Plant Archives **Vol. 25, Special Issue (ICTPAIRS-JAU, Junagadh) Jan. 2025 pp. 507-516**
e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.SP.ICTPAIRS-072

APPLICATION OF BIONANOCOMPOSITES IN FOOD PACKAGING: A NOVEL APPROACH TOWARD GREENER PACKAGING

B.M. Devani[1]*, V.P. Sangani[1] and B.L. Jani[2]

[1]Department of Processing and Food Engineering, College of Agricultural Engineering and Technology,
Junagadh Agricultural University, Junagadh, Gujarat, India.
[2]College of Food Technology, Sardar Krushinagar Dantiwada Agricultural University, Dantiwada, Banaskatha, Gujarat, India.
*Corresponding author E-mail : bdevani@jau.in

ABSTRACT

The primary function of food packaging is to ensure the quality and safety of food products during storage and transportation by extending their shelf life and protecting them from spoilage, contaminants and environmental factors like moisture, oxygen, and light. Packaging materials provide both physical protection and the necessary physicochemical conditions to maintain food quality, acting as barriers against water vapor, gases, and other volatile compounds. Unlike other durable goods, food packaging plays a critical role as both a container and a protective barrier, emphasizing its importance in preserving food safety and extending shelf life. The development of packaging materials with advanced functionalities and a reduced environmental impact is an urgent need in today's society. Extending the shelf life of packaged products is essential to meet the rapidly growing global demand for food, while the volatility of crude oil prices and concerns over its long-term availability have highlighted the need for alternative raw materials to replace oil-derived polymers. Additionally, increasing consumer awareness of environmental issues is driving industries to seek more sustainable, "green" solutions. In response, various polymers have been explored to develop biodegradable food packaging materials. Although biopolymers have traditionally faced limitations due to their poor mechanical and barrier properties, these can be significantly improved by incorporating nano-sized reinforcing components to create nanocomposites. Among these, cellulose stands out as one of the most widely used and well-known renewable and sustainable raw materials. Its mechanical properties, reinforcing capabilities, abundance, low density and biodegradability make nanosized filler materials an ideal candidate for polymer nanocomposites. This review explores the potential applications of bio-based nanocomposites in food packaging, highlighting the various types of biopolymers combined with nano-fillers to form bio nanocomposite materials and discussing emerging trends in packaging applications.

Key words : Bionanocomposites, Biodegradable, Biopolymers, Green food packaging.

Introduction

Food packaging is the art and science to protect the food from different factors causing spoilage and extend its shelf life for better quality. The food package is not only used for containment of the product but also must be superior enough to provide barrier against water vapour, oxygen and allied gases, light, temperature and other volatiles to preserve the quality and make the food safer. The different packaging materials used for food are paper and paper based, plastic, metal, glass and combination of thereof. The choice for selecting the packaging materials depend upon the nature of food to be packed, storage condition, transportation, cost effectiveness. Among these packaging materials plastic-based packaging materials offer number of advantages over others. They are light in weight, effective barrier properties against light, moisture, gases and volatiles and excellent mechanical and thermal properties. These synthetic plastic polymers like polyethylene (PE), polypropylene (PP), nylon, polyester (PS), polytetrafluoroethylene (PTFE), and epoxy (commonly known as plastic) are derived from petroleum hydrocarbons. However having the widespread use in different forms such as films, sheet, cups, trays, bottle, glass, etc. it caused environmental problem being non-biodegradable in nature. Also they are obtained from petroleum based non-renewable sources there is a big threat on depletion of these sources and the environmental issues. It is reported that a single plastic bag could take as much as 500 years to break down and difficult to degrade in the nature. There is an increasing demand for biodegradable and natural packaging materials to solve the issue and protect the food to maintain its quality and safety.

