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ADVANCED NANOCARBON POLYMER BIOCOMPOSITES

SUSTAINABILITY TOWARDS ZERO BIOWASTE

Edited by
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.

–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

Mohammad Amran
Faculty of Science, Department of Chemistry, Bioorganic and Medicinal Chemistry Laboratory, University of Chittagong, Hathajari, Chittagong, Bangladesh

Sayeda Halima Begum
Faculty of Science, Department of Chemistry, Bioorganic and Medicinal Chemistry Laboratory, University of Chittagong, Hathajari, Chittagong, Bangladesh

Muhammad Khusairy Bin Bakri
Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia; Composite Materials and Engineering Center, Washington State University, Pullman, WA, United States

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

Andrey Burkov
Building Structures and Machines Department, Vyatka State University, Kirov, Russia

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

Bijoy Chandra Ghos
Department of Chemistry, Comilla University, Cumilla, Bangladesh

Syed Ragibul Haque
Department of Physics, Comilla University, Cumilla, Bangladesh

Mohin Hasnain
Faculty of Science, Department of Chemistry, Bioorganic and Medicinal Chemistry Laboratory, University of Chittagong, Hathajari, Chittagong, Bangladesh

Durul Huda
Department of Mechanical Engineering and Product Design Engineering, Swinburne University of Technology, Hawthorn, VIC, Australia

Md. Badrul Islam
Faculty of Science, Department of Chemistry, Bioorganic and Medicinal Chemistry Laboratory, University of Chittagong, Hathajari, Chittagong, Bangladesh

Anthonette Anak James
Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia

Perry Law Nyuk Khui
Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia

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

Mohammed Mahbubul Matin
Faculty of Science, Department of Chemistry, Bioorganic and Medicinal Chemistry Laboratory, University of Chittagong, Hathajari, Chittagong, Bangladesh

Murtala Namakka
Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia

Al-Khalid Othman
Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia

Md. Abdul Majed Patwary
Department of Chemistry, Comilla University, Cumilla, Bangladesh

Md Rezaur Rahman
UNIMAS Water Centre (UWC), Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak, Malaysia; Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia

Mohammad Atiqur Rahman
Department of Chemistry, Comilla University, Cumilla, Bangladesh

Mohammed Muzibur Rahman
Faculty of Science, Department of Chemistry, Center of Excellence for Advanced Materials Research (CEAMR), King Abdulaziz University, Jeddah, Saudi Arabia

Ain Zaienah Sueraya
Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia

Jamal Uddin
Department of Natural Science, Coppin State University, Science and Technology Center, Baltimore, MD, United States

Yuriy Yurkin
Building Structures and Machines Department, Vyatka State University, Kirov, Russia

Md. Shahid Uz Zaman
Faculty of Electrical and Computer Engineering, Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh

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. He has also been a Visiting Research Fellow at the Faculty of Engineering, Tokushima University, Japan, since June 2012. Previously, he worked as a Teaching Assistant at the Faculty of Engineering, Bangladesh University of Engineering and Technology (BUET), and as a Research Project Leader supported by the Ministry of Higher Education, Malaysia. He was appointed an External Supervisor for the Faculty of Engineering, Swinburne University of Technology, Melbourne, Australia, in 2015. He received his PhD from the Universiti Malaysia Sarawak, Malaysia. He has more than 15 years of experience in teaching, research, and working with industry. His areas of research include carbon, conducting polymers, silica/clay dispersed elastomeric polymer nanocomposites, hybrid filled loaded polymer composites, advanced materials: graphene/nanoclay/fire retardants, nanocellulose (cellulose nanocrystals and nano-fibrillar) cellulose reinforced/filled polymer composites, chemical modification, and treatment of lignocellulosic fibers, including jute, coir, sisal, kenaf, hemp and solid wood, nanocomposites and nanocellulose fibers, and polymer blends. He has more than 300 publications, listed among the Top 2% Scientists Worldwide 2023 by Stanford University.

