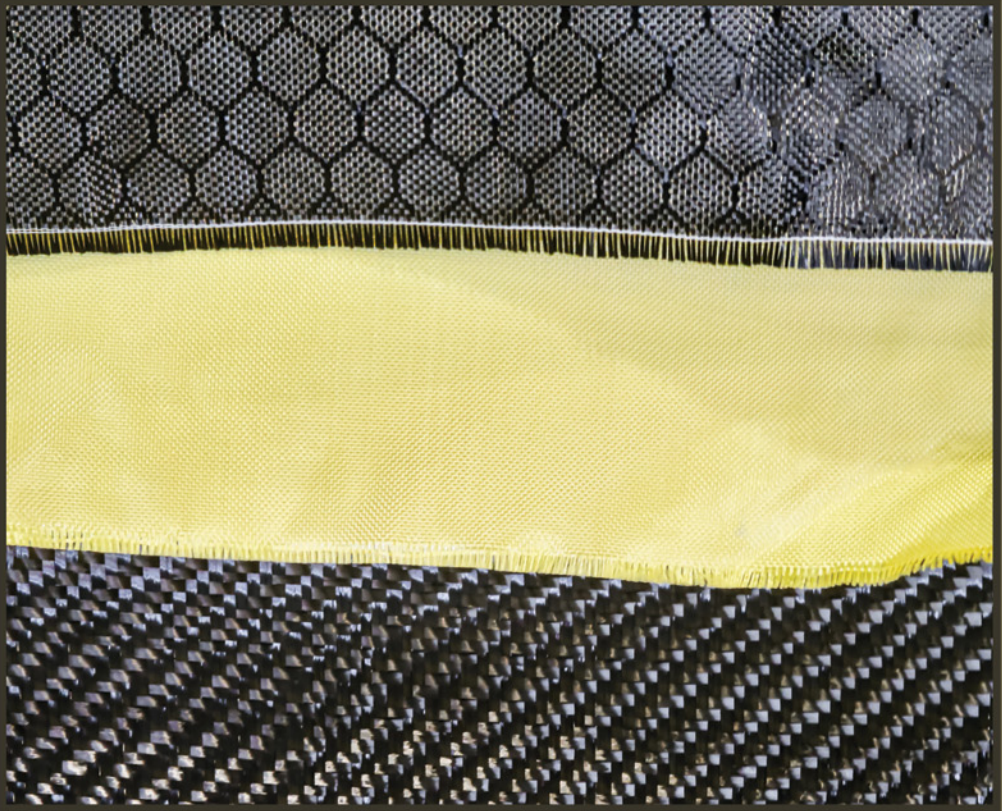


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SMART BIOCOMPOSITE MATERIALS

FABRICATION, APPLICATIONS, AND
SUSTAINABILITY



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Smart Biocomposite Materials

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Woodhead Publishing Series in Composites Science and
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Smart Biocomposite Materials

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Md. Rezaur Rahman

Muhammad Khusairy Bin Bakri



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Dedication

This work is dedicated to my amazing wife and daughters, Shirin Akther, Fahriah Rahman, and Faizah Rahman, who are very special to me and made it possible for me to complete this work.

—Associate Professor Ts. Dr. Md. Rezaur Rahman

First, I would like to thank the Almighty God for the guidance, strength, power of mind, protection, and for giving us a healthy life. All of these we offer to you. Every difficult task needs self-effort as well as the guidance of elders, particularly those who are near to our hearts. I offer my humble dedications to my beautiful and loving father, mother, wife, and brothers, whose devotion, love, support, and nightly prayers have enabled me to work toward this significant achievement, along with all the dedicated, well-liked, and well-respected teachers and supervisors.

—Ts. Dr. Hj. Muhammad Khusairy Bin Bakri

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Contents

List of contributors	xi
About the editors	xiii
Preface	xv
1 Introduction to intelligent biocomposite materials	1
<i>Muhammad Khusairy Bin Bakri, Md. Rezaur Rahman and Murtala Namakka</i>	
1.1 Introduction	1
1.2 Natural biocomposite materials	2
1.3 The emergence of intelligent biocomposite materials	6
1.4 Current research trends	8
1.5 Future directions	11
1.6 Conclusion	14
References	14
2 Natural fiber–reinforced materials: towards biosustainability	23
<i>Murtala Namakka, Md. Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
2.1 Introduction	23
2.2 Natural fibers, types, and classification	25
2.3 Natural fiber processing techniques	30
2.4 Conclusion	41
References	41
3 The role of polymer matrices and compositions	59
<i>Perry Law Nyuk Khui, Md. Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
3.1 Introduction	59
3.2 Role of polymer matrices in polymer biocomposites	59
3.3 Composition effect on polymer composite or biocomposite properties	64
3.4 Summary	68
References	68
4 Fabrication techniques for smart biocomposites	75
<i>Anjelina Joffery Kalimuthu, Md. Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
4.1 Introduction	75

4.2	Raw materials of smart biocomposite	76
4.3	Fabrication techniques for smart biocomposites	79
4.4	Conclusion	91
	Acknowledgment	92
	References	92
5	Exploration of functional fillers in biocomposites	101
	<i>Anthonette Anak James, Md. Rezaur Rahman, Ain Zaienah Sueraya and Muhammad Khusairy Bin Bakri</i>	
5.1	Introduction	101
5.2	Carbon black	103
5.3	Carbon nanotubes	108
5.4	Graphene	112
5.5	Natural based fillers	115
5.6	Montmorillonite clay	123
5.7	Future prospects of biocomposites	126
5.8	Conclusion	126
	References	127
6	Integration of intelligent sensors and actuators in materials	149
	<i>Khairul Anwar Mohamad Said, Md. Rezaur Rahman, Sinin Hamdan and Kuok King Kuok</i>	
6.1	Introduction	149
6.2	What are intelligent materials and how are they made?	150
6.3	Humidity sensor and smart actuator	151
6.4	Intelligent polymers	157
6.5	Intelligent piezoelectric	162
6.6	Biosmart actuator	164
6.7	Conclusions	168
	Acknowledgment	168
	References	169
7	Shape-memory smart biocomposites	179
	<i>Muhammad Khusairy Bin Bakri and Md. Rezaur Rahman</i>	
7.1	Introduction	179
7.2	Activation mechanisms	180
7.3	Shape-memory polymer and shape-memory smart biocomposite applications	189
7.4	Summary and future works	191
	References	191
8	Biocomposites utilization in drug delivery applications	199
	<i>Ain Zaienah Sueraya, Md. Rezaur Rahman, Anthonette Anak James, Murtala Namakka and Muhammad Khusairy Bin Bakri</i>	
8.1	Introduction	199

8.2	Types of biocomposites in drug delivery applications	199
8.3	Drug release mechanisms	200
8.4	Fabrication of biocomposites in drug delivery applications	207
8.5	Roles of biocomposites in drug delivery applications	209
8.6	Biocomposites utilization in different drug delivery applications	209
8.7	Conclusion	213
	References	213
9	Investigation into self-healing in biocomposites	227
	<i>Murtala Namakka, Md. Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
9.1	Introduction	227
9.2	Fundamental mechanisms of self-healing	228
9.3	Biocomposite materials	230
9.4	Polymeric matrix for biocomposite materials	232
9.5	Strategies for achieving self-healing in biocomposites	233
9.6	Wood-based composites with embedded healing agents	239
9.7	Natural fiber composites with self-healing polymers	239
9.8	Conclusions	240
	References	241
10	Intelligent biocomposite materials in construction	257
	<i>Kuok King Kuok, Md. Rezaur Rahman, Muhammad Khusairy Bin Bakri, Khairul Anwar Mohamad Said and Chiu Po Chan</i>	
10.1	Introduction	257
10.2	Components of intelligent biocomposite materials	258
10.3	Characteristics of intelligent biocomposite materials	259
10.4	Advantages of intelligent biocomposite materials in construction	261
10.5	Application of intelligent biocomposite materials	263
10.6	Challenges and future directions	278
10.7	Conclusion	279
	References	280
11	Applications of biocomposites in biomedical engineering	287
	<i>Ain Nadirah Binti Mohd Sufian, Md Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
11.1	Introduction	287
11.2	Application of smart biocomposites in tissue engineering	288
11.3	Application of smart biocomposites as wound healing management	293
11.4	Utilization of smart biocomposites in drug delivery systems	295
11.5	Role of smart biocomposites in cancer and tumor therapeutic applications	296
11.6	Challenges and future perspectives	299
11.7	Conclusion	300
	References	301

12	Aerospace and automotive applications of biocomposites	309
	<i>Nur-Azzah Afifah binti Taib, Md Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
12.1	Overview of biocomposites in modern engineering	309
12.2	Understanding biocomposites: basics and beyond	309
12.3	Key properties of biocomposites	313
12.4	How biocomposites are made	317
12.5	Benefits and drawback of biocomposites	321
12.6	Biocomposites in aerospace and automotive: addressing industry needs	321
12.7	Why biocomposites matter: redefining aerospace and automotive materials	322
12.8	Cutting-edge applications: biocomposites in aerospace structures and automotive components	322
12.9	Automotive	327
12.10	Evaluating environmental impact: the life cycle analysis of biocomposite in aerospace and automotive	328
12.11	Conclusion	331
	References	331
13	Assessment of environmental sustainability	337
	<i>M. Rahnuma Iqbal Ifte, M. Kaisher Ahmed, Faisal Islam Chowdhury, Md. Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
13.1	Introduction	337
13.2	Smart composites	338
13.3	Bionanocomposites	340
13.4	Matrix impregnation	348
13.5	Natural fiber-reinforced PLA green composites	352
13.6	Environmental assessment of the CF/PPS thermo-stamping process	356
13.7	Biopolymer-based nanocomposites for smart food packaging	357
13.8	Bio-nanocomposite for treatment and disease diagnosis	359
13.9	Impacts of using smart biocomposite materials	369
13.10	Conclusion	369
	References	370
14	Challenges and future directions of biocomposite materials	387
	<i>Lelly Marini, Mohammad Abdul Mannan, Md. Rezaur Rahman and Muhammad Khusairy Bin Bakri</i>	
14.1	Introduction	387
14.2	Challenges in biocomposite material development	388
14.3	Case study insights: lessons from geopolymer concrete	389
14.4	Future directions	420
14.5	Recommendations for future research	421
	References	421
	Index	431

List of contributors

M. Kaisher Ahmed Department of Chemistry, University of Chittagong, Chittagong, Bangladesh

Muhammad Khusairy Bin Bakri Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia; Composite Materials and Engineering Center, Washington State University, Pullman, WA, United States

Chiu Po Chan Faculty of Computer Science and Information Technology, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Faisal Islam Chowdhury Department of Chemistry, University of Chittagong, Chittagong, Bangladesh

Sinin Hamdan Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Malaysia, Kota Samarahan, Sarawak, Malaysia

M. Rahnuma Iqbal Ifte Department of Chemistry, University of Chittagong, Chittagong, Bangladesh

Anthonette Anak James Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, University of Malaysia, Kota Samarahan, Sarawak, Malaysia

