

A BIODEGRADABLE NANOCOMPOSITE FOR STRUCTURAL APPLICATIONS

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.

Keywords: nanocomposites; structural; biodegradable; mechanical properties

Authors

Shobhit Dixit

Department of Chemical Engineering
Dr. Ambedkar Institute of Technology
for Handicapped
Kanpur, India

Ghazi Mohd Sawood

Department of Chemical Engineering
Dr. Ambedkar Institute of Technology
for Handicapped
Kanpur, India

Ashutosh Mishra

Department of Chemical Engineering
Dr. Ambedkar Institute of Technology
for Handicapped
Kanpur, India

Neeta Singh

Department of Chemical Engineering
Dr. Ambedkar Institute of Technology
for Handicapped
Kanpur, India

Shashi Bala Gautam

Department of Chemical Engineering
Government Polytechnic
Kanpur, India

Sanjiv Kumar Gupta

Department of Chemical Engineering
HBTU, Kanpur, India

I. 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. 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, Sawood et al., 2021, Sawood et al., 2022).

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).

- 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).

- **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).
- **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 (Dixit and Yadav, 2019a).
- **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).

II. 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).

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:
 - **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).

- **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).
- **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. Properties and Advantages of Biodegradable Polymers: Biodegradable polymers offer a range of properties that make them suitable for various structural applications:

- Mechanical Properties
- Biocompatibility
- Low Toxicity
- Renewable and Sustainable
- Reduced Landfill Waste
- Customizable Properties

III. 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:

- 1. Tailoring Properties:** The high surface area-to-volume ratio of materials at the nano scale 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 nano composites for particular applications by adjusting these parameters.

2. **Enhanced Mechanical Properties:** Compared to their macro-scale counterparts, nano composites often exhibit better mechanical properties. By adding additional reinforcement from nano fillers, strength, stiffness, and toughness are all improved. In structural applications where materials must bear enormous loads and external pressures, this improvement is essential.
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.
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.
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.
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:
 - **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.
 - **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.
 - **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.
 - **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.

- **Corrosion and Wear Resistance:** The corrosion and wear resistance of nanocomposites can be improved by using specific nanofillers such as nanoparticles and nanoclays. This is especially crucial in situations where materials are subjected to harsh temperatures or abrasive environments.
- **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 (Mitra et al., 2003).

IV. SELECTION OF NANOFILLERS FOR BIODEGRADABLE NANOCOMPOSITES

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:

- **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).
- **Nanoclays:** Layered silicate minerals having nanoscale dimensions are known as nanoclays. Some of the most often utilized 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).
- **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).
- **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).

V. 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:

1. Extrusion and Injection Molding

- **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.
- **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.
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.
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.
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.

VI. 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:

1. Mechanical Testing: Tensile, Flexural, and Impact Strength Analysis

- **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).
- **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).
- **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).

2. Thermal Analysis: Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA)

- **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.
- **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).

3. Morphological Analysis: Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM)

- **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).
- **Transmission 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.
- **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).

4. 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.

- **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).
- **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).

- **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).

VII. 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:

1. Packaging and Single-Use Products

- **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).
- **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.
- **Agricultural 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).

2. Construction and Building Materials

- **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.

- **Sustainable Insulation Materials:** Building insulation materials that are environmentally friendly can be made from biodegradable nano composites. High thermal conductivity nano fillers, like graphene or carbon nano tubes, 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).
- **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.

3. Automotive and Transportation Applications:

- **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).
- **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).
- **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.

4. Biomedical and Healthcare Applications

- **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).

- **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.

Table 1: Previous Published Literatures 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)
Poly(lactic 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)

VIII. CONCLUSION

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 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.

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