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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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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 SIX

Impact on biocomposites using various types of nanocarbon and polymer

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6.1 Introduction

The development of environmentally friendly and sustainable materials is improving rapidly in various types of industries worldwide. This includes the development of biocomposites which is defined as a material that is composed of either two or more different types of materials where one of the materials is naturally derived and these materials are combined to produce a new material with enhanced performance compared to its individual constituent materials (Abenojar et al., 2021). The usage of nanotechnology by using natural resources is able to improve the structural and functional properties of the biocomposites (Adamu et al., 2019). Hence, the production of nanocarbon polymer biocomposites are developing rapidly as it combines the superior properties of nanocarbon and natural polymers. Nanocarbon is one of the materials that is able to enhance the mechanical and thermal strength of the polymers and it offers a range of advantages such as energy-efficient, abundant, and high thermal stability (Rizal et al., 2021). To further improve the properties of biocomposites, the usage of natural polymers is also applied which can improve biocompatibility, abundant, less toxic, and biodegradable (Amini et al., 2021). This chapter aims to extensively study the impact of a variety type

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of nanocarbon and natural polymer materials, focusing on the improvement of properties of the reinforced nanocarbon polymer biocomposites. On top of that, the selection of suitable types of nanocarbon and polymer materials is important as the materials are able to give a major difference in the structure of the biocomposites via the effective interaction during the production of biocomposites (Adamu et al., 2019). One of the properties that can be improved include thermal and mechanical properties of the biocomposites (Adamu et al., 2019). When the impacts of nanocarbon and polymers are comprehensively studied, they can be used in a variety of applications such as the aerospace engineering, medical, automotive, construction, and packaging industries.

6.2 Impact of different nanocarbon materials on biocomposites

Different types of nanocarbon materials such as carbon black (CB), carbon nanotubes (CNTs), and graphene (GR) have different impacts on biocomposites as they have different properties and chemical structures (Adamu et al., 2020). The impact of three different types of nanocarbon materials is discussed as follows.

6.2.1 Carbon black

CB is made up of micro and nanosized carbon particles which are fabricated through procedures such as partial combustion of hydrocarbons or thermal decomposition (Cougo et al., 2018). The unique properties of CB as nanofillers are especially attractive in their applications for nanocarbon multiscale composites. According to Akbayrak and Özkar (2018), the properties of CB include chemical inertness, high electron conductivity, mechanical and thermal stability, large surface area and cost-effectiveness. Hence, the applications of CB have several impacts on biocomposites which are tabulated in Table 6.1.

6.2.2 Carbon nanotubes

CNTs are nanocarbon materials that are made up of rolled-up GR sheets in the cylindrical structure (Maruyama, 2021). CNTs exhibit astonishing properties along with their unique structures. Based on Maruyama (2021),

Table 6.1 The impact of carbon black on biocomposites.

Impacts	Explanation	References
Enhanced mechanical properties	CB has a high degree of toughness and strength which can enhance the mechanical properties of biocomposites. The improved mechanical properties of biocomposites which are enhanced with the amounts of CB include: • Increased tensile strengths. • Increased stiffness. • Increased hardness. Therefore, the enhanced mechanical properties of biocomposites ensure that the biocomposites are able to withstand greater loads which makes them more durable.	Szadkowski et al. (2020)
Improved electrical conductivity	CB is an electrically conductive material which can improve the electrical properties of biocomposites. The presence of CB in biocomposites is able to improve electrical conductivity due to its high specific surface area. The high specific surface area is able to form a conductive network even in small amounts where which allows the movements of electrons and ions throughout the network.	Choi et al. (2019)
Enhanced thermal conductivity	The thermal conductivity of biocomposites can be improved with the presence of carbon black. This is because the thermal conductivity of electrons in biocomposites is based on the movement and collision of the electrons. A specific lattice vibration is produced due to the heat transfer that occurs in the biocomposites. Hence, CB can enhance thermal conductivity by improving heat conduction and electronic thermal conduction due to the structure of CB.	Song et al. (2019)
Increased ultraviolet (UV) resistance	The application of CB in biocomposites is able to enhance the UV resistance of biocomposites. The exposure of UV rays results in the degradation of biocomposites which causes the material to lose its mechanical properties. The change in mechanical properties is due to	Sahu et al. (2020)

(*Continued*)

Table 6.1 (Continued)

Impacts	Explanation	References
	the chemical crosslinking or chain scission. Hence, the application of CB is able to solve this issue as CB are able to absorb rays from various ranges of the solar spectrum and protect the biocomposites from high-energy photons.	
Improved opacity	The dark pigment of CB is able to improve the opacity of biocomposites. This results in improved opacity of the biocomposites as the dark pigment makes the material opaquer. This is one of the significant factors for commercial purposes such as in packaging applications.	Jaseem and Ali (2019)

CNTs have a unique structure which leads to attractive properties including a high aspect ratio, excellent electrical and thermal conductors, chemical stability, and high intrinsic mobility. Therefore, when CNTs are applied to biocomposites, it results in several improved properties as seen in Table 6.2.

6.2.3 Graphene

GR is a single layer of graphite which is made up of only carbon atoms that are arranged in a honeycomb structure which is a hexagonal pattern extending in a single layer of atoms (Armano & Agnello, 2019). The 2D structure of GR results in various attractive properties of GR (Armano & Agnello, 2019). The properties of GR include high Young's modulus, high thermal conductivity, high molecular barrier abilities, and high electrical conductivity (Rahat Rahman et al., 2019; Smith et al., 2019). Thus, the impact of GR on nanocarbon polymer biocomposites is tabulated in Table 6.3.

6.3 Impact of different polymer materials on biocomposites

Natural polymers are mainly obtained from natural sources such as animals, microorganisms, and plants. Different types of polymer materials

Table 6.2 The impact of carbon nanotubes on biocomposites.

Impacts	Explanation	References
High aspect ratio and increased mechanical strength	CNTs have a high aspect ratio which ranges from 100 to 1000 where this ratio is significantly higher compared to conventional fiber materials. The higher aspect ratio of CNTs results in the higher transfer of stress from the polymer matrix to the dispersed CNTs. This is due to the adequate load transmission by interfacial stress which is affected by the aspect ratio. Therefore, this results in the full utilization of the strength of CNTs. Other than that, the high aspect ratio of CNTs also results in improved mechanical strength by implementing the fiber bridging mechanism. This mechanism involves CNTs performing as a bridge to hinder the propagation of cracks and distribute the stress. As a result, this improves the mechanical strength of the biocomposites.	Abazari et al., (2020); Al-Maharma et al. (2019); Nurazzi et al. (2021)
Improved mechanical properties	CNTs are well known for their superior mechanical properties which in return, can improve the mechanical properties of nanocarbon polymer biocomposites. CNTs consist of C−C covalent bonds in the carbon rings which is one of the most stable chemical bonds which leads to the astonishing mechanical	Abazari et al. (2020); Radhamani et al. (2018)

(*Continued*)

Table 6.2 (Continued)

Impacts	Explanation	References
	properties of CNTs. CNTs have a significant Young's modulus value which is similar to the Young's modulus of a diamond. On top of that, CNTs also have an exceptionally high mechanical strength which is 100 times more than steel. Even the CNTs with low mechanical strength also have a significantly high strength worth several GPa. In addition, CNTs also have a low density which can reach as low as 1.3 g/cm^3 and this value is about 1/6 of the density of steel. Lastly, since CNTs have a hollow and closed structure, this results in CNTs having excellent bendability and plasticity. As a result, CNTs are able to return to their original shape even after high external stress. Even when the external stresses applied are higher than the elastic deformation, the deformed CNTs will not obtain a brittle fracture as it is able to withstand more than 40% of the tensile strength due to its Stone-Wales defects.	
Enhance electrical properties	The 1D characteristics along with the electronic structure of CNTs result in special electrical properties of CNTs which can improve the electrical properties of nanocarbon polymer biocomposites. CNTs have	Dubey et al. (2021)

(*Continued*)

Table 6.2 (Continued)

Impacts	Explanation	References
	an extremely low electrical resistance along with a high current density. The current density of CNTs is the highest compared to any other materials which can amount to 10^9 A/cm^2. CNTs are also known to have superconducting properties during low temperatures.	
Improved thermal conductivity	CNTs have a high thermal conductivity which is around 3000 W/m/K and it is higher than the thermal conductivity of diamond which is known as an excellent thermal conductor. The high thermal conductivity enables efficient heat transfer in the nanocarbon polymer biocomposites. In addition, CNTs form a 3D conductive network within the polymer matrix, enabling the thermal energy to flow rapidly and overcome the resistance created by the insulation of the polymer matrix. Lastly, CNTs have high thermal stability which enables CNTs to withstand various high temperatures with minimal material degradation.	Abazari et al. (2020); Aly et al. (2021); Barathi Dassan et al. (2020)

have different effects on biocomposites; however, natural polymers are known to be biocompatible and biodegradable due to the presence of responsive chemical linkages (Pal et al., 2022).

Table 6.3 The impact of graphene on biocomposites.