Ts. Dr. Hj. Muhammad Khusairy Bin Capt. Hj. Bakri obtained his doctor of philosophy, PhD (2018), master of engineering (by research), MEng (2016), and bachelor of engineering (mechanical engineer), BEng (2014) from Swinburne University of Technology, Australia (SUT). Currently, he is working with Washington State University (WSU) as a Postdoctoral Research Associate in Composite Materials and Engineering Center (CMEC), focusing on materials science, wood composites, polymer composites, biomaterials, and biocarbons. Previously, he was a Research Fellow at Universiti Malaysia Sarawak (UNIMAS) from 2019 to 2021, prioritizing materials science, membrane, concrete, polymer composites, biomaterials, and education. He was also a Higher Degree Researcher/Teaching Assistant from 2014 to 2018 in Swinburne University of Technology Sarawak Campus (SUTS). During that time, he taught subjects such as computer-aided design (CAD), materials and processes, materials and manufacturing, and thermodynamics. He has published over 200 local and international publications (journals, book chapters, conference papers, newspapers, bulletin, etc.). He is a finalist of the Alumni Impact Awards 2022 under the Innovative Planet Impact Award recognized by Swinburne University of Technology, Australia. He is also listed in the Fifth Edition of *Successful People in Malaysia* of Britishpaedia, published by British Publishing House Ltd.

Preface

Integrating nanotechnology and polymer composites has emerged as a transformative paradigm in the rapidly evolving landscape of materials science and engineering, offering unprecedented opportunities to develop advanced materials with tailored properties and multifunctional applications. This book, *Advanced Nanocarbon Polymer Biocomposites*, represents a comprehensive exploration of the synergistic possibilities of the fusion of nanocarbons, polymers, and biocompatible elements.

Nanocarbon materials extracted from wood (pine and aspen) biomass (natural fiber, etc.) exhibit exceptional mechanical, thermal, and electrical properties. Harnessing the unique characteristics of these nanoscale entities and combining them with polymers, which provide flexibility, processability, and a wide range of functionalities, opens new frontiers in material design. Moreover, incorporating biocompatible components facilitates the development of materials that excel in mechanical, morphological, and chemical performance and demonstrate compatibility with living systems, paving the way for applications in biomedicine, construction and building, packaging, and sustainable technologies.

This book is crafted to provide a comprehensive overview of the fundamental and state-of-the-art research and developments in nanocarbon polymer biocomposites. Each chapter is meticulously crafted by experts in the respective areas, covering fundamental principles, synthesis methods, characterization techniques, and diverse applications. The chapters are organized to guide readers through the intricate landscape of nanocarbon polymer biocomposites, from theoretical foundations to practical applications, fostering a holistic understanding of this burgeoning field.

The multidisciplinary nature of this book makes it an invaluable resource for researchers, academics, and practitioners working at the intersection of nanotechnology, polymer science, and biocompatible materials. Whether delving into the fundamental science behind nanocarbon interactions with polymers or seeking insights into the practical applications of these advanced materials, this book serves as a roadmap to navigate the complexities and potentials of nanocarbon polymer biocomposites.

As editors, we would like to express our gratitude to the contributing authors for their scholarly contributions and dedication to advancing the knowledge in this field. We believe this compilation will inspire further exploration, foster collaboration, and contribute to the evolution of nano-carbon polymer biocomposites as a transformative technology.

Md Rezaur Rahman
Muhammad Khusairy Bin Bakri

CHAPTER ONE

Introduction to nanocarbon biocomposites

Md Rezaur Rahman[1], Muhammad Khusairy Bin Bakri[1,2] and Murtala Namakka[1]

[1]Faculty of Engineering, Department of Chemical Engineering and Energy Sustainability, Universiti Malaysia Sarawak, Jalan Datuk Mohammad Musa, Kota Samarahan, Malaysia
[2]Composite Materials and Engineering Center, Washington State University, Pullman, WA, United States