Anjelina Joffery Kalimuthu Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Perry Law Nyuk Khui Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Kuok King Kuok Faculty of Engineering, Computing and Science, Swinburne University of Technology, Sarawak Campus, Kuching, Sarawak, Malaysia

Mohammad Abdul Mannan Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Lelly Marini Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Ain Nadirah Binti Mohd Sufian Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Murtala Namakka Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

Md. Rezaur Rahman Faculty of Engineering, Universiti Malaysia Sarawak, Sarawak, Kota Samarahan, Malaysia

Khairul Anwar Mohamad Said Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia; Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, UNIMAS Water Centre (UWC), Universiti Malaysia, Kota Samarahan, Sarawak, Malaysia; UNIMAS Water Centre, Faculty of Engineering, Universiti Malaysia, Kota Samarahan, Sarawak, Malaysia

Ain Zaienah Sueraya Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, University of Malaysia, Kota Samarahan, Sarawak, Malaysia

Nur-Azzah Afifah binti Taib Faculty of Engineering, University Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

About the editors

Ts. Dr. Md. Rezaur Rahman is an Associate Professor in the Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Malaysia. Since 2012 he has also served as a Visiting Research Fellow at the Faculty of Engineering, Tokushima University, Japan. His academic journey includes experience as a Teaching Assistant at Bangladesh University of Engineering and Technology (BUET) and as a Research Project Leader under the Malaysian Ministry of Higher Education. In 2015 he was appointed as an External Supervisor at the Faculty of Engineering, Swinburne University of Technology, Melbourne, Australia. Dr. Rahman holds a PhD from UNIMAS and brings over 12 years of experience in teaching, research, and industry collaboration. His research expertise spans conducting polymers, nanocomposites, and advanced materials, including graphene, nanoclay, fire retardants, and nanocellulose-reinforced polymer composites. He has made significant contributions to the development of hybrid-filled polymer blends and the chemical modification of lignocellulosic fibers, such as jute, coir, and kenaf. To date, Dr. Rahman has authored 7 books, 20 book chapters, and over 200 articles in international journals, establishing himself as a prominent researcher in polymer science and nanotechnology. He is also listed in Stanford University's Top 2% Scientists list of the world's most cited scientists.

Ts. Dr. Hj. Muhammad Khusairy Bin Capt. Hj. Bakri is a Postdoctoral Research Associate at Washington State University (WSU), specializing in materials and mechanical engineering. He holds a PhD (2018), MEng (2016), and BEng (2014) from Swinburne University of Technology. Dr. Khusairy's research focuses on enhancing the durability, interfacial interaction, and stability of composites through advanced thermal and chemical treatments, with an emphasis on biocomposites for sustainable and economically viable applications. With expertise in wood composites, biocomposites, biomaterials, and wastewater treatment, he has published over 279 scholarly works, including journal articles, book chapters, newspaper/bulletin, and conference proceedings. Dr. Khusairy has previously served as a Research Fellow at UNIMAS and has collaborated on international research projects across Malaysia and abroad. A certified Graduate Engineer and Professional Technologist under the Malaysian Board of Technologists (MBOT), he is also a lifetime member of the Association of Professional Technicians and Technologists (APTT). Dr. Khusairy's contributions have been recognized internationally, including being a finalist for the Alumni Impact Awards 2022 and featured in Successful People in Malaysia, 2023.

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Preface

Materials science has now reached a critical phase of development, where combining sustainability, intelligence, and functionality is no longer visionary but the absolute requirement of the time. While the world is facing increasingly aggravated environmental concerns and its industries face growing demands for responsive and high-performance materials, the combination of biobased components with intelligent attributes is an opportunity for innovation, at the same time as it is eco-friendly and technologically advanced.

Intelligent biocomposite materials are one class of engineered systems combining renewable natural fibers with biodegradable or recyclable matrices and functional fillers or additives with responsive behaviors to external stimuli. These materials successfully address the imperative of reducing dependency on fossil-derived resources and possess enhanced features like self-healing, shape memory, and active sensing or actuation functions as well. The last 10 years have seen tremendous development in this field, driven by interdisciplinarity among materials engineering, biotechnology, polymer science, nanotechnology, and applied mechanics.

At the core of this discussion is a deep understanding of the interactions between different components, natural fibers, polymer matrices, and added functionalities. Advances in fabrication technologies, ranging from conventional compounding methods to advanced additive manufacturing methods, have enabled the large-scale production of biocomposites with tailored mechanical, thermal, and functional properties. The combination of responsive functionalities, such as sensors, stimuli-responsive fillers, or drug delivery systems, greatly expands their utility in high-end markets, such as biomedical devices, aerospace components, structural health monitoring, and soft robotics.

An important aspect of research in this area is mirroring the built-in self-sufficiency of nature with the development of materials with self-healing tendencies, the ability to change their shape in the presence of outside stimuli, and the ability to perform regulated-release functions. These attributes improve the potential of biocomposites and open up new prospects for research and application.

Sustainability remains the underlying tenet of this field, including not just the origin of materials but also life cycle assessment, recyclability, and environmental impact considerations. As the world economy increasingly moves toward more circular and biobased models of development, novel biocomposites are expected to play a key role in enabling this transformational process.

This book aims to act as a comprehensive scholarly reference for researchers, engineers, and postgraduate instructors to explore the scientific basis, processing methodologies, functional characteristics, and potential uses of intelligent

biocomposite materials. This book integrates fundamental knowledge and state-of-the-art advancements to prompt further research and enable the development of advanced materials with features like intelligence, long-term performance, and sustainability.

**Associate Professor Ts. Dr. Md. Rezaur Rahman
Ts. Dr. Hj. Muhammad Khusairy Bin Capt. Hj. Bakri**

Introduction to intelligent biocomposite materials

1

Muhammad Khusairy Bin Bakri^{1,2}, Md. Rezaur Rahman², and Murtala Namakka²

¹Composite Materials and Engineering Center, Washington State University, Pullman, WA, United States, ²Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

1.1 Introduction

Due to climate change, resource constraints, and environmental deterioration, the global industrial ecosystem is indeed undergoing a transformation toward sustainability. Industry participants must reduce their environmental impact while preserving technical competitiveness, which spurs the development of innovative materials science. Biocomposites play a significant role among those various innovations since it is part of sustainable engineering. The circular economy principles drive the biocomposite development by epitomizing the combination of natural fibers or bio-based matrices, with or without synthetic or bio-derived reinforcements. While providing a sustainable alternative to conventional composites, biocomposite materials can reduce industrial waste and its dependency on nonrenewable resources (Adamu et al., 2019; Bakri et al., 2018; Fatema et al., 2024). With intelligent functionalities, biocomposites have transformed the systems that evolved from being mere substitutes for traditional materials (Phiri et al., 2023). A growing demand causes biocomposite materials to become sustainable, adaptive, and multifunctional (Andrew & Dhakal, 2022). Integration of intelligent biocomposites allows the materials to change from stagnant entities to active movable systems, which are capable of interacting with their environment changes, especially to adapt accordingly (Bakri et al., 2017; Hari et al., 2021; James et al., 2024; Jayamani et al., 2015, 2016). This influences sophisticated biocomposite technologies, nanotechnology, sensor integration, and artificial intelligence (AI) to give self-healing, stimulus response, and real-time monitoring. This promotes adoption in crucial industries, including construction, transportation, healthcare, and consumer products, where sustainability and technology innovation combine (Javaid et al., 2022).

Adding natural fibers like flax, hemp, or jute to biodegradable binders like polylactic acid (PLA) or polyhydroxyalkanoates (PHA) optimizes mechanical qualities and environmental compatibility (Andrew & Dhakal, 2022). Fibers provide strength and stiffness, while the matrix binds, distributes stress, and resists environmental deterioration. Biocomposites offer the added advantage of biodegradability and renewability, which is the opposite of traditional composites, which makes them more globally sustainable (Jayamaui et al., 2020; Kiew et al., 2013; Kuok et al., 2024; Lai et al., 2015; Namakka et al., 2023; Namakka, Rahman, Bin Mohamad Said,

et al., 2024; Namakka, Rahman, Mohamad Bin Said, et al., 2024; Rahman et al., 2013, 2017, 2019, 2024; Rahman et al., 2011; Rahman, Hamdan, Hasan, et al., 2015; Rahman, Hamdan, Hashim, et al., 2015; Sueraya et al., 2024). Likewise, biocomposites utilize agricultural and forestry waste, reducing waste streams and making it more sustainable in its lifecycle. Intelligent biocomposites incorporating sensors, self-healing agents, or adaptive systems will respond to environmental changes, recover themselves, or enhance structural health (Ogunleye et al., 2024). Real-time adaptability, such as smart panels that react to load changes in construction or fuel economy from lightweight vehicle components, is achieved. Intelligent biocomposites in healthcare implants may monitor biological signals or administer medications on demand, a new technique.

To mitigate climate change, resource depletion, and the circular economy, intelligent biocomposites are needed. Intelligent biocomposites minimize greenhouse gas emissions, petroleum usage, and waste. Economically, it can offer long-term cost savings due to its enhanced performance, which reduces maintenance and increases the material lifespans, which in the end make it viable for investment despite higher initial costs (Nilimaa, 2023). Research into biocomposites, along with the Industrial 4.0 advancement, demonstrated the intelligent biocomposites' versatility, which covers everything from construction to automotive, healthcare, and consumer goods. Bamboo-reinforced panels and hempcrete blocks are sustainable building materials (Yemesegen & Memari, 2023). Flax-reinforced biocomposite dashboard panels and door trims are lightweight and improve fuel economy; thus automakers use them. Smart biocomposite bandages and biodegradable implants change medical and healthcare technologies.

Intelligent biocomposites are hard to fabricate, especially when scaling up manufacturing and reducing costs while establishing material consistency (Islam et al., 2024). Depending on the feedstock source, quality, structural integrity, and durability are important throughout material life. These issues need interdisciplinary collaboration, material design, and technology integration. Nanofillers like graphene and carbon nanotubes, which boost strength and conductivity, and bioinspired designs that replicate natural systems may unleash new functions and improve material performance.

1.2 Natural biocomposite materials

1.2.1 Definition and composition of natural biocomposites

Natural biocomposites blend the properties of natural fibers and bio-based polymer matrices to create sustainable and environment-friendly alternatives that optimize mechanical performance, promote sustainability, and minimize environmental impacts. Natural fibers in biocomposites provide the material with strength, stiffness, and durability (Pickering et al., 2016). These plants and animal fibers are derived from renewable resources, which are widely accessible and sustainable. Jute, hemp, luffa, bamboo, coir, silk, and flax are known for their mechanical properties, availability, and compatibility with bio-based binders. Flax fibers are known to

have high tensile strength and low density and are used in lightweight applications (Baley, 2002). Hemp fibers have a robust structure and high resistance to pests, making them suitable for construction materials (Ahmed et al., 2022). Bamboo grows rapidly and has good mechanical properties, which is used in architectural and industrial applications (Yadav & Mathur, 2021). Coir fiber extracted from coconut husks is known for its resilience in thermal and water resistance, ideal for outdoor and marine environments (Mahmud et al., 2023). Another critical component of biocomposites is the matrix that binds and distributes stress in the biocomposites. Biocomposites rely on bio-based polymers such as PLA, PHA, or natural rubber. These polymers are derived from corn starch, sugarcane, and/or bacterial fermentation. PLA is known for its biodegradability and thermal processability, suitable for medical devices and packaging (Hussain et al., 2024). While PHA offers superior mechanical properties and is useful in high-strength and durability automotive parts and industrial components (Naser et al., 2021), natural rubber provides elasticity, resilience, and water resistance, making it suitable for flexible composites (Pittayavinai et al., 2023). These matrices not only bind the fibers together but also contribute to the composite's environmental profile by ensuring that the material is biodegradable and sustainable.

