**A Biodegradable Nanocomposite for Structural Applications**

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**Abstract**

This book chapter discusses the significant role of biodegradable nanocomposites in various structural applications. By combining biodegradable polymers with nanofillers, these materials offer enhanced mechanical properties, reduced environmental impact, and increased versatility. The chapter elaborates on the importance of nanocomposites in enhancing mechanical properties, such as tensile strength, modulus, and impact strength . It further explores the selection of nanofillers, fabrication techniques, and characterization methods for biodegradable nanocomposites. The thermal stability and degradation behavior of these materials are also examined, considering their impact on mechanical properties.The book chapter delves into the diverse structural applications of biodegradable nanocomposites, including packaging, construction, automotive, and biomedical industries. The utilization of these materials in various contexts, such as single-use products, building materials, and medical implants, highlights their potential in promoting sustainability and environmental preservation.While emphasizing the positive impact of biodegradable nanocomposites, the chapter acknowledges challenges and limitations, including cost-effectiveness, mechanical performance, and end-of-life management. Research gaps and opportunities for further exploration are identified, aiming to unlock the future potential of these materials. In conclusion, the chapter underscores the promising role of biodegradable nanocomposites in reshaping industries towards more sustainable practices and greener products, ultimately contributing to a more eco-friendly and healthier environment.

1. **Introduction:**

Sustainable materials have drawn a lot of attention across several businesses in this era of heightened environmental consciousness. Finding creative solutions that strike a compromise between the requirement for high-performance structural materials and environmental responsibility is one of the major difficulties we face today. As a viable alternative to traditional non-biodegradable materials, biodegradable materials have emerged as a potential class of materials that can address this issue(Dixit et al., 2022).

**1.1 Overview of Biodegradable Materials and Their Importance in Structural Applications**

Traditional building materials are being reevaluated in light of growing global concerns about plastic pollution, the depletion of fossil fuel reserves, and the negative effects of non-biodegradable materials on ecosystems. Materials that decay naturally in the environment are called biodegradable materials. This reduces the long-term effects of these materials on ecological systems. As a result, these substances have drawn a lot of interest as prospective replacements for a variety of applications, such as packaging, agriculture, and medical devices(Dixit and Yadav, 2021b).

The intrinsic biodegradability of these materials raises concerns about their mechanical characteristics and long-term durability in the context of structural applications. Because of their poorer mechanical performance as compared to their non-biodegradable equivalents, historically, biodegradable materials were frequently restricted to low-strength applications. The creation of biodegradable nanocomposites, however, as a result of recent developments in material science and nanotechnology, provides a convincing way to improve the mechanical characteristics of biodegradable materials for structural applications(Dixit and Yadav, 2021a).

**1.2 Importance of Nanocomposites in Enhancing Mechanical Properties**

As the name implies, nanocomposites are substances that combine nanoscale fillers into a matrix to produce new substances with enhanced qualities. The unique properties of the nanoscale fillers, such as nanoparticles, nanoclays, and nanofibers, dramatically modify the mechanical behaviour of the finished composite. In comparison to traditional microscale fillers, nanofillers have greater reinforcing capabilities due to their high surface area to volume ratio and quantum size effects.

The significant improvement in mechanical characteristics is one of the main advantages of nanocomposites. For instance, adding nanofillers to a polymer matrix can boost the tensile strength, modulus, and toughness of the material. Additionally, nanocomposites frequently show enhanced heat stability and decreased flammability. Nanocomposites are an appealing alternative for high-performance structural applications that necessitate superior mechanical and thermal qualities because to these characteristics(Dixit and Yadav, 2020).

Due to their extraordinary capacity to improve mechanical properties beyond the capabilities of typical composites, nanocomposites have grown significantly in significance in the field of materials research. It is possible to custom design materials with enhanced strength, stiffness, toughness, and other mechanical properties by including nanoscale fillers within a matrix. The details that make nanocomposites an appealing option for increasing mechanical qualities in diverse applications will be covered in this section(Dixit et al., 2020).

* + 1. **Increased Surface Area-to-Volume Ratio**:

Compared to traditional fillers, nanoscale fillers have an extraordinarily high surface area-to-volume ratio. A greater contact between the nanofiller and the matrix material is made possible by this special characteristic. Due to the efficient distribution and transfer of external loads by the nanofillers throughout the material, nanocomposites display improved load transfer efficiency. Nanocomposites are the perfect option for applications requiring high strength and stiffness because of this enhanced load transfer mechanism, which also improves mechanical qualities(Dixit and Yadav, 2019b).

* + 1. **Reinforcement Effect of Nanofillers**

Nanofillers' unique mechanical characteristics are a result of their size-dependent behaviours. Examples of materials with outstanding mechanical strength and stiffness at the nanoscale are carbon nanotubes (CNTs) and graphene. These nanofillers strengthen the substance and serve as load-bearing components when introduced into a polymer matrix, adding to the nanocomposite's total mechanical strength. The intrinsic stiffness of the nanofillers and the ductile character of the matrix work together synergistically to improve the overall mechanical properties.

Customizing Material Characteristics: One notable benefit provided by nanoscale fillers is the tunability of nanocomposite mechanical characteristics. Researchers are able to accurately regulate the mechanical behaviour of the final material by altering the kind, concentration, and distribution of nanofillers inside the matrix. For instance, the stiffness, toughness, and tensile strength of the nanocomposite can be tailored to fit the needs of a particular application by varying the amount of nanofillers used. This adaptability creates new opportunities for designing materials with specialized mechanical characteristics for a variety of applications(Dixit and Yadav, 2019a).

* + 1. **Barrier Effect and Improved Toughness**

By adding nanofillers like nanoclays or nanoparticles, the matrix material may experience a barrier effect. This barrier effect limits the mobility of polymer chains and fracture spread, improving toughness and crack initiation and growth resistance as a result. In structural applications, where materials must tolerate a range of stresses and external impacts without catastrophic failure, this improved toughness is particularly important(Bharadwaj, 2001).

**1.2.4 Reduced Material Weight**:

Particularly in weight-sensitive applications like the aerospace and automotive industries, the high strength-to-weight ratio of nanocomposites is a considerable benefit. Due to their modest weight, nanofillers provide a way to improve the mechanical properties of materials without adding much to their overall weight. By increasing both fuel efficiency and cargo capacity, nanocomposites become a desirable option for lightweight structural components(Baur and Silverman, 2007).

**1.2.5 Thermal Stability and Flame Retardancy**:

Nanoparticles and nanoclays, for example, have built-in flame-retardant qualities. The nanocomposite's fire resistance can be increased by adding these flame-retardant nanofillers to a polymer matrix, making it ideal for uses where fire safety is important. Additionally, some nanofillers' strong thermal stability boosts the total thermal stability of the nanocomposite, increasing its potential for use in hotter conditions(Leszczyńska et al., 2007).

**1.2.6 Reduced Creep and Improved Dimensional Stability**:

In many engineering applications, creep resistance—the propensity of materials to distort over time under steady load—is an important factor. In comparison to their conventional equivalents, nanocomposites frequently show less creep because nanofillers prevent polymer chain disruption and movement. When it comes to structural components, where long-term stability and dimensional precision are crucial, this improved dimensional stability and resistance to creep deformation are favorable(Zhang et al., 2004).

**1.3 Objective and Scope of the Chapter**

This chapter's main goal is to give readers a thorough introduction of biodegradable nanocomposites for structural applications. We will examine the scientific underpinnings of these materials, look at the different nanofillers and biodegradable polymers used in their synthesis, talk about fabrication methods, characterize the mechanical and thermal properties, assess the biodegradability, and highlight potential structural applications. We hope to shed light on the enormous potential of biodegradable nanocomposites in fostering sustainability and reducing environmental effects through this investigation.

This chapter's scope includes a thorough analysis of the literature, academic publications, and technological advancements related to biodegradable nanocomposites. Although the subject is broad and always changing, we will make an effort to provide the most pertinent and latest developments. We'll also concentrate on various nanofillers and how well they work with various biodegradable polymers, emphasizing how the choice of nanofiller affects the characteristics of the resulting nanocomposites.

We will also go into detail about fabrication methods since they are essential for attaining uniform dispersion of nanofillers within the polymer matrix. The methodologies for evaluating the mechanical, thermal, and morphological characteristics of biodegradable nanocomposites will also be covered in detail in this chapter. We will investigate how the distinct structure and characteristics of nanofillers affect the general effectiveness of these materials.

We will also highlight the biodegradability of these nanocomposites and how they might help reduce waste and protect the environment. A sustainable strategy to lessen the buildup of plastic waste in landfills and oceans is to use biodegradable nanocomposites. We'll talk about the processes involved in biodegradation and how nanofillers affect how these materials degrade.

We will then look at structural applications for biodegradable nanocomposites, including those in the packaging, building, automotive, and biomedical industries. We hope to demonstrate the usefulness and adaptability of these materials in diverse industries by exhibiting real-world applications.

1. **Biodegradable Polymers for Structural Applications**

Biodegradable polymers are a subset of polymers that undergo degradation in the environment through natural processes, such as microbial action or enzymatic hydrolysis, into simpler compounds, such as water, carbon dioxide, and biomass. This environmentally friendly degradation sets them apart from conventional non-biodegradable polymers, which often persist in the environment for long periods, contributing to plastic waste pollution. Biodegradable polymers offer a sustainable alternative that aligns with the principles of the circular economy, as they can be reused, recycled, or composted after their useful life(Dixit et al., 2020).

**2.1 Sources of Biodegradable Polymers**

Diverse renewable and biologically generated resources can be used to make biodegradable polymers, reducing reliance on fossil fuels. The following are some typical sources of biodegradable polymers:

**2.1.1 Plant-Based Polymers**

Such plant-based feedstocks as corn, sugarcane, and potato starch are used to create these polymers. A well-known illustration of a plant-based biodegradable polymer is polylactic acid (PLA), which is frequently used in packaging, agricultural films, and medical applications(Chandran et al., 2022).

**2.1.2 Microbial Polymers**

These polymers can be created by fermentation processes and are created by microbes. A well-known class of microbial biodegradable polymers with characteristics resembling those of traditional plastics are polyhydroxyalkanoates (PHA)(Hashim et al., 2018).

**2.1.3 Synthetic Biodegradable Polymers**

Some biodegradable polymers can be made using monomers produced from petroleum, but because of their chemical makeup, they can break down spontaneously in the environment. A synthetic biodegradable polymer called polybutylene succinate (PBS) is utilised in products including packaging and disposable cutlery(Yang et al., 2007).

**2.2 Properties and Advantages of Biodegradable Polymers**

Biodegradable polymers offer a range of properties that make them suitable for various structural applications:

**2.2.1 Mechanical Properties:**

Flexible and ductile to stiff and robust are just a few examples of the mechanical characteristics that biodegradable polymers can display. While some may not be as strong as non-biodegradable polymers in terms of mechanical performance, continued research and development have resulted in substantial advancements, making them appropriate for an increasing variety of applications(Dixit and Yadav, 2021a).

**2.2.2 Biocompatibility:**

Many biodegradable polymers are biocompatible, which means that living things can accept them. They are excellent for biomedical applications because of this quality, including sutures, scaffolds for tissue engineering, and drug delivery systems(Yuan et al., 2010).

**2.2.3 Low Toxicity**

Biodegradable polymers typically have low toxicity and present little danger to the environment or human health. They are frequently employed in medical applications where biocompatibility and safety are crucial.

* + 1. **Renewable and Sustainable**

Biodegradable polymers are a sustainable option due to the renewable nature of the feedstocks used in their production, which helps to reduce the carbon footprint and reliance on limited fossil fuel resources.

**2.2.5 Reduced Landfill Waste**

The load of plastic waste in landfills and marine habitats can be considerably reduced by using biodegradable polymers that degrade quickly in natural settings, solving one of the most important environmental issues of our day.

**2.2.6** **Customizable Properties**

By modifying their chemical make-up, molecular weight, and manufacturing processes, biodegradable polymers can be tailored for certain uses. Due to their adaptability, materials can be created with the appropriate characteristics for structural purposes.

**2.3 Current Applications of Biodegradable Polymers in Different Industries**

Biodegradable polymers are being used in many different industries due to their adaptable qualities. A few noteworthy applications are:

**2.3.1 Packaging**

In order to create environmentally friendly bags, sheets, and containers, biodegradable polymers are increasingly being used in the packaging sector. They help lessen the pollution caused by plastic waste and provide an environmentally friendly substitute for conventional petroleum-based plastics(Dixit and Yadav, 2020).

**2.3.2 Agriculture:**

Agriculture uses biodegradable mulch films manufactured of PLA and PHA to improve soil quality, increase crop yield, and lessen the environmental impact of plastic waste left over after crop harvesting.

**2.3.3 Medical and Pharmaceutical**

Biodegradable polymers are widely employed in pharmaceutical and medical applications, including implanted medical devices, tissue engineering scaffolds, drug delivery systems, and surgical sutures. They are suitable for biomedical applications due to their biocompatibility and capacity to harmlessly breakdown in the body(Murugesan and Scheibel, 2021).

**2.3.4 Single-Use Products**

Disposable cutlery, cups, plates, and straws are made from biodegradable polymers as an environmentally beneficial substitute for single-use plastic products.

**2.3.5 Textiles and Apparel**

The textile and apparel industry are looking at the use of some biodegradable polymers in an effort to provide more sustainable and ecologically friendly clothing options.

**2.4 Challenges and Limitations**

Although biodegradable polymers have a lot of potential, they are not without difficulties and restrictions:

**2.4.1 Mechanical Performance**

It is still difficult to achieve mechanical qualities that are comparable to those of conventional non-biodegradable polymers. Though advances in material science and nanotechnology have enhanced their mechanical performance, more study is required to match or even surpass the strength and durability of non-biodegradable substitutes(Dixit and Yadav, 2021b).

**2.4.2 Cost:**

Due to the use of specialty processing methods and renewable feedstocks, the cost of biodegradable polymers can be higher than that of conventional plastics. The cost is anticipated to reduce as production volumes rise and technology develops, making biodegradable polymers more commercially viable(Mazhar et al., 2023).

**2.4.3 Processing Complexity**

Some biodegradable polymers need particular processing conditions, which might complicate production procedures and restrict their suitability for use in particular sectors of the economy.

**2.4.4 Timeframe for Biodegradation:**

Depending on the type of biodegradable polymer, the environment, and the presence of the right microbial activity, different biodegradable polymers take different amounts of time to completely biodegrade. It can be difficult to get exact control over the deterioration rate to meet the specified application lifespan.

The development of sustainable materials with the potential to revolutionize structural applications is made possible by biodegradable polymers. They are an appealing option for tackling the urgent problems of plastic waste pollution and resource depletion due to their renewable nature, low environmental effect, and variety of features. Even though the field of biodegradable polymers is always changing, ongoing investigations and developments in material science, manufacturing methods, and nanotechnology are anticipated to open up new possibilities and get over existing constraints. We can open the door to a greener and more sustainable future by embracing the special qualities of biodegradable polymers and incorporating them into a variety of sectors. Biodegradable polymers are a crucial enabler in attaining a more peaceful cohabitation between human activities and the environment as we work to establish a circular economy where resources are intended to be reused, repurposed, or returned to nature(Dixit and Yadav, 2021b).

1. **Introduction to Nanotechnology and its Significance in Materials Science**

Materials science is only one of the many fields where nanotechnology, the study of altering materials at the nanoscale level, offers enormous potential. Materials display distinctive characteristics and behaviors at the nanoscale that are different from those of their bulk counterparts. Scientists and engineers can use nanotechnology to design and produce innovative materials with outstanding features by taking advantage of these distinguishing qualities.

Nanotechnology has created new opportunities in materials science for creating nanocomposites, which are materials made up of a matrix and scattered nanoscale fillers. Nanoparticles, nanoclays, nanotubes, nanofibers, and other nanoscale structures can all be used as these nanofillers. Nanocomposites, which frequently exhibit improved qualities compared to conventional composites, are created when nanofillers are incorporated into a matrix(Fulekar, 2010).

The following succinct statement captures the significance of nanotechnology in materials science:

**3.1 Tailoring Properties**

The high surface area-to-volume ratio of materials at the nanoscale causes substantial changes in their characteristics. For instance, depending on their size, shape, and composition, nanoparticles have distinctive optical, electrical, and mechanical properties. Researchers can fine-tune the characteristics of nanocomposites for particular applications by adjusting these parameters.

**3.2 Enhanced Mechanical Properties**

Compared to their macro-scale counterparts, nanocomposites often exhibit better mechanical properties. By adding additional reinforcement from nanofillers, strength, stiffness, and toughness are all improved. In structural applications where materials must bear enormous loads and external pressures, this improvement is essential.

**3.3 Lightweight and High Strength**

An appealing mix of lightweight and high strength is provided by nanocomposites. Nanofillers' small size and high aspect ratio produce effective load transfer mechanisms that produce remarkable mechanical performance without significantly increasing the weight of the material.

**3.4 Improved Thermal and Electrical Conductivity**

Nanofillers with high thermal and electrical conductivity include carbon nanotubes and graphene. The thermal and electrical properties of nanocomposites can be considerably improved by including these nanofillers into a matrix, making them appropriate for applications requiring heat dissipation or electrical conductivity.

**3.5 Barrier Properties**

Nanocomposites can display high barrier qualities against gases and liquids due to the convoluted routes generated by nanofillers in the matrix. This makes them attractive for applications where permeability control is crucial, such as food packaging and gas storage.

**3.6 Explanation of Nanocomposites and their Benefits in Structural Applications**

Nanoscale fillers are placed within a matrix material to create nanocomposites, a class of sophisticated materials with a distinctive set of features. The matrix could be made of a metal, ceramic, polymer, or even a mixture of elements(Pinheiro et al., 2011). Due to the following advantages, nanocomposites have drawn significant attention in structural applications:

**3.6.1** **Enhanced Mechanical Performance**

Nanoscale reinforcements result in improved tensile strength, stiffness, and impact resistance, giving nanocomposites remarkable mechanical qualities that make them the perfect choice for structural components demanding high performance.

**3.6.2 Reduced Weight and Improved Efficiency**

The exceptional strength-to-weight ratio of nanocomposites makes them a lighter alternative to conventional materials. This weight loss correlates to better fuel economy, larger cargo capacity, and improved overall performance in sectors like aircraft and automobiles.

* + 1. **Tailored Properties**

Nanocomposites' adaptability enables their qualities to be customised to meet the needs of certain applications. Engineers can create nanocomposites with the desired properties, such as increased fatigue resistance, thermal stability, and dimensional stability, by altering the kind, content, and arrangement of nanofillers.

* + 1. **Cost-Efficiency**

Nanocomposites may occasionally be more economical than utilising conventional materials. For instance, using lightweight nanocomposites instead of pricey metals can result in cost reductions without sacrificing performance.

* + 1. **Corrosion and Wear Resistance**

The corrosion and wear resistance of nanocomposites can be improved by using specific nanofillers such nanoparticles and nanoclays. This is especially crucial in situations where materials are subjected to harsh temperatures or abrasive environments.

* + 1. **Multifunctionality:**

Because different nanofillers with various characteristics are combined, nanocomposites can display several functionalities. A nanocomposite, for instance, can have electrical conductivity, flame retardancy, and mechanical strength all at once, making it useful for a variety of applications.

By enabling the creation of nanocomposites with extraordinary properties and a wide range of applications, nanotechnology has transformed the field of materials science. Nanocomposites are useful for structural applications because they have improved mechanical performance, are lighter, and can be customised to have particular features. Nanocomposites offer a fascinating possibility to develop sustainable and ecologically friendly structural materials in the context of biodegradable materials. The potential of biodegradable nanocomposites is projected to increase with more study and technical development given the variety of methods now available for their synthesis(Mitra et al., 2003).

**4. Selection of Nanofillers for Biodegradable Nanocomposites**

**4.1 Overview of Different Types of Nanofillers**

Nanoscale components called nanofillers act as reinforcement in nanocomposites, enhancing their barrier, thermal, and mechanical properties. Biodegradable nanocomposites frequently contain a variety of nanofillers, each with distinct properties and uses:

**4.1.1 Nanoparticles:**

Particles known as nanoparticles typically have sizes between 1 and 100 nanometers. They may be made of metal, ceramic, or organic material. Silver nanoparticles, which have antibacterial qualities, and titanium dioxide nanoparticles, which are well-known for their UV-blocking properties, are two examples of metallic nanoparticles. Due to their large surface area and superior mechanical qualities, nanosilica and nanotitania are frequently utilised as reinforcing agents in ceramic nanoparticles. Organic nanoparticles, like chitosan and nanocellulose, are made from natural materials and biodegrade, making them appropriate for use in environmentally friendly nanocomposites(Naito et al., 2018).

**4.1.2 Nanoclays**

Layered silicate minerals having nanoscale dimensions are known as nanoclays. Some of the most often utilised nanoclays are montmorillonite, hectorite, and halloysite. They have vast surface areas, high aspect ratios, and lots of reactive sites. Nanoclays are useful in packaging applications because they can make winding routes that improve gas and moisture barrier qualities when disseminated in a polymer matrix. The mechanical performance and flame resistance of biodegradable nanocomposites are also enhanced by nanoclays(Guo et al., 2018).

**4.1.3 Nanofibers**

Long, thin fibres having sizes in the nanometer range are called nanofibers. They can be made from a variety of substances, such as polymers, carbon, and cellulose. Examples of carbon-based nanofibers with excellent mechanical strength, thermal conductivity, and electrical characteristics include carbon nanotubes (CNTs) and graphene. Since they are renewable and biodegradable, cellulose nanofibers generated from plants or microorganisms are suitable for use in ecologically friendly nanocomposites(Lim, 2017).

**4.1.4 Nanowires and Nanorods**

Elongated nanoscale structures with widths typically in the range of a few nanometers are known as nanowires and nanorods. They might be made of oxides, semiconductors, or metals. For specialised applications, biodegradable nanocomposites can be made using these nanostructures' specific electrical, optical, and mechanical characteristics(Patolsky et al., 2006).

**4.2 Factors Affecting Nanofiller Selection for Biodegradable Nanocomposites**

The choice of nanofillers for biodegradable nanocomposites is an important choice that has an immediate effect on the final characteristics and functionality of the materials. The following variables are important in choosing a nanofiller(Mehta et al., 2022):

**4.2.1Target Application and Property Requirements**

The intended use of the nanocomposite and the necessary particular qualities are the main factors to be taken into account. For instance, nanofillers like carbon nanotubes or nanoclays might be selected if the application calls for increased mechanical strength. On the other hand, nanoparticles with certain functions can be used if barrier qualities or UV protection are essential.

**4.2.2 Biodegradability and Sustainability**

The biodegradability and environmental impact of the nanofiller are crucial considerations because the aim is to produce biodegradable nanocomposites. Biodegradable nanofillers, like nanocellulose or chitosan nanoparticles, support the composite's sustainability goals.

**4.2.3 Nanofiller Dispersion and Compatibility**

To achieve the best performance, the polymer matrix's nanofillers must be well dispersed. High aspect ratio nanofillers, such as nanoclays and CNTs, can be more difficult to disseminate uniformly. To improve the interaction between the nanofiller and the biodegradable polymer, surface changes and compatibilization agents may be required.

**4.2.4 Cost and Availability**

The price and accessibility of nanofillers also have a big impact on choice. Due of their intricate manufacturing procedures, some nanofillers, such CNTs and graphene, can be pricey. Thus, it is essential to take into account cost-effective options without sacrificing performance, especially for large-scale applications.

**4.2.5 Toxicity and Health Concerns:**

Concerns concerning the toxicity and potential negative health impacts of some nanofillers, such as metal-based nanoparticles, may arise. Particularly if the nanocomposites are intended for biomedical or food-contact applications, it is crucial to choose nanofillers with a track record of reliability and biocompatibility.

**4.2.6 Synergistic Effects:**

In some circumstances, combining various nanofillers can produce synergistic effects, where the characteristics of the resulting nanocomposite outperform those of its component parts alone. Nanofillers can be combined and chosen wisely to provide multifunctionality and customized features.

**4.2.7 Processing Compatibility:**

The chosen biodegradable polymer and the nanofiller must work together well during processing. For instance, some nanofillers might need particular processing conditions, and their integration might affect the composite materials processing parameters.

**4.2.8 Regulatory and Environmental Considerations:**

It is crucial to adhere to legal requirements and obtain environmental approvals, especially in applications where the nanocomposites will come into contact with food, water, or living things. The applicability of the nanocomposites for particular markets and sectors is ensured by adherence to safety standards.

**4.3 Compatibility of Nanofillers with Biodegradable Polymers**

For the creation of high-performance biodegradable nanocomposites, it is essential to have optimal compatibility between nanofillers and biodegradable polymers. The dispersion of nanofillers, interfacial adhesion, and overall mechanical and thermal properties of the nanocomposite are all impacted by compatibility. Several strategies are used to improve compatibility(Jagadeesh et al., 2021):

**4.3.1 Surface Fictionalization**

In order to enhance their interaction with the biodegradable polymer, nanofillers might have their surfaces functionalized with particular chemical groups. Between the polymer matrix and nanofiller, functionalization either increases hydrogen bonding or provides anchor points for covalent bonding.

**4.3.2 Compatibilization Agents:**

The compatibility between nanofillers and biodegradable polymers is frequently improved by the application of compatibilizers, also known as coupling agents. These substances have two distinct functions; one end interacts with the surface of the nanofiller, and the other with the polymer matrix, enabling a robust contact between the two phases.

**4.3.3 In-situ Polymerization:**

During in-situ polymerization, nanofillers are incorporated while the biodegradable polymer is simultaneously formed. Nanofillers can chemically connect to the developing polymer chains during polymerization, ensuring good molecular compatibility.

**4.3.4 Pre-dispersion Techniques**

Pre-dispersion techniques involve adding surfactants or other additives to the nanofillers to enhance their dispersion in the polymer matrix. A more uniform distribution is produced by properly dispersed nanofillers, which also reduces agglomeration and improves all other qualities.

**4.3.5 Polymer Modification**

Functional groups can be added to the biodegradable polymer itself to increase its compatibility with nanofillers. This alteration can take the form of copolymerization or grafting using functional monomers that get along well with the nanofiller.

**4.3.6 Nanostructure Design:**

Nanofillers' shape and size can be adjusted to improve their compatibility with the polymer matrix. An increase in interfacial adhesion and mechanical qualities can be achieved by adjusting the aspect ratio, particle size, or surface roughness.

The particular pairing of nanofiller and biodegradable polymer will determine the choice and implementation of the proper compatibilization procedures. These techniques enable the creation of biodegradable nanocomposites with enhanced characteristics and performance by creating a solid interfacial link between the nanofillers and the polymer matrix.

Consideration must be given to the application requirements, biodegradability, compatibility, cost, toxicity, and regulatory compliance when choosing nanofillers for biodegradable nanocomposites. The wide variety of nanofillers, including nanoparticles, nanoclays, and nanofibers, each have special qualities that can be modified to suit certain uses. In biodegradable nanocomposites, homogeneous dispersion, strong interfacial adhesion, and improved characteristics are all made possible by the careful blending of nanofillers and compatibilization processes. The creation of innovative nanocomposites holds enormous potential for producing sustainable and high-performance materials for structural applications and beyond as research in nanotechnology and biodegradable materials advances(Sun et al., 2018).

**5. Fabrication Techniques for Biodegradable Nanocomposites**

The advantages of biodegradable polymers and nanofillers are combined in biodegradable nanocomposites, which have drawn a lot of interest as sustainable materials with improved characteristics. Precision in the dispersion and distribution of the nanofillers within the polymer matrix is essential for the successful construction of these nanocomposites. To ensure consistent integration and interaction between the nanofillers and biodegradable polymers, a number of approaches have been devised. We will go into more detail about the following fabrication processes for biodegradable nanocomposites in this section:

**5.1 Extrusion and Injection Molding**

**5.1.1 Extrusion:** A popular processing method for biodegradable polymers and their nanocomposites is extrusion. In this procedure, a plasticizing screw pushes heated nanofillers and biodegradable polymer through a barrel, where they melt and combine. The desired shape, such as rods, sheets, or profiles, are subsequently produced by forcing the homogeneous melt through a die. Achieving uniform nanofiller dispersion inside the polymer matrix in the case of nanocomposites is essential for ensuring the desired attributes of the finished product(Dixit and Yadav, 2021a).

**Advantages:**

* High throughput and cost-effective for large-scale production.
* Continuous process, suitable for producing long sections of nanocomposite materials.

**Challenges:**

* Poor dispersion of nanofillers can lead to agglomeration and non-uniform properties.
* The high shear forces during extrusion may damage delicate nanofillers or affect their properties.

**5.1.2 Injection Molding**: A common method for creating intricately formed biodegradable nanocomposite components is injection moulding. It entails melting biodegradable polymer and nanofillers and delivering the molten mixture under intense pressure into a mould cavity. The mould opens and the finished part is released once the material has cooled and solidified(Dixit and Yadav, 2021a).

**Advantages:**

* Suitable for mass production of complex shapes with high precision.
* Precise control over the nanofiller content and distribution in the molded part.

**Challenges:**

* Properly dispersing nanofillers within the polymer melt is crucial to achieving uniform properties.
* High shear rates during injection can lead to nanofiller degradation or aggregation.

**5.2 Compression Molding:**

Thermosetting biodegradable polymers are frequently molded using compression technology. In this procedure, a heated mould cavity is filled with a pre-measured quantity of biodegradable polymer and nanofillers. The material is then compressed into the required shape using pressure. The thermosetting polymer begins to cross-link while under pressure and heat, which results in the creation of the final nanocomposite(Dixit and Yadav, 2021b).

**Advantages:**

* Suitable for producing large parts with complex geometries.
* Can be used with a wide range of biodegradable polymers, including those that are not suitable for extrusion or injection molding.

**Challenges:**

* Requires longer processing times compared to other methods.
* Achieving uniform nanofiller dispersion can be challenging due to the limited mobility of the polymer matrix during compression.

**5.3 Solution Casting:**

Biodegradable polymers and nanofillers are dissolved in a solvent to create a solution, which is then used in solution casting. The solvent is then allowed to evaporate, leaving the nanocomposite material behind, and the solution is cast onto a support or mold(Dixit et al., 2022).

**Advantages:**

* Offers precise control over nanofiller dispersion in the polymer matrix.
* Suitable for producing thin films, coatings, and intricate structures.

**Challenges:**

* Solvent selection is crucial, as it must be compatible with both the biodegradable polymer and nanofiller.
* Post-processing steps are required to remove all solvent residues completely.

**5.4 In-situ Polymerization:**

The biodegradable polymer is created concurrently with the addition of nanofillers during in-situ polymerization. The nanofillers are added during polymerization, resulting in homogeneous dispersion throughout the developing polymer matrix. This method works best when the nanofillers have functional groups that can take part in the polymerization process(Jia et al., 2018).

**Advantages:**

* Provides covalent bonding between the nanofillers and the polymer matrix, leading to excellent interfacial adhesion.
* Offers precise control over nanofiller dispersion and distribution.

**Challenges:**

* Requires careful control of reaction conditions to avoid premature or incomplete polymerization.
* May not be suitable for all types of biodegradable polymers and nanofillers.

**5.5 3D Printing/Additive Manufacturing of Biodegradable Nanocomposites:**

The cutting-edge production method of 3D printing, commonly referred to as additive manufacturing, enables the exact layer-by-layer construction of intricate 3D objects. The use of 3D printing in the context of biodegradable nanocomposites creates new opportunities for specialised and unique applications(Shahrubudin et al., 2019).

**Advantages:**

* Enables the creation of intricate and customized shapes without the need for molds or tooling.
* Offers the ability to precisely control nanofiller distribution within the nanocomposite.

**Challenges:**

* Material compatibility with 3D printing techniques may limit the choice of biodegradable polymers and nanofillers.
* Nanofiller loading may be limited in some 3D printing processes, affecting the properties of the nanocomposite.

Based on the unique requirements of the application for biodegradable nanocomposite, it is crucial to choose the fabrication method that is most appropriate. The selection of a technology should take into account elements such nanofiller dispersion, compatibility with polymers, processing complexity, and scalability for mass production. A crucial factor to take into account is whether the chosen technology is compatible with the environmental objectives of manufacturing biodegradable materials.

A variety of processes are used to create biodegradable nanocomposites, each with its own benefits and difficulties. Compression molding is appropriate for thermosetting biodegradable polymers, while extrusion and injection molding are frequently used techniques for mass production. Nanofiller dispersion can be precisely controlled by solution casting, but in-situ polymerization offers robust interfacial adherence by covalent bonding. Last but not least, 3D printing creates new opportunities for elaborate and customized creations. Optimizing nanofiller dispersion and distribution, as well as guaranteeing compatibility with the selected biodegradable polymer, are essential for the success of each technique. These fabrication methods have the potential to revolutionize the creation of sustainable and high-performance biodegradable nanocomposites for a variety of applications as research and technology continue to evolve.

1. **Characterization Methods for Biodegradable Nanocomposites**

Methods of characterization are essential for comprehending the composition, characteristics, and functionality of biodegradable nanocomposites. Using these techniques, researchers may evaluate how nanofillers affect the materials' mechanical, thermal, morphological, and rheological characteristics. We will go into more detail about the following characterization techniques for biodegradable nanocomposites in this section:

**6.1 Mechanical Testing: Tensile, Flexural, and Impact Strength Analysis**

**6.1.1 Tensile Testing:**

Tensile testing analyses a material's mechanical characteristics when subjected to tensile (pulling) forces. In a typical tensile test, the specimen is stretched until it snaps, and the load and displacement are then recorded. Tensile testing on biodegradable nanocomposites reveals details on their strength, modulus, and elongation at break. Nanofillers can increase the tensile characteristics of materials, increasing stiffness and strength(Dixit and Yadav, 2021a).

**6.1.2 Flexural Testing:**

Flexural testing evaluates a material's capacity to withstand bending forces. A specimen is supported at two places during this test and is under load in the middle. The flexural modulus and strength of the nanocomposite are calculated using the obtained deflection and load data. For applications where the material must survive bending loads, such as in structural components, flexural testing is very important(Sahoo and Rao, 2018).

**6.1.3 Impact Strength Analysis**

A material's capacity to absorb energy during a sudden impact or shock loading is assessed by impact testing. In applications where biodegradable nanocomposites may experience unexpected impact stresses, such as in automobile components or packaging materials, it is particularly crucial to evaluate their toughness and endurance(Dixit and Yadav, 2021a).

**6.2 Thermal Analysis: Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA)**

**6.2.1 Differential Scanning Calorimetry (DSC**):

DSC is a thermal analysis method used to investigate the heat flow connected with material thermal transitions. DSC can determine the melting points, glass transition temperatures, and crystallinity of biodegradable nanocomposites. These thermal transitions can be influenced by the addition of nanofillers, which can change the processing characteristics and thermal stability of the nanocomposite.

**6.2.2 Thermogravimetric Analysis (TGA):**

TGA calculates a material's weight change in relation to temperature or time. The thermal stability and breakdown behavior of biodegradable nanocomposites are frequently assessed using this method. The thermal resistance of the nanocomposite and its potential for high-temperature applications can be determined by TGA by determining the onset temperature and rate of degradation(Dixit and Yadav, 2021a).

**6.3 Morphological Analysis: Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM)**

**6.3.1 Scanning Electron Microscopy (SEM)**

The surface morphology of materials can be visualised in high resolution using the effective imaging method known as SEM. SEM can show the dispersion and distribution of nanofillers within the polymer matrix in biodegradable nanocomposites. The existence of agglomerates or interfacial interactions between the nanofillers and the biodegradable polymer can also be found using this method(Dixit et al., 2022).

**6.3.2Transmission Electron Microscopy (TEM)**

When compared to SEM, TEM provides an even better resolution that enables imaging at the nanoscale level. The internal structure of biodegradable nanocomposites is examined using TEM, which also provides precise information on the positioning and arrangement of the nanofillers within the polymer matrix. Studying nanocomposites with extremely small or low-dimensional nanofillers makes use of it particularly well.

**6.4 X-ray Diffraction (XRD) Analysis**

To understand the crystalline structure of materials, X-ray diffraction is used. The degree of crystallinity and the crystal phase of the nanofillers and biodegradable polymers in biodegradable nanocomposites can be identified using XRD. The mechanical and thermal properties of a nanocomposite can change as a result of changes in crystallinity brought on by the presence of nanofillers(Dixit et al., 2022).

**6.5 Rheological Analysis**

Rheological analysis evaluates how materials behave in terms of flow and deformation under various circumstances. Rheological investigation can shed light on the viscoelastic properties, melt processing behaviour, and dispersion characteristics of biodegradable nanocomposites. Measurements of the melt flow index (MFI), oscillatory shear testing, and dynamic mechanical analysis (DMA) are examples of common rheological tests.

**6.5.1 Melt Flow Index (MFI)**

MFI measures a material's melt viscosity under a particular set of circumstances. It is especially helpful for determining how well biodegradable nanocomposites may be processed during extrusion or injection moulding. The processing parameters can be impacted by the presence of nanofillers, which can alter the melt viscosity and flow behaviour(Saini, 1986).

**6.5.2 Oscillatory Shear Testing**

The viscoelastic characteristics of materials under recurrent shear strains are assessed by oscillatory shear testing. It details the storage modulus (elastic behaviour) and loss modulus (viscous behaviour) of the nanocomposite as a function of frequency and temperature. Understanding how nanofillers affect the mechanical properties and viscoelasticity of the material is made easier by oscillatory shear testing(Hyun et al., 2011).

**6.5.3 Dynamic Mechanical Analysis (DMA)**

DMA is an effective method for studying materials' viscoelastic behavior over a broad temperature and frequency range. DMA can show the glass transition temperature, storage modulus, and damping properties of biodegradable nanocomposites. It is helpful for comprehending how dynamically mechanical nanocomposites respond to various loading scenarios(Menard and Menard, 2020).

These characterization techniques offer a thorough understanding of the composition and characteristics of biodegradable nanocomposites. They support researchers in achieving targeted performance levels for particular applications by assisting in the optimisation of nanofiller content, dispersion, and processing conditions. Scientists and engineers can create biodegradable nanocomposites with tailored performance for a variety of sustainable and ecologically friendly applications by learning more about the links between nanofiller morphology, interface interaction, and material properties.

1. **Mechanical Properties of Biodegradable Nanocomposites**

By combining biodegradable polymers with nanofillers, biodegradable nanocomposites provide a novel way to improve mechanical qualities and expand their range of potential applications. The use of nanofillers results in special synergistic effects that have a considerable impact on the tensile strength, modulus, and elongation at break, flexural strength, flexural modulus, and impact strength of biodegradable polymers. We will go into more detail on the mechanical characteristics of biodegradable nanocomposites in this part, concentrating on how nanofillers affect these characteristics.

**7.1 Effect of Nanofillers on Tensile Strength, Modulus, and Elongation at Break**

**7.1.1Tensile Strength**

The capacity of a substance to sustain stretching pressures without breaking is measured by its tensile strength. Tensile strength of biodegradable polymers can be significantly increased by the inclusion of nanofillers. Nanofillers with high aspect ratios and wide surface areas, like carbon nanotubes (CNTs), nanoclays, and nanoparticles, reinforce the nanocomposite by facilitating load transmission. The improvement of tensile strength is also facilitated by the strong interfacial interaction between nanofillers and the polymer matrix(Atchudan et al., 2015).

**7.1.2 Tensile Modulus**

The term "young's modulus," which also refers to the tensile modulus, describes the stiffness or resistance to deformation of a material under tensile stress. The stiffness of the resulting nanocomposite is increased by adding nanofillers to biodegradable polymers. Rigid nanofillers prevent the polymer chain from moving freely, making the material stiffer. Additionally, high-modulus nanofillers like CNTs and graphene contribute their mechanical characteristics to the nanocomposite, significantly raising its tensile modulus(Atchudan et al., 2015).

**7.1.3 Elongation at Break**

An indicator of a material's ductility or capacity to stretch before failure is the elongation at break. The elongation at break of biodegradable nanocomposites can be improved by adding certain nanofillers, like nanoclay and cellulose nanofibers. As reinforcement, these nanofillers spread the stress more evenly throughout the matrix and encourage ductile deformation.

In particular, the kind, size, and loading of the nanofillers as well as their compatibility with the biodegradable polymer matrix will all have an impact on how much the tensile qualities will increase(Atchudan et al., 2015).

**7.2 Enhancement of Flexural Strength and Modulus through Nanocomposite Formation**

**7.2.1 Flexural Strength**

Also referred to as bending strength, flexural strength describes a material's ability to withstand deformation when subjected to bending forces. Flexural strength of biodegradable polymers can be greatly increased by the inclusion of nanofillers. The use of nanofillers enhances the nanocomposite's ability to support weight and stops cracks from spreading. For instance, nanoclays make it difficult for cracks to spread, improving flexural strength.

* + 1. **Flexural Modulus**:

Similar to tensile modulus, the flexural modulus of the resultant nanocomposite is raised by adding nanofillers to biodegradable polymers. Rigid nanofillers prevent the polymer chains from moving during bending, making the material stiffer. As a result, biodegradable nanocomposites have a higher flexural modulus than their pure polymer counterparts(Alhavaz et al., 2017).

In applications where the material must survive bending pressures or where high stiffness is required, such as in structural components and packaging materials, the improvement in flexural characteristics is particularly significant.

**7.3 Impact Strength Improvement of Biodegradable Polymers with Nanofillers**

**7.3.1 Impact Strength**

The capacity of a material to absorb energy following a sudden impact or shock loading is known as impact strength. Comparing biodegradable polymers to conventional engineering polymers, they often have lesser impact strength. The impact strength of biodegradable nanocomposites can be greatly increased by the addition of nanofillers(Sanusi et al., 2021).

**7.3.2 Toughening Mechanisms**

Through a number of processes, nanofillers can toughen biodegradable polymers. One typical method is the addition of nanoparticles that function as toughening agents, such as rubber nanoparticles or core-shell structures. These nanoparticles can deflect impact force and stop cracks from spreading, increasing impact resistance.

**7.3.3 Fiber Reinforcement**

In addition to nanoparticles, biodegradable nanocomposites' impact strength can also be improved by nanofibers like cellulose or aramid nanofibers. Nanofibers' aligned structure efficiently stops crack formation while reducing energy and enhancing toughness.

**7.3.4 Synergistic Effects**

Combining several nanofiller kinds can increase impact strength in a synergistic way. By combining the toughening mechanisms of nanoparticles and nanofibers, for instance, a hybrid nanocomposite with increased toughness can be produced.

The prospective uses of biodegradable polymers with nanofillers are expanded due to the improvement in impact strength, particularly in sectors where impact resistance and energy absorption are crucial features.

A possible method to improve the mechanical properties of nanocomposites is the inclusion of nanofillers into biodegradable polymers. Nanocomposite production can greatly enhance tensile strength, modulus, elongation at break, flexural strength, flexural modulus, and impact strength. The particular kind, size, and loading of nanofillers have a significant impact on how much a property is enhanced. Researchers may create biodegradable nanocomposites with specific mechanical properties for a variety of applications, from packaging and automotive components to biomedical devices and beyond, by carefully choosing and adding the right nanofillers(Liu et al., 2021).

1. **Thermal Stability and Degradation Behavior of Biodegradable Nanocomposites**

When creating biodegradable nanocomposites for varied applications, thermal stability and degradation behavior are crucial factors to take into account. The addition of nanofillers can have a considerable impact on the thermal characteristics of biodegradable polymers, influencing their stability and functionality at various temperatures. We will go into more detail about the following topics in this part regarding the heat stability and behavior of biodegradable nanocomposites:

**8.1 Thermal Stability Analysis of Biodegradable Nanocomposites**

Thermal stability analysis is critical for understanding how biodegradable nanocomposites react when exposed to elevated temperatures. Thermogravimetric analysis (TGA) is routinely used to determine the thermal stability of materials. In TGA, the sample's weight change is measured as a function of temperature under a controlled atmosphere. Several major aspects influence the thermal stability of biodegradable nanocomposites(Atchudan et al., 2015):

**8.1.1Decomposition Temperature**

The decomposition temperature, which is typically lower for biodegradable polymers than for conventional non-biodegradable polymers, is determined by the TGA curve; however, the presence of nanofillers can affect this temperature. Certain nanofillers, such as nanoclays or nanoparticles, can act as thermal barriers, delaying the onset of decomposition and enhancing the stability of the material.

**8.1.2 Mass Loss Profile**

The mass loss profile throughout degradation is also shown by the TGA curve. The first weight loss is frequently attributable to the moisture content or evaporation of volatile substances. At higher temperatures, the polymer chains break down, which is the primary stage of degradation. Nanofillers can change the mass loss profile, resulting in several phases of degradation or improved char formation.

**8.1.3 Residue Analysis**

The char-forming capacity of the nanocomposite can be understood by analysing the residue that remains following heat degradation. High thermally stable nanofillers may serve as char formation nucleation locations, increasing residual mass. The flame retardant qualities of the nanocomposite may be enhanced as a result(Atchudan et al., 2015).

**8.2 Evaluation of Thermal Degradation and Its Impact on Mechanical Properties**

Biodegradable nanocomposites' mechanical characteristics, which are essential for performance in a variety of applications, may be impacted by thermal deterioration. When assessing the impact of heat degradation on mechanical qualities, the following factors are crucial:

**8.2.1 Mechanical Property Changes**

The mechanical characteristics of the nanocomposite may vary as a result of chain scission, crosslinking, or other chemical changes caused by the heat breakdown of biodegradable polymers. Thermal deterioration can change a material's tensile strength, modulus, elongation at break, and impact strength. It's critical to comprehend whether nanofillers lessen or increase these adjustments.

**8.2.2 Aging Effects**

During prolonged exposure to high temperatures, biodegradable nanocomposites may age or degrade. This may be especially important in situations where the material is subjected to high temperatures for a lengthy period of time. For the purpose of choosing materials and designing applications, it is essential to comprehend the long-term effects of thermal ageing on mechanical properties.

**8.2.3 Reinforcing Effect of Nanofillers**

In some circumstances, nanofillers can reinforce the nanocomposite even as it degrades thermally. The nanofillers can serve as structural reinforcements, enhancing the nanocomposite's mechanical and thermal stability even at high temperatures.

**8.3 Influence of Nanofillers on Thermal Properties of Biodegradable Polymers**

The incorporation of nanofillers in biodegradable polymers can alter their thermal properties in various ways(Atchudan et al., 2015):

* + 1. **Melting and Crystallization Behavior**

In order to understand the behavior of biodegradable polymers' melting and crystallisation, differential scanning calorimetry (DSC) is frequently performed. The degree of crystallinity and melting temperature can alter as a result of variations in the crystallisation kinetics and crystal structure of the polymer matrix caused by nanofillers.

* + 1. **Glass Transition Temperature (Tg)**

An important thermal characteristic that impacts a material's mechanical and processing behavior is the glass transition temperature. The Tg of biodegradable polymers can be affected by the presence of nanofillers. In some circumstances, nanofillers can prevent the polymer chains from moving in segments, increasing Tg.

**8.3.3** **Thermal Conductivity**

The thermal conductivity of the biodegradable nanocomposite can be improved by adding nanofillers with high thermal conductivity, such as graphene and carbon nanotubes. Applications requiring effective heat dissipation, such as thermal management or electrical equipment, can benefit from this characteristic.

* + 1. **Flame Retardancy**

Biodegradable polymers' ability to withstand flames can be improved by specific nanofillers like nanoclays or nanofibers. During burning, the nanofillers can create a shielding char layer that lessens the flammability and smoke emission of the nanocomposite.

When creating biodegradable nanocomposites for varied applications, thermal stability and degradation behaviour are essential considerations. Thermogravimetric analysis offers important details regarding the nanocomposite's mass loss profile and breakdown temperature, and differential scanning calorimetry aids in understanding its melting and crystallization behavior. The thermal behaviour of the nanocomposite is further complicated by the impact of nanofillers on thermal characteristics including the glass transition temperature and thermal conductivity. To assure the dependability and performance of biodegradable nanocomposites in various temperature environments, it is crucial to understand the thermal stability and degradation behavior of materials and to optimize manufacturing conditions. Additionally, taking into account how thermal degradation affects mechanical properties helps create nanocomposites with improved long-term performance for environmentally friendly and sustainable applications.

1. **Structural Applications of Biodegradable Nanocomposites**

In recent years, biodegradable nanocomposites have drawn a lot of attention as environmentally friendly substitutes for conventional non-biodegradable materials in a variety of structural applications. Nanofillers and biodegradable polymers work well together to increase a variety of qualities, including mechanical performance, environmental impact, and adaptability. We will go into more detail about the structural uses of biodegradable nanocomposites in this part, concentrating on the following areas:

**9.1 Packaging and Single-Use Products**

**9.1.1 Flexible Packaging:**

Flexible packaging applications frequently use biodegradable nanocomposites. The superior gas and moisture barriers of packing materials can be improved with nanoparticles or nanoclays thanks to their great barrier capabilities, extending the shelf life of perishable items and shielding them from outside pollutants. Nanofillers can also increase the packaging's tensile strength and toughness, ensuring its dependability during handling and transportation(Jagadeesh et al., 2021).

**9.1.2 Single-Use Cutlery and Tableware**

Additionally, single-use tableware and cutlery, including plates, cups, and spoons, are made using biodegradable nanocomposites. The advantage of being lightweight while still being rigid and strong enough to accomplish their intended function is provided by nanocomposite materials. Since biodegradable materials can greatly lessen the environmental impact associated with single-use plastics, these single-use products are excellent candidates for biodegradable materials.

**9.1.3Agricultural Films:**

Agricultural films including mulch films and greenhouse films are made using biodegradable nanocomposites. These coatings can raise soil warmth, moisture retention, and weed control, which will increase crop output and have a smaller negative impact on the environment. The mechanical qualities of the films can be improved by nanofillers, increasing their resistance to tearing and deterioration over time(Jagadeesh et al., 2021).

**9.2 Construction and Building Materials**

**9.2.1 Biodegradable Composites for Building Structures**

The use of biodegradable nanocomposites for panels, cladding, and roofing materials is being investigated. The use of nanofillers improves the materials' stiffness, strength, and thermal stability, making them ideal for structural applications. Through the application of flame-retardant nanofillers, these materials can also be created with specialized fire-resistant qualities.

**9.2.2 Sustainable Insulation Materials**

Building insulation materials that are environmentally friendly can be made from biodegradable nanocomposites. High thermal conductivity nanofillers, like graphene or carbon nanotubes, can enhance the insulating material's thermal performance. These environmentally friendly insulation materials can aid in lowering heating and cooling energy requirements, resulting in more energy-efficient buildings(Dixit and Yadav, 2019b).

**9.2.3 Biodegradable Geotextiles**

Applications for soil stabilization, drainage, and erosion management all utilize geotextiles composed of biodegradable nanocomposites. In building projects, these materials can act as reinforcement and improve the mechanical qualities of soils. Biodegradable geotextiles degrade over time, leaving a stable, natural soil structure in their wake.

**9.3 Automotive and Transportation Applications**:

**9.3.1 Interior Components**

Vehicle interior parts including door panels, dashboard trim, and storage compartments are made with the help of biodegradable nanocomposites. Comparing the nanocomposites to conventional biodegradable polymers, the former offer better aesthetics, mechanical performance, and durability. In order to make sure that these components sustain normal wear and tear, nanofillers can increase impact resistance and lower material deformation(Arjmandi et al., 2017).

**9.3.2 Exterior Body Panels:**

Biodegradable nanocomposites are being explored for use in exterior body panels of vehicles. The incorporation of nanofillers improves the mechanical properties of the nanocomposites, making them more robust and impact-resistant. Additionally, nanofillers with UV-protective properties can enhance the weatherability of the materials, reducing degradation and discoloration due to exposure to sunlight(Arjmandi et al., 2017).

**9.3.3 Sustainable Transportation Solutions**

The automotive and transportation sectors are using biodegradable nanocomposites in response to the rising need for environmentally friendly solutions. Vehicles and transportation systems can greatly lessen their negative effects on the environment by using biodegradable materials in place of conventional non-biodegradable ones.

**9.4 Biomedical and Healthcare Applications**

**9.4.1 Biodegradable Implants:**

Biodegradable nanocomposites are promising materials for sutures, screws, and other types of medical implants. The needed mechanical strength, biocompatibility, and degradation properties are provided by the combination of biodegradable polymers and nanofillers for effective implantation. The implant is eventually replaced by the body's own tissues as the nanocomposite deteriorates over time(Navarro-Baena et al., 2015).

**9.4.2 Drug Delivery Systems:**

Drug delivery systems use biodegradable nanocomposites to enable controlled and prolonged release of medicinal medicines. The stability and release rate of drug-loaded nanocomposites can be altered by nanofillers. These methods provide tailored distribution, cutting down on side effects and enhancing therapeutic effectiveness.

**9.4.3 Wound Dressings**

Biodegradable nanocomposites are used in tissue engineering scaffolds and wound treatments. The nanocomposite materials support cell adhesion and tissue regeneration to create the ideal environment for wound healing. The scaffold or dressing is eventually replaced by freshly generated tissue thanks to the carefully controlled disintegration of the nanocomposites.

In conclusion, biodegradable nanocomposites have several structural uses in a variety of industries, including packaging and single-use products as well as the building, automotive, and biomedical sectors. Biodegradable polymers can serve as feasible substitutes for conventional non-biodegradable materials thanks to the addition of nanofillers, which improve their mechanical qualities, thermal stability, and degradation characteristics. Biodegradable nanocomposites have enormous promise for building a greener, more eco-friendly future across a variety of structural applications as research and development in the sector continue to grow.

**Table 1 Previous Published Litratures of Biodegradable Polymer nanocomposites for numerous applications**

|  |  |  |  |
| --- | --- | --- | --- |
| **Raw material** | **Nana material** | **Applications** | **References** |
| Polyethylene glycol (PEG) | Quantum Dots | Drug Delivery | (Duan and Nie, 2007) |
| Chitosan | QDs /Drug | Drug Delivery | (Yuan et al., 2010) |
| Polylactic acid (PLA) | calcium phosphate nanoparticles | Tissue Engineering | (Fan et al., 2005) |
| Poly (allylamine hydrochloride) | Graphene Oxide | Enhanced Mechanical Properties | (Qi et al., 2014) |
| Poly (vinyl alcohol) (PVA) | Reduced Graphene Oxide | Biomedical Applications | (Yang et al., 2011) |
| Polyvinyl diene Fluoride (PVDF) | Silver nanoparticles (Ag-NPs) | Enhance tensile strength and thermal stability | (Issa et al., 2017, Jaleh et al., 2017) |
| Polyvinyl diene Fluoride (PVDF | rGO/ZnO | Enhance tensile strength and thermal stability | (Issa et al., 2017) |
| Epoxy | Single-Walled Carbon Nanotubes | EMI Shielding Applications | (Li et al., 2006) |
| Epoxy | Graphene | EMI Shielding Applications | (Liang et al., 2009) |
| Bacterial Cellulose | Metal and Metal Oxides Nanoparticles | EMI Shielding and antibacterial applications | (Wasim et al., 2022a) |
| Polypyrrole | MnZn ferrite (MZF) | EMI Shielding Applications | (Yavuz et al., 2005) |
| Polyurethane | Carbon Nanotubes (CNT’s) | Good EMI Shielding Efectiveness | (Joshi and Datar, 2015) |
| Poly (Lactic Acid) PLA | Carbon Nanotubes (CNT’s) | Good EMI Shielding Efectiveness | (Ren et al., 2018) |
| poly(lactic-co-glycolic acid) | Graphene Oxide | Enhance Mechanical and Thermal properties | (Park et al., 2014) |
| Polyurethane (PU) | Graphene Oxide | Enhance Mechanical and Thermal properties | (Zhang et al., 2015) |
| Bacterial Cellulose | copper/zinc nanoparticles | EMI Shielding Applications | (Wasim et al., 2022b) |
| LLDPE, , CEO | silver-copper (Ag-Cu) nanoparticles (NPs) | Chicken meat Packaging | (Ahmed et al., 2018) |
| LDPE, LLDPE, thermoplastic starch | Nanoclay | Packaging | (Sabetzadeh et al., 2016) |
| HDPE, WSF | Nanoclay (NC) | Packaging | (Babaei et al., 2014) |

**10. Future Perspectives and Challenges of Biodegradable Nanocomposites**

**10.1 Potential Future Advancements in Biodegradable Nanocomposite Technology**

**10.1.1 Advanced Nanofillers**

Future progress is likely to be made in the creation of innovative nanofillers with special qualities and capabilities. For particular applications, researchers may investigate nanofillers with specialised surface chemistries, customizable mechanical characteristics, and improved biocompatibility. Furthermore, using nanofillers with stimuli-responsive characteristics, like pH or temperature sensitivity, could produce dynamic and flexible biodegradable nanocomposites.

**10.1.2 Multifunctional Nanocomposites**

Future biodegradable nanocomposites might be created to perform numerous tasks inside of a single substance. Researchers can build multifunctional nanocomposites with a wide range of applications, including in smart textiles, wearable technology, and tissue engineering, by merging several types of nanofillers, such as reinforcing nanoparticles, conductive nanofibers, and drug-delivery nanocarriers.

**10.1.3 Bioactive Nanocomposites:**

The domains of biomedicine and healthcare could be completely transformed by biodegradable nanocomposites having bioactive features, such as fostering cell adhesion, tissue growth, and antibacterial activity. In order to improve the interactions of nanocomposites with biological systems, researchers may investigate the inclusion of bioactive molecules into them, such as growth factors, peptides, or enzymes.

**10.1.4 Sustainability and Biocompatibility**

The sustainability and biocompatibility of biodegradable nanocomposites will be improved continuously. This entails looking at alternative sources of biodegradable polymers, using nanofillers made from biowaste, and adjusting processing methods to minimize energy use and environmental impact(Mittal, 2011).

**10.2 Challenges and Limitations in Widespread Adoption of Biodegradable Nanocomposites**

**10.2.1 Cost-Effectiveness**

Currently, it might cost more to make biodegradable nanocomposites than traditional, non-biodegradable materials. The affordability of these materials continues to be a major barrier to their broad use, particularly in high-volume industries like packaging and construction. Economies of scale could assist in lowering production costs as research and manufacturing techniques progress.

**10.2.2 Mechanical Performance**

Even though biodegradable nanocomposites have demonstrated promising mechanical improvements using nanofillers, it is still difficult to achieve qualities that are on par with other high-performance non-biodegradable materials. To attain improved mechanical performance in an economical way, more study is required to optimize nanofiller loading, dispersion, and interfacial interactions.

**10.2.3 Standardization and Regulation:**

The development of standardized testing procedures and regulations is essential for assuring consistent quality and safety as the field of biodegradable nanocomposites expands. To promote market acceptance and wide usage, regulatory frameworks and certifications for biodegradability, biocompatibility, and environmental effect will be crucial.

**10.2.4 Recycling and End-of-Life Management**

Not all applications, especially those demanding long-term durability or recycling, may be acceptable for biodegradable materials. To ensure minimal environmental impact and avoid the potential for recycling streams to become contaminated, proper end-of-life management is crucial. This includes composting or recycling of biodegradable nanocomposites(Chong et al., 2022).

**10.3 Research Gaps and Opportunities for Further Exploration**

**10.3.1 Long-Term Performance**

Further research is required to understand how biodegradable nanocomposites behave over time and degrade in a variety of settings, including soil, water, and marine environments. To ensure the secure and efficient use of these materials, it is essential to comprehend the kinetics of degradation, potential leaching of nanofillers, and impact of environmental conditions.

**10.3.2 Biodegradation in Specific Applications**

There is a need for in-depth research on the biodegradation behaviour of nanocomposites in various application scenarios. For instance, compared to those used in agricultural films or packaging materials, biodegradable nanocomposites utilised in medical implants may have distinct degradation rates and mechanisms.

**10.3.3 Lifecycle Assessment**

Biodegradable nanocomposites must be subjected to thorough lifecycle assessments (LCA) that compare their environmental impact to that of traditional materials. To effectively analyze the environmental advantages of adopting biodegradable nanocomposites, life cycle assessments (LCAs) should take into account all phases of the product's life cycle, including production, usage, and end-of-life scenarios.

**10.3.4 Multiscale Modeling and Simulation**

Predicting the behavior and performance of biodegradable nanocomposites can be made easier with the development of multiscale modelling and simulation approaches. Designing nanocomposite systems with specific qualities, enhancing material compositions, and comprehending the nanoscale interactions between the polymer matrix and nanofillers may all be done with the help of computational tools.

**10.3.5 Biomedical Applications**

Exploration of biocompatibility, cytotoxicity, and long-term biodegradation behaviour must be done in-depth in order to advance biodegradable nanocomposites for biomedical and healthcare applications. Future research in this area has the potential to tailor the properties of nanocomposite materials to the unique requirements of tissue engineering, medication delivery, and medical implants.

From packaging and construction to the automotive and biomedical industries, biodegradable nanocomposites have enormous potential for sustainable structural applications. Future developments in bioactive nanocomposites, multifunctional materials, and improved nanofillers will all contribute to the field of biodegradable nanocomposite technology. To enable widespread implementation, however, issues with cost-effectiveness, mechanical performance, standardization, and end-of-life management must be resolved. In order to fully realize the potential of biodegradable nanocomposites and usher in a more environmentally friendly, sustainable future, it will be essential to address research gaps and look into chances for more development. Research and innovation in this exciting area of materials science will be greatly aided by partnerships between academia, business, and government regulatory agencies.

**11. Conclusion**

**11.1 Recapitulation of the Significance of Biodegradable Nanocomposites in Structural Applications**

In structural applications, biodegradable nanocomposites have become a ground-breaking solution that is revolutionizing sectors like packaging, building, automotive, and healthcare. These materials provide a variety of advantages by fusing biodegradable polymers with nanofillers that address major problems with conventional non-biodegradable materials. We have looked at the important roles that biodegradable nanocomposites play in numerous structural applications throughout this study.

Biodegradable nanocomposites in packaging and single-use products offer improved barrier qualities and mechanical strength, minimizing the environmental impact of plastic waste and single-use items. By guaranteeing less environmental pollution and encouraging circular economy principles, they provide a sustainable option.

Biodegradable nanocomposites are leading the way for environmentally friendly building materials with enhanced mechanical, thermal, and biodegradability in the construction sector. By assisting in the creation of environmentally responsible and energy-efficient buildings, these materials help to reduce the built environment's ecological impact.

Biodegradable nanocomposites are making it possible to create lightweight, durable components for automotive and transportation applications, which increases fuel efficiency and reduces emissions. The use of these materials in the automotive industry is consistent with the movement towards more environmentally friendly and sustainable transportation options on a worldwide scale.

Biodegradable nanocomposites are revolutionising tissue engineering, drug delivery systems, and medical devices in the fields of biomedicine and healthcare. These materials improve patient outcomes and lower medical waste by providing biocompatibility, controlled biodegradation, and targeted medication release.

**11.2 Overall Impact on Sustainability and Environmental Preservation**

The use of biodegradable nanocomposites in structural applications has a significant impact on environmental protection and sustainability. These substances help to reduce the environmental crisis brought on by the buildup of non-biodegradable materials and plastics in landfills and marine environments. Biodegradable nanocomposites lessen the strain on natural ecosystems and enable a more sustainable approach to waste management since they degrade into non-toxic byproducts.

The carbon footprint and resource consumption of industries can be greatly reduced by substituting biodegradable materials for non-biodegradable ones. The environmental advantages of these materials are further enhanced by the use of biodegradable polymers made from renewable resources. The usage of nanofillers with sustainable sources, such as nanocellulose from agricultural waste or nanoparticles made from biowaste, also encourages the circular economy and resource efficiency.

Biodegradable polymers' mechanical qualities are improved by the use of nanofillers, making the resulting goods more robust and long-lasting. As a result, structural parts last longer, requiring fewer replacements less frequently and using less material overall.

Furthermore, by lowering the amount of dangerous compounds and microplastics in the ecosystem, biodegradable nanocomposites help create a safer and healthier environment. Future generations will enjoy a cleaner, less contaminated world thanks to the biodegradation of these minerals.

**11.3 Final Thoughts on the Future Potential of Biodegradable Nanocomposites**

Biodegradable nanocomposites have a very bright future. We may anticipate seeing much more advancements in the creation and use of these materials as research, technology, and production techniques proceed. Future developments, such as multifunctional materials, bioactive nanocomposites, and improved nanofillers, could lead to new uses and solutions in a variety of industries.

In the global transition to sustainable and ecologically friendly materials, biodegradable nanocomposites are crucial. Their widespread implementation has the ability to change industries, bringing forth more environmentally friendly procedures and goods. Biodegradable nanocomposites are ready to take centre stage as adaptable materials for a variety of structural applications as the demand for environmentally friendly solutions rises.

To enable the successful integration of biodegradable nanocomposites into diverse industries, it is crucial to solve issues including cost-effectiveness, mechanical performance, standardization, and end-of-life management. In order to overcome these obstacles and advance research and innovation in the field, collaboration between academics, business, and policymakers will be crucial.

The continuing study and improvement of biodegradable nanocomposites will be essential for achieving their full potential in the future. In the drive for a more sustainable and environmentally friendly world, these materials provide a distinctive blend of environmental advantages, performance, and sustainability. We may advance towards a future where materials are not only durable and dependable but also considerate of the planet we call home by embracing biodegradable nanocomposites in structural applications.

**References**

AHMED, J., MULLA, M., ARFAT, Y. A., BHER, A., JACOB, H. & AURAS, R. 2018. Compression molded LLDPE films loaded with bimetallic (Ag-Cu) nanoparticles and cinnamon essential oil for chicken meat packaging applications. *Lwt,* 93**,** 329-338.

ALHAVAZ, A., REZAEI DASTJERDI, M., GHASEMI, A., GHASEMI, A. & ALIZADEH SAHRAEI, A. 2017. Effect of untreated zirconium oxide nanofiller on the flexural strength and surface hardness of autopolymerized interim fixed restoration resins. *Journal of Esthetic and Restorative Dentistry,* 29**,** 264-269.

ARJMANDI, R., HASSAN, A. & ZAKARIA, Z. 2017. Polylactic acid green nanocomposites for automotive applications. *Green Biocomposites: Design and Applications***,** 193-208.

ATCHUDAN, R., PANDURANGAN, A. & JOO, J. 2015. Effects of nanofillers on the thermo-mechanical properties and chemical resistivity of epoxy nanocomposites. *Journal of nanoscience and nanotechnology,* 15**,** 4255-4267.

BABAEI, I., MADANIPOUR, M., FARSI, M. & FARAJPOOR, A. 2014. Physical and mechanical properties of foamed HDPE/wheat straw flour/nanoclay hybrid composite. *Composites Part B: Engineering,* 56**,** 163-170.

BAUR, J. & SILVERMAN, E. 2007. Challenges and opportunities in multifunctional nanocomposite structures for aerospace applications. *MRS bulletin,* 32**,** 328-334.

BHARADWAJ, R. K. 2001. Modeling the barrier properties of polymer-layered silicate nanocomposites. *Macromolecules,* 34**,** 9189-9192.

CHANDRAN, G. U., PARAPPANAL, A. S., SAMBHUDEVAN, S. & SHANKAR, B. 2022. A critical review on cellulose nano structures based polymer nanocomposites for packaging applications. *Polymer-Plastics Technology and Materials,* 61**,** 1933-1958.

CHONG, W. J., SHEN, S., LI, Y., TRINCHI, A., PEJAK, D., KYRATZIS, I. L., SOLA, A. & WEN, C. 2022. Additive manufacturing of antibacterial PLA-ZnO nanocomposites: Benefits, limitations and open challenges. *Journal of Materials Science & Technology,* 111**,** 120-151.

DIXIT, S., JOSHI, B., KUMAR, P. & YADAV, V. L. 2020. Novel hybrid structural biocomposites from alkali treated-date palm and coir fibers: morphology, thermal and mechanical properties. *Journal of Polymers and the Environment,* 28**,** 2386-2392.

DIXIT, S., MISHRA, G. & YADAV, V. L. 2022. Optimization of novel bio-composite packaging film based on alkali-treated Hemp fiber/polyethylene/polypropylene using response surface methodology approach. *Polymer Bulletin,* 79**,** 2559-2583.

DIXIT, S. & YADAV, V. L. 2019a. Optimization of polyethylene/polypropylene/alkali modified wheat straw composites for packaging application using RSM. *Journal of Cleaner Production,* 240**,** 118228.

DIXIT, S. & YADAV, V. L. 2019b. Synthesis of green thermally resistant composite: A review. *Indian Journal of Chemical Technology (IJCT),* 26**,** 494-503.

DIXIT, S. & YADAV, V. L. 2020. Comparative study of polystyrene/chemically modified wheat straw composite for green packaging application. *Polymer Bulletin,* 77**,** 1307-1326.

DIXIT, S. & YADAV, V. L. 2021a. Biodegradable polymer composite films for green packaging applications. *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications***,** 177-193.

DIXIT, S. & YADAV, V. L. 2021b. Green Composite Film Synthesized from Agricultural Waste for Packaging Applications. *In:* THOMAS, S. & BALAKRISHNAN, P. (eds.) *Green Composites.* Singapore: Springer Singapore.

DUAN, H. & NIE, S. 2007. Cell-penetrating quantum dots based on multivalent and endosome-disrupting surface coatings. *Journal of the American Chemical Society,* 129**,** 3333-3338.

FAN, H. S., WEN, X. T., TAN, Y. F., WANG, R., CAO, H. & ZHANG, X. D. Compare of electrospinning PLA and PLA/β-TCP scaffold in vitro. Materials Science Forum, 2005. Trans Tech Publ, 2379-2382.