1.1 Introduction to sawdust

Sawdust is a by-product of wood processing activities (Mallakpour et al., 2021), such as milling (Green et al., 1999), sawing (Mackes et al., 2001), and sanding generated by industries and agricultural activities (Bates & Davies, 2018; Boča & Miegroet, 2017; Gamfeldt et al., 2013; Kivinen et al., 2020; Rogers et al., 2020). It also consists of fine particles and shavings of wood that are generated as waste during these operations. Sawdust is typically dry, powdery, and lightweight. The size and texture of sawdust can vary depending on the type of wood being worked with and the cutting tools used. It may range from fine particles resembling dust to coarser shavings. Sawdust can be reused or repurposed in woodworking projects, such as using it as filler material or in wood-based composite products like particleboard (Bakri, 2018). Sawdust is sometimes used as bedding material for animals, especially in agricultural settings or for pets like hamsters and guinea pigs. Sawdust can also be used as a raw material for the production of bioenergy through processes like wood pellets or briquettes for heating and power generation. In gardening and landscaping, sawdust can be utilized as mulch to help retain moisture, regulate soil temperature, and control weed growth. Sawdust has absorbent properties and can be used to soak up spills or liquids in certain situations (Bakri, 2018). However, it's essential to note that some types of wood can produce sawdust with health hazards, such as certain hardwoods that may release harmful dust particles when inhaled (Bakri, 2018). Proper safety measures should always be taken when handling and disposing of sawdust,

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especially in industrial settings. Sawdust is routinely dumped, burned, or landfilled (Adu, 2014; Ogundipe & Jimoh, 2012). Difficult to dispose in cleanest way (Olaiya et al., 2023), and when burned, contributes to greenhouse gas emissions despite the pollution and accompanying threats to public health (Mwango & Kambole, 2019; Okedere et al., 2017). Different physical and chemical properties of sawdust may vary from tree to tree (Olaiya et al., 2023).

1.2 Aspen and pinewoods

1.2.1 Aspen

Aspen trees, also known as *Populus tremuloides*, are deciduous trees belonging to the *Populus* genus. They are native to cold regions like North America, Scotland, and Russia and are well-known for their distinctive characteristics and ecological importance. They are part of the Salicaceae family (Kivinen et al., 2020), and play a crucial role in preserving biodiversity and supporting ecosystems. Aspen trees are medium-sized deciduous trees that typically grow to heights of 20—80 feet (6—24 m). It can live for up to 200 years. They have smooth, white to grayish bark with black markings, which often stand out prominently against the dark green leaves. One of the most recognizable features of Aspen trees is their leaves. They are small, roundish, and have serrated edges. The leaves are vibrant green in the spring and summer, turning into a brilliant golden-yellow hue during the fall, creating stunning displays of color. Aspen trees are famous for their "quaking" or "trembling" leaves. This characteristic occurs due to the flattened leaf stalks that allow the leaves to flutter and rustle in even the slightest breeze, creating a unique and calming sound. Aspen trees are highly adaptable and can be found in a wide range of environments across North America. They thrive in moist, well-drained soils and are commonly found in riparian areas, near rivers, streams, and wetlands. Aspens often form large, clonal colonies through their interconnected root systems, known as "aspen groves." Aspen trees play a crucial role in various ecosystems. They provide habitat and food sources for numerous wildlife species, including deer, elk, beavers, and birds. Their shade and fallen leaves also contribute to soil enrichment and moisture retention. Aspen wood is lightweight, soft, and easy to work with, making it valuable for various purposes. They provide valuable services to the environment (Bates & Davies, 2018;), such as carbon storage, and wood products like paddles, and furniture (Bates & Davies, 2018; Boča & Miegroet, 2017). Historically, Native American tribes used aspen for crafting baskets, bowls, and other items. Today, it is used for making paper, plywood, and other wood products. Aspen trees face certain threats, including habitat destruction due to human activities such as logging and land development. Additionally, some areas experience issues with sudden aspen decline (SAD), a condition that causes widespread dieback of aspen trees. Overall, Aspen trees are not only visually striking but also ecologically important components of North American forests, contributing to biodiversity and environmental stability. Their unique features and significant role in ecosystems make them an essential and cherished part of the natural landscape.