Impacts	Explanation	References
Improved mechanical properties	GR has exceptionally great mechanical properties with a high Young's modulus amounting to 1. TPa, break strength of 42 N/m, and tensile strength valued at 130.5 GPa. GR also has a low fracture toughness which can be as low as 4.0 ± 0.6 MPA.m$^{1/2}$. The biocomposites have a significant improvement in the mechanical properties specifically in terms of stiffness even with low amounts of graphene.	Fortunato et al. (2020); Smith et al. (2019)
Increased electrical conductivity	GR has high electrical conductivity along with high electron mobility which allows the incorporation of GR to improve the electrical properties of nanocarbon polymer biocomposites. GR has also significantly improved the electrical conductivity of biocomposites even in lower amounts of GR incorporated in the biocomposites. The enhanced electrical conductivity is able to improve the functions of the biocomposites which also extends the usage of biocomposites in various applications.	Alemour et al. (2018); Smith et al. (2019)
Improved barrier properties	GR has a high aspect ratio which can improve the barrier properties of nanocarbon polymer biocomposites. GR is known to improve the barrier properties of biocomposites as the permeability of biocomposites increases with the incorporation of GR. In addition, the barrier properties improvement of GR includes gas and moisture barrier properties which can be advantageous for biocomposites in a variety of applications.	Cosquer et al. (2021); Yao et al. (2021)

(*Continued*)

Table 6.3 (Continued)

Impacts	Explanation	References
Anti-corrosive properties	GR also has attractive properties such as anti-corrosion which can be used for commercial uses in various industries. The 2D morphology and chemical inertness of GR contribute to these anti-corrosive properties of GR. Since polymers are permeable to water, chloride, and sulfites, this would be toxic for the biocomposites. However, GR can be used as a fillers to reduce the diffusion of toxic materials to the biocomposites by generating an anti-corrosive layer on the surface of the biocomposites.	Luo et al. (2018); Smith et al. (2019)

6.3.1 Cellulose

Cellulose is one of the primary parts of a plant cell which is the most versatile biopolymer on Earth (Joseph et al., 2020). According to Norizan et al. (2022), cellulose is biodegradable, abundant, natural, and renewable which can be found in algae, plants, animals, bacteria, or fungi. Among those various sources, plants and wood are the main sources of cellulose for natural biocomposites as it consists of microfibril cellulose, lignin, pectin, and hemicellulose (Norizan et al., 2022). The astonishing properties of cellulose result in high studies of cellulose incorporation as natural polymers in nanocarbon polymer biocomposites which is discussed in Table 6.4.

6.3.2 Chitin

Chitin is also a naturally occurring polysaccharide which is the second most abundant after cellulose where it has various similarities of physicochemical properties with cellulose (Mishra & Militky, 2018). Nevertheless, cellulose is mainly obtained from plants, while the primary sources of chitin come from the exoskeleton of crustaceans, insects, and in the cell walls of a few types of fungi (Mishra & Militky, 2018). The unique properties of chitin include biocompatibility, biodegradability, chemical versatility, high adsorption capacity, and antimicrobial properties (Merzendorfer & Cohen, 2019). Therefore, when

Table 6.4 The impact of cellulose on biocomposites.

Impacts	Explanation	References
More sustainable	As mentioned before, cellulose is obtained from natural sources, especially plants and wood. These sources are sustainable and renewable as they can be obtained as by-products from various industries such as agricultural industries and forest wastes. In addition, cellulose is also sustainable as it can be naturally degraded by microorganisms even though the degradation of cellulose is dependent on the microbial population. Furthermore, the production of cellulose is readily scalable and does not involve toxic chemicals. On top of that, the production such as enzymatic hydrolysis, does not produce any toxic wastes. Hence, the usage of cellulose in nanocarbon polymer biocomposites is more sustainable compared to other polymer sources.	Egan and Salmon (2022); El-Gendi et al. (2022); Janaswamy et al. (2022); Yu et al. (2021)
Improved moisture barrier properties	The structure of cellulose especially when it is reduced to nanosize leads to significant barrier properties in terms of moisture which is advantageous for the fabrication of nanocarbon polymer biocomposites. Cellulose has impermeable properties, and it can form a physical barrier in the matrix. It is determined that biocomposites that are incorporated with cellulose have a better moisture barrier compared to other	Li et al. (2021); Tan et al. (2022)

(*Continued*)

Table 6.4 (Continued)

Impacts	Explanation	References
	composites. Moisture barrier is a crucial property for biocomposites especially in packaging applications. This is because water vapor is a permeate that can diffuse rapidly in biocomposites affecting the quality and shelf life of the biocomposites. Hence, the high aspect ratio of cellulose creates physically entangled networks that can hinder the diffusions of permeate like water.	
Excellent selectivity	Cellulose has a porous structure that allows the size-sieving mechanism of the biocomposites whereas cellulose has an excellent selectivity in allowing particular sizes of materials to pass through the biocomposites. This mechanism ensures that the cellulose enables the smaller size materials that is desired and removes the larger materials that are not needed. This is advantageous for biocomposites that require filtration application.	Yue et al. (2020)
Improved mechanical properties	The mechanical properties of cellulose are attributed to the molecular structure of cellulose where it has high crystallinity because of its superior hydrogen bonds. The cellulose fibers perform as a reinforcement agent in biocomposites by increasing the strength and stiffness of the structure of the biocomposites.	Joseph et al. (2020); Liu and Lv (2021); Noor Azammi et al. (2019); Zakuwan and Ahmad (2018)

(*Continued*)

Table 6.4 (Continued)

Impacts	Explanation	References
	On top of that, the porous structure of cellulose also has a significant impact on the toughness of the biocomposites. The toughness of the cellulose in biocomposites also enhances the crack resistance of the biocomposites by greatly reducing the number of initial cracks, long-term cracks, and the possibility of future cracks forming throughout the biocomposites. Lastly, cellulose can exhibit synergistic effects by combining with other materials to improve its mechanical properties. Since nanocarbon also has superior mechanical properties, the reinforcement of nanocarbon and cellulose can produce a synergistic effect that significantly enhances the mechanical properties of biocomposites.	

applied to nanocarbon polymer biocomposites, the properties of the biocomposites can be improved as discussed below in Table 6.5.

6.3.3 Starch

Starch is an abundant and renewable source which can be obtained from various types of plants such as corn, potato, and wheat (Adigwe et al., 2022). Starch is also a naturally occurring biopolymer which is made up of highly branched amylopectin and linear amylose residues. Even though there are a few drawbacks of starch, it can still be incorporated in nanocarbon polymer biocomposites for the following impacts discussed below in Table 6.6.

Table 6.5 The impact of chitin on biocomposites.

Impacts	Explanation	References
Improved biocompatibility	When chitin is incorporated into biocomposites, it has a biomimetic property that enhances the biocompatibility of the biocomposites. Chitin is able to mimic the biological properties of material which makes it more compatible with living organisms especially in medical applications. In addition, biocompatibility also refers to the biocomposites having no cytotoxicity which can be harmful for cells. It is crucial to have no cytotoxicity in order to fabricate a safe material for biocomposites. Hence, incorporating chitin in the biocomposites is able to reduce the cytotoxicity of the biocomposites enabling it to be more biocompatible.	Chraniuk et al. (2022); Ding et al. (2019); Zhang et al. (2021)
Improved biodegradability	Chitin is highly biodegradable which can be advantageous in the disposal of biocomposites. Chitin can easily be decomposed by an enzyme called bacterial chitinases where the biodegradation of chitin in the soil can have fertilizer effects, especially on compounds that are ammonia-derived. At the end of the decomposition cycle, chitin decomposes to ammonia and nitrates	Mukarram et al. (2021); Shamshina et al. (2019)

(*Continued*)

Table 6.5 (Continued)

Impacts	Explanation	References
	which can be beneficial for plant growths and useful microorganisms.	
High adsorption capacity	Chitin and its primary derivatives are known as the best polymers for adsorption due to their high specific surface area. Chitin is an effective bioadsorbent for various types of pollutants along with a wide range of biological functions. In addition, the high adsorption capacity of chitin also enables the chitin to achieve fast regeneration. The ability to regenerate possessed by chitin also enables long-term usage of the biocomposites making it more cost-effective.	Ahmed et al. (2020); Lin et al. (2021); Nawaz et al. (2023); Tarique et al. (2023)
Enhanced mechanical properties	Chitin has a semi-crystalline structure with a very high specific surface area and excellent mechanical properties with Young's modulus valued at about 41 GPa. The functional groups of chitins which are hydroxyl and amide groups are able to form hydrogen bonds with other materials specifically nanocarbon to fabricate a strong reinforced biocomposite performance. Chitin also has a good wear resistance which can also improve the durability of the biocomposites.	Haider et al. (2022); Wei et al. (2021)

Table 6.6 The impact of starch on biocomposites.

Impacts	Explanation	References
Improved biocompatibility	The incorporation of starch in the nanocarbon polymer biocomposites can improve the biocompatibility of the composites. This is due to starch being a natural biopolymer that has excellent biological properties which is useful for tissue engineering. On top of that, it is also determined that starch can reduce the cytotoxicity of biocomposites as it does not induce any toxicity in mammalian cells.	Mohd Roslan et al. (2021)
Improved biodegradability and environmentally friendly	The preparation of starch can be done by physical methods such as ultrasonication, milling, gamma irradiation, and high-pressure homogenization. This physical method does not involve any chemicals or solvents which makes it more environmentally friendly. The time taken for this process is also short which means that it is more energy efficient. On the other hand, starch is also very biodegradable where it can degrade due to the microorganisms' activities which include bacteria, fungi, and microalgae. A higher relative humidity can also speed up the degradation process of starch resulting in a higher degradation rate.	Marta et al. (2022)
Reduces water vapor and oxygen permeability	Starch can form a strong bond to ensure that the pathways for water and air in the polymer matrix become	Ahmad et al. (2020); Hakke et al. (2022); Marta et al. (2022)

(*Continued*)

Table 6.6 (Continued)

Impacts	Explanation	References
	torturous. This enables the nanocarbon polymer biocomposites to become impermeable from water vapor and air. In addition, increasing the concentration of starch can also result in the biocomposites becoming denser, reducing the pore size, and becoming more impermeable. Nevertheless, it requires an optimum value of starch concentration to ensure that the biocomposites are effective in creating a barrier between water vapor and air.	
Acts as a reinforcing material to improve mechanical properties	Starch chains have a high tendency to form intermolecular associations between the chains which results in the starch becoming more brittle and very soluble in water. Water sorption of starch leads to poor mechanical properties in terms of Young's modulus, tensile strength, and elongation at break. However, starch can be used as a reinforcing material to improve mechanical properties, especially with the incorporation of nanocarbon in the nanocarbon polymer biocomposites. The usage of starch as reinforcing material is able to distribute the stress evenly through friction mechanism thus, enhancing the tensile strength.	Marta et al. (2022); Othman et al. (2019)

6.4 Fabrication of nanocarbon polymer biocomposites

There are several methods for the production of nanocarbon polymer biocomposites which are tabulated in Table 6.7. The procedure for each nanocarbon polymer biocomposites varies depending on the type of nanofiller, type of polymer matrix, system of nanofillers or the desired properties of the final product (Paszkiewicz et al., 2020). There are four fabrication methods discussed in the following table where the illustrations for the method are depicted in Figs. 6.1–6.4.