The interaction between fibers and matrices in biocomposites determines their performance. The fibers usually provide the load-bearing capacity, whereas the matrix helps to ensure that the fibers remain in position and function cohesively under stress. The interface interaction between the fiber and the matrix determines the composite's mechanical properties, durability, and resistance to environmental degradation (Wu et al., 2023). Therefore various surface treatments and compatibilizers are employed. Alkaline treatment of fibers alters their surfaces and improves adhesion by removing impurities and increasing the surface area for bonding (Bakri et al., 2017; Widodo et al., 2024). Coupling agents such as silanes improve the overall performance of the composite and enhance the compatibility between hydrophilic natural fibers and hydrophobic polymer matrices (Xie et al., 2010). The natural biocomposite composition includes additional elements, that is, nanofillers, additives, and coatings, to tailor the material properties for specific applications. Nanofillers, that is, nanocrystal cellulose or nano-graphene, enhance the strength, thermal stability, and barrier properties of biocomposites (Tedeschi et al., 2020). Some additives are incorporated into biocomposites like flame retardants, UV stabilizers, or plasticizers, which are known to improve safety, longevity, and processability. Some coatings that are derived from bio-based materials are applied to enhance the resistance of biocomposites to expand their applicability in demanding environments from moisture, chemicals, or wear (Balakrishnan et al., 2024).

Changing the type, proportion, and treatment of fibers and matrices can modify the biocomposite for specific applications. For example, a high fiber-to-matrix ratio can increase stiffness and strength, making it suitable for load-bearing structures. A higher matrix percentage may increase flexibility and impact resistance, which is good for dynamic applications like vehicle interiors and flexible packaging (Ahirwar et al., 2022). This versatility makes biocomposites ideal for building, transportation, healthcare, and consumer products. The lifespan of natural biocomposites is intended

to reduce environmental effects. Fibers and matrices are made from renewable sources, generally agricultural leftovers or by-products, which eliminates waste and promotes circularity (Samir et al., 2022). Natural biocomposites are known to emit less greenhouse gas than synthetic composites since their manufacture is less energy-intensive. Natural biocomposites are usually biodegraded, composted, or recycled after use, decreasing their environmental impact. These traits support worldwide plastic pollution reduction and sustainable material transition initiatives.

1.2.2 Properties

Biocomposites' lightness is an advantage. Biocomposites reinforced with jute, hemp, or flax are known to be lighter than nonnatural composites. This decrease in density creates a lightweight material, making it ideal for transportation, aircraft, and construction. Lighter materials enhance fuel economy and minimize greenhouse gas emissions in the automobile sectors, supporting global sustainability initiatives. Biocomposites are lightweight due to the low density of natural fibers ($1.2\text{--}1.5\pm 2\text{ g/cm}^3$) compared to glass fibers ($2.7\pm 2\text{ g/cm}^3$) (Malik et al., 2024). This allows the creation of easier-to-handle, transport, and install items, lowering energy consumption across their lifespan. While natural biocomposites may not be as strong as composites reinforced with high-performance synthetic fibers, they perform well for their weight. Structural applications need materials to endure heavy loads without adding bulk. Flax fiber-reinforced composites exhibit tensile strengths of ($1300\text{ vs }1350\text{ MPa/g/cm}^3$), almost comparable to fiberglass (Mahboob et al., 2017). These mechanical qualities depend on fiber characteristics and the fiber-matrix interface, which may be enhanced by surface treatments and manufacturing processes. The strength-to-weight ratio of natural biocomposites makes them suitable for lightweight buildings and minimizes manufacturing, installation, and transportation energy, making them sustainable. Under certain situations, natural biocomposites dissolve and return to the ecosystem, unlike manmade composites that endure decades. Due to their renewable and organic components, natural fiber and binder make it biodegradable. Microorganisms like bacteria and fungi degrade organic matter into water, carbon dioxide, and biomass. Packaging, agriculture, and single-use items, where end-of-life disposal is crucial, benefit from this trait. The pace and amount of biodegradation depend on fiber type, matrix composition, environmental conditions, and additives or coatings.

The thermal and acoustic properties of natural biocomposites make them useful for insulation and noise reduction (Mohammadi et al., 2024). In construction materials, jute- and hemp-based composites enhance energy efficiency and save heating and cooling expenses. Porous natural fibers absorb sound waves and attenuate noise, making them acoustic insulation (Mohammadi et al., 2024). Natural biocomposites are useful for soundproofing automobile interiors, offices, and homes. These features improve the functional performance and sustainability of natural biocomposites. For outdoor and load-bearing applications, natural biocomposites must be durable and environmentally resistant. Natural fibers are hydrophilic and absorb moisture, which may affect their mechanical qualities and dimensional

stability; however, surface treatments and protective coatings have greatly enhanced their longevity (Mohammed et al., 2022). Lanification and acetylation improve fiber compatibility with hydrophobic matrices, minimizing moisture absorption and environmental deterioration (Andrew & Dhakal, 2022). Bio-based coatings may also prolong the lifetime of natural biocomposites in harsh settings by protecting them from UV radiation, fungal development, and weathering.

1.2.3 Applications

Hempcrete, made from hemp fibers and lime, is gaining recognition for its sustainable building material known for its great thermal insulation and carbon capture abilities. Jute and flax fiber–reinforced composites are used in sandwich panels and prefabricated elements, offering a lightweight yet strong solution for load-bearing applications (Arya et al., 2023; Cionita et al., 2024). Biocomposites in construction cut environmental impact and boost energy efficiency by reducing heat loss and lowering heating and cooling energy use. Automakers are using biocomposites to lighten vehicles, boost fuel efficiency, and lessen environmental harm, whereas more interior parts like door panels, dashboards, and seatbacks are now made with biocomposites that use natural fibers such as kenaf, sisal, and coir (Naik et al., 2022). These materials have similar mechanical properties to traditional synthetic composites but are lighter and more sustainable. Car makers like BMW and Mercedes-Benz use flax and hemp composites in their vehicles to cut weight and boost recyclability (Tedesco, 2024; Vieyra et al., 2022). Natural biocomposites are also being studied for use in bumpers and underbody shields, as their lightweight and impact-resistant properties can enhance vehicle performance (Soares et al., 2024). The move to electric and hybrid vehicles has increased interest in natural biocomposites, as lightweight materials are essential for improving battery efficiency and extending driving range.

Natural biocomposites are also important for consumer goods, especially in packaging, furniture, and sports gear, where most of the packaging industry is increasingly using biocomposites made from agricultural waste and bio-based polymers due to the rising demand for sustainable and biodegradable materials, which provide a sustainable option for packaging, cutting down on plastic waste and supporting a circular economy (Trivedi et al., 2023). One of the examples is sugarcane bagasse and wheat straw, which are used to make compostable food containers and trays that are eco-friendly when disposed of. Biocomposites offer a sustainable and attractive solution for making furniture lightweight, durable, and attractive items like chairs, tables, and decorative panels, whereas using renewable materials boosts furniture sustainability and meets consumer demand for eco-friendly products. The sporting goods industry has gained from the unique traits of natural biocomposites, offering strength, flexibility, and lightweight features, in which the natural fiber–reinforced composite materials, like bamboo and flax, are used to make products such as tennis rackets, surfboards, and bicycle frames (Pil et al., 2016). These products perform similarly to synthetic composites but have a smaller environmental impact during production. Using biocomposites in

sports gear improves the recyclability of products at the end of their life, supporting sustainability in the industry. Biocomposites are also being used in new areas like renewable energy and marine engineering, where it was studied for wind turbine blades in renewable energy, as their lightweight and stiffness can enhance energy efficiency (Thomas & Ramachandra, 2018). Natural fiber–reinforced composites are also used in marine applications for making boat hulls, decks, and other parts, enhancing resistance to corrosion and impact, which helps prolong the lifespan of marine structures. These applications showcase the adaptability of natural biocomposites and their ability to tackle unique engineering challenges in specialized areas.

1.3 The emergence of intelligent biocomposite materials

Materials science has advanced greatly to meet the growing demand for sustainable and flexible solutions to modern challenges, whereas smart or intelligent biocomposite materials are a game-changer, merging the eco-friendliness of natural biocomposites with the cutting-edge qualities of advanced materials. These materials can adjust, react, and even fix themselves according to changes in their environment or operational requirements. Smart or intelligent biocomposites merge natural fibers and bio-based materials with advanced technologies like sensors and AI, revolutionizing material design and application (Sagdic et al., 2022). Intelligent biocomposites are notable for their ability to self-heal, whereas traditional materials can develop small cracks or damages that, if overlooked, may weaken their structure over time. Smart biocomposites solve this problem with self-healing features that automatically repair damage, whereas the microcapsules in the material release healing agents upon crack detection, and the reversible chemical bonds and thermally responsive polymers enable materials to change shape under specific conditions (Choi et al., 2023). Self-healing abilities enhance the lifespan and reliability of biocomposites, making them ideal for infrastructure, aerospace, and automotive applications, where durability and safety are essential.

Another unique feature of intelligent biocomposites is stimulus reactivity. These materials were designed to dynamically respond to temperature, humidity, light, and mechanical stress. Biocomposites containing thermo-responsive polymers may modify heat conductivity or mechanical stiffness depending on environmental conditions, improving building and vehicle energy efficiency (Saba & Jawaid, 2018). Light-responsive biocomposites may change their optical characteristics, allowing smart windows and energy-harvesting devices, which are adaptable to a variety of uses in dynamic situations because they may react to environmental cues (Oh et al., 2024). Intelligent biocomposites improve with integrated sensors and AI. The material structure of these biocomposites contains microscopic sensors that can measure strain, temperature, moisture, and pressure in real-time (Ramakrishnan et al., 2016). AI algorithms may analyze sensor data to detect problems, optimize operations, and analyze performance patterns. In construction, intelligent biocomposites in building

materials may give continuous structural health input, allowing predictive maintenance and minimizing catastrophic failures (Vasconcelos et al., 2024). These materials can detect and adapt to vehicle dynamics and environmental changes in the automobile industry, improving safety. Intelligent biocomposites are also supported by material science and manufacturing advances. Using additive manufacturing and nanotechnology, functional components may be precisely integrated into biocomposites without affecting their qualities. Nanocellulose-based composites may be made stronger and more stimuli-responsive while remaining biodegradable and lightweight. In addition, 3D printing allows complicated geometries and bespoke material compositions, boosting the design options for intelligent biocomposites in numerous sectors (Iftekar et al., 2023). Intelligent biocomposites support global sustainability objectives in addition to their technological skills, where renewable natural fibers and bio-based polymers make these composites more environment-friendly than conventional ones. Intelligent biocomposites' long lifetime and self-repairing abilities limit replacements, saving resources and waste, which are desirable in green buildings, renewable energy systems, and eco-friendly consumer items due to their sustainability. Intelligent biocomposites have great promise but face several obstacles to development and commercialization. For materials with sophisticated sensors, stimuli-responsive components, and bio-based matrix integrations, manufacturing scalability is a major issue, whereas uniform performance across large-scale applications demands strict quality control and standardization (Zhou et al., 2024). The expense of adding new functionality to biocomposites may further restrict their adoption in cost-sensitive sectors, whereas the manufacturing, material design, and economic models must improve to enable intelligent biocomposites' broad use.