1.2.2 Pine

Pine trees, members of the genus *Pinus*, are coniferous evergreen trees that belong to the family *Pinaceae*. They have a characteristic conical or columnar shape, with branches that extend horizontally from the trunk. Pinewoods are high-quality joinery woods (Mao et al., 2014). These trees are widely distributed across the Northern Hemisphere, with various species adapted to diverse environments and climates. Pine trees vary in size, depending on the species, ranging from small shrubs to large, towering trees. The bark is often thick, scaly, and dark brown to gray. Pine trees are distinguished by their needle-like leaves, which grow in bundles, or fascicles. Each fascicle typically contains two to five needles. The needles are evergreen, meaning they persist on the tree year-round and can remain functional for several years before dropping. Another defining feature of pine trees is their reproductive structures known as cones. Cones are woody, protective structures that house and disperse the tree's seeds. Female cones are typically larger and located towards the top of the tree, while male cones are smaller and often found near the lower branches. Pine trees produce a sticky, fragrant resin that acts as a protective agent against pests and pathogens. The resin has been used traditionally for various purposes, including in medicines, adhesives, and varnishes. Pine trees are incredibly adaptable and can thrive in a wide range of environments, from cold boreal forests to dry, arid regions. They often dominate landscapes in temperate and coniferous forests, forming extensive stands that play critical ecological roles. Pine wood is valuable for its versatility and is commonly used in construction, furniture-making, and paper production. They produce lignocellulosic biomass, accounting for up to 20% of input mass (Foo & Hameed, 2012; Mao et al., 2014). Additionally, pine nuts, found in certain pinecone species, are edible and used in various culinary dishes. Pine trees serve vital ecological functions. They provide habitat and food sources for numerous wildlife species, including birds, squirrels, and other small mammals. The dense foliage of pine forests also contributes to soil protection and moisture retention. Pine resin has long been used for medicinal purposes. It has been applied to wounds as an antiseptic and for its purported antiinflammatory properties. Additionally, pine resin is used in the production of turpentine, which is employed as a solvent and in the creation of varnishes and paints. Pine wood is also used in furniture, windows, doors, and architectural millwork (Foo & Hameed, 2012). A plethora of sawdust composites have been developed (Olaiya et al., 2023) with improved mechanical properties (Martins et al., 2022), flexural forces, and utilized in a variety of applications (Kumar et al., 2014), viz. particle boards, bricks, floor slabs, and attic insulation. Overall, pine trees are iconic and ecologically significant components of many ecosystems around the world. Their unique characteristics, adaptability, and economic value make them essential and cherished trees in various cultures and landscapes.

1.3 Nanotechnology

Nanotechnology in composite materials involves integrating nanoscale components into traditional composite structures to significantly enhance their properties and performance (Bakri & Rahman, 2021; Nyuk Khui et al., 2019; Rahman & Bakri, 2021). Composites are materials composed of two or more distinct phases, typically reinforcement and matrix phases. Combining these phases creates a material with superior mechanical, thermal, and electrical properties compared to the individual components. Incorporating nanotechnology in polymer composites development is imperative as demands for developing environmentally benign and sustainable materials are soaring in all industries, including biocomposites (Bakri & Rahman, 2021). When nanotechnology is applied to composite materials, it introduces nanoscale reinforcements, such as nanoparticles, nanofibers, or nanotubes, into the matrix material. It also refers to manipulating matter at scales between 1 and 100 nm. It encompasses various research fields and technologies (Khadir et al., 2020), including nanoelectronics, biomaterials, and energy production (Lawal, 2019). These nanoscale reinforcements can be made from various materials, including carbon, ceramics, polymers, and metals, depending on the desired properties of the composite.

Incorporating nanoscale reinforcements into composites offers several advantages and leads to novel characteristics. Nanoparticles and nanofibers provide higher surface area and superior strength, stiffness, and toughness, resulting in composites with improved mechanical properties (Bakri & Rahman, 2021). These composites are used in aerospace, automotive, and sports equipment, where lightweight and robust materials are critical (Jayamani et al., 2022; Rahman, Bin Bakri, et al., 2022). Nanoscale reinforcements can improve composite materials' thermal stability and resistance to heat. This property is valuable in applications that expose materials to high temperatures, such as aerospace and electronics. Some nanomaterials, like carbon nanotubes (CNTs), exhibit excellent electrical conductivity. They can make composites conductive or provide electromagnetic shielding when integrated into composite materials. Nanotechnology allows the design of composites with specific optical and electrical properties, making them suitable for use in sensors, displays, and optoelectronics. Nanoparticles can improve the barrier properties of composites, making them useful for packaging materials or protective coatings. Nanoparticles with self-healing properties can be incorporated into composites to repair damage and increase the material's lifespan. Nanotechnology can lead to the development of composites with improved sustainability and reduced environmental impact, such as lightweight materials for fuel-efficient vehicles or wind turbine blades.

Nanotechnology also allows for precise control over the dispersion and alignment of nanoscale reinforcements within the composite matrix, which is critical to achieving the desired properties. However, the production and handling of nanoscale materials pose specific challenges, including cost, scalability, and potential health and safety concerns. As research in nanotechnology progresses, developing new nanomaterials and innovative manufacturing processes will further expand the possibilities and applications of nanotechnology in composite materials. Recent advancements in nanotechnology in process optimization and sustainability development paved the way for many scientific investigations in green nanotechnologies. The ongoing advancements in this field hold the potential to revolutionize various industries and lead to the creation of high-performance materials with unprecedented capabilities. Green nanotechnology encompasses the development of eco-friendly technologies that aim to mitigate the potential environmental and health risks associated with producing and utilizing sustainable nanoproducts (Liew et al., 2018), such as nanocarbon and other nanoproducts.

1.4 Nanocarbons

Nanocarbon in composite materials refers to using carbon-based nanomaterials, such as CNTs, graphene, and carbon nanofibers (CNFs), as reinforcements within a composite matrix (Bakri & Rahman, 2021). Nanocarbons are carbon-based materials with nanoscale particles and unique properties, classified into distinct categories based on shapes and structures. These nanoscale carbon materials have unique properties that can significantly enhance the resulting composite's mechanical, electrical, and thermal performance. CNTs are cylindrical structures made of rolled-up graphene sheets. They possess exceptional mechanical strength, high aspect ratios, and excellent electrical conductivity. Activated carbon, characterized by nano-sized particles, is produced by activating carbonaceous materials like bamboo, petroleum pitch, coir, coconut husk, wild peat, ash, lignite, and coal. Carbonaceous substances are incorporated into green nanotechnology to produce biocomposites, naturally derived materials combined as one for enhanced performance (Abenojar et al., 2021), with superior performances in thermal conductivity, electroconductivity, adsorption, and mechanical properties (Perathoner & Centi, 2018). When embedded in a composite matrix, CNTs act as solid and lightweight reinforcements, substantially improving the material's mechanical properties, such as tensile strength and stiffness.

Moreover, their high electrical conductivity makes composites electrically conductive, enabling applications in electronic devices and electromagnetic shielding. Graphene is a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. It exhibits remarkable mechanical strength, thermal conductivity, and electrical conductivity. Graphene in composites enhances their mechanical properties, such as stiffness and fracture toughness, while improving thermal and electrical conductivity. Graphene-based composites find applications in various industries, including aerospace, automotive, and electronics. CNFs are similar to CNTs but have an extended, fibrous structure. They provide excellent mechanical properties and thermal stability to composite materials. CNFs can reinforce polymers and ceramics, leading to composites with enhanced strength and thermal resistance.

Incorporating nanocarbon into composite materials can be achieved using various manufacturing methods, such as solution mixing, melt blending, or chemical vapor deposition (Rahman, Bin Bakri, et al., 2022; Rahman, Taib, et al., 2022b). The dispersion and alignment of nanocarbon within the composite matrix play a crucial role in determining the final properties of the composite (Rahman et al., 2023). The advantage of using nanocarbon in composite materials is that nanocarbon reinforcements add minimal weight while significantly improving the strength of the composite. This property is especially desirable in industries like aerospace and automotive, where lightweight materials are critical for fuel efficiency and performance. Nanocarbon materials are highly conductive, enabling composites to have enhanced electrical and thermal conductivity. This feature is useful in electrical circuits, thermal management systems, and electronic devices. Nanocarbon reinforcements improve composites' toughness and damage tolerance, making them more resistant to cracks and fractures. By varying the type, concentration, and alignment of nanocarbon reinforcements, the properties of the resulting composite can be tailored for specific applications. Despite their outstanding properties, challenges exist in composite materials' large-scale production and uniform nanocarbon dispersion. Researchers are continuously exploring new techniques to optimize these processes and unlock the full potential of nanocarbon-based composites in a wide range of industries.