Table 6.7 The fabrication methods of nanocarbon polymer biocomposites.

Method	Explanation	References
Electrospinning	The electrospinning method involves the production of nanofibers which are usually fabricated by a nanocarbon solution dispersed in a polymer solution which is electrospun. The yielded nanofibers are the nanocarbon polymer biocomposites and this method is a straightforward technique. However, the complex interaction between the nanocarbon, polymer and solvent affects the desired properties of the nanocarbon polymer biocomposites. Hence, this method requires a particular optimization of the electrospinning solution along with the electrospinning parameters.	Lee et al. (2018)
In situ polymerization	The in situ polymerization method is a method where the nanocarbon is dispersed in a polymer solution then the polymerization occurs. The polymerization facilitates strong interaction between the nanocarbon and polymer matrix where which allows the polymer to penetrate the bundled or layered nanocarbon in the solution. The polymerization also occurs in between the	Cohen et al. (2020); Ehsani et al. (2021)

(*Continued*)

Table 6.7 (Continued)

Method	Explanation	References
	interfibers or interlayers to fabricate exfoliated or intercalated nanocarbon polymer biocomposites. Hence, the in situ polymerization allows covalent bonding between the nanocarbon and polymer matrix by implementing different types of chemical reactions.	
Melt blending	The melt blending method involves nanocarbon being directly mixed with the polymer in a molten state with a twin-screw extruder. The parameters of the screw are adjusted according depending on the materials where the parameters consist of blending time, screw speed and temperature.	Chen et al. (2018); Paszkiewicz et al. (2020)
Solution blending	The solution blending method enables easy dispersion of nanocarbon or the hybrid system of nanocarbon into the suitable solvent with polymer. Firstly, the nanocarbon is dispersed in the solvent, which is followed by the polymer, and then the solvent is removed. There are a few methods to ensure the distribution of nanocarbon in the polymer matrix which include magnetic stirring, shear mixing, and ultrasonic irradiation.	Chen et al. (2018); Paszkiewicz et al. (2020)

6.5 Impact of nanocarbon surface modification on biocomposite properties

As mentioned in Section 6.2, nanocarbons have various impacts on improving the nanocarbon polymer biocomposites' electrical, mechanical, and thermal properties. Nevertheless, different materials have different impacts on the biocomposites and depending on the desired applications, specific properties are required in the production of biocomposites.

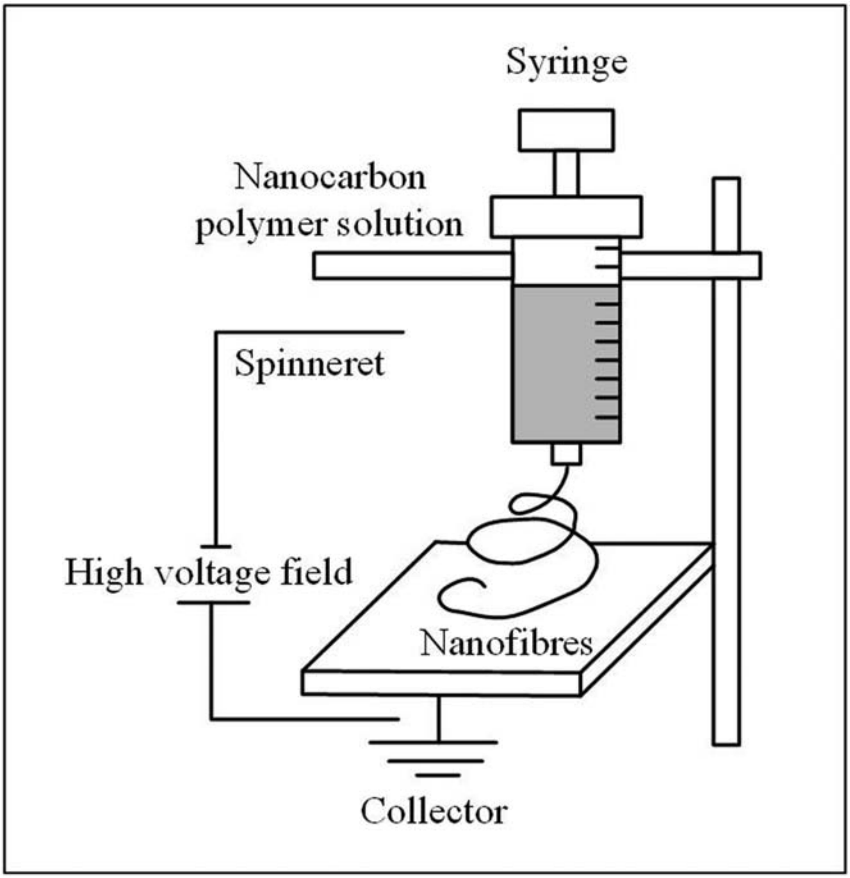

Figure 6.1 The electrospinning method for nanocarbon polymer biocomposites.

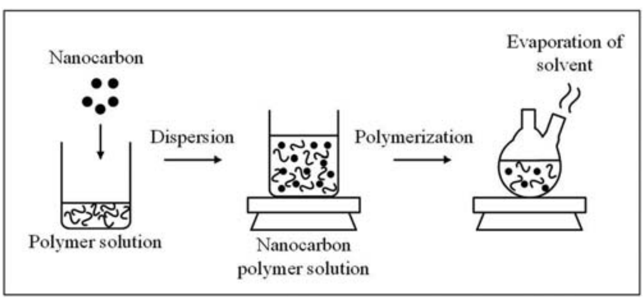

Figure 6.2 The in-situ polymerization method for nanocarbon polymer biocomposites.

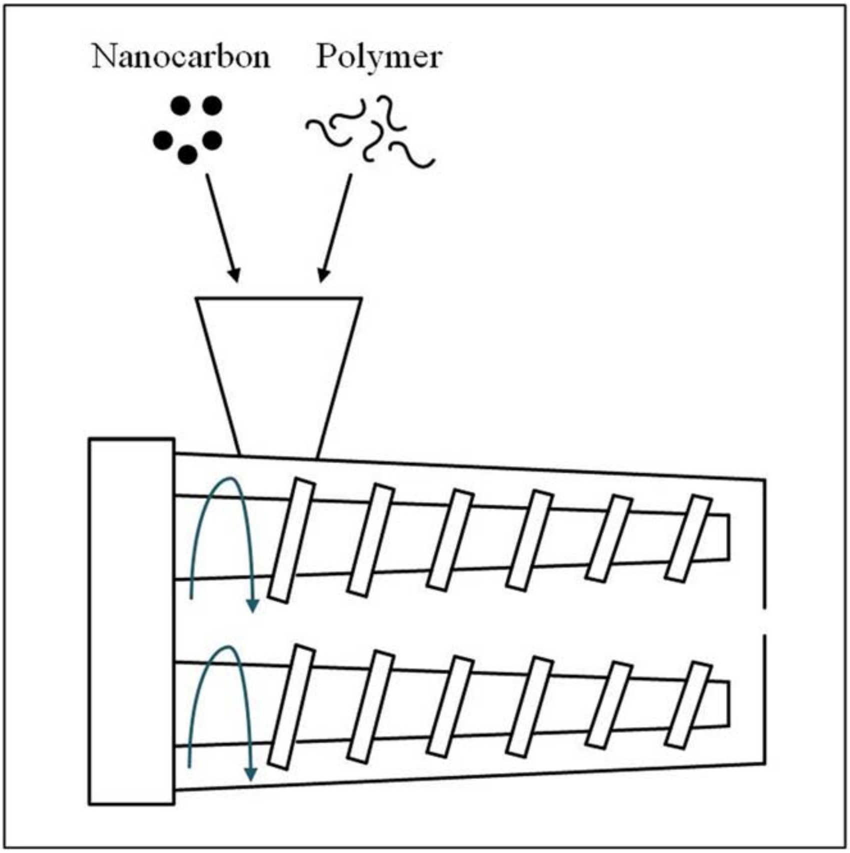

Figure 6.3 The melt blending method for nanocarbon polymer biocomposites.

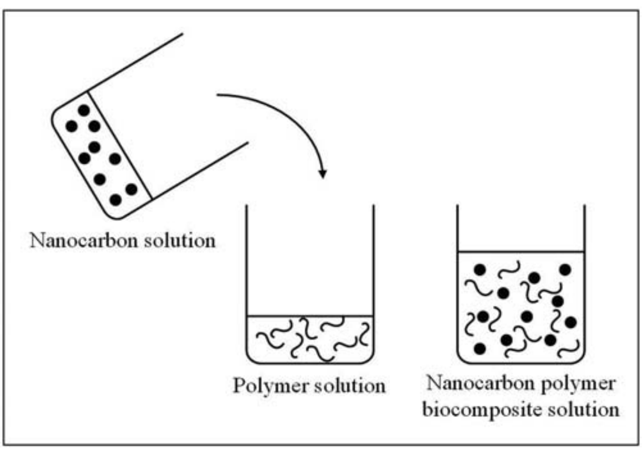

Figure 6.4 The solution blending method for nanocarbon polymer biocomposites.

