, T., Korjenic, A., & Korjenic, S. (2015). Equilibrium moisture content of earth bricks biocomposites stabilized with cement and gypsum. *Cement and Concrete Composites*, *59*, 18–25. https://doi.org/10.1016/j.cemconcomp.2015.03.005

Atan, E., Sutcu, M., & Cam, A. S. (2021). Combined effects of bayer process bauxite waste (red mud) and agricultural waste on technological properties of fired clay bricks. *Journal of Building Engineering*, *43*, Article 103194. https://doi.org/10.1016/j.jobe.2021.103194

Bernardi, D., DeJong, J. T., Montoya, B. M., & Martinez, B. C. (2014). Bio-bricks: Biologically cemented sandstone bricks. *Construction and Building Materials*, *55*, 462–469. https://doi.org/10.1016/j.conbuildmat.2014.01.019

Binici, H., Aksogan, O., & Shah, T. (2005). Investigation of fiber reinforced mud brick as a building material. *Construction and Building Materials*, *19*(4), 313–318. https://doi.org/10.1016/j.conbuildmat.2004.07.013

Biswas, S., Hossiney, N., Mohan, M. K., & Kumar, S. L. (2024). Valorisation of coffee husk as replacement of sand in alkali-activated bricks. *Case Studies in Construction Materials*, *21*, Article e03440. https://doi.org/10.1016/j.cscm.2024.e03440

Bordoloi, U., Das, B., & Kalita, P. (2025). Experimental investigation on biocomposite phase change material-filled bricks for passive temperature regulation in buildings in a hot and humid climate. *Journal of Energy Storage*, *139*, Article 118761. https://doi.org/10.1016/j.est.2025.118761

Bordoloi, U., & Kalita, P. (2026). Experimental and numerical study of brick walls integrated with bio-composite phase change material for energy-efficient thermal management in buildings. *Applied Thermal Engineering*, *300* (Part 4), Article 131427. https://doi.org/10.1016/j.applthermaleng.2026.131427

Bories, C., Aouba, L., Vedrenne, E., & Vilarem, G. (2015). Fired clay bricks using agricultural biomass wastes: Study and characterization. *Construction and Building Materials*, *91*, 158–163. https://doi.org/10.1016/j.conbuildmat.2015.05.006

Boussaa, N., Kheloui, F., & Chelouah, N. (2023). Mechanical, thermal and durability investigation of compressed earth bricks stabilized with wood biomass ash. *Construction and Building Materials*, *364*, Article 129874. https://doi.org/10.1016/j.conbuildmat.2022.129874

Cheng, L., Kobayashi, T., & Shahin, M. A. (2020). Microbially induced calcite precipitation for production of "bio-bricks" treated at partial saturation condition. *Construction and Building Materials*, *231*, Article 117095. https://doi.org/10.1016/j.conbuildmat.2019.117095

Claudel, H. H. A., Yves, O. R., Rolland, D., Salomon, N. E. P., Parfait, T. C., Florent, B., & Theodore, T. (2025). Thermomechanical and physicochemical investigation of raw clay bricks derived from Nomayo clay and palm shell powder lignocellulosic material. *Scientific Reports*, *15*(1), Article 29540. https://doi.org/10.1038/s41598-025-13839-x

Çevik, M., & Diambu, A. N. (2024). Advancing sustainable development goals through the use of biocomposites for a greener future. In M. Çevik (Ed.), *Scientific Research Reports* (pp. 1–13). Duvar Publications.

Das, B., Bordoloi, U., Singh, P., & Kalita, P. (2026). Integration of bio-composite phase change materials in autoclaved aerated concrete bricks for enhanced thermal energy storage performance. *Journal of Energy Storage*, *148*, Article 120324. https://doi.org/10.1016/j.est.2025.120324

Demir, I. (2008). Effect of organic residues addition on the technological properties of clay bricks. *Waste Management*, *28*(3), 622–627. https://doi.org/10.1016/j.wasman.2007.03.019

Demirel, C. (2026). A new approach in environmentally friendly brick production: Use of rice husk. *Alexandria Engineering Journal*, *147*, 208–219. https://doi.org/10.1016/j.aej.2026.05.034