1.5 Bioplastic and biopolymers

Bioplastics and biopolymers are polymers derived from renewable biomass sources, such as plants, algae, or microorganisms, as opposed to traditional plastics derived from fossil fuels. These biobased polymers are considered more environmentally friendly and sustainable since they reduce the dependence on nonrenewable resources and can contribute to a lower carbon footprint. When bioplastics and biopolymers are used as reinforcements or matrix materials in composite materials, they form what is known as "biocomposites" or "green composites." These composite materials combine the benefits of biobased polymers with other natural fibers or nanoparticles to create eco-friendly and functional materials. Plastics have grown in popularity due to corrosion resistance, low density, and user-friendly design, but they cannot be decomposed, thereby increasing environmental concerns. However, biopolymers address these environmental concerns, plus the threat of resource depletion (Samir et al., 2022), ushering in cheap nanotechnology-based composites promoting reliable, affordable, and sustainable materials. Bioplastics and biopolymers are composed of long chains of molecules, just like traditional plastics. However, they are derived from natural sources like corn, sugarcane, potatoes, or microorganisms. Common examples include PLA, polyhydroxyalkanoates, starch-based polymers, and cellulose-based polymers. Biobased polymers offer a sustainable alternative to conventional petroleum-based plastics. Natural fibers like jute, hemp, flax, bamboo, or kenaf are often used as reinforcements alongside biopolymers in biocomposites. These natural fibers contribute to the mechanical properties of the composite, providing strength, stiffness, and impact resistance. Combining biopolymers and natural fibers results in lightweight, biodegradable, and renewable materials.

Chemical substances are incorporated in their polymer matrix to enhance their lifespan and improve composites' qualities. Additives, substances combined with a polymer matrix, such as colorants, antioxidants, plasticizers, fillers, reinforcement, and blowing agents, enhance polymeric materials' color, stiffness, and durability (Jaafar, 2017; Rahman et al., 2011, 2017; Rahman, Bin Bakri, et al., 2022). Natural and synthetic (organic and inorganic) fillers are used in various applications (Adamu et al., 2019, 2020), including nanocomposite materials (Jaafar, 2017). Over 200 million tons of synthetic polymers are produced globally (Sam et al., 2015), causing waste disposal issues. Hence, finding sustainable, biodegradable, and environmentally benign polymer materials is crucial. Nanocellulose derived from wood pulp or other plant sources is an example of a nanomaterial used as a reinforcement in biocomposites. Nanoparticles can improve the mechanical properties and barrier properties of the biocomposite material (Bakri & Rahman, 2021). One of the significant advantages of bioplastics and biopolymers in composite materials is their potential biodegradability, depending on the specific formulation. They can break down naturally when exposed to the right conditions, reducing environmental pollution and waste. Bioplastics and biopolymers in composite materials find applications in various industries, including automotive, construction, packaging, consumer goods, and biomedical. These materials are commonly used in nonstructural components, disposable products, and items where sustainability and environmental considerations are essential. Despite their benefits, bioplastics and biopolymers face challenges, including cost, scalability, and processing issues. Some biobased polymers may have lower mechanical properties than traditional plastics, limiting their use in specific high-performance applications. Additionally, achieving consistent properties and maintaining biodegradability throughout the composite's life cycle requires careful design and testing. As research and technology advancements continue, bioplastics and biopolymers are becoming more viable and competitive alternatives to traditional plastics in composite materials. With a growing emphasis on sustainability and environmental consciousness, biobased materials in composite manufacturing will likely increase adoption in various industries.

1.6 Conclusion

Nanocomposite materials, like nanocarbon and nano clay, are growing in interest due to their potential as natural fillers. However, devising a new approach is evidently required as current nanotubes or graphene are not economically viable (Bhattacharya, 2016). Hybrid fillers, such as Montmorillonite and graphene, have been studied (Ali Mohsin et al., 2014) for improved thermal (Shtein et al., 2015) and mechanical properties (Aguilar et al., 2014; Gill et al., 2019). Selecting the right filler enhances economics, mechanical behavior, and stability in polymer composites (Adamu et al., 2020). Research reports on bio-nanocomposites using green filler from biomass and biodegradable polymers are limited, insinuating the need to develop hybrid biocomposite fillers (which is also addressed herein). Cost-effective production of these biocomposite products ensures material sustainability and offers environmental benefits (Wataniyakul et al., 2018). Iron-based compounds, for instance, are chemical substances, which enhance adsorption characteristics in carbon-based composites and remove heavy metals (Nata et al., 2010). Additional valuable nano oxides that could be activated with nanocarbon include titanium oxides, montmorillonites, and MMT, among others. Herein, opens a new horizon in green nanotechnologies and will pave the way for advancements in the production of nanocomposites.