Hence, the surface modification of nanocarbon is able to solve several issues regarding the nanocarbon polymer biocomposites production which are discussed below.

6.5.1 Improved dispersion

According to Lee et al. (2019), the mechanical properties of nanocarbon polymer biocomposites are affected by the effectiveness of the transfer of polymers to the nanocarbon. Hence, it is crucial to obtain a high interfacial affinity between the nanocarbon and the polymer matrix to obtain high-performance nanocarbon polymer biocomposites (Lee et al., 2019). Lee et al. (2019) also mentioned that nanocarbon has a smooth surface and a small interfacial area which leads to a low interfacial affinity and results in limited improvements in the mechanical properties of biocomposites. Therefore, surface modification of nanocarbon is done to ensure that there is an improved dispersion of the nanocarbon in the polymer matrix. Based on Zhang et al. (2020), modified nanocarbon is able to improve the dispersion of nanocarbon polymer biocomposites by improving the affinity between the nanocarbon and polymer.

Other than that, CNTs are also known to be insoluble in various aqueous and organic solvents as CNTs have a stable structure as a pure carbon element (Dubey et al., 2021). Dubey et al. (2021) also mentioned that CNTs consist of a long range of van der Waals forces of attraction which increases the aggregation and results in low dispersion of the biocomposites. Hence, surface modification of nanocarbon is able to solve this issue in order to improve the dispersion of biocomposites. Surface modification of nanocarbon can produce a series of functional groups that can aid in decreasing the long range of van der Waals forces of attraction by increasing the interaction of nanocarbon and polymer matrix (Dubey et al., 2021). As a result, this improves the dispersion of the nanocarbon polymer biocomposites by improving the solubility and reactivity of the nanocarbon.

6.5.2 Improved interfacial adhesion

The significant mechanical properties of nanocarbon are one of the highlights of nanocarbon polymer biocomposites as the mechanical properties result in various advantages. However, the mechanical properties of the biocomposites are not only dependent on the mechanical properties of nanocarbon, but they also involve the interfacial adhesion of the nanocarbon and the polymer matrix (Yan et al., 2023). Low interfacial adhesion can cause crack formation and stress concentration which causes the biocomposites to deteriorate (Wang et al., 2019). Wang et al. mentioned that the interfacial adhesion of biocomposites is based on the interaction and molecular interface structure. Hence, the surface modification of nanocarbon enables the nanocarbon to become highly stable, nonpolar, and has a smooth graphitic surface where the surface of nanocarbon is layered with specific types of monomers or polymers (Wang et al., 2019).

Next, the surface modification of nanocarbon can improve the interfacial adhesion by mechanical interlocking. Mechanical interlocking occurs between the rough surface of the nanocarbon and the polymer matrix where the interfacial adhesion can be improved by increasing the surface roughness of the nanocarbon (Mohammed et al., 2022). The increase of surface roughness which is done by surface modification of nanocarbon will increase the binding area between the nanocarbon and polymer matrix (Mohammed et al., 2022). As a result, the bond strength in the biocomposites is improved and this maximizes the desired mechanical properties of nanocarbon into the nanocarbon polymer biocomposites (Mohammed et al., 2022).

6.5.3 Tailored functionality

As mentioned previously, the high thermal conductivity of nanocarbon leads to nanocarbon becoming an attractive material for biocomposites that are thermally conductive. Nevertheless, the thermal conductivity of nanocarbon polymer biocomposites is relatively low compared to nanocarbon itself (Rivas-Cruz et al., 2022). Surface modification of nanocarbon by utilizing oxygen functional groups can enhance the interaction between water and nanocarbon particles which will cause the hydrophobic carbon particles to become more hydrophilic, hence, improving the dispersibility (Mohd Saidi et al., 2022). By doing so, the thermal conductivity of the heat transfer media can also be improved (Mohd Saidi et al., 2022).

Pristine nanocarbons are known to be very insoluble in water which limits the functionality of nanocarbons to possess enzyme mimicking mechanisms (Dhiman et al., 2022). Surface modification of nanocarbon with functional groups that have hydrophilic moieties such as oxygen is able to improve water solubility and modify the physiochemical properties of nanocarbon (Das et al., 2019b; Kaushik et al., 2022). According to Dhiman et al. (2022), the surface modification of nanocarbon is able to enable the enzymatic activity in the biocomposites and this is due to the increase in the density of the functional groups which leads to high catalytic sites and improves the electron transportation activity.

6.6 Impact of polymer surface modification on biocomposites properties

6.6.1 Improves homogeneity

One of the issues of natural polymers such as cellulose in nanocarbon polymer biocomposites is the difficulty in obtaining a homogenous mixture between nanocarbon and polymer which will affect the properties, structure, and performance of the biocomposites (Jaffar et al., 2022). Hence, Jaffar et al. also proposed a solution where the surface modification of the cellulose can alter the surface chemistry by minimizing the fibril entanglement without changing the structure of the cellulose but still improves the dispersion that results in a more homogenous mixture.

6.6.2 Improves dispersion

The dispersion issue in natural polymers requires the addition of salt or pH adjustment to recover the polymer even after introducing a negatively charged sulfate group that is required to ensure a stable dispersion (Jaffar et al., 2022). Hence, surface modification is required to improve the dispersion of the polymers so that the biocomposites can be recovered easily without extra adjustments. Therefore, the dispersion can be improved by surface modification of the natural polymers with low molecular weight polymers (Hassan et al., 2020).

6.6.3 Controls degradation rate

As mentioned previously, natural polymers like cellulose, chitin, and starch are highly biodegradable and can be degraded by microorganisms easily. However, this might limit the usage of the biocomposites since it has a fast degradation, resulting in lower shelf-life. Hence, surface modification can be done on the polymers to solve this issue, as mentioned by

Cai et al. (2020), surface modification can control the degradation rate along with promoting the cell adhesion resulting in a longer shelf-life of the biocomposites.

6.7 Applications of nanocarbon polymer biocomposites

6.7.1 Aerospace engineering

Based on the mechanical properties along with the anti-corrosion properties of nanocarbon polymer biocomposites as mentioned in the previous section, this enables the nanocarbon polymer biocomposites to become very attractive for aerospace engineering. The applications of the nanocarbon polymer biocomposites in aerospace engineering are tabulated in Table 6.8.

6.7.2 Automotive industry

The superior mechanical properties, thermal properties, along with the anti-corrosive properties of nanocarbon polymer biocomposites are applicable to the automotive industry as it is quite similar to the aerospace engineering industry in terms of the structural components. The applications of nanocarbon polymer biocomposites for the automotive industry are discussed in Table 6.9.

6.7.3 Construction

The mechanical properties in terms of stiffness, toughness, and tensile strength along with the moisture barrier properties and UV-resistance properties of nanocarbon polymer biocomposites enable various applications of the biocomposites in the construction industry. Table 6.10 discusses the applications of nanocarbon polymer biocomposites in the construction industry.

6.7.4 Medical industry

The medical industry requires more consideration in incorporating materials in the production as it may cost human lives. Hence, the biocompatibility and minimized cytotoxicity of the biocomposites play a crucial role

Table 6.8 The applications of nanocarbon polymer biocomposites in aerospace engineering.

Applications	Explanation	References
Electrical components	As mentioned previously, nanocarbon has high electrical conductivity which allows the biocomposites to also have electrical properties. The high electrical conductivity of the biocomposites is applicable for aerospace engineering in the production of electrical components such as space antennas and sensors.	Anderson et al. (2020); Rocha et al. (2021); Zeranska-Chudek et al. (2021)
Propulsion systems	The enhanced thermal properties of nanocarbon polymer biocomposites result in various applications of the biocomposites in the propulsion system in aerospace engineering. For example, nanocarbon polymer biocomposites can be used as internal insulation materials for the production of solid rocket motors and the thermal protection systems of aircraft.	Guo et al. (2020)
Structural components	The significant properties of the nanocarbon polymer biocomposites such as anti-corrosive, thermal stability, UV resistance, and high mechanical strength result in the biocomposites becoming a suitable material for structural components in aerospace engineering applications. The structural components of aircraft that can be fabricated using nanocarbon polymer biocomposites include airframes, fuselage, tail bottom, and wings.	Kausar et al. (2023); Malucelli and Kausar (2022)

in the medical industry to prevent any unwanted issues. The application of nanocarbon polymer biocomposites in various types of the medical industry is explained in Table 6.11.

Table 6.9 The applications of nanocarbon polymer biocomposites in the automotive industry.

Applications	Explanation	References
Interior components	Nanocarbon polymer biocomposites are advantageous in the fabrication of interior components in the automotive industry due to their design flexibility, and lightweight. Examples of interior components that can be fabricated using nanocarbon polymer biocomposites include seat cushions, door trim, real panel shelves, and dashboard components.	Agarwal et al. (2020); Shah et al. (2022)
Structural components	The significant mechanical properties of nanocarbon polymer biocomposites such as their toughness, anti-corrosive, and high strength-to-weight ratio are crucial in the structural components of the automotive industry. The structural components in the automotive industry like the underbody panels and the exterior body panels require these properties to reduce the gasoline intake and drain gas emissions.	Agarwal et al. (2020); Shah et al. (2022)
Tires	The tread compounds of tires play an important role in the rolling resistance of the tires which can also affect gasoline consumption. The improved mechanical properties of nanocarbon polymer biocomposites like tensile strength and hardness can improve the production of tires to have better handling and traction properties. Nanocarbon polymer biocomposites are also fabricated as transistors to sense the environmental pressure on tires.	Andrews et al. (2018); Nurazzi et al. (2021); Shah et al. (2022)

Table 6.10 The applications of nanocarbon polymer biocomposites in the construction industry.

Applications	Explanation	References
Waterproofing materials	The improved moisture barrier and UV-resistance properties of nanocarbon polymer biocomposites can be applied to the production of waterproof materials in the construction industry such as paints, coatings, sealants, and glue. The superior mechanical properties such as durability, and flexibility also enable the waterproof materials to be able to withstand harsh environmental conditions.	Idrees et al. (2022); Laza et al. (2022)
Reinforcing materials	Reinforcing materials in the construction industry such as concrete requires excellent mechanical properties, along with moisture barrier properties. Nanocarbon polymer biocomposites are able to be applied as reinforcing materials due to their large specific surface area, durability, and high tensile strength. On top of that, the dispersion properties of the biocomposites are also suitable for concrete production and improve the mechanical properties.	Divya et al. (2022)
Flooring materials	The mechanical properties of nanocarbon polymer biocomposites are applicable in flooring materials of the construction industry as it has high toughness and strength. This will ensure that the flooring materials are more durable which results in the materials having a longer lifespan and makes it more cost-effective.	Das et al. (2019a)

6.7.5 Packaging

The packaging industry requires properties like excellent moisture barriers, and excellent mechanical properties as it is used to store products that can degrade such as food, drugs, and electrical products.

Table 6.11 The applications of nanocarbon polymer biocomposites in the medical industry.

Applications	Explanation	References
Dental implants	The crucial factors that need to be taken into consideration in the production of dental implants include biocompatibility, mechanical strength, corrosion resistance, costs, and availability. The nanocarbon polymer biocomposites are a suitable material that can be used in dental implants as they fulfil the requirements of dental implants. Since the biocomposites are anti-corrosive and biocompatible, this will provide mechanical strength to the dental implants without giving allergic reactions compared to using other materials like stainless steel, titanium, and zirconium.	Krishnakumar and Senthilvelan (2021)
Tissue engineering	The mechanical properties and biocompatibility of nanocarbon polymer biocomposites are crucial factors in tissue engineering. Tissue engineering also requires biomimetic properties that obtain strong mechanical properties as well. It is also important that the biocomposites have the ability to reduce cytotoxicity as they can be used for nerve tissue engineering, bone regeneration, and myogenesis.	Gao et al. (2019)
Drug delivery system	The nanocarbon polymer biocomposites are applicable as drug delivery systems due to their high specific surface area and biocompatibility. This allows the biocomposites to be conjugated with other therapeutics, typically anti-cancer drugs. In addition, as mentioned previously, natural polymers can reduce cytotoxicity which makes them safe for human consumption.	Bacakova et al. (2020)

Therefore, the usage of nanocarbon polymer biocomposites is a good alternative to improve the packaging industry which is discussed in Table 6.12.

Table 6.12 The applications of nanocarbon polymer biocomposites in the packaging industry.

Applications	Explanation	References
Electronic packaging	Nanocarbon polymer biocomposites have a huge demand as it has high thermal conductivity and excellent mechanical properties for the production of electronic packaging. Biocomposites have a high electrical conductivity compared to metals which makes them a better alternative in electronic packaging. This is due to the high specific area of the biocomposites which creates a heat conduction network and mutual contact will prevent the formation of microcapacitors.	Li et al. (2022)
Food packaging	Food packaging requires the materials to be able to extend the shelf-life of the food and the packaging should be able to withstand environmental interactions along with safety measures. The properties to ensure this application is to include temperature control, nontoxic, and biocompatible. The nanocarbon polymer biocomposites are a good alternative as it has high thermal stability, biocompatible, biodegradable and have high Young's modulus which makes them safe for human consumption after food storage.	Carvalho and Conte Junior (2020)
Medical packaging	The biocompatibility, moisture barrier properties, and UV-resistance properties of nanocarbon polymer biocomposites are a good alternative for medical packaging such as the storage of drugs. The medical packaging is sensitive to UV rays and also moisture, as it can degrade the quality of the drugs. Other than that, the biocompatibility of the composites also ensures that the packaging is nontoxic and safe for human consumption.	Kim et al. (2020)

6.8 Summary

In conclusion, combining nanocarbon and natural polymers is a great alternative as the nanocarbon polymer biocomposites have various advantages obtained from combining the superior properties of nanocarbon and polymers. It can be determined that nanocarbon is a promising material for biocomposites as it offers a wide range of properties including mechanical, electrical, and thermal properties along with corrosion resistance, UV-resistance and improved barrier properties. On top of that, natural polymers also have various advantages specifically in terms of biocompatibility, biodegradability, and abundance. Even though there are a few drawbacks of these materials, the surface modification of nanocarbon and natural polymers can solve the issues in the fabrication of nanocarbon polymer biocomposites. Therefore, the improvements made during the fabrication of the nanocarbon polymer biocomposites lead to various applications of the biocomposites such as aerospace engineering, the automotive industry, the construction industry, the medical industry, and the packaging industry.

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References

Abazari, S., Shamsipur, A., Bakhsheshi-Rad, H. R., Ismail, A. F., Sharif, S., Razzaghi, M., Ramakrishna, S., & Berto, F. (2020). Carbon nanotubes (CNTs)-reinforced magnesium-based matrix composites: A comprehensive review. *Materials*, *13*(19), 1–38. Available from https://doi.org/10.3390/ma13194421, https://www.mdpi.com/1996-1944/13/19/4421/pdf.

Abenojar, J., Martínez, M. A., Armentia, S. L. D., Paz, E., Real, J. C. D., & Velasco, F. (2021). Mechanical properties and fire-resistance of composites with marble particles. *Journal of Materials Research and Technology*, *12*, 1403–1417. Available from https://doi.org/10.1016/j.jmrt.2021.03.071, http://www.elsevier.com/journals/journal-of-materials-research-and-technology/2238-7854.

Adamu, M., Rahman, M. R., Hamdan, S., Bakri, M. K. B., & Yusof, F. A. B. M. (2020). Impact of polyvinyl alcohol/acrylonitrile on bamboo nanocomposite and optimization of mechanical performance by response surface methodology. *Construction and Building Materials*, *258*. Available from https://doi.org/10.1016/j.conbuildmat.2020.119693, https://www.journals.elsevier.com/construction-and-building-materials.

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*. Available from https://doi.org/

10.1016/j.compositesb.2019.107297, https://www.journals.elsevier.com/composites-part-b-engineering.

Adigwe, O.P., Egharevba, H.O., Emeje, M.O. (2022). *Starch: A veritable natural polymer for economic revolution*. Available from https://doi.org/10.5772/INTECHOPEN.102941.

Agarwal, J., Sahoo, S., Mohanty, S., & Nayak, S. K. (2020). Progress of novel techniques for lightweight automobile applications through innovative eco-friendly composite materials: A review. *Journal of Thermoplastic Composite Materials*, *33*(7), 978−1013. Available from https://doi.org/10.1177/0892705718815530.

Ahmad, A. N., Lim, S. A., Navaranjan, N., Hsu, Y. I., & Uyama, H. (2020). Green sago starch nanoparticles as reinforcing material for green composites. *Polymer*, *202*. Available from https://doi.org/10.1016/j.polymer.2020.122646, http://www.journals.elsevier.com/polymer/.

Ahmed, M. J., Hameed, B. H., & Hummadi, E. H. (2020). Review on recent progress in chitosan/chitin-carbonaceous material composites for the adsorption of water pollutants. *Carbohydrate Polymers*, *247*, 116690. Available from https://doi.org/10.1016/j.carbpol.2020.116690.

Akbayrak, S. & Özkar, S. (2018). Supported nanoparticles for liquid-phase catalysis. Encyclopedia of interfacial chemistry: Surface science and electrochemistry. Elsevier, Turkey, 607−624. Available from https://doi.org/10.1016/B978-0-12-409547-2.12999-3.

Al-Maharma, A. Y., Sendur, P., & Al-Huniti, N. (2019). Critical review of the factors dominating the fracture toughness of CNT reinforced polymer composites. *Materials Research Express*, *6*(1), 012003. Available from https://doi.org/10.1088/2053-1591/aae867.

Alemour, B., Yaacob, M. H., Lim, H. N., & Hassan, M. R. (2018). Review of electrical properties of graphene conductive composites. *International Journal of Nanoelectronics and Materials*, *11*(4), 371−398. Available from http://ijneam.unimap.edu.my/images/PDF/IJNEAM%20OCT%20PDF/Vol_11_No_4_2018_1_371-398.pdf.

Aly, K., Lubna, M., & Bradford, P. D. (2021). Low density, three-dimensionally interconnected carbon nanotube/silicon carbide nanocomposites for thermal protection applications. *Journal of the European Ceramic Society*, *41*(1), 233−243. Available from https://doi.org/10.1016/j.jeurceramsoc.2020.06.020, http://www.journals.elsevier.com/journal-of-the-european-ceramic-society/.

Amini, S., Salehi, H., Setayeshmehr, M., & Ghorbani, M. (2021). Natural and synthetic polymeric scaffolds used in peripheral nerve tissue engineering: Advantages and disadvantages. *Polymers for Advanced Technologies*, *32*(6), 2267−2289. Available from https://doi.org/10.1002/pat.5263, http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-1581.

Anderson, M. J., Kareer, S., Mahdavi Ardakani, S. E., Thomson, S. D., Koehne, J. E., Park, J., & Park, J. (2020). *Nanocarbons for flexible sensing applications* (pp. 273−310). Informa UK Limited. Available from https://doi.org/10.1201/9781003043089-6.

Andrews, J. B., Cardenas, J. A., Lim, C. J., Noyce, S. G., Mullett, J., & Franklin, A. D. (2018). Fully printed and flexible carbon nanotube transistors for pressure sensing in automobile tires. *IEEE Sensors Journal*, *18*(19), 7875−7880. Available from https://doi.org/10.1109/JSEN.2018.2842139, http://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber = 7361.

Armano, A., & Agnello, S. (2019). Two-dimensional carbon: A review of synthesis methods, and electronic, optical, and vibrational properties of single-layer graphene. *C—Journal of Carbon Research*, *5*(4), 67. Available from https://doi.org/10.3390/c5040067.

Azammi, A. M. N., Ilyas, R. A., Sapuan, S. M., Ibrahim, R., Atikah, M. S. N., Asrofi, M., Atiqah, A. (2019). Characterization studies of biopolymeric matrix and cellulose fibres based composites related to functionalized fibre-matrix interface. Interfaces in particle and fibre reinforced composites: Current perspectives on polymer, ceramic, metal and extracellular matrices. Elsevier, Malaysia, 29−93, http://www.sciencedirect.com/science/book/9780081026656, https://doi.org/10.1016/B978-0-08-102665-6.00003-0.

Bacakova, L., Pajorova, J., Tomkova, M., Matejka, R., Broz, A., Stepanovska, J., Prazak, S., Skogberg, A., Siljander, S., & Kallio, P. (2020). Applications of nanocellulose/nanocarbon composites: Focus on biotechnology and medicine. *Nanomaterials*, *10*(2), 196. Available from https://doi.org/10.3390/nano10020196.

Barathi Dassan, E. G., Anjang Ab Rahman, A., Abidin, M. S. Z., & Akil, H. M. (2020). Carbon nanotube-reinforced polymer composite for electromagnetic interference application: A review. *Nanotechnology Reviews*, *9*(1), 768−788. Available from https://doi.org/10.1515/ntrev-2020-0064, http://www.degruyter.com/view/j/ntrev?rskey = tED3So&result = 1.

Cai, S., Wu, C., Yang, W., Liang, W., Yu, H., & Liu, L. (2020). Recent advance in surface modification for regulating cell adhesion and behaviors. *Nanotechnology Reviews*, *9* (1), 971−989. Available from https://doi.org/10.1515/ntrev-2020-0076, http://www.degruyter.com/view/j/ntrev?rskey = tED3So&result = 1.

Carvalho, A. P. A. D., & Conte Junior, C. A. (2020). Green strategies for active food packagings: A systematic review on active properties of graphene-based nanomaterials and biodegradable polymers. *Trends in Food Science and Technology*, *103*, 130−143. Available from https://doi.org/10.1016/j.tifs.2020.07.012, http://www.elsevier.com/wps/find/journaldescription.cws_home/601278/description#description.

Chen, W., Weimin, H., Li, D., Chen, S., & Dai, Z. (2018). A critical review on the development and performance of polymer/graphene nanocomposites. *Science and Engineering of Composite Materials*, *25*(6), 1059−1073. Available from https://doi.org/10.1515/secm-2017-0199, http://www.degruyter.com/view/j/secm.2012.19.issue-1/issue-files/secm.2012.19.issue-1.xml.

Choi, H. J., Kim, M. S., Ahn, D., Yeo, S. Y., & Lee, S. (2019). Electrical percolation threshold of carbon black in a polymer matrix and its application to antistatic fibre. *Scientific Reports*, *9*(1). Available from https://doi.org/10.1038/s41598-019-42495-1, http://www.nature.com/srep/index.html.

Chraniuk, M., Panasiuk, M., Hovhannisyan, L., Żołędowska, S., Nidzworski, D., Ciołek, L., Woźniak, A., Jaegermann, Z., Biernat, M., & Gromadzka, B. (2022). The preliminary assessment of new biomaterials necessitates a comparison of direct and indirect cytotoxicity methodological approaches. *Polymers*, *14*(21), 4522. Available from https://doi.org/10.3390/polym14214522.

Cohen, S., Zelikman, E., & Suckeveriene, R. Y. (2020). Ultrasonically induced polymerization and polymer grafting in the presence of carbonaceous nanoparticles. *Processes*, *8* (12), 1680. Available from https://doi.org/10.3390/pr8121680.

Cosquer, R., Pruvost, S., & Gouanvé, F. (2021). Improvement of barrier properties of biodegradable polybutylene succinate/graphene nanoplatelets nanocomposites prepared by melt process. *Membranes*, *11*(2), 151. Available from https://doi.org/10.3390/membranes11020151.

Cougo, C. Md. S., Pezzin, S. H., Pachekoski, W. M., Amico, S. C. (2018). Multiscale hybrid composites with carbon-based nanofillers. Nanocarbon and its composites: Preparation, properties and applications. Elsevier, Brazil, 449−470. Available from http://www.sciencedirect.com/science/book/9780081025093, https://doi.org/10.1016/B978-0-08-102509-3.00014-6.

Das, T. K., Ghosh, P., & Das, N. C. (2019a). Preparation, development, outcomes, and application versatility of carbon fiber-based polymer composites: A review. *Advanced Composites and Hybrid Materials*, *2*(2), 214−233. Available from https://doi.org/10.1007/s42114-018-0072-z, http://springer.com/journal/42114.

Das, G. S., Tripathi, K. M., Kumar, G., Paul, S., Mehara, S., Bhowmik, S., Pakhira, B., Sarkar, S., Roy, M., & Kim, T. (2019b). Nitrogen-doped fluorescent graphene nanosheets as visible-light-driven photocatalysts for dye degradation and selective sensing of ascorbic acid. *New Journal of Chemistry*, *43*(36), 14575−14583. Available from https://doi.org/10.1039/c9nj02344e, http://pubs.rsc.org/en/journals/journal/nj.

Dhiman, N., Ghosh, S., Mishra, Y. K., & Tripathi, K. M. (2022). Prospects of nanocarbons as emerging catalysts for enzyme-mimetic applications. *Materials Advances*, *3* (7), 3101−3122. Available from https://doi.org/10.1039/d2ma00034b, http://www.rsc.org/journals-books-databases/about-journals/materials-advances/.

Ding, B., Huang, S., Shen, K., Hou, J., Gao, H., Duan, Y., & Zhang, J. (2019). Natural rubber bio-nanocomposites reinforced with self-assembled chitin nanofibers from aqueous KOH/urea solution. *Carbohydrate Polymers*, *225*, 115230. Available from https://doi.org/10.1016/j.carbpol.2019.115230.

Divya, S., Praveenkumar, S., & Tayeh, B. A. (2022). Performance of modified nano carbon blended with supplementary materials in cement composite − An interpretive review. *Construction and Building Materials*, *346*, 128452. Available from https://doi.org/10.1016/j.conbuildmat.2022.128452.

Dubey, R., Dutta, D., Sarkar, A., & Chattopadhyay, P. (2021). Functionalized carbon nanotubes: synthesis, properties and applications in water purification, drug delivery, and material and biomedical sciences. *Nanoscale Advances*, *3*(20), 5722−5744. Available from https://doi.org/10.1039/d1na00293g, http://pubs.rsc.org/en/journals/journalissues/na?_ga2.190536939.1555337663.1552312502-1364180372.1550481316#!issueid-na001002&typecurrent&issnonline2516-0230.

Egan, J., & Salmon, S. (2022). Strategies and progress in synthetic textile fiber biodegradability. *SN Applied Sciences*, *4*(1). Available from https://doi.org/10.1007/s42452-021-04851-7, http://springer.com/snas.

Ehsani, M., Rahimi, P., & Joseph, Y. (2021). Structure−function relationships of nanocarbon/polymer composites for chemiresistive sensing: A review. *Sensors* (9). Available from https://doi.org/10.3390/S21093291.

El-Gendi, H., Taha, T. H., Ray, J. B., & Saleh, A. K. (2022). Recent advances in bacterial cellulose: A low-cost effective production media, optimization strategies and applications. *Cellulose*, *29*(14), 7495−7533. Available from https://doi.org/10.1007/s10570-022-04697-1, http://www.springer.com/journal/10570.

Fortunato, M., Bellagamba, I., Tamburrano, A., & Sarto, M. S. (2020). Flexible Ecoflex®/graphene nanoplatelet foams for highly sensitive low-pressure sensors. *Sensors*, *20*(16), 4406. Available from https://doi.org/10.3390/s20164406.

Gao, X., Han, S., Zhang, R., Liu, G., & Wu, J. (2019). Progress in electrospun composite nanofibers: Composition, performance and applications for tissue engineering. *Journal of Materials Chemistry B*, *7*(45), 7075−7089. Available from https://doi.org/10.1039/c9tb01730e, http://pubs.rsc.org/en/journals/journal/tb.

Guo, M., Li, J., Xi, K., Liu, Y., Ji, J., & Ye, C. (2020). Effects of multi-walled carbon nanotubes on char residue and carbothermal reduction reaction in ethylene propylene diene monomer composites at high temperature. *Composites Science and Technology*, *186*, 107916. Available from https://doi.org/10.1016/j.compscitech.2019.107916.

Haider, M. M., Jian, G., Li, H., Wolcott, M., Fernandez, C., & Nassiri, S. (2022). Impact of chitin nanofibers and nanocrystals from waste shrimp shells on mechanical properties, setting time, and late-age hydration of mortar. *Scientific Reports*, *12*(1). Available from https://doi.org/10.1038/s41598-022-24366-4, https://www.nature.com/srep/.

Hakke, V. S., Landge, V. K., Sonawane, S. H., Uday Bhaskar Babu, G., Ashokkumar, M., & Flores, E. M. M. (2022). The physical, mechanical, thermal and barrier properties of starch nanoparticle (SNP)/polyurethane (PU) nanocomposite films synthesised by an ultrasound-assisted process. *Ultrasonics Sonochemistry*, *88*. Available from https://doi.org/10.1016/j.ultsonch.2022.106069, http://www.elsevier.com/inca/publications/store/5/2/5/4/5/1.

Hassan, M. L., Fadel, S. M., Abouzeid, R. E., Abou Elseoud, W. S., Hassan, E. A., Berglund, L., & Oksman, K. (2020). Water purification ultrafiltration membranes using nanofibers from unbleached and bleached rice straw. *Scientific Reports*, *10*(1).

Available from https://doi.org/10.1038/s41598-020-67909-3, http://www.nature.com/srep/index.html.

Idrees, M., Akbar, A., Saeed, F., Saleem, H., Hussian, T., & Vatin, N. I. (2022). Improvement in durability and mechanical performance of concrete exposed to aggressive environments by using polymer. *Materials*, *15*(11). Available from https://doi.org/10.3390/ma15113751, https://www.mdpi.com/1996-1944/15/11/3751/pdf?version = 1653385283.

Jaffar, S. S., Saallah, S., Misson, M., Siddiquee, S., Roslan, J., Saalah, S., & Lenggoro, W. (2022). Recent development and environmental applications of nanocellulose-based membranes. *Membranes*, *12*(3). Available from https://doi.org/10.3390/membranes12030287, https://www.mdpi.com/2077-0375/12/3/287/pdf.

Janaswamy, S., Yadav, M. P., Hoque, M., Bhattarai, S., & Ahmed, S. (2022). Cellulosic fraction from agricultural biomass as a viable alternative for plastics and plastic products. *Industrial Crops and Products*, *179*, 114692. Available from https://doi.org/10.1016/j.indcrop.2022.114692.

Jaseem, S. M., & Ali, N. A. (2019). Antistatic packaging of carbon black on plastizers biodegradable polylactic acid nanocomposites. *Journal of Physics: Conference Series*, *1279*(1). Available from https://doi.org/10.1088/1742-6596/1279/1/012046, http://iopscience.iop.org/journal/1742-6596.

Joseph, B., Sagarika, V. K., Sabu, C., Kalarikkal, N., & Thomas, S. (2020). Cellulose nanocomposites: Fabrication and biomedical applications. *Journal of Bioresources and Bioproducts*, *5*(4), 223−237. Available from https://doi.org/10.1016/j.jobab.2020.10.001, https://www.sciencedirect.com/journal/journal-of-bioresources-and-bioproducts.

Kausar, A., Ahmad., Maaza, M., & Bocchetta, P. (2023). Self-healing nanocomposites—Advancements and aerospace applications. *Journal of Composites Science*, 7(4). Available from https://doi.org/10.3390/JCS7040148.

Kaushik, J., Gunture., Tripathi, K. M., Singh, R., & Sonkar, S. K. (2022). Thiourea-functionalized graphene aerogel for the aqueous phase sensing of toxic Pb(II) metal ions and H_2O_2. *Chemosphere*, *287*. Available from https://doi.org/10.1016/j.chemosphere.2021.132105, http://www.elsevier.com/locate/chemosphere.

Kim, Y., Kim, J. S., Lee, S. Y., Mahajan, R. L., & Kim, Y. T. (2020). Exploration of hybrid nanocarbon composite with polylactic acid for packaging applications. *International Journal of Biological Macromolecules*, *144*, 135−142. Available from https://doi.org/10.1016/j.ijbiomac.2019.11.239, http://www.elsevier.com/locate/ijbiomac.

Krishnakumar, S., & Senthilvelan, T. (2021). Polymer composites in dentistry and orthopedic applications-A review. *Materials Today: Proceedings*, *46*, 9707−9713. Available from https://doi.org/10.1016/j.matpr.2020.08.463.

Laza, J. M., Veloso-Fernández, A., Sanchez-Bodon, J., Martín, A., Goitandia, A. M., Monteserín, C., Mendibil, X., Vidal, K., Lambarri, J., Aranzabe, E., Blanco, M., & Vilas-Vilela, J. L. (2022). Analysis of the influence of microencapsulated phase change materials on the behavior of a new generation of thermo-regulating shape memory polyurethane fibers. *Polymer Testing*, *116*. Available from https://doi.org/10.1016/j.polymertesting.2022.107807, https://www.journals.elsevier.com/polymer-testing.

Lee, J. K. Y., Chen, N., Peng, S., Li, L., Tian, L., Thakor, N., & Ramakrishna, S. (2018). Polymer-based composites by electrospinning: Preparation & functionalization with nanocarbons. *Progress in Polymer Science*, *86*, 40−84. Available from https://doi.org/10.1016/j.progpolymsci.2018.07.002, http://www.sciencedirect.com/science/journal/00796700.

Lee, Y. M., You, J., Kim, M., Kim, T. A., Lee, S. S., Bang, J., & Park, J. H. (2019). Highly improved interfacial affinity in carbon fiber-reinforced polymer composites via oxygen and nitrogen plasma-assisted mechanochemistry. *Composites Part B: Engineering*, *165*, 725−732. Available from https://doi.org/10.1016/j.compositesb.2019.02.021.

Lin, Z., Chen, L., Ye, Z., Chen, X., Wang, X., & Wei, Y. (2021). Film-like chitin/polyethylenimine biosorbent for highly efficient removal of uranyl-carbonate compounds from water. *Journal of Environmental Chemical Engineering*, *9*(4), 105340. Available from https://doi.org/10.1016/j.jece.2021.105340.

Liu, J., & Lv, C. (2021). Research progress on durability of cellulose fiber-reinforced cement-based composites. *International Journal of Polymer Science*, *2021*, 16879430. Available from https://doi.org/10.1155/2021/1014531, http://www.hindawi.com/journals/ijps/.

Li, M. C., Wu, Q., Moon, R. J., Hubbe, M. A., & Bortner, M. J. (2021). Rheological aspects of cellulose nanomaterials: Governing factors and emerging applications. *Advanced Materials*, *33*(21). Available from https://doi.org/10.1002/adma.202006052, http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1521-4095.

Li, R., Yang, X., Li, J., Shen, Y., Zhang, L., Lu, R., Wang, C., Zheng, X., Chen, H., & Zhang, T. (2022). Review on polymer composites with high thermal conductivity and low dielectric properties for electronic packaging. *Materials Today Physics*, *22*, 100594. Available from https://doi.org/10.1016/j.mtphys.2021.100594.

Luo, X., Zhong, J., Zhou, Q., Du, S., Yuan, S., & Liu, Y. (2018). Cationic reduced graphene oxide as self-aligned nanofiller in the epoxy nanocomposite coating with excellent anticorrosive performance and its high antibacterial activity. *ACS Applied Materials and Interfaces*, *10*(21), 18400−18415. Available from https://doi.org/10.1021/acsami.8b01982, http://pubs.acs.org/journal/aamick.

Malucelli, G., & Kausar, A. (2022). *Green composites and nanocomposites for aerospace applications. Polymeric nanocomposites with carbonaceous nanofillers for aerospace applications* (pp. 297−316). Italy: Elsevier. Available from https://www.sciencedirect.com/book/9780323996570, https://doi.org/10.1016/B978-0-323-99657-0.00014-4.

Marta, H., Wijaya, C., Sukri, N., Cahyana, Y., & Mohammad, M. (2022). A comprehensive study on starch nanoparticle potential as a reinforcing material in bioplastic. *Polymers*, *14*(22), 4875. Available from https://doi.org/10.3390/polym14224875.

Maruyama, T. (2021). *Carbon nanotubes*. Handbook of carbon-based nanomaterials (pp. 299−319). Japan: Elsevier. Available from https://www.sciencedirect.com/book/9780128219966, https://doi.org/10.1016/B978-0-12-821996-6.00009-9.

Merzendorfer, H., & Cohen, E. (2019). Chitin/chitosan: Versatile ecological, industrial, and biomedical applications. Springer Science and Business Media LLC, 541−624. Available from https://doi.org/10.1007/978-3-030-12919-4_14.

Mishra, R., & Militky, J. (2018). Nature, nanoscience, and textile structures. Nanotechnology in textiles: Theory and application. Elsevier, Czech Republic, 1−34. Available from https://www.sciencedirect.com/book/9780081026090, https://doi.org/10.1016/B978-0-08-102609-0.00001-8.

Mohammed, M., Rasidi, M. S. M., Mohammed, A. M., Rahman, R., Osman, A. F., Adam, T., Betar, B. O., & Dahham, O. S. (2022). Interfacial bonding mechanisms of natural fibre-matrix composites: An overview. *BioResources.*, *17*(4), 7031−7090. Available from https://doi.org/10.15376/BIORES.17.4.MOHAMMED, https://bioresources.cnr.ncsu.edu/resources/interfacial-bonding-mechanisms-of-natural-fibre-matrix-composites-an-overview/.

Mohd Roslan, M. R., Kamal, N. L., Khalid., Nasir, N. F., Cheng, E. M., Beh, C. Y., & Tan, J. S. (2021). The state of starch/hydroxyapatite composite scaffold in bone tissue engineering with consideration for dielectric measurement as an alternative characterization technique. *Materials*, *14*(8), 1960. Available from https://doi.org/10.3390/MA14081960.

Mohd Saidi, N., Abdullah, N., Norizan, M. N., Janudin, N., Mohd Kasim, N. A., Osman, M. J., Mohamad, I. S., & Mohd Rosli, M. A. (2022). Surface-oxidised carbon nanofibre-based nanofluids: Structural, morphological, stability and thermal properties.