FULEKAR, M. 2010. *Nanotechnology: importance and applications*, IK International Pvt Ltd.

GUO, F., ARYANA, S., HAN, Y. & JIAO, Y. 2018. A review of the synthesis and applications of polymer–nanoclay composites. *Applied Sciences,* 8**,** 1696.

HASHIM, A., AGOOL, I. R. & KADHIM, K. J. 2018. Modern developments in polymer nanocomposites for antibacterial and antimicrobial applications: a review. *Journal of Bionanoscience,* 12**,** 608-613.

HYUN, K., WILHELM, M., KLEIN, C. O., CHO, K. S., NAM, J. G., AHN, K. H., LEE, S. J., EWOLDT, R. H. & MCKINLEY, G. H. 2011. A review of nonlinear oscillatory shear tests: Analysis and application of large amplitude oscillatory shear (LAOS). *Progress in Polymer Science,* 36**,** 1697-1753.

ISSA, A. A., AL-MAADEED, M. A., LUYT, A. S., PONNAMMA, D. & HASSAN, M. K. 2017. Physico-mechanical, dielectric, and piezoelectric properties of PVDF electrospun mats containing silver nanoparticles. *C,* 3**,** 30.

JAGADEESH, P., PUTTEGOWDA, M., MAVINKERE RANGAPPA, S. & SIENGCHIN, S. 2021. Influence of nanofillers on biodegradable composites: A comprehensive review. *Polymer composites,* 42**,** 5691-5711.

JALEH, B., KHALILIPOUR, A., HABIBI, S., NIYAIFAR, M. & NASROLLAHZADEH, M. 2017. Synthesis, characterization, magnetic and catalytic properties of graphene oxide/Fe 3 O 4. *Journal of Materials Science: Materials in Electronics,* 28**,** 4974-4983.

JIA, X., WANG, L. & DU, J. 2018. In situ polymerization on biomacromolecules for nanomedicines. *Nano Research,* 11**,** 5028-5048.

JOSHI, A. & DATAR, S. 2015. Carbon nanostructure composite for electromagnetic interference shielding. *Pramana,* 84**,** 1099-1116.

LESZCZYŃSKA, A., NJUGUNA, J., PIELICHOWSKI, K. & BANERJEE, J. 2007. Polymer/montmorillonite nanocomposites with improved thermal properties: Part I. Factors influencing thermal stability and mechanisms of thermal stability improvement. *Thermochimica acta,* 453**,** 75-96.

LI, N., HUANG, Y., DU, F., HE, X., LIN, X., GAO, H., MA, Y., LI, F., CHEN, Y. & EKLUND, P. C. 2006. Electromagnetic interference (EMI) shielding of single-walled carbon nanotube epoxy composites. *Nano letters,* 6**,** 1141-1145.

LIANG, J., WANG, Y., HUANG, Y., MA, Y., LIU, Z., CAI, J., ZHANG, C., GAO, H. & CHEN, Y. 2009. Electromagnetic interference shielding of graphene/epoxy composites. *Carbon,* 47**,** 922-925.

LIM, C. T. 2017. Nanofiber technology: current status and emerging developments. *Progress in polymer science,* 70**,** 1-17.

LIU, H., ZHANG, B., ZHOU, L., LI, J., ZHANG, J., CHEN, X., XU, S. & HE, H. 2021. Synergistic effects of cellulose nanocrystals‐organic montmorillonite as hybrid nanofillers for enhancing mechanical, crystallization, and heat‐resistant properties of three‐dimensional printed poly (lactic acid) nanocomposites. *Polymer Engineering & Science,* 61**,** 2985-3000.

MAZHAR, H., ULLAH, I., ALI, U., ABBAS, N., HUSSAIN, Z., ALI, S. S. & ZHU, H. 2023. Optimization of low-cost solid-state fermentation media for the production of thermostable lipases using agro-industrial residues as substrate in culture of Bacillus amyloliquefaciens. *Biocatalysis and Agricultural Biotechnology,* 47**,** 102559.

MEHTA, J., DAS, P. P., MEHTA, S., CHAUDHARY, V., GUPTA, S., GUPTA, N., RINAWA, M. L. & GUPTA, P. 2022. Effect of nanofillers and nanotoxicity on the performance of composites: Influencing factors, future scope, challenges and applications. *Polymer Composites,* 43**,** 3335-3349.

MENARD, K. P. & MENARD, N. 2020. *Dynamic mechanical analysis*, CRC press.

MITRA, S. B., WU, D. & HOLMES, B. N. 2003. An application of nanotechnology in advanced dental materials. *The Journal of the American Dental Association,* 134**,** 1382-1390.

MITTAL, V. 2011. *Nanocomposites with biodegradable polymers: synthesis, properties, and future perspectives*, Oxford University Press.

MURUGESAN, S. & SCHEIBEL, T. 2021. Chitosan‐based nanocomposites for medical applications. *Journal of Polymer Science,* 59**,** 1610-1642.

NAITO, M., YOKOYAMA, T., HOSOKAWA, K. & NOGI, K. 2018. *Nanoparticle technology handbook*, Elsevier.

NAVARRO-BAENA, I., ARRIETA, M. P., SONSECA, A., TORRE, L., LÓPEZ, D., GIMÉNEZ, E., KENNY, J. M. & PEPONI, L. 2015. Biodegradable nanocomposites based on poly (ester-urethane) and nanosized hydroxyapatite: Plastificant and reinforcement effects. *Polymer Degradation and Stability,* 121**,** 171-179.

PARK, J. J., YU, E. J., LEE, W. K. & HA, C. S. 2014. Mechanical properties and degradation studies of poly (D, L‐lactide‐co‐glycolide) 50: 50/graphene oxide nanocomposite films. *Polymers for advanced technologies,* 25**,** 48-54.

PATOLSKY, F., ZHENG, G. & LIEBER, C. M. 2006. Nanowire sensors for medicine and the life sciences.

PINHEIRO, A. V., HAN, D., SHIH, W. M. & YAN, H. 2011. Challenges and opportunities for structural DNA nanotechnology. *Nature nanotechnology,* 6**,** 763-772.

QI, W., XUE, Z., YUAN, W. & WANG, H. 2014. Layer-by-layer assembled graphene oxide composite films for enhanced mechanical properties and fibroblast cell affinity. *Journal of Materials Chemistry B,* 2**,** 325-331.

REN, F., LI, Z., XU, L., SUN, Z., REN, P., YAN, D. & LI, Z. 2018. Large-scale preparation of segregated PLA/carbon nanotube composite with high efficient electromagnetic interference shielding and favourable mechanical properties. *Composites Part B: Engineering,* 155**,** 405-413.

SABETZADEH, M., BAGHERI, R. & MASOOMI, M. 2016. Effect of nanoclay on the properties of low density polyethylene/linear low density polyethylene/thermoplastic starch blend films. *Carbohydrate polymers,* 141**,** 75-81.

SAHOO, M. K. & RAO, G. R. 2018. Fabrication of NiCo2S4 nanoball embedded nitrogen doped mesoporous carbon on nickel foam as an advanced charge storage material. *Electrochimica Acta,* 268**,** 139-149.

SAINI, D. 1986. Melt flow index: More than just a quality control rheological parameter. Part I. *Advances in Polymer Technology,* 6**,** 125-145.

SANUSI, O. M., BENELFELLAH, A., BIKIARIS, D. N. & AÏT HOCINE, N. 2021. Effect of rigid nanoparticles and preparation techniques on the performances of poly (lactic acid) nanocomposites: A review. *Polymers for Advanced Technologies,* 32**,** 444-460.

SHAHRUBUDIN, N., LEE, T. C. & RAMLAN, R. 2019. An overview on 3D printing technology: Technological, materials, and applications. *Procedia Manufacturing,* 35**,** 1286-1296.

SUN, J., SHEN, J., CHEN, S., COOPER, M. A., FU, H., WU, D. & YANG, Z. 2018. Nanofiller reinforced biodegradable PLA/PHA composites: Current status and future trends. *Polymers,* 10**,** 505.

WASIM, M., MUSHTAQ, M., KHAN, S. U., FAROOQ, A., NAEEM, M. A., KHAN, M. R., SALAM, A. & WEI, Q. 2022a. Development of bacterial cellulose nanocomposites: An overview of the synthesis of bacterial cellulose nanocomposites with metallic and metallic-oxide nanoparticles by different methods and techniques for biomedical applications. *Journal of Industrial Textiles,* 51**,** 1886S-1915S.

WASIM, M., NAEEM, M. A., KHAN, M. R., MUSHTAQ, M. & WEI, Q. 2022b. Preparation and characterization of copper/zinc nanoparticles-loaded bacterial cellulose for electromagnetic interference shielding. *Journal of Industrial Textiles,* 51**,** 7072S-7088S.

YANG, K.-K., WANG, X.-L. & WANG, Y.-Z. 2007. Progress in nanocomposite of biodegradable polymer. *Journal of Industrial and Engineering Chemistry,* 13**,** 485-500.

YANG, X., SHANG, S. & LI, L. 2011. Layer‐structured poly (vinyl alcohol)/graphene oxide nanocomposites with improved thermal and mechanical properties. *Journal of applied polymer science,* 120**,** 1355-1360.

YAVUZ, Ö., RAM, M. K., ALDISSI, M., PODDAR, P. & SRIKANTH, H. 2005. Polypyrrole composites for shielding applications. *Synthetic Metals,* 151**,** 211-217.

YUAN, Q., HEIN, S. & MISRA, R. 2010. New generation of chitosan-encapsulated ZnO quantum dots loaded with drug: synthesis, characterization and in vitro drug delivery response. *Acta biomaterialia,* 6**,** 2732-2739.

ZHANG, J., ZHANG, C. & MADBOULY, S. A. 2015. In situ polymerization of bio‐based thermosetting polyurethane/graphene oxide nanocomposites. *Journal of Applied Polymer Science,* 132.

ZHANG, Z., YANG, J.-L. & FRIEDRICH, K. 2004. Creep resistant polymeric nanocomposites. *Polymer,* 45**,** 3481-3485.