1.7 Summary

This book also provides a comprehensive knowledge of aspen wood sawdust, pinewood sawdust, and their biocomposites applications. The chapters describe the production of nanocarbon from pine wood sawdust, explain the impact on biocomposites using various types of nanocarbon and polymer, the developments of MMT-activated bio-nanocarbon from pine wood sawdust and its biocomposites, titanium(IV) oxide activated micro−nanocarbon from pine wood sawdust and its biocomposites, iron (III) chloride activated nanocarbon from pine wood sawdust and its biocomposites, zinc oxide activated nanocarbon from aspen wood sawdust and its biocomposites, as well as the activated MMT nanocarbon from aspen wood sawdust and its biocomposites. Recommendations were also included to shade more lights and serve as a guide for future research in this area.

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The book covers the latest research findings on nanocarbon polymer biocomposites, their properties and manufacturing, as well as the possible ways to reduce waste and improve their sustainability.

Nanocarbon polymer biocomposites have gained increased attention from both researchers and manufacturers due to the significant improvement in their physico-mechanical, thermal, and barrier properties when compared to conventional materials. Their dimensions, biodegradable character, cost-effectiveness, and sustainability are among the main drivers for increasing demand. However, it is difficult to achieve uniform dispersion between the carbon filler and matrix as it easily forms agglomerations. Production of nanocarbon polymer biocomposites with high mechanical and thermal properties is also limited, but there has been rapid progress in processing possibilities to produce nanocomposites based on various biodegradable fillers. Advanced Nanocarbon Polymer Biocomposites collects all these novel scientific findings in one place. It discusses in detail their physical, chemical, and electrical properties and presents the latest research findings on nanocarbon polymer biocomposites with filler loadings and their improvement on compatibility. The book will be of great interest for those researchers who are concerned with the production and use of nanocarbon polymer biocomposites as a new innovative advanced material.

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- Emphasizes on nanoscale fillers and their improvement on compatibility
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About the Editors

Md Rezaur Rahman is a senior lecturer (assistant professor) in the Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, University Malaysia Sarawak, Malaysia. He is also a visiting research fellow at the Faculty of Engineering, Tokushima University, Japan since 2012. He previously worked as a teaching assistant at the Faculty of Engineering, Bangladesh University of Engineering and Technology and as a research project leader supported by the Ministry of Higher Education, Malaysia. He was appointed as an external supervisor for the Faculty of Engineering, Swinburne University of Technology, Australia in 2015. He received his PhD degree from the University Malaysia Sarawak, Malaysia. He has more than 12 years of experience in teaching, research, and working with industry. His areas of research include conducting polymers; silica/clay dispersed elastomeric polymer nanocomposites; hybrid filler–loaded polymer composites; advanced materials: graphene/nanoclay/fire retardants; nanocellulose (cellulose nanocrystals and nanofibrillar) and cellulose-reinforced/filled polymer composites; chemical modification and treatment of lignocellulosic fibers including jute, coir, sisal, kenaf, hemp, and solid wood; nanocomposites and nanocellulose fibers; and polymer blends. He has published 7 books and 20 book chapters and more than 100 International journal papers.

Muhammad Khusairy Bin Bakri obtained his Doctor of Philosophy, PhD (2018), Master of Engineering (by Research), MEng (2016), and Bachelor of Engineering (Mechanical Engineer), BEng (2014) from Swinburne University of Technology, Australia. Currently, he is working with UNIMAS as a research fellow with priority on materials science, polymer composites, biomaterials, and education. He is working under the supervision of Dr. Md Rezaur Rahman at the Faculty of Engineering, University Malaysia Sarawak. Previously, he joined as a higher degree researcher/teaching assistant from 2014 to 2018. During that time, he taught subjects such as computer-aided design, materials and process, materials and manufacturing, and thermodynamics. He also assists his supervisors in monitoring undergraduate final-year projects. He has published more than 60 publications, both local and international (journal, book chapters, and conference papers). He is also one of the main contributors for the book on "Silica and Clay Dispersed Polymer Nanocomposites," published by Elsevier.

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