Nanomaterials, *12*(21). Available from https://doi.org/10.3390/nano12213922, http://www.mdpi.com/journal/nanomaterials.
Mukarram, M., Naeem, M., Aftab, T., Khan, M. M. A. (2021). Chitin, chitosan, and chitooligosaccharides: Recent advances and future perspectives. Radiation-processed polysaccharides: Emerging roles in agriculture. Elsevier, India, 339−353. Available from https://www.sciencedirect.com/book/9780323856720, https://doi.org/10.1016/B978-0-323-85672-0.00012-X.
Nawaz, S., Tabassum, A., Muslim, S., Nasreen, T., Baradoke, A., Kim, T. H., Boczkaj, G., Jesionowski, T., & Bilal, M. (2023). Effective assessment of biopolymer-based multifunctional sorbents for the remediation of environmentally hazardous contaminants from aqueous solutions. *Chemosphere*, *329*, 138552. Available from https://doi.org/10.1016/j.chemosphere.2023.138552.
Norizan, M. N., Shazleen, S. S., Alias, A. H., Sabaruddin, F. A., Asyraf, M. R. M., Zainudin, E. S., Abdullah, N., Samsudin, M. S., Kamarudin, S. H., & Norrrahim, M. N. F. (2022). Nanocellulose-based nanocomposites for sustainable applications: A review. *Nanomaterials*, *12*(19). Available from https://doi.org/10.3390/nano12193483, http://www.mdpi.com/journal/nanomaterials.
Nurazzi, N. M., Sabaruddin, F. A., Harussani, M. M., Kamarudin, S. H., Rayung, M., Asyraf, M. R. M., Aisyah, H. A., Norrrahim, M. N. F., Ilyas, R. A., Abdullah, N., Zainudin, E. S., Sapuan, S. M., & Khalina, A. (2021). Mechanical performance and applications of CNTs reinforced polymer composites—A review. *Nanomaterials*, *11*(9), 2186. Available from https://doi.org/10.3390/nano11092186.
Othman, S. H., Kechik, N. R. A., Shapi'i, R. A., Talib, R. A., & Tawakkal, I. S. M. A. (2019). Water sorption and mechanical properties of starch/chitosan nanoparticle films. *Journal of Nanomaterials*, *2019*. Available from https://doi.org/10.1155/2019/3843949, http://www.hindawi.com/journals/jnm/.
Pal, A., Prabhakar, S., Bajpai, J., Bajpai A. K. (2022). Antiviral behavior of metal oxide-reinforced polymer nanocomposites. Nanoparticle-based polymer composites. Elsevier, India, 439−467. Available from https://www.sciencedirect.com/book/9780128242728, https://doi.org/10.1016/B978-0-12-824272-8.00019-1.
Paszkiewicz, S., Pypeć, K., Irska, I., & Piesowicz, E. (2020). Functional polymer hybrid nanocomposites based on polyolefins: A review. *Processes*, *8*(11), 1475. Available from https://doi.org/10.3390/pr8111475.
Radhamani, A. V., Lau, H. C., & Ramakrishna, S. (2018). CNT-reinforced metal and steel nanocomposites: A comprehensive assessment of progress and future directions. *Composites Part A: Applied Science and Manufacturing*, *114*, 170−187. Available from https://doi.org/10.1016/j.compositesa.2018.08.010.
Rahat Rahman, M., Rashid, M. M., Islam, M. M., & Akanda, M. M. (2019). Electrical and chemical properties of graphene over composite materials: A technical review. *Material Science Research India*, *16*(2), 142−163. Available from https://doi.org/10.13005/msri/160208.
Rivas-Cruz, F., Hernandez-Martinez, E. G., Portillo-Velez, R. de J., & Rejón-García, L. (2022). Nanotechnology applications in ground heat exchanger pipes: A review. *Applied Sciences*, *12*(8), 3794. Available from https://doi.org/10.3390/app12083794.
Rizal, S., Mistar, E. M., Rahman, A. A., Abdul, Khalil, Oyekanmi, A. A., Olaiya, N. G., Abdullah, C. K., & Alfatah, T. (2021). Bionanocarbon functional material characterisation and enhancement properties in nonwoven kenaf fibre nanocomposites. *Polymers*, *13*(14). Available from https://doi.org/10.3390/polym13142303.
Rocha, H., Semprimoschnig, C., & Nunes, J. P. (2021). Sensors for process and structural health monitoring of aerospace composites: A review. *Engineering Structures*, *237*, 112231. Available from https://doi.org/10.1016/J.ENGSTRUCT.2021.112231.

Sahu, A. K., Sudhakar, K., & Sarviya, R. M. (2020). UV light effect on the mechanical behaviour of HDPE/Carbon black composites. *IOP Conference Series: Materials Science and Engineering*, *788*(1), 012054. Available from https://doi.org/10.1088/1757-899X/788/1/012054.

Shah, V., Bhaliya, J., Patel, G. M., & Deshmukh, K. (2022). Advances in polymeric nanocomposites for automotive applications: A review. *Polymers for Advanced Technologies*, *33*(10), 3023−3048. Available from https://doi.org/10.1002/PAT.5771.

Shamshina, J. L., Oldham (Konak), T., & Rogers, R. D. (2019). Applications of Chitin in Agriculture, 125−146. Available from https://doi.org/10.1007/978-3-030-16581-9_4.

Smith, A. T., LaChance, A. M., Zeng, S., Liu, B., & Sun, L. (2019). Synthesis, properties, and applications of graphene oxide/reduced graphene oxide and their nanocomposites. *Nano Materials Science*, *1*(1), 31−47.

Song, J. P., Tian, K. Y., Ma, L. X., Li, W., & Yao, S. C. (2019). The effect of carbon black morphology to the thermal conductivity of natural rubber composites. *International Journal of Heat and Mass Transfer*, *137*, 184−191. Available from https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2019.03.078.

Szadkowski, B., Marzec, A., & Zaborski, M. (2020). Use of carbon black as a reinforcing nano-filler in conductivity-reversible elastomer composites. *Polymer Testing*, *81*, 106222. Available from https://doi.org/10.1016/J.POLYMERTESTING.2019.106222.

Tan, J. Y., Tey, W. Y., Panpranot, J., Lim, S., & Lee, K. M. (2022). Valorization of oil palm empty fruit bunch for cellulose fibers: A reinforcement material in polyvinyl alcohol biocomposites for its application as detergent capsules. *Sustainability (Switzerland)*, *14*(18), 11446. Available from https://doi.org/10.3390/SU141811446/S1.

Tarique, J., Sapuan, S. M., Aqil, N. F., Farhan, A., Faiz, J. I., & Shahrizan, S. (2023). A comprehensive review based on Chitin and Chitosan composites, 15−66. Available from https://doi.org/10.1007/978-981-19-5327-9_1.

Wang, G., Ma, L., Yang, X., Li, X., Han, P., Yang, C., Cong, L., Song, W., & Song, G. (2019). Improving the interfacial and flexural properties of carbon fiber−epoxy composites via the grafting of a hyperbranched aromatic polyamide onto a carbon fiber surface on the basis of solution polymerization. *Journal of Applied Polymer Science*, *136*(12), 47232. Available from https://doi.org/10.1002/APP.47232.

Wei, A., Fu, J., & Guo, F. (2021). Mechanical properties of chitin polymorphs: A computational study. *Journal of Materials Science*, *56*(20), 12048−12058. Available from https://doi.org/10.1007/S10853-021-06086-8.

Yan, C., Zhu, Y., Liu, D., Xu, H., Chen, G., Chen, M., & Cai, G. (2023). Improving interfacial adhesion and mechanical properties of carbon fiber reinforced polyamide 6 composites with environment-friendly water-based sizing agent. *Composites Part B: Engineering*, *258*, 110675. Available from https://doi.org/10.1016/J.COMPOSITESB.2023.110675.

Yao, X., Raine, T. P., Liu, M., Zakaria, M., Kinloch, I. A., & Bissett, M. A. (2021). Effect of graphene nanoplatelets on the mechanical and gas barrier properties of woven carbon fibre/epoxy composites. *Journal of Materials Science*, *56*(35), 19538−19551. Available from https://doi.org/10.1007/S10853-021-06467-Z/FIGURES/10.

Yu, K., Spiesz, E. M., Balasubramanian, S., Schmieden, D. T., Meyer, A. S., & Aubin-Tam, M. E. (2021). Scalable bacterial production of moldable and recyclable biomineralized cellulose with tunable mechanical properties. *Cell Reports Physical Science*, *2*(6), 100464. Available from https://doi.org/10.1016/J.XCRP.2021.100464.

Yue, X., Li, W., Li, Z., Qiu, F., Pan, J., & Zhang, T. (2020). Laminated superwetting aerogel/membrane composite with large pore sizes for efficient separation of surfactant-stabilized water-in-oil emulsions. *Chemical Engineering Science*, *215*, 115450. Available from https://doi.org/10.1016/J.CES.2019.115450.

Zakuwan, S. Z., & Ahmad, I. (2018). Synergistic effect of hybridized cellulose nanocrystals and organically modified montmorillonite on κ-carrageenan bionanocomposites. *Nanomaterials*, *8*(11), 874. Available from https://doi.org/10.3390/NANO8110874.

Zeranska-Chudek, K., Wróblewska, A., Kowalczyk, S., Plichta, A., & Zdrojek, M. (2021). Graphene infused ecological polymer composites for electromagnetic interference shielding and heat management applications. *Materials*, *14*(11), 2856. Available from https://doi.org/10.3390/MA14112856/S1.

Zhang, L.-H., Shi, Y., Wang, Y., Shiju, N. R., Zhang, L.-H., Shi, Y., Shiju, N. R., & Wang, Y. (2020). Nanocarbon catalysts: recent understanding regarding the active sites. *Advanced Science*, 7(5), 1902126. Available from https://doi.org/10.1002/ADVS.201902126.

Zhang, Z., Zhang, L., Li, C., Xie, X., Li, G., Hu, Z., & Li, S. (2021). Research progress of chitosan-based biomimetic materials. *Marine Drugs*, *19*(7), 372. Available from https://doi.org/10.3390/md19070372.

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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.

Key Features

- Emphasizes on nanoscale fillers and their improvement on compatibility
- Evaluates the impact of polymer production through life cycle analysis of both single and hybrid polymers and nanocomposites
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