1.3.1 Advancements in intelligent biocomposites

Nanotechnology is a major development in intelligent biocomposites. Nanocellulose and graphene are being employed to improve biocomposites' mechanical, electrical, and thermal characteristics. The strength, low density, and biodegradability of plant-based nanocellulose are well known. Nanocellulose improves biocomposite matrices' tensile strength, elasticity, and barrier characteristics, which makes it ideal for lightweight, robust applications like aircraft components and packaging. Biocomposites respond well to graphene's conductivity and permit the creation of materials with embedded sensing capabilities for real-time environmental or operational monitoring (Chowdhury et al., 2025). Graphene-enhanced biocomposites can sense temperature changes and mechanical stress for adaptive responses, whereas these qualities are essential for smart automotive, construction, and medicinal materials (Li et al., 2019). Multifunctional, intelligent, and ecologically sustainable materials are emerging from nanotechnology and biocomposites.

Another innovative approach to intelligent biocomposites is bioinspired design, where researchers are creating materials that adjust to changing surroundings by replicating natural adaptive systems (Badini et al., 2025). Plant structures have exceptional water retention, nutrient delivery, and mechanical stability systems, which, sometimes mimicking these traits, could improve water management and

load-bearing. Biocomposites with optimum strength-to-weight ratios and impact resistance are inspired by insects' lightweight, robust exoskeletons. Bioinspired design includes self-cleaning biocomposites, where most researchers designed surfaces that stay clean in varied environments, inspired by the lotus leaf's water and dirt repellence (Collins & Safiuddin, 2022). These materials are used in building facades, car exteriors, and consumer items to reduce maintenance and lengthen lifespans. Biocomposites with bioinspired photonic structures manipulate light for solar energy, sensing, and decoration, whereas the natural adaptation methods enable sustainable and innovative functions (Bigham et al., 2024).

Intelligent biocomposites are also expanding with hybrid materials that blend bio-based and synthetic components, which this able to create high-performance biocomposites by combining the strengths of both materials. Composites made from bio-based polymers and carbon fibers are lightweight, robust, and environmentally resistant and are useful in aerospace and automotive, where materials must fulfill strict performance and safety norms (Andrew & Dhakal, 2022). Integrating functional additives into hybrid biocomposites enhances their capabilities, such as the addition of form-memory polymers that make the material return to a preset form when stimulated (Huang et al., 2021). Deployable structures, medical gadgets, and responsive fabrics benefit from this characteristic. Adding conductive polymers or piezoelectric materials to hybrid biocomposites enables mechanical deformation to create electrical impulses for energy harvesting and wearable electronics (Pan et al., 2024). Manufacturing innovations are also helping produce intelligent biocomposites, whereas 3D printing allows the accurate creation of complicated shapes and bespoke material structures, which helps create biocomposites with customized characteristics and functions (Iftekar et al., 2023). Gradient biocomposites with spatially changing compositions may maximize performance in certain material locations. Nanomaterials in biocomposite inks enable direct printing of functional components like sensors and actuators, where the bioinspired design and hybrid materials help intelligent biocomposites to be environment-friendly. Renewable resources and sophisticated manufacturing reduce waste and energy utilization. These materials' endurance and versatility decrease replacements, saving resources during their lifespan. For renewable energy, eco-friendly transportation, and sustainable building, intelligent biocomposites are a good option.

1.4 Current research trends

1.4.1 Functionalization techniques

Biocomposite functionalization relies on chemical treatments to overcome the poor interfacial interaction between natural fibers and polymer matrix, whereas the hydrophilic natural fibers frequently do not mix well with hydrophobic polymer matrices, reducing composite mechanical characteristics (Kamran et al., 2022; Tavares et al., 2020). Alkali, silane coupling, and acetylation change natural fiber surfaces to improve matrix bonding. Alkali treatment eliminates lignin, hemicellulose, and other impurities from fiber surfaces, improving roughness and adhesion

(Kamran et al., 2022). A chemical bridge between the fiber and matrix is created by silane coupling agents, enhancing stress transmission at the interface, which makes the composite stronger and more resistant to moisture and UV radiation after these treatments (Adwani et al., 2023). Functionalizing biocomposites with coatings and fillers is another option, whereas the specialized coatings may provide biocomposites with fire resistance, water repellency, and antibacterial qualities (Balakrishnan et al., 2024). Safety-critical activities like construction and transportation need fire-resistant coatings, which include flame-retardants such as phosphorus-based or halogen-free chemicals to minimize smoke and combustion (Soares et al., 2024). Hydrophobic polymers or nano-coatings protect biocomposites against water absorption, swelling, and deterioration in humid or watery settings, increasing their lifetime. In medical and packaging applications, antimicrobial coatings containing silver nanoparticles or bioactive chemicals limit bacterial development and ensure cleanliness. Fillers are also important for biocomposites' functioning, where they improve the mechanical, thermal, and barrier performance by adding nanoclay, calcium carbonate, or biochar to the matrix (Botta et al., 2024). Nanoclay's tortuous gas and liquid penetration route improves its barrier qualities and makes it appropriate for packaging. Biochar from biomass pyrolysis improves mechanical characteristics, carbon sequestration, and thermal conductivity. By strategically using coatings and fillers, biocomposites may enhance certain functional criteria, expanding their application possibilities (Amalina et al., 2022). 3D printing has revolutionized biocomposites by creating complicated geometries and adding customized functions, whereas the additive printing method allows exact material composition, structure, and property control, making biocomposite components extremely customizable (Ligon et al., 2017). 3D-printing biocomposite filaments with functional additives like conductive polymers or piezoelectric materials create smart materials with sensing, energy-harvesting, or self-healing capabilities, whereas the conductive pathways may be utilized in flexible electronics or wearable devices, while piezoelectric ones can produce electricity from mechanical stress (Osman & Lu, 2023).

3D printing permits gradient biocomposites, where material characteristics change spatially inside a component, which is useful in multifunctional applications like aerospace and medical implants, where various parts of the component may require different mechanical or thermal qualities (Park et al., 2022). The layer-by-layer manufacturing technique of 3D printing decreases material waste and energy consumption, supporting biocomposite sustainability, which allows the creation of next-generation materials with unmatched performance and sustainability (Park et al., 2022). Bio-based coatings and fillers in biocomposites are under study and might lead to innovation, such as those made from natural oils, proteins, or polysaccharides, which are known to reduce the composite's environmental impact (De et al., 2023). Antimicrobial and barrier coatings created from crustacean shell chitosan are biodegradable and nontoxic. Fillers like lignin, a paper and pulp by-product, may improve biocomposites' UV resistance and mechanical strength, valorizing waste streams and contributing to the circular economy (Tardy et al., 2023). Smart additives that react to environmental stimuli are also used in advanced functionalization, whereas the shape-memory polymers allow biocomposites to change shape or return

to a preset form when heated or illuminated (Kantaros & Ganetsos, 2023). These materials are used in actuators, medical equipment, and deployable constructions. Biocomposites with thermochromic or photochromic additives change color in response to temperature or light, indicating environmental or material state, which makes them versatile and attractive for cutting-edge applications. Computational tools and AI expedite functionalization method development and implementation design tools may analyze vast datasets to find ideal fibers, matrices, and functional additives, which can forecast the impact of treatments, coatings, and additives on biocomposite characteristics using computational modeling and simulation, eliminating trial-and-error testing (Hamilton & Kingston, 2024), especially to produce high-performance biocomposites faster. These approaches improve functionalization efficiency and enable biocomposite material creation.

1.4.2 Applications in intelligent systems

Smart packaging is a potential use of intelligent biocomposites compared to traditional packaging materials, which are practical but cannot give real-time product condition feedback. Smart or intelligent biocomposites incorporating sensors or stimuli-responsive additives overcome this constraint, whereas the biocomposites containing pH-sensitive dyes or temperature-responsive polymers may indicate food freshness (Rodrigues et al., 2021). These materials change color in reaction to chemical or environmental changes, indicating product quality, which is useful in the food and pharmaceutical sectors, where product integrity is crucial. In addition to monitoring, biocomposites may have antibacterial qualities that improve the shelf life of perishable items and reduce the need for synthetic preservatives, which also improves healthcare. Biocompatibility and biodegradability make natural fibers and bio-based polymers attractive for medicinal applications, where most of the time patient comfort and movement in prostheses due to their lightweight and adaptable qualities (Ornaghi et al., 2023). Implant-compatible biocomposites with self-healing properties are being investigated, where they may self-repair small damage, prolonging their lifespan and minimizing the need for intrusive replacement operations (Jiang et al., 2023). In medication delivery systems, intelligent biocomposites seem promising, where this device releases medicine regulated by temperature or pH using stimuli-responsive polymers.

Intelligent biocomposites are revolutionizing energy harvesting, where the creation of piezoelectric materials in biocomposites converts mechanical energy into electrical energy, providing green energy solutions (Cui et al., 2024). In wearable technology, biocomposite-based piezoelectric devices may produce electricity from walking or running, which is used in gadgets that power tiny electronics like fitness trackers and medical sensors with sustainable and portable energy (Kang & Yeo, 2024). Intelligent biocomposites are being used to develop energy-harvesting flooring that transforms foot traffic stress into power, which transforms a new energy source for lighting or low-energy gadgets in public places that might help maintain urban infrastructure. The automotive and aerospace sectors are also investigating intelligent biocomposites for lightweight constructions and adaptable systems, which may be employed in car

interiors to respond to temperature and humidity, where they started to expand or contract to ensure thermal comfort might lessen energy-intensive climate control (Giampieri et al., 2020). Aerospace constructions may use intelligent biocomposites to measure stress and strain in real time, which may provide engineers valuable input, improving aviation component safety and lowering maintenance costs.