These issues give birth to the development of biodegradable products using renewable raw materials derived from plant and animal sources those have suitable features to address these persevering ecological problems. Also to reduce the dependency on non-renewable source of petro-chemical based materials, the attempts have been made to prepare the composites materials i.e conjoining at least two nonmiscible components, i.e., the matrix as the continuous phase and the filler as the dispersed phase, to achieve distinctive properties that would not be achievable from the singular constituents.

Biocomposites or green composites are termed where both phases (reinforced polymer and matrix) are derived from natural sources, renewable and completely biodegradable. The green polymeric matrices, also called "bioplastics" are derived from 100% renewable or fossil fuel based materials, which are either degradable or compostable by the microorganisms. The bio-polymer or green polymer matrices can be obtained from the renewable sources such as cellulose, lignin, and starch, chitin, proteins, poly (lactic) acid (PLA), hydroxyl alkanoates (PHA), poly-3-hydroxybutyrate (PHB), polyhydroxyvalerate (PHV) and polyhydroxyhexanoate (PHH) etc. Also there are many matrices which are completely fossil fuel based or mixed source of both renewable and fossil fuel based monomers which are biodegradable. These biobased packaging materials limit their application in food industry due to relatively poor mechanical and high hydrophilic properties with poor processability. Considering the protein and carbohydrate packaging films they possess good barriers against oxygen at low to intermediary relative humidity and have worthy mechanical properties; however they do not obstacle water vapor due to their hydrophilic nature. To improve the various properties of the biobased packaging materials the fillers are reinforced into matrix.

To overcome the disadvantages associated with the biobased plastic the reinforcement is done through chemical and physical cross-linking treatments to increase the strength of the bioplastics. The filler is mixed with the polymer matrix to reinforce it as the dispersed phase which improves the various properties of the packaging. These reinforcing fillers may be inorganic or organic with certain geometries (fibers, flakes, spheres, particulates). Biocomposites comprise a biopolymer matrix reinforced with natural fibers or particles. To create biocomposites, natural fibers undergo treatment to ensure compatibility with a biopolymer matrix. Once treated, the fibers are combined with the matrix and shaped through processes such as compression molding or extrusion. These resulting materials offer strong mechanical properties, are eco-friendly, and can be disposed of with minimal environmental impact. Bionanocomposites are usually based on biopolymer matrices reinforced by nanofillers. Bionanocomposites are advanced materials that incorporate nanoscale reinforcing agents, like nanoparticles, nanofibers, or Nanoclays, into a biopolymer matrix. These agents enhance the material's strength, stiffness and toughness. Biodegradable bionanocomposites offer improved barrier properties, flame resistance and thermal stability, making them ideal for applications like food packaging and agricultural films, where both performance and environmental sustainability are critical (Mir *et al.*, 2018).

Biopolymers

In the synthesis of biodegradable biocomposites various types of bio-based polymers have been used. Starch, cellulose, chitin and chitosan are the polysaccharides extracted from the biomass. While wheat gluten, soy protein, collagen, and gelatine based proteins have also extracted from the biomass and used in preparation of biocomposites. Polylactic acid, polycaprolactone, polylactide, polyglycolide etc. biobased polymers have also been synthesized from monomers and widely used in the biocomposites. Also, the biobased polymers can be produced by micro-organisms such as polyhydroxybutyrate and polyhydroxyalkanoates, etc. Polymeric films and coatings made from biopolymers are increasingly used in food packaging to preserve quality and extend shelf life. They can incorporate antibacterial agents, antioxidants, natural ingredients and colors for added protection. Biopolymers face challenges that limit their industrial use, including poor mechanical strength and barrier properties namely brittleness, low heat resistance, high permeability to gases, vapors and difficulty in withstanding extended processing, along with high costs.