Diambu, A. N., & Çevik, M. (2024). Sustainable reuse of food waste in the Democratic Republic of the Congo for biocomposite reinforcement. *Sürdürülebilir Çevre Dergisi*, *4*(1), 41–54. https://doi.org/10.62816/cevder.1497294

Elhady, R. E. A., Tarek, D., Ahmed, M. M., Yousef, A., & Ragab, A. (2025). Energy efficiency and economic feasibility of bio-waste-enhanced clay bricks in hot-arid climates. *Journal of Engineering and Applied Science*, *72*, Article 67. https://doi.org/10.1186/s44147-025-00636-6

Et-Tanteny, R., Manssouri, I., Bouayad, A., Limami, H., Azzouzi, A., El Amrani, B., & El Khadiri, K. (2025). Physicochemical and thermomechanical performance of eco-friendly unfired clay-biopolymer composite bricks. *Journal of Building Material Science*, *7*(3), 166–182. https://doi.org/10.30564/jbms.v7i3.7994

Fernández, N., Basso, A. V., Peisino, L. E., López, S., Tapia, A., & Kreiker, J. (2025). A novel biocomposite made of citrus peel waste and mushroom mycelium: Mechanical, thermal, and bio-repellency studies. *Recycling*, *10*(6), Article 216. https://doi.org/10.3390/recycling10060216

Formisano, A., Dessì, E., Jr., & Landolfo, R. (2017). Mechanical-physical experimental tests on lime mortars and bricks reinforced with hemp. *AIP Conference Proceedings*, *1906*(1), Article 090006. https://doi.org/10.1063/1.5012363

Ganasen, N., Bahrami, A., & Loganathan, K. (2023). A scientometric analysis review on agricultural wastes used as building materials. *Buildings*, *13*(2), Article 426. https://doi.org/10.3390/buildings13020426

Ganasen, N., Krishnaraj, L., Onyelowe, K. C., & Stephen, L. U. (2024). Machine learning optimization of bio-sandcrete brick modelling using response surface methodology. *Scientific Reports*, *14*, Article 3438. https://doi.org/10.1038/s41598-024-54029-5

Gandhi, H., Beladiya, U., Poriya, M., Vaghela, J., Mevada, V., Patel, R., & Kothari, C. (2025). Carbon capture and sequestration through landfill-derived *Bacillus* strains: Enhanced microbially induced calcite precipitation for sustainable bio-brick production. *Construction and Building Materials*, *491*, Article 142600. https://doi.org/10.1016/j.conbuildmat.2025.142600

Giroudon, M., Laborel-Préneron, A., Aubert, J.-E., & Magniont, C. (2019). Comparison of barley and lavender straws as bioaggregates in earth bricks. *Construction and Building Materials*, *202*, 254–265. https://doi.org/10.1016/j.conbuildmat.2018.12.126

Görhan, G., & Şimşek, O. (2013). Porous clay bricks manufactured with rice husks. *Construction and Building Materials*, *40*, 390–396. https://doi.org/10.1016/j.conbuildmat.2012.09.110

Harb, E., Maalouf, C., Bliard, C., Tenpierik, M., Lachi, M., Bogard, F., & Polidori, G. (2023). Thermal performance of starch/beet-pulp composite bricks for building insulation at a wall scale. *Case Studies in Construction Materials*, *18*, Article e01851. https://doi.org/10.1016/j.cscm.2023.e01851

Ibrahim, J. E. F. M., Kotova, O. B., Sun, S., Kurovics, E., Tihtih, M., & Gömze, L. A. (2022). Preparation of innovative eco-efficient composite bricks based on zeolite-poor rock and Hen's eggshell. *Journal of Building Engineering*, *45*, Article 103491. https://doi.org/10.1016/j.jobe.2021.103491

Jaramillo, H. Y., Vasco-Echeverri, O., López-Barrios, R., & García-León, R. A. (2025a). Optimization of bio-brick composition using agricultural waste: Mechanical properties and sustainable applications. *Sustainability*, *17*(5), Article 1914. https://doi.org/10.3390/su17051914

Jaramillo, H. Y., Zuluaga-Gallego, R., Arango-Correa, A., & García-León, R. A. (2025b). Thermoacoustic, physical, and mechanical properties of bio-bricks from agricultural waste. *Buildings*, *15*(13), Article 2183. https://doi.org/10.3390/buildings15132183

Jin, Y., De, G., Wilson, N., Qin, Z., & Dong, B. (2026). Towards carbon-neutral built environment: A critical review of mycelium-based composites. *Energy and Built Environment, 7*(3), 552–570. https://doi.org/10.1016/j.enbenv.2025.01.004

Jones, M., Mautner, A., Luenco, S., Bismarck, A., & John, S. (2020). Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Materials & Design, 187*, Article 108397. https://doi.org/10.1016/j.matdes.2019.108397

Jwaida, Z., & Di Sarno, L. (2026). Towards eco-friendly construction: A comprehensive review of agricultural and industrial waste in sustainable masonry production. *Buildings, 16*(16), Article 3331. https://doi.org/10.3390/buildings16163331

Kamar, N. A. F., Ismail, L. H., & Kamaruddin, K. (2025). Impact of bio-adhesive addition on the properties of cement bricks incorporating quarry dust and kenaf core. *Recent Trends in Civil Engineering and Built Environment*, *6*(1), 8–18. https://periodical.uthm.edu.my/index.php/rtcebe/article/view/14918

Khoudja, D., Taallah, B., Izemmouren, O., Aggoun, S., Herihiri, O., & Guettala, A. (2021). Mechanical and thermophysical properties of raw earth bricks incorporating date palm waste. *Construction and Building Materials*, *270*, Article 121824. https://doi.org/10.1016/j.conbuildmat.2020.121824

Kizinievič, O., Kizinievič, V., Pundiene, I., & Molotokas, D. (2018). Eco-friendly fired clay brick manufactured with agricultural solid waste. *Archives of Civil and Mechanical Engineering, 18*(4), 1156–1165. https://doi.org/10.1016/j.acme.2018.03.003

Kumar, J. P. P. J., Rajan Babu, B., Nandhagopal, G., Ragumaran, S., Ramakritinan, C. M., & Ravichandran, V. (2019). In vitro synthesis of bio-brick using locally isolated marine ureolytic bacteria, a comparison with natural calcareous rock. *Ecological Engineering, 138*, 97–105. https://doi.org/10.1016/j.ecoleng.2019.07.017

Kumar, N., Mehta, V., Kumar, S., Singh, J. P., Kumar, R., Sharma, S., Dwivedi, S. P., Kozak, D., Lozanovic, J., & Abbas, M. (2024). An investigation of various properties of hybrid bricks using Natural fibers and waste fiber-based materials. *Journal of Engineered Fibers and Fabrics*, *19*, 1–23. https://doi.org/10.1177/15589250241240073

Labaied, I., Douzane, O., Lajili, M., & Promis, G. (2022). Bricks using clay mixed with powder and ashes from lignocellulosic biomass: A review. *Applied Sciences*, *12*(20), Article 10669. https://doi.org/10.3390/app122010669

Laborel-Préneron, A., Aubert, J.-E., Magniont, C., Maillard, P., & Poirier, C. (2017). Effect of plant aggregates on mechanical properties of earth bricks. *Journal of Materials in Civil Engineering*, *29*(12), Article 04017244. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002096

Laborel-Préneron, A., Magniont, C., & Aubert, J.-E. (2018). Hygrothermal properties of unfired earth bricks: Effect of barley straw, hemp shiv and corn cob addition. *Energy and Buildings*, *178*, 265–278. https://doi.org/10.1016/j.enbuild.2018.08.021

Lachheb, M., Youssef, N., & Younsi, Z. (2023). A comprehensive review of the improvement of the thermal and mechanical properties of unfired clay bricks by incorporating waste materials. *Buildings, 13*(9), Article 2314. https://doi.org/10.3390/buildings13092314

Lambert, S. E., & Randall, D. G. (2019). Manufacturing bio-bricks using microbial induced calcium carbonate precipitation and human urine. *Water Research, 160*, 158–166. https://doi.org/10.1016/j.watres.2019.05.069

Le, D. L., Salomone, R., & Nguyen, Q. T. (2023). Circular bio-based building materials: A literature review of case studies and sustainability assessment methods. *Building and Environment, 244*, Article 110774. https://doi.org/10.1016/j.buildenv.2023.110774

Le, D. L., Salomone, R., & Nguyen, Q. T. (2024). Sustainability assessment methods for circular bio-based building materials: A literature review. *Journal of Environmental Management*, *352*, Article 120137. https://doi.org/10.1016/j.jenvman.2024.120137

Lewo Nkondi, B., Azama, N., Blaysat, B., de Baynast, H., & Moutou Pitti, R. (2025). Fired clay bricks made by incorporating organic additives: A review. *Case Studies in Construction Materials*, *23*, Article e05037. https://doi.org/10.1016/j.cscm.2025.e05037

Li, Y., Wen, K., Li, L., Huang, W., Bu, C., & Amini, F. (2020). Experimental investigation on compression resistance of bio-bricks. *Construction and Building Materials*, *265*, Article 120751. https://doi.org/10.1016/j.conbuildmat.2020.120751

Liu, S., Du, K., Huang, W., Wen, K., Amini, F., & Li, L. (2021). Improvement of erosion-resistance of bio-bricks through fiber and multiple MICP treatments. *Construction and Building Materials*, *271*, Article 121573. https://doi.org/10.1016/j.conbuildmat.2020.121573

Moussa, T., Maalouf, C., Bliard, C., Abbes, B., Badouard, C., Lachi, M., do Socorro Veloso Sodré, S., Bufalino, L., Bogard, F., Beaumont, F., & Polidori, G. (2022). Spent coffee grounds as building material for non-load-bearing structures. *Materials*, *15*(5), Article 1689. https://doi.org/10.3390/ma15051689

Moussa, R. R. (2024). Embedding sugarcane bagasse (SCB) in clay bricks used in building envelop to reduce the electricity consumption. *Ain Shams Engineering Journal*, *15*(8), Article 102840. https://doi.org/10.1016/j.asej.2024.102840

Muñoz, P., Letelier, V., Muñoz, L., & Bustamante, M. A. (2020). Adobe bricks reinforced with paper & pulp wastes improving thermal and mechanical properties. *Construction and Building Materials*, *254*, Article 119314. https://doi.org/10.1016/j.conbuildmat.2020.119314

Nakkeeran, G., Krishnaraj, L., Shakor, P., & Rajkumar, S. (2024). Mechanical properties optimization and cost analysis of agricultural waste as an alternative in brick production. *Scientific Reports*, *14*, Article 24075. https://doi.org/10.1038/s41598-024-74970-9

Olacia, E., Pisello, A. L., Chiodo, V., Maisano, S., Frazzica, A., & Cabeza, L. F. (2020). Sustainable adobe bricks with seagrass fibers. Mechanical and thermal properties characterization. *Construction and Building Materials*, *239*, Article 117669. https://doi.org/10.1016/j.conbuildmat.2019.117669

Ongpeng, J. M. C., Inciong, E., Sendo, V., Soliman, C., & Siggaoat, A. (2020). Using waste in producing bio-composite mycelium bricks. *Applied Sciences*, *10*(15), Article 5303. https://doi.org/10.3390/app10155303

Öncül, M., Atagür, M., Atan, E., & Sever, K. (2025). A preliminary evaluation of bing cherry tree (*Prunus avium* L.) pruning waste as an alternative lignocellulosic filler for lightweight composite material applications. *Polymer Composites*, *46*(4), 3655–3667. https://doi.org/10.1002/pc.29197

Pandey, U., Saini, K., Matsagar, V. A., & Kodur, V. (2026). Thermal effects on compression behavior and microstructure of wheat and rice fiber-reinforced polymer hybrid composite bricks for civil infrastructure. *Journal of Natural Fibers*, *23*(1), Article 2679183. https://doi.org/10.1080/15440478.2026.2679183

Paul, G., Kuppusamy, S., Pauline, A. L., & Sugumaran, P. (2026). Sustainable biochar-based bricks: Evaluating the mechanical, thermal and durability properties of paddy stubble biochar for structural applications. *Innovative Infrastructure Solutions*, *11*(3), Article 153. https://doi.org/10.1007/s41062-026-02569-2

Piñas, J. M., Lira, L., Horn, M., Solis, J. L., & Gómez, M. M. (2020). Influence of *Stipa ichu* on the thermal and mechanical properties of adobe as a biocomposite material. *Journal of Physics: Conference Series*, *1433*(1), Article 012003. https://doi.org/10.1088/1742-6596/1433/1/012003

Rao, A. U., Bhandary, R. P., Tantri, A., Narayana, S., & Kamath, M. (2024). Low carbon multi-binder composite using lithomargic soil, biomass, and calcined seashell powder for sustainable bricks. *Discover Sustainability*, *5*(1), Article 192. https://doi.org/10.1007/s43621-024-00399-9

Riffi, S., Ghorbel, E., Schmidt, F., & Cuccagna, F. (2026). Review of natural fiber-reinforced compressed earth blocks: Toward enhanced performance and environmental sustainability. *Journal of Natural Fibers*, *23*(1), Article 2619017. https://doi.org/10.1080/15440478.2026.2619017

Rima, B., & Nadir, B. (2024). Thermal and physiochemical characterization of bricks incorporating date palm fiber for use as insulation materials in buildings. *Journal of Engineered Fibers and Fabrics*, *19*. https://doi.org/10.1177/15589250241276842

Sakhare, V. V., & Ralegaonkar, R. V. (2016). Use of bio-briquette ash for the development of bricks. Journal of Cleaner Production, 112(1), 684–689. https://doi.org/10.1016/j.jclepro.2015.07.088

Shahat, M. A., & Soliman, W. (2025). Lightweight thermally insulating fired clay bricks enhanced with chitosan-based clay nanocomposites for sustainable construction. *Scientific Reports*, *15*(1), Article 26528. https://doi.org/10.1038/s41598-025-11790-5

Stelzer, L., Hoberg, F., Bach, V., Schmidt, B., Pfeiffer, S., Meyer, V., & Finkbeiner, M. (2021). Life cycle assessment of fungal-based composite bricks. *Sustainability*, *13*(21), Article 11573. https://doi.org/10.3390/su132111573

Sutcu, M., Erdogmus, E., Gencel, O., Gholampour, A., Atan, E., & Ozbakkaloglu, T. (2019). Recycling of bottom ash and fly ash wastes in eco-friendly clay brick production. *Journal of Cleaner Production*, *233*, 753–764. https://doi.org/10.1016/j.jclepro.2019.06.017

Şahin, H. (2026). Tarımsal atıklarından elde edilen biyo-kompozitler: Malzemeler, işleme yöntemleri ve performans değerlendirmesi. *Tarım Makinaları Bilimi Dergisi*, *22*. https://izlik.org/JA72HM93AW

Türkan, M. O., Öncül, M., & Savran, M. (2026). Characterization and RSM-based modeling of sustainable *Malva sylvestris* L./polypropylene composites. *BioResources*, *21*(3), 7848–7870. https://doi.org/10.15376/biores.21.3.7848-7870

Utami, A. R. I., Haryati, P. D., Sulaeman, M. F., Handayani, I. P., & Abdullah, A. H. D. (2021). Effect of lignocellulosic corn waste addition on the porosity, density, and compressive strength of fired clay brick. *AIP Conference Proceedings*, *2320*(1), Article 050027. https://doi.org/10.1063/5.0037448

Wang, Y., & Abuel-Naga, H. (2025). Unfired bricks from wastes: A review of stabiliser technologies, performance metrics, and circular economy pathways. *Buildings*, *15*(11), Article 1861. https://doi.org/10.3390/buildings15111861

Waskar, V. G., & Anadinni, S. B. (2026). Design optimization and performance prediction of biocomposite based brick using machine learning techniques. *Asian Journal of Civil Engineering*, *27*(6), 3715–3732. https://doi.org/10.1007/s42107-026-01694-8

Yavaş, A., Atan, E., & Sutcu, M. (2023). Self-cleaning and photocatalytic properties of eco-friendly clay-based facing bricks from industrial and natural wastes. *Environmental Science and Pollution Research*, *30*(32), 78152–78167. https://doi.org/10.1007/s11356-023-27798-1

Zhang, X., Hu, J., Fan, X., & Yu, X. (2022). Naturally grown mycelium-composite as sustainable building insulation materials. *Journal of Cleaner Production*, *342*, Article 130784. https://doi.org/10.1016/j.jclepro.2022.130784

Zhang, S., Zheng, C., Wang, X., He, R., & Li, S. (2024). Fabrication and characterization of recycled construction waste bricks modified with sisal fibers. *Alexandria Engineering Journal*, *105*, 1–11. https://doi.org/10.1016/j.aej.2024.06.048