1.5 Future directions

1.5.1 Challenges

Intelligent biocomposites struggle with material stability, especially in different environments, whereas sustainable natural fibers and bio-based matrices tend to degrade in the environment. Moisture, temperature variations, UV exposure, and microbial activity may destroy biocomposites' mechanical and functional integrity, and continuous exposure to high humidity may cause edema, stiffness loss, and natural fiber disintegration (Chaudhary et al., 2018). UV light degrades bio-based polymers, discoloring, embrittling, and reducing mechanical characteristics, while chemical treatments and coatings may reduce these concerns, but they complicate and expense of manufacturing (Yousif & Haddad, 2013). Innovative material engineering and surface treatments are needed to create durable, ecologically friendly biocomposites, but integrating intelligent characteristics into biocomposites challenges their stability (Andrew & Dhakal, 2022). Environmental tolerances may make stimuli-responsive materials, embedded sensors, and self-healing components sensitive to severe circumstances, whereas microcapsule or reversible chemical bond self-healing techniques may fail at high temperatures or under mechanical stress (Yuan et al., 2024). Moisture and heat fluctuations, on the other hand, may also degrade real-time biocomposite sensor accuracy and reliability; therefore it must be compatible and durable in biocomposites for real-world use (Andrew & Dhakal, 2022). Cost and scalability are other problems that hinder the industrial deployment of intelligent biocomposites, whereas natural fibers and bio-based matrices are more sustainable than synthetic ones, although processing, functionalization, and sophisticated features might make them more expensive. Self-healing biocomposites may include costly additions such as encapsulated healing agents or stimuli-responsive polymers, increasing their cost. Integrating embedded sensors or piezoelectric materials needs specific manufacturing methods that may not be accessible or cost-effective for large-scale products and are also harder to scale. The quality and characteristics of natural fiber vary according to growing circumstances, harvesting procedures, and processing processes, resulting in product discrepancies.

Standardization is another major obstacle to intelligent biocomposites' broad adoption. Manufacturers, consumers, and regulators face uncertainty due to the absence of common testing and categorization standards. In contrast, most of the time, intelligent biocomposites need extra parameters for mechanical qualities, including tensile strength, modulus, and impact resistance, unlike ordinary composites. These include stimuli-responsive materials, self-healing processes, and embedded sensor accuracy, which can ensure the safety, performance, and reliability of intelligent

biocomposites in diverse applications. Rigorous and reliable testing procedures for these attributes are needed (Meng & Li, 2013). The lack of established categories affects intelligent biocomposites' marketing and communication, whereas the manufacturers may use multiple terms or measurements to describe comparable qualities, confusing customers and limiting market growth. Global standards and certifications for intelligent biocomposites will guide their development and commercialization, boosting stakeholder trust and uptake. Sustainability issues connect with these problems. Intelligent biocomposites are more sustainable than standard composites; however, their functionalization might have environmental impacts, where the chemical treatments to strengthen fiber-matrix bonding or add characteristics may require nonrenewable or dangerous chemicals (Andrew & Dhakal, 2022). Biocomposites with electrical components or sensors might make recycling harder, lowering their environmental advantages, whereas material design and manufacturing are needed to address these concerns and ensure product sustainability. Market views and regulations can affect intelligent biocomposite adoption, where many sectors are wary of novel materials owing to performance dependability, cost, and regulatory compliance (Andrew & Dhakal, 2022). Construction, automobile, and aircraft industries prioritize safety and durability, making these problems especially important. Overcoming these limitations requires extensive testing and real-world deployments of intelligent biocomposites' long-term advantages and dependability.

1.5.2 Opportunities

Intelligent biocomposite development using circular economy concepts may boost resource efficiency and reduce waste, which, due to resource depletion and environmental issues, linear production methods like extraction, use, and disposal, are unsustainable. Instead, circular economy models prioritize strategies such as reuse, recycling, and regeneration, which fit biocomposites' sustainable philosophy, whereas most of them can be used as agricultural wastes, forestry by-products, and industrial organic waste to make biocomposites. Wasted agricultural leftovers, including rice husks, wheat straw, and coconut coir, may be used to make biocomposites, which decrease virgin resource use and waste disposal implications like methane emissions. Sawdust and wood shavings may be mixed with biocomposites to create high-performance materials. Biocomposites may be made from industrial organic waste, including food processing and paper wastes, closing the material flow loop. Beyond raw material sourcing, circular economy integration includes end-of-life management. Intelligent biocomposites may be recycled or degraded into ecologically friendly components. Chemical recycling and enzymatic degradation technologies are making circular biocomposites more feasible, assuring long-term sustainability. Intelligent biocomposites enhance resource efficiency and support worldwide efforts to move to more sustainable manufacturing systems by adopting circular economy concepts. The creation and optimization of intelligent biocomposites using AI presents another appealing prospect. AI-driven methods like machine learning algorithms and predictive modeling are revolutionizing material design with unparalleled accuracy and efficiency. AI can anticipate and optimize

biocomposites' material qualities depending on composition and processing. Machine learning methods can analyze large fiber-matrix interaction datasets to find the best combinations for mechanical, thermal, and functional aspects.

AI models stimuli-responsive biocomposites' behavior under different environmental circumstances to help create them. This is useful for adaptable applications like smart packaging and environmental sensors. AI technologies may help build biocomposites that fulfill performance objectives by modeling material reactions to temperature, humidity, and mechanical stress. AI optimizes intelligent biocomposites production. Additive manufacturing and chemical functionalization include complicated parameters that are hard to tune manually. AI-driven process control systems can evaluate real-time industrial data to improve efficiency, waste reduction, and quality. This capacity scales biocomposite manufacturing and decreases prices, making these materials more affordable for businesses and consumers. AI is used in end-user applications where biocomposites' sensors and smart systems provide real-time monitoring and feedback. Biocomposites used in construction or automotive components may have sensors for structural integrity, temperature, and moisture. These sensors' data may be analyzed by AI systems to forecast maintenance requirements and failures. AI and intelligent biocomposites improve application safety, dependability, and efficiency, increasing their attractiveness. Multifunctional systems give another opportunity to construct intelligent biocomposites that can solve numerous problems at once. Traditional materials frequently have a single purpose, such as structural support or thermal insulation. However, multifunctional biocomposites combine these fundamental qualities with sophisticated features such as energy storage, environmental sensing, and self-regeneration, enabling new applications.

Energy storage is a potential multifunctionality field. Biocomposites may store mechanical or thermal energy using piezoelectric or thermoelectric components. These materials can create and store energy, making them useful in wearable electronics, smart packaging, and renewable energy systems. Shoes using piezoelectric biocomposites might power sensors and gadgets by converting walking energy into electricity. Thermoelectric biocomposites might collect industrial or electronic waste heat to boost energy efficiency. Another use of multifunctional biocomposites is environmental sensing. These materials may be implanted with sensors to detect pollution, temperature, and moisture, making them useful for environmental monitoring. Agricultural biocomposites can monitor soil moisture and nutrient levels in real-time to improve irrigation and fertilization. Biocomposites in packaging might detect food contamination and freshness, minimizing waste and maintaining customer safety. The developing ability of multifunctional biocomposites to regenerate themselves boosts their potential. Biocomposites may self-heal wear and tear damage using microcapsules or reversible chemical connections. This feature increases material longevity, saves maintenance costs, and improves sustainability by reducing replacements. Self-regenerative biocomposites may heal fractures in building materials and recover from slight impacts in automobile components. Intelligent biocomposites' multifunctional systems stimulate nanotechnology, bioengineering, and materials science collaboration. Nanocellulose and graphene boost biocomposites' mechanical strength, conductivity, and responsiveness, improving

their multifunctionality. Bioinspired concepts mimic natural adaptive systems to create dynamic materials that respond to their environment.

1.6 Conclusion

In conclusion, intelligent biocomposite materials offer a unique blend of sustainability, especially through their advanced functionality, and adaptability. Intelligent biocomposites address challenges across industries, including the energy, healthcare, and construction sectors. These materials create multifunctional systems capable of meeting the demands of modern society while reducing environmental impact, which cover lightweight structures, biodegradability, and renewability, with advanced functionalities, including self-healing, environmental sensing, and stimuli responsiveness, which are enhanced through nanotechnology, AI, and bioinspired design. Intelligent biocomposites improve resource efficiency and waste minimization, which improve the environmental footprint of material production and promote economic sustainability by closing the loop in material life cycles. Furthermore, intelligent biocomposites enable recyclability or biodegradability to ensure minimal environmental impact. The integration of AI enables precision in material design, process optimization, and application monitoring. Predictive modeling, powered by machine learning algorithms, has become a critical tool for understanding the complex interactions between fibers, matrices, and additives, facilitating the design of materials with tailored properties. The fusion of AI and biocomposites creates interdisciplinary collaboration to drive innovation and solve complex problems. Energy-harvesting biocomposites harness mechanical or thermal stimuli to generate renewable energy. Similarly, self-healing biocomposites enhance durability and reduce maintenance requirements. The incorporation of nanocellulose, graphene, and other nanomaterials demonstrated significant enhancements in mechanical, thermal, and functional properties.

References

- Adamu, M., Rahman, M. R., & Hamdan, S. (2019). Formulation optimization and characterization of bamboo/polyvinyl alcohol/clay nanocomposite by response surface methodology. *Composites Part B: Engineering*, 176, 107297. <https://doi.org/10.1016/j.compositesb.2019.107297>.
- Adwani, S., Elsubeihi, E., Zebari, A., Aljanahi, M., Moharamzadeh, K., & Elbishari, H. (2023). Effect of different silane coupling agents on the bond strength between hydrogen peroxide-etched epoxy-based- fiber-reinforced post and composite resin core. *Dentistry Journal*, 11(6), 142. <https://doi.org/10.3390/dj11060142>.
- Ahirwar, D., Telang, A., Purohit, R., & Namdev, A. (2022). A short review on polyurethane polymer composite. *Materials Today: Proceedings*, 62, 3804–3810. <https://doi.org/10.1016/j.matpr.2022.04.481>.
- Ahmed, A. T. M. F., Islam, M. Z., Mahmud, M. S., Sarker, M. E., & Islam, M. R. (2022). Hemp as a potential raw material toward a sustainable world: A review. *Heliyon*, 8(1), e08753. <https://doi.org/10.1016/j.heliyon.2022.e08753>, <http://www.journals.elsevier.com/heliyon/>.

- Amalina, F., Razak, A. S. A., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications—A review. *Journal of Hazardous Materials Advances*, 7, 100134. <https://doi.org/10.1016/j.hazadv.2022.100134>.
- Andrew, J. J., & Dhakal, H. N. (2022). Sustainable biobased composites for advanced applications: Recent trends and future opportunities—A critical review. *Composites Part C: Open Access*, 7, 100220. <https://doi.org/10.1016/j.jcomc.2021.100220>.
- Arya, M., Malmek, E. M., Ecoist, T. K., Pettersson, J., Skrifvars, M., & Khalili, P. (2023). Enhancing sustainability: Jute fiber-reinforced bio-based sandwich composites for use in battery boxes. *Polymers*, 15(18), 3842. <https://doi.org/10.3390/polym15183842>, <http://www.mdpi.com/journal/polymers>.
- Badini, S., Regondi, S., & Pugliese, R. (2025). Enhancing mechanical and bioinspired materials through generative AI approaches. *Next Materials*, 6(1), 100275. <https://doi.org/10.1016/j.nxmte.2024.100275>.
- Bakri, M. K. B., Jayamani, E., & Hamdan, S. (2017). Processing and characterization of banana fiber/epoxy composites: Effect of alkaline treatment. *Materials Today: Proceedings*, 4, 2871–2878. <https://doi.org/10.1016/j.matpr.2017.02.167>, <https://www.sciencedirect.com/journal/materials-today-proceedings>.
- Bakri, M. K. B., Jayamani, E., Hamdan, S., Rahman, M. R., & Kakar, A. (2018). Potential of Borneo Acacia wood in fully biodegradable bio-composites' commercial production and application. *Polymer Bulletin*, 75(11), 5333–5354. <https://doi.org/10.1007/s00289-018-2299-9>, <https://rd.springer.com/journal/289>.
- Balakrishnan, T. S., Sultan, M. T. H., Shahar, F. S., Ahmad, K. A., Dol, S. S., & Naning, F. H. (2024). Bio-inspired coatings for natural fibre composites. *Journal of Science: Advanced Materials and Devices*, 10, 100841. <https://doi.org/10.1016/j.jsamd.2024.100841>.
- Baley, C. (2002). Analysis of the flax fibres tensile behaviour and analysis of the tensile stiffness increase. *Composites Part A: Applied Science and Manufacturing*, 33(7), 939–948. [https://doi.org/10.1016/s1359-835x\(02\)00040-4](https://doi.org/10.1016/s1359-835x(02)00040-4).
- Bigham, A., Zarepour, A., Safarkhani, M., Huh, Y. S., Khosravi, A., Rabiee, N., Irvani, S., & Zarrabi, A. (2024). Inspired by nature: Bioinspired and biomimetic photocatalysts for biomedical applications. *Nano Materials Science*, 7(1), 1–23. <https://doi.org/10.1016/j.nanoms.2024.02.006>.
- Botta, C., Grottola, C. M., Amato, D., & Acocella, M. R. (2024). Biochar as sustainable filler of recycled polylactic acid (PLA): A new generation of processable biocomposites. *Polymers*, 16(23), 3347. <https://doi.org/10.3390/polym16233347>, <http://www.mdpi.com/journal/polymers>.
- Chaudhary, V., Bajpai, P. K., & Maheshwari, S. (2018). Effect of moisture absorption on the mechanical performance of natural fiber reinforced woven hybrid bio-composites. *Journal of Natural Fibers*, 17(1), 84–100. <https://doi.org/10.1080/15440478.2018.1469451>.
- Choi, K., Noh, A., Kim, J., Hong, P. H., Ko, M. J., & Hong, S. W. (2023). Properties and applications of self-healing polymeric materials: A review. *Polymers*, 15(22), 4408. <https://doi.org/10.3390/polym15224408>, <http://www.mdpi.com/journal/polymers>.
- Chowdhury, M. K. H., Anik, H. R., Akter, M., Hasan, S. M. M., Tushar, S. I., Mahmud, S., Nahar, N., & Tania, I. S. (2025). Sensing the future with graphene-based wearable sensors: A review. *Results in Materials*, 100646. <https://doi.org/10.1016/j.rinma.2024.100646>.
- Cionita, T., Hamdan, M. H. M., Siregar, J. P., Fitriyana, D. F., Junid, R., Shing, W. L., Jaafar, J., Irawan, A. P., Rihayat, T., Ismail, R., Bayuseno, A. P., & Jehadus, E. (2024). Overview of jute fibre as thermoplastic matrix polymer reinforcement. *Journal of Renewable Materials*,

- 12(3), 457–483. <https://doi.org/10.32604/jrm.2024.045814>, https://cdn.techscience.cn/files/jrm/2024/TSP_JRM-12-3/TSP_JRM_45814/TSP_JRM_45814.pdf.
- Collins, C. M., & Safiuddin, M. (2022). Lotus-leaf-inspired biomimetic coatings: Different types, key properties, and applications in infrastructures. *Infrastructures*, 7(4), 46. <https://doi.org/10.3390/infrastructures7040046>.
- Cui, K., Lau, D., & Chang, J. (2024). Advancements in energy harvesting through building materials: A critical review. *Journal of Building Engineering*, 98(1), 111412. <https://doi.org/10.1016/j.jobe.2024.111412>.
- De, S., James, B., Ji, J., Wasti, S., Zhang, S., Kore, S., Tekinalp, H., Li, Y., Ureña-Benavides, E. E., Vaidya, U., Ragauskas, A. J., Webb, E., Ozcan, S., & Zhao, X. (2023). Biomass-derived composites for various applications. *Advances in Bioenergy*, 8, 145–196. <https://doi.org/10.1016/bs.aibe.2023.01.001>, <https://www.sciencedirect.com/bookseries/advances-in-bioenergy>.
- Fatema, K., Sharmin, A. A., Sharna, J. F., Haque, M. A., Rahman, M., Sarker, S., Kazi, M., Rahman, M. R., Namakka, M., Uzzaman, M., & Patwary, M. A. M. (2024). Antioxidant and antidiabetic effects of *Flemingia macrophylla* leaf extract and fractions: In vitro, molecular docking, dynamic simulation, pharmacokinetics, and biological activity studies. *BioResources*, 19(3), 4960–4983. <https://doi.org/10.15376/biores.19.3.4960-4983>, https://bioresources.cnr.ncsu.edu/wp-content/uploads/2024/06/BioRes_19_3_4960_Fatema_SSHRSKRNU_P_Antioxid_Antidiabet_Leaf_Extract_Docking_23487.pdf.
- Giampieri, A., Ling-Chin, J., Ma, Z., Smallbone, A., & Roskilly, A. P. (2020). A review of the current automotive manufacturing practice from an energy perspective. *Applied Energy*, 261, 114074. <https://doi.org/10.1016/j.apenergy.2019.114074>.
- Hamilton, S., & Kingston, B. R. (2024). Applying artificial intelligence and computational modeling to nanomedicine. *Current Opinion in Biotechnology*, 85, 103043. <https://doi.org/10.1016/j.copbio.2023.103043>.
- Hari, H. P., Jayamani, E., Soon, K. H., Wong, Y. C., Rahman, M. R., & Bakri, M. K. B. (2021). Interfacial polarization effects on dielectric properties in flax reinforced polypropylene/strontium titanate composites. *Materials Chemistry and Physics*, 265, 124489. <https://doi.org/10.1016/j.matchemphys.2021.124489>, <http://www.journals.elsevier.com/materials-chemistry-and-physics>.
- Huang, X., Panahi-Sarmad, M., Dong, K., Li, R., Chen, T., & Xiao, X. (2021). Tracing evolutions in electro-activated shape memory polymer composites with 4D printing strategies: A systematic review. *Composites Part A: Applied Science and Manufacturing*, 147, 106444. <https://doi.org/10.1016/j.compositesa.2021.106444>.
- Hussain, M., Khan, S. M., Shafiq, M., & Abbas, N. (2024). A review on PLA-based biodegradable materials for biomedical applications. *Giant*, 18, 100261. <https://doi.org/10.1016/j.giant.2024.100261>.
- Iftekar, S. F., Aabid, A., Amir, A., & Baig, M. (2023). Advancements and limitations in 3D printing materials and technologies: A critical review. *Polymers*, 15(11), 2519. <https://doi.org/10.3390/polym15112519>.
- Islam, M. A., Mobarak, M. H., Rimon, M. I. H., Al Mahmud, M. Z., Ghosh, J., Ahmed, M. M. S., & Hossain, N. (2024). Additive manufacturing in polymer research: Advances, synthesis, and applications. *Polymer Testing*, 132, 108364. <https://doi.org/10.1016/j.polymertesting.2024.108364>, <https://www.sciencedirect.com/science/journal/01429418>.
- James, A., Rezaur Rahman, M., Anwar Mohamed Said, K., Namakka, M., Kuok Kuok, K., Uddin Khandaker, M., Al-Humaidi, J. Y., Althomali, R. H., & Rahman, M. M. (2024). Lithium chloride-mediated enhancement of dye removal capacity in Borneo bamboo

- derived nanocellulose-based nanocomposite membranes (NCMs). *Journal of Molecular Liquids*, 413, 125973. <https://doi.org/10.1016/j.molliq.2024.125973>.
- Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *KeAi Communications Co., India Sustainable Operations and Computers*, 3, 203–217. <https://doi.org/10.1016/j.susoc.2022.01.008>, <https://www.sciencedirect.com/science/journal/26664127>.
- Jayamani, E., Hamdan, S., Rahman, M. R., Bakri, M. K. B., & Kakar, A. (2015). An investigation of sound absorption coefficient on sisal fiber poly lactic acid bio-composites. *Journal of Applied Polymer Science*, 132(34), 1–8. <https://doi.org/10.1002/app.42470>, <http://onlinelibrary.wiley.com/journal/10.1002/>.
- Jayamani, E., Hamdan, S., Kok Heng, S., Rahman, M. R., & Bin Bakri, M. K. (2016). Acoustical, thermal, and morphological properties of zein reinforced oil palm empty fruit bunch fiber bio-composites. *Journal of Applied Polymer Science*, 133(43), 1–8. <https://doi.org/10.1002/app.44164>, <http://onlinelibrary.wiley.com/journal/10.1002/>.
- Jayamaui, E., Rahman, M. R., Benhur, D. A., Bakri, M. K. B., Kakair, A., & Khan, A. (2020). Comparative study of fly ash/sugarcane fiber reinforced polymer composites properties. *BioResources*, 15(3), 5514–5531. <https://doi.org/10.15376/biores.15.3.5514-5531>, https://bioresources.cnr.ncsu.edu/wp-content/uploads/2020/05/BioRes_15_3_5514_Jayamani_RBBK_Comparative-Study_FLy-Ash_Sugarcane-Fiber_Reinforced_Polymer_17489.pdf.
- Jiang, Y., Ng, E. L. L., Han, D. X., Yan, Y., Chan, S. Y., Wang, J., & Chan, B. Q. Y. (2023). Self-healing polymeric materials and composites for additive manufacturing. *Polymers*, 15(21), 4206. <https://doi.org/10.3390/polym15214206>, <http://www.mdpi.com/journal/polymers>.
- Kamran, M. J., Jayamani, E., Heng, S. K., Wong, Y. C., Rahman, M. R., Al-Bogami, A. S., Huda, D., Bakri, M. K. B., & Rahman, M. M. (2022). Characterization and comparative study on chemically treated luffa fiber as reinforcement for polylactic acid bio-composites. *BioResources*, 17(2), 2576–2597. <https://doi.org/10.15376/biores.17.2.2576-2597>, https://bioresources.cnr.ncsu.edu/wp-content/uploads/2022/03/BioRes_17_2_2576_Kamran_JHWAHBR_Charact_Chem_Treated_Luffa_Fiber_PLA_Compos_19843.pdf.
- Kang, M., & Yeo, W. H. (2024). Advances in energy harvesting technologies for wearable devices. *Micromachines*, 15(7), 884. <https://doi.org/10.3390/mi15070884>, <http://www.mdpi.com/journal/micromachines>.
- Kantaros, A., & Ganetsos, T. (2023). From static to dynamic: Smart materials pioneering additive manufacturing in regenerative medicine. *International Journal of Molecular Sciences*, 24(21), 15748. <https://doi.org/10.3390/ijms242115748>.
- Kiew, K. S., Hamdan, S., & Rahman, M. R. (2013). Comparative study of dielectric properties of chicken feather/kenaf fiber reinforced unsaturated polyester composites. *BioResources*, 8(2), 1591–1603. <https://doi.org/10.15376/biores.8.2.1591-1603>, http://www.ncsu.edu/bioresources/BioRes_08/BioRes_08_2_1591_Kiew_HR_Dielectric_Prop_Feather_Kenaf_PE_Composite_3628.pdf.
- Kuok, K. K., Bakri, M. K. B., Chan, C. P., Rahman, M. R., Namakka, M., Said, K. A. M., Yun, C. M., & Rahman, M. M. (2024). Merits of bamboo utilization in earth preservation, water and wastewater treatment: A mini review. *BioResources*, 19(2), 1–24. <https://doi.org/10.15376/biores.19.2.Kuok>, https://bioresources.cnr.ncsu.edu/wp-content/uploads/2024/03/BioRes_19_2_Review_Kuok_BCRNSYR_Merits_Bamboo_Utiliz_Water_Treatment_23312.pdf.

- Lai, J. C. H., Rahman, M. R., Hamdan, S., Liew, F. K., Rahman, M. M., & Hossen, M. F. (2015). Impact of nanoclay on physicomechanical and thermal analysis of polyvinyl alcohol/fumed silica/clay nanocomposites. *Journal of Applied Polymer Science*, *132*(15), 1–7. <https://doi.org/10.1002/app.41843>, <http://onlinelibrary.wiley.com/journal/10.1002/>
- Li, Y., Feng, Z., Huang, L., Essa, K., Bilotti, E., Zhang, H., Peijs, T., & Hao, L. (2019). Additive manufacturing high performance graphene-based composites: A review. *Composites Part A: Applied Science and Manufacturing*, *124*, 105483. <https://doi.org/10.1016/j.compositesa.2019.105483>.
- Ligon, S. C., Liska, R., Stampfl, J., Gurr, M., & Mühlaupt, R. (2017). Polymers for 3D printing and customized additive manufacturing. *Chemical Reviews*, *117*(15), 10212–10290. <https://doi.org/10.1021/acs.chemrev.7b00074>, <http://pubs.acs.org/journal/chreay>.
- Mahboob, Z., El Sawi, I., Zdero, R., Fawaz, Z., & Bougherara, H. (2017). Tensile and compressive damaged response in flax fibre reinforced epoxy composites. *Composites Part A: Applied Science and Manufacturing*, *92*, 118–133. <https://doi.org/10.1016/j.compositesa.2016.11.007>.
- Mahmud, M. A., Abir, N., Anannya, F. R., Nabi Khan, A., Rahman, A. N. M. M., & Jamine, N. (2023). Coir fiber as thermal insulator and its performance as reinforcing material in biocomposite production. *Heliyon*, *9*(5), e15597. <https://doi.org/10.1016/j.heliyon.2023.e15597>, <http://www.journals.elsevier.com/heliyon/>.
- Malik, K., Ahmad, F., Dawood, M. S., Islam, M. S., Ali, S., Raza, A., & Shahed, C. A. (2024). Mechanical property enhancement of graphene-kenaf-epoxy multiphase composites for automotive applications. *Composites Part A: Applied Science and Manufacturing*, *177*, 107916. <https://doi.org/10.1016/j.compositesa.2023.107916>, <https://www.sciencedirect.com/science/journal/1359835X>.
- Meng, H., & Li, G. (2013). A review of stimuli-responsive shape memory polymer composites. *Polymer*, *54*(9), 2199–2221. <https://doi.org/10.1016/j.polymer.2013.02.023>.
- Mohammadi, M., Taban, E., Tan, W. H., Che Din, N. B., Putra, A., & Berardi, U. (2024). Recent progress in natural fiber reinforced composite as sound absorber material. *Journal of Building Engineering*, *84*, 108514. <https://doi.org/10.1016/j.jobee.2024.108514>.
- Mohammed, M., Rahman, R., Mohammed, A. M., Adam, T., Betar, B. O., Osman, A. F., & Dahham, O. S. (2022). Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: Recent advancement. *Polymer Testing*, *115*, 107707. <https://doi.org/10.1016/j.polymertesting.2022.107707>, <https://www.journals.elsevier.com/polymer-testing>.
- Naik, V., Kumar, M., & Kaup, V. (2022). A review on natural fiber composite material in automotive applications. *Engineered Science*, *18*(1), 1–10. <https://doi.org/10.30919/es8d589>.
- Namakka, M., Rahman, M. R., Said, K. A. M. B., Abdul Mannan, M., & Patwary, A. M. (2023). A review of nanoparticle synthesis methods, classifications, applications, and characterization. *Environmental Nanotechnology, Monitoring and Management*, *20*, 100900. <https://doi.org/10.1016/j.enmm.2023.100900>, <http://www.journals.elsevier.com/environmental-nanotechnology-monitoring-and-management/>.
- Namakka, M., Rahman, M. R., Bin Mohamad Said, K. A., & Muhammad, A. (2024). Insights into micro-and nano-zero valent iron materials: Synthesis methods and multifaceted applications. *RSC Advances*, *14*(41), 30411–30439. <https://doi.org/10.1039/d4ra03507k>, <http://pubs.rsc.org/en/journals/journal/ra>.
- Namakka, M., Rahman, M. R., Mohamad Bin Said, K. A., Kuok, K. K., Md Yusof, F. A., Al-Saleem, M. S. M., Al-Humaidi, J. Y., & Rahman, M. M. (2024). Unveiling the synergistic

- effect of an nZVI-SiO₂-TiO₂ nanocomposite for the remediation of dye contaminated wastewater. *Materials Advances*, 5(23), 9292–9313. <https://doi.org/10.1039/d4ma00853g>, <https://www.rsc.org/journals-books-databases/about-journals/materials-advances/>.
- Naser, A. Z., Deiab, I., Defersha, F., & Yang, S. (2021). Expanding poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs) applications: A review on modifications and effects. *Polymers*, 13(23), 4271. <https://doi.org/10.3390/polym13234271>.
- Nilimaa, J. (2023). Smart materials and technologies for sustainable concrete construction. *Developments in the Built Environment*, 15, 100177. <https://doi.org/10.1016/j.dibe.2023.100177>.
- Ogunleye, R. O., Rusnáková, S., Javořík, J., Žaludek, M., & Kotlánová, B. (2024). Advanced sensors and sensing systems for structural health monitoring in aerospace composites. *Advanced Engineering Materials*, 26(22), 2401745. <https://doi.org/10.1002/adem.202401745>, <http://onlinelibrary.wiley.com/journal/10.1002/>.
- Oh, H.-W., Jeong, Y.-J., & Park, S.-Y. (2024). Reconfigurable light-responsive liquid crystal elastomer/carbon nanotube nanocomposite actuators operated by photothermal effects and dynamic exchange reaction. *Chemical Engineering Journal*, 497(1), 154976. <https://doi.org/10.1016/j.cej.2024.154976>.
- Ornaghi, H. L., Jr., Monticeli, F. M., & Agnol, L. D. (2023). A review on polymers for biomedical applications on hard and soft tissues and prosthetic limbs. *Polymers*, 15(19), 4034. <https://doi.org/10.3390/polym15194034>.
- Osman, A., & Lu, J. (2023). 3D printing of polymer composites to fabricate wearable sensors: A comprehensive review. *Materials Science and Engineering: R: Reports*, 154, 100734. <https://doi.org/10.1016/j.mser.2023.100734>.
- Pan, X., Wu, Y., Wang, Y., Zhou, G., & Cai, H. (2024). Mechanical energy harvesting based on the piezoelectric materials: Recent advances and future perspectives. *Chemical Engineering Journal*, 497, 154249. <https://doi.org/10.1016/j.cej.2024.154249>.
- Park, S., Shou, W., Makatura, L., Matusik, W., & Fu, K. (2022). 3D printing of polymer composites: Materials, processes, and applications. *Matter*, 5(1), 43–76. <https://doi.org/10.1016/j.matt.2021.10.018>, www.cell.com/matter.
- Phiri, R., Mavinkere Rangappa, S., Siengchin, S., Oladijo, O. P., & Dhakal, H. N. (2023). Development of sustainable biopolymer-based composites for lightweight applications from agricultural waste biomass: A review. *Advanced Industrial and Engineering Polymer Research*, 6(4), 436–450. <https://doi.org/10.1016/j.aiepr.2023.04.004>, www.keaipublishing.com/en/journals/advanced-industrial-and-engineering-polymer-research/.
- Pickering, K. L., Efendy, M. G. A., & Le, T. M. (2016). A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, 83(1), 98–112. <https://doi.org/10.1016/j.compositesa.2015.08.038>.
- Pil, L., Bensadoun, F., Pariset, J., & Verpoest, I. (2016). Why are designers fascinated by flax and hemp fibre composites? *Composites Part A: Applied Science and Manufacturing*, 83, 193–205. <https://doi.org/10.1016/j.compositesa.2015.11.004>.
- Pittayavinai, P., Tangchirapat, W., Johns, J., & Nakaramontri, Y. (2023). Flexible canvas produced from uncured-natural rubber composites filled with high calcium oxide fly ash/cement hybrid filler. *Construction and Building Materials*, 368, 130438. <https://doi.org/10.1016/j.conbuildmat.2023.130438>.
- Rahman, M. R., Hamdan, S., Ahmed, A. S., Islam, M. S., Talib, Z. A., Abdullah, W. F. W., & Mat, M. S. C. (2011). Thermogravimetric analysis and dynamic Young's modulus measurement of N,N-dimethylacetamide-impregnated wood polymer composites. *Journal of Vinyl and Additive Technology*, 17(3), 177–183. <https://doi.org/10.1002/vnl.20275>.

- Rahman, M. R., Hui, J. L. C., Hamdan, S., Ahmed, A. S., Bains, R., & Saleh, S. F. (2013). Combined styrene/MMA/nanoclay cross-linker effect on wood-polymer composites (WPCs). *BioResources*, 8(2), 4227–4237. http://www.ncsu.edu/bioresources/Back_Issues.htm.
- Rahman, M. R., Hamdan, S., Hasan, M., Bains, R., & Salleh, A. A. (2015). Physical, mechanical, and thermal properties of wood flour reinforced maleic anhydride grafted unsaturated polyester (UP) biocomposites. *BioResources*, 10(3), 4557–4568. <https://doi.org/10.15376/biores.10.3.4557-4568>, https://www.ncsu.edu/bioresources/BioRes_10/BioRes_10_3_4557_Rahman_HHBS_Phys_Mech_Therm_Prop_Wood_Flour_Reinf_7280.pdf.
- Rahman, M. R., Hamdan, S., Hashim, D. M. A., Islam, M. S., & Takagi, H. (2015). Bamboo fiber polypropylene composites: Effect of fiber treatment and nano clay on mechanical and thermal properties. *Journal of Vinyl and Additive Technology*, 21(4), 253–258. <https://doi.org/10.1002/vnl.21407>, <http://onlinelibrary.wiley.com/journal/10.1002/>.
- Rahman, M. R., Hamdan, S., Lai, J. C. H., Jawaid, M., & Md Yusof, F. A. (2017). Physico-mechanical, thermal and morphological properties of furfuryl alcohol/2-ethylhexyl methacrylate/halloysite nanoclay wood polymer nanocomposites (WPNCs). *Heliyon*, 3(7), e00342. <https://doi.org/10.1016/j.heliyon.2017.e00342>, <http://www.journals.elsevier.com/heliyon/>.
- Rahman, M. R., Hamdan, S., Jayamani, E., Kakar, A., Bakri, M. K. B., & Yusof, F. A. B. M. (2019). Tert-butyl catechol/alkaline-treated kenaf/jute polyethylene hybrid composites: Impact on physico-mechanical, thermal and morphological properties. *Polymer Bulletin*, 76(2), 763–784. <https://doi.org/10.1007/s00289-018-2404-0>.
- Rahman, M. R., James, A., Mohamed Said, K. A., Namakka, M., Khandaker, M. U., Jiunn, W. H., Al-Humaidi, J. Y., Althomali, R. H., & Rahman, M. M. (2024). A TiO₂ grafted bamboo derivative nanocellulose polyvinylidene fluoride (PVDF) nanocomposite membrane for wastewater treatment by a photocatalytic process. *Materials Advances*, 5(19), 7617–7636. <https://doi.org/10.1039/d4ma00716f>, <https://www.rsc.org/journals-books-databases/about-journals/materials-advances/>.
- Ramakrishnan, M., Rajan, G., Semenova, Y., & Farrell, G. (2016). Overview of fiber optic sensor technologies for strain/temperature sensing applications in composite materials. *Sensors (Basel, Switzerland)*, 16(1), 99. <https://doi.org/10.3390/s16010099>.
- Rodrigues, C., Souza, V. G. L., Coelho, I., & Fernando, A. L. (2021). Bio-based sensors for smart food packaging—current applications and future trends. *Sensor*, 21(6), 2148. <https://doi.org/10.3390/s21062148>.
- Saba, N., & Jawaid, M. (2018). A review on thermomechanical properties of polymers and fibers reinforced polymer composites. *Journal of Industrial and Engineering Chemistry*, 67, 1–11. <https://doi.org/10.1016/j.jiec.2018.06.018>.
- Sagdic, K., Eş, I., Sitti, M., & İnci, F. (2022). Smart materials: Rational design in biosystems via artificial intelligence. *Trends in Biotechnology*, 40(8), 987–1003. <https://doi.org/10.1016/j.tibtech.2022.01.005>, www.elsevier.com/locate/tibtech.
- Samir, A., Ashour, F. H., Hakim, A. A. A., & Bassyouni, M. (2022). Recent advances in biodegradable polymers for sustainable applications. *NPJ Materials Degradation*, 6(1), 68. <https://doi.org/10.1038/s41529-022-00277-7>, nature.com/npjmatdeg/.
- Soares, R. V., Dias, R. Y. C., Maia, P. V. D. M., Junior, W. G. P., & Fujiyama, R. T. (2024). *Presentation of biocomposites for proposal for use in car bumpers*. SAE Mobilus, 1–7. [10.4271/2024-36-0148](https://doi.org/10.4271/2024-36-0148).
- Sueraya, A. Z., Rahman, M. R., Said, K. A. B. M., Namakka, M., Kanakaraju, D., Al-Humaidi, J. Y., Al-Baqami, S. M., Rahman, M. M., & Khandaker, M. U. (2024). Impact of titanium dioxide/graphene in polyvinylidene fluoride nanocomposite

- membrane to intensify methylene blue dye removal, antifouling performance, and reusability. *Journal of Applied Polymer Science*, 141(47), e56257. <https://doi.org/10.1002/app.56257>, <http://onlinelibrary.wiley.com/journal/10.1002/>.
- Tardy, B. L., Lizundia, E., Guizani, C., Hakkarainen, M., & Sipponen, M. H. (2023). Prospects for the integration of lignin materials into the circular economy. *Materials Today*, 65, 122–132. <https://doi.org/10.1016/j.matmod.2023.04.001>, <http://www.journals.elsevier.com/materials-today/>.
- Tavares, T. D., Antunes, J. C., Ferreira, F., & Felgueiras, H. P. (2020). Biofunctionalization of natural fiber-reinforced biocomposites for biomedical applications. *Biomolecules*, 10(1), 148. <https://doi.org/10.3390/biom10010148>, <https://www.mdpi.com/2218-273X/10/1/148/pdf>.
- Tedeschi, G., Guzman-Puyol, S., Ceseracciu, L., Benitez, J. J., Cataldi, P., Bissett, M., Heredia, A., Athanassiou, A., & Heredia-Guerrero, J. A. (2020). Sustainable, high-barrier poly-aleuritate/nanocellulose biocomposites. *ACS Sustainable Chemistry and Engineering*, 8(29), 10682–10690. <https://doi.org/10.1021/acssuschemeng.0c00909>, <http://pubs.acs.org/journal/ascecg>.
- Tedesco, L. (2024). A commitment between the auto industry and hemp. <https://www.benzinga.com/markets/cannabis/24/09/40734229/5-auto-giants-embracing-hemp-for-sustainability-from-ford-to-bmw>.
- Thomas, L., & Ramachandra, M. (2018). Advanced materials for wind turbine blade—A review. *Materials Today: Proceedings*, 5(1), 2635–2640. <https://doi.org/10.1016/j.matpr.2018.01.043>.
- Trivedi, A. K., Gupta, M. K., & Singh, H. (2023). PLA based biocomposites for sustainable products: A review. *Advanced Industrial and Engineering Polymer Research*, 6(4), 382–395. <https://doi.org/10.1016/j.aiepr.2023.02.002>.
- Vasconcelos, A. R. C., de Matos, R. A., Silveira, M. V., & Mesquita, E. (2024). Applications of smart and self-sensing materials for structural health monitoring in civil engineering: A systematic review. *Buildings*, 14(8), 2345. <https://doi.org/10.3390/buildings14082345>, www.mdpi.com/journal/buildings.
- Vieyra, H., Molina-Romero, J. M., Calderón-Nájera, J. de D., & Santana-Díaz, A. (2022). Engineering, recyclable, and biodegradable plastics in the automotive industry: A review. *Polymers*, 14(16), 3412. <https://doi.org/10.3390/polym14163412>.
- Widodo, E., Sugiarto, P., & Widodo, T. D. (2024). Comprehensive investigation of raw and NaOH alkalinized sansevieria fiber for enhancing composite reinforcement. *Case Studies in Chemical and Environmental Engineering*, 9, 100546. <https://doi.org/10.1016/j.cscee.2023.100546>.
- Wu, R., Wang, X. Q., Zhao, D., Hou, J., Wu, C., Lau, D., & Tam, L. H. (2023). Degradation of fiber/matrix interface under various environmental and loading conditions: Insights from molecular simulations. *Construction and Building Materials*, 390, 131101. <https://doi.org/10.1016/j.conbuildmat.2023.131101>, <https://www.journals.elsevier.com/construction-and-building-materials>.
- Xie, Y., Hill, C. A. S., Xiao, Z., Militz, H., & Mai, C. (2010). Silane coupling agents used for natural fiber/polymer composites: A review. *Composites Part A: Applied Science and Manufacturing*, 41(7), 806–819. <https://doi.org/10.1016/j.compositesa.2010.03.005>.
- Yadav, M., & Mathur, A. (2021). Bamboo as a sustainable material in the construction industry: An overview. *Materials Today: Proceedings*, 43, 2872–2876. <https://doi.org/10.1016/j.matpr.2021.01.125>.

- Yemesegen, E. B., & Memari, A. M. (2023). A review of experimental studies on Cob, Hempcrete, and bamboo components and the call for transition towards sustainable home building with 3D printing. *Construction and Building Materials*, 399(1), 132603. <https://doi.org/10.1016/j.conbuildmat.2023.132603>.
- Yousif, E., & Haddad, R. (2013). Photodegradation and photostabilization of polymers, especially polystyrene: Review. *SpringerPlus*, 2(1), 398. <https://doi.org/10.1186/2193-1801-2-398>.
- Yuan, W., Zhang, Z., Li, Y., Huang, Y., Zhong, Z., & Hu, Z. (2024). Self-healing and in-situ real-time damage-reporting fiber-reinforced composite. *Composites Science and Technology*, 245, 110344. <https://doi.org/10.1016/j.compscitech.2023.110344>.
- Zhou, L., Miller, J., Vezza, J., Mayster, M., Raffay, M., Justice, Q., Al Tamimi, Z., Hansotte, G., Sunkara, L. D., & Bernat, J. (2024). Additive manufacturing: A comprehensive review. *Sensors (Basel, Switzerland)*, 24(9), 2668. <https://doi.org/10.3390/s24092668>, <http://www.mdpi.com/journal/sensors>.

Smart Biocomposite Materials: Fabrication, Applications, and Sustainability presents the latest advancements in this important research field. This book starts with a brief introduction to the classification of these materials and proceeds to discuss their innovative fabrication techniques. There is also a dedicated chapter on functional fillers. This book offers a holistic view, covering mechanical performance, environmental impact, bio-sustainability, high-performance applications, and their practical implementation. It also addresses ethical, cultural, and societal aspects as well as key challenges and future directions.

This book offers a comprehensive examination of the environmental aspects and provides in-depth technical insights into the science and engineering of these materials, helping professionals to make informed decisions about adopting these sustainable materials in their future research projects.

Key Features

- Presents the latest research findings on the properties, manufacturing, and potential future applications of intelligent biocomposite materials
- Includes practical guidelines and best practices for incorporating intelligent biocomposite materials into various industrial products, offering step-by-step approaches and real-world examples
- Provides quantifiable sustainability metrics and LCA, helping readers to assess the environmental impact of their material choices, to make informed decisions
- Covers applications in intelligent sensors and actuators, in drug delivery, and in biomedical, aerospace, automotive, and construction sectors
- Features case studies from various global regions and industries to showcase how these materials can be used in different cultural and economic contexts, emphasizing the inclusivity of sustainable practices

About the Editors

Md. Rezaur Rahman - Department of Chemical Engineering, Faculty of Engineering, University Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia.

Muhammad Khusairy Bin Bakri - Composite Materials and Engineering Center, Washington State University, Pullman, WA, United States.



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