Biocomposites

Interest in biodegradable materials like biocomposites and bionanocomposites has grown, as they offer a balance of biodegradability and mechanical strength with reinforcing agents. Biocomposites comprise a biopolymer matrix reinforced with natural fibers or particles. Blending biopolymers with other biodegradable polymers enhances mechanical and gas barrier properties through molecular entanglement, improving performance and reducing costs. This approach allows for tailoring material characteristics to meet specific application needs. The biobased polymers along with natural fibers make the biocomposites with superior qualities as compared to the biopolymer packaging material alone. The suitability as fillers of different lignocellulosic fibers, such as wheat straw (Awella *et al*., (1993), flax fibers (Wong *et al*., 2021), jute (Ma *et al*., 2011), coconut (Macedo *et al*., 2010), kenaf (Kuciel *et al*., 2011) or olive pomace (Berthet *et al*., 2015), etc., has been explored.

Bio-nanocomposites

Bio-nanocomposites, made from biodegradable and renewable materials are also known as green nanocomposites. Bionanocomposites are advanced materials with nanoscale reinforcing agents embedded in a biopolymer matrix. They are composites made from a bio-based polymer matrix reinforced with nanometer-scale fillers (1-100 nm). Various techniques can be used to incorporate reinforcements, enhancing the mechanical properties of biodegradable materials like biocomposites and bionanocomposites. These materials offer improved barrier properties, flame resistance and thermal stability, making them superior to nonbiodegradable alternatives. They are ideal for food packaging and agricultural films, providing both mechanical benefits and environmental sustainability. Bio-nanocomposites have antibacterial properties, efficiently inactivating bacteria due to their increased surface area and higher reactivity of nanosized agents. Starch, chitosan, chitin and alginate nanoparticles based bionanofilms shows enhanced properties. These agents come in nanoparticles, nanofibers or nanoclays and can significantly boost the material's mechanical properties by improving its strength, stiffness and toughness (Mir *et al*., 2018)

Nanofillers

Reinforcing nanoparticles can be derived from materials like polymers, metals and metal oxides. Their high surface area-to-weight ratio enhances interactions with polymer chains, improving material properties and performance. This makes nanocomposites ideal for barrier applications. The properties of bionanocomposites depend on factors such as the nanoparticles' origin, size, shape, surface chemistry and the polymer used. Nanoparticles enhance the mechanical properties of bionanocomposites by increasing the interfacial area with the matrix, improving load transfer and stress distribution. This leads to greater stiffness, strength and toughness. Nanoparticles can act as catalysts, improving thermal stability by lowering the activation energy for thermal degradation, making them suitable for high-temperature applications. For example, metal oxide nanoparticles enhance the thermal stability of polymers by catalysing the oxidation of volatile organic compounds, delaying polymer breakdown and boosting durability.

Nanoclays

The term of "nanoclay" refers to the particles of clay minerals in a nanoscale range from 1 nm to 100 nm. Nanoclays encompass a large family of minerals, classified into four main groups: montmorillonite/smectite, kaolinite, illite and chlorite, based on their chemical composition and nanoparticle morphology. Montmorillonite (MMT) is one of the most widely used and researched clays due to its affordability, large surface area and its ability to enhance mechanical strength and barrier properties in bionanocomposites. However, because of its natural polarity, MMT requires a modification process based on cation exchange, resulting in organo-modified layered silicates. MMT consists of hydrated alumino-silicate layers, with its negative charge balanced by exchangeable cations like Na^+ and Ca^{2+}. Another commonly used nanoclay for reinforcement is Halloysite (Hal), a naturally occurring aluminosilicate mineral. Unlike MMT, Halloysite has a unique hollow, tubular structure, making it suitable for various applications where nanoscale reinforcement is needed. These nanoclays contribute significantly to improving the performance of bionanocomposites by enhancing their structural, mechanical, and functional properties. Mathew *et al*. (2019) reported the improvement of mechanical and barrier properties of the rice starch, polyvinyl alcohol based Montmorillonite bionanocomposites. While a study showing improvement in mechanical and barrier properties was conducted by Orsuwan and Sothornvit (2017) using banana flour and starch nanoparticles and Montmorillonite bionanocomposites.

Metal and Metal Oxide Nanoparticles

Inorganic nanoparticles, commonly used as reinforcements in bionanocomposites, include metal nanoparticles like silver (AgNPs), zinc (ZnNPs), and gold (AuNPs), as well as metal oxide nanoparticles such as zinc oxide (ZnO NPs), titanium oxide (TiO2 NPs), and magnesium oxide (MgO NPs) (Bagal-Kestwal *et al*., 2019; Nwabor *et al*., 2021; Youssef and El-Sayed, 2018).

The different metal oxide nanoparticles have been explored by many researched in synthesis for the bionanocomposites for their distinct properties. ZnO nanoparticles (ZnO NPs) enhance packaging material properties with their high stability, photocatalytic activity, and antibacterial effects (Espitia *et al*., 2012). Titanium dioxide nanoparticles (TiO_2 NPs) are utilized for their ability to reduce water vapor permeability, creating an effective barrier against moisture due to their low hydrophilicity (Oleyaei *et al*., 2016). Conversely, biogenic silver nanoparticles (AgNPs have been known for their antimicrobial and antioxidant capabilities (Nwabor *et al*., 2020). Silver nanoparticles are used widely to functionalize polymeric material for packaging application because of their strong antibacterial effect toward viruses, bacteria and fungi (Russell and Hugo, 1994). The action of silver ions and silver nanoparticles is responsible for the antibacterial activity. The deformation of bacterial cell membranes and cell walls occurs because of interaction between negatively charged components of cell (sulfhydryl or disulfide groups of enzymes and nucleic acid) (Butkus *et al*., 2003; Feng *et al*., 2000).

Nanocellulose

Nanocellulose is derived from lignocellulosic materials, such as wood, agricultural residues and plant fibers. When incorporated into a polymeric matrix, nanocellulose significantly enhances both mechanical strength and gas barrier properties, particularly against oxygen permeation. This improvement is crucial for packaging applications, as it helps preserve food quality and extends shelf life by reducing oxidation. Additionally, nanocellulose is a renewable and recyclable material, making it an environmentally friendly option for use in packaging products. Its sustainable nature, combined with its excellent reinforcing capabilities, positions nanocellulose as an ideal nanofiller in the development of advanced packaging solutions. By utilizing nanocellulose, manufacturers can create lightweight, durable, and effective packaging that meets both performance and sustainability goals, ultimately contributing to reduced environmental impact. Nanocellulose can be classified into three main types for reinforcement in bionanocomposites: Nanocrystalline Cellulose (NCC), Nanofibrillated Cellulose (NFC) and Bacterial Nanocellulose (BNC). NCC is derived from the acid hydrolysis of cellulose fibers and is characterized by short, rod-like crystals with high crystallinity. Its particle size typically ranges from 100 nm to a few micrometers. In contrast, NFC is obtained through mechanical disintegration or enzymatic treatment of cellulose fibers, resulting in long, entangled fibrils that form a web-like structure. NFC has moderate crystallinity, and the fibrils can range from several micrometers in length to about 20-100 nm in diameter. BNC is produced by specific bacteria, such as *Acetobacter xylinum*, via fermentation processes, leading to a network of interconnected nanofibers with a gel-like consistency and high crystallinity. The particle size of BNC generally consists of nanofibers with diameters around 100-200 nm. These three types of nanocellulose differ in their source and extraction methods, morphology, degree of crystallinity, and particle size, enabling tailored applications in bionanocomposites to meet specific requirements (Phanthong *et al*., 2018).

Carbon nanotubes

Carbon nanotubes (CNTs) are organic nanofillers made from extremely thin layers of carbon fibers. These nanomaterials are typically classified into two types: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). A SWCNT consists of a single cylindrical layer of carbon atoms with a diameter of about 1 nm, whereas MWCNTs are composed of multiple concentric cylinders, with diameters ranging from 2 to 100 nm and separated by approximately 0.35 nm. These tubes can be several microns long, extending up to tens of microns. The incorporation of carbon nanotubes into materials offers significant benefits, particularly in enhancing antibacterial, thermal, and mechanical properties. CNTs are known to improve the strength and durability of packaging while maintaining low weight and good processability, making them ideal for advanced packaging applications. However, challenges remain in their widespread use, especially in food packaging, due to difficulties in processing and dispersion within the polymer matrix. Additionally, the high cost of CNTs limits their accessibility. Despite these constraints, their ability to significantly improve the performance of packaging materials continues to make CNTs a promising option in the development of nanocomposite materials for various industries.

Properties and advantages of each type in packaging

The conventional packaging materials such as plastic in food packaging has numerous advantages such as excellent properties, quality, processability, low cost and many more. However, the main disadvantage of such material is environmental safety. As they are not biodegradable they cause huge environmental problems and takes long period of years to get degraded in soil. An alternate to this the biocomposites and bionanocomposites can come into picture as they are biodegradable in nature. They have improved water and gas barrier properties, mechanical strength, thermal strength, UV barrier properties, antimicrobial properties that makes their use prominent in food packaging. Reinforcing nanoparticles from materials like polymers, metals, and metal oxides are added for their high surface area, which improves interactions with polymer chains. This enhances material performance, such as improved gas and liquid barriers, making nanocomposites ideal as barrier materials. The properties of bionanocomposites depend on factors like nanoparticle origin, size, shape, surface chemistry and the type of polymer used. Key materials used (*e.g.*, biopolymers, natural fibers, nanoparticles).

The petroleum based plastic packaging materials used in food packaging owns superior barrier, mechanical, thermal and processing properties but threatens the environment due to non-biodegradability. As an alternate to this biobased composite materials imparts different and new properties suitable for food packaging especially they are biodegradable in nature. Incorporation of some active agents to this give the antimicrobial and antioxidant properties to the packaging. These biobased materials used in food packaging shows some inferior properties especially poor barrier properties and mechanical strength. The hydrophilic nature of some of the polymers results in poor water vapor and moisture barrier properties. Reinforcement of biobased polymers with nanoparticles alters the diffusion path of different molecules and can contribute to improving their barrier properties. As reported by Choudalakis *et al*. (2009), nanocomposites with organoclays significantly improve the mechanical properties of biopolymers, even at low filler levels (<5 wt%). This enhancement is due to the nanoclay's rigidity, high aspect ratio, and strong interfacial interaction with the polymer matrix. Nanoclay is key to enhancing the gas barrier properties of polymer nanocomposites, significantly reducing permeability to gases like O_2 and CO_2, as well as water vapor. The effectiveness of this barrier depends heavily on the type of clay used, its compatibility with the polymer matrix, and the aspect ratio of the clay platelets. Fully exfoliated nanoclay with a large aspect ratio provides the best barrier performance, making it essential for improving the protective qualities of nanocomposites. Abral *et al*. (2021) reported that the addition of bacterial cellulose (BC) nanofibers in tapioca starch/ chitosan-based films resulted in improved tensile strength thermal resistance, moisture resistance, and water vapor barrier properties.

A study reported by Alexandre *et al*. (2016) indicates the increase in the thickness of the film as the loading of Montmorillonite nanoparticles increased in the gelatin/ ginger essential oil bionanocomposites. Also the decreasing trend in water solubility, moisture content and superficial hydrophobicity was shown with the increased amount of nanoparticles. A study incorporating polyvinyl alcohol/carboxymethylcellulose/cellulose nanocrystals bionanocomposites shown improvement in barrier and mechanical properties of the films. The CNC decreased the water vapour permeability of the film while increased the tensile modulus and tensile strength with the addition of CNC to PVA/CMC films (Achaby *et al*., 2017). ZnO based PLA bionanocomposites shown enhanced mechanical and water vapour barrier improvement and also found profound effect as antibacterial on minced fish paste packed within (Marra *et al*., 2016). A study conducted by Li *et al*., (2019) on bionanocomposites of Chitosan/starch/clove oil/TiO_2 suggests the improvement in tensile strength and antioxidant activity of the film. Wheat gluten based TiO_2 and CNC added bionanocomposites also improved the tensile strength and water resistance and exhibited good antimicrobial activity.

The biodegradability of bio-nanocomposites is a key but debated topic. In biodegradable polymers, it can involve fragmentation, loss of mechanical properties, or degradation by microorganisms like bacteria, fungi, and algae. This complex process often occurs through enzyme-catalyzed hydrolysis or oxidation. Biopolymers are used in bionanocomposites for their biodegradability, which should be preserved after nanocomposite formation. Around 370 million tons of synthetic polymers are believed to be introduced into the environment as industrial waste. Of this, only 9% is recycled, 12% is burned and the rest remains in the ecosystem (Jayakumar *et al*., 2021). Polymer degradation in the environment is primarily driven by biotic and abiotic processes. Key factors influencing degradation include the polymer's chemical structure, composition, molecular weight, crystallinity, complexity and functional groups. Environmental conditions like humidity, pH, carbon dioxide levels, oxygen availability, temperature and the presence of soil nutrients also play a crucial role in determining the rate of microbial polymer breakdown.

Materials and Methods

Bionanocomposites are created by combining two or more materials with distinct properties. The concentration of these materials plays a crucial role in determining the overall performance of polymer-based nanocomposites. With a growing demand for sustainable solutions, synthetic materials are increasingly being replaced by biodegradable, greener alternatives. The uniform dispersion of nanofillers is key to enhancing bionanocomposite performance. Common methods for preparing bionanocomposites include solvent casting, in situ polymerization, and melt intercalation (Darder *et al*., 2007; Fernandes *et al*., 2013; Puiggalí and Katsarava, 2017, Zhao *et al*., 2008).

Solvent casting is a widely used method for small-scale bionanocomposite production. In this process, the polymer is dissolved in a solvent, nanomaterials or additives are mixed in, and the solution is spread on a flat surface. After solvent evaporation, the resulting film is peeled off. In situ polymerization involves mixing nanoparticles with a liquid monomer, followed by the addition of an initiator to start the polymerization process. The mixture is then exposed to heat or radiation, resulting in a nanoparticle-bound polymer nanocomposite. Melt intercalation, a commonly used method, mixes additives and polymers at a temperature above the polymer's melting point. The mixture is then sheared and held at that temperature to create the bionanocomposite.

In bionanocomposites, various interactions contribute to enhancing their overall performance and functionality. These interactions include electrostatic forces, intermolecular bonding, mechanical interlocking and chemical bonding. Additional processes such as diffusion, surface tension, absorption and surface wettability also play critical roles in determining the composite's properties (Akpan *et al*., 2019). The effectiveness of these interactions is largely influenced by factors like the size, shape and structural changes that occur during the preparation and development of bionanocomposites.

For example, electrostatic interactions can significantly impact the distribution and stability of nanoparticles within the polymer matrix, while mechanical interlocking helps reinforce the material's structural integrity. Chemical bonding between nanoparticles and polymer chains ensures a strong connection, enhancing mechanical strength and durability. Additionally, surface-related phenomena like wettability and surface tension affect how well the material resists moisture or adheres to different surfaces. Ultimately, these interactions and processes collectively determine the bionanocomposite's strength, flexibility and barrier properties, which are critical for applications such as food packaging, biomedical devices, and environmental protection.

Antimicrobial and Active Packaging Applications

Antimicrobial packaging extends food shelf life by inhibiting pathogen growth. It can be made by: (i) adding antimicrobials to packages, (ii) incorporating them into polymers, (iii) coating polymer surfaces, (iv) immobilizing them via ionic or covalent bonds or (v) using antimicrobial polymers with film-forming properties. Combinations of these methods have also been explored in various studies. Common antimicrobials added to bionanocomposites include phytochemicals like polyphenols, garlic extract, and essential oils, as well as various nanoparticles—silver, zinc oxide, magnesium, titanium, copper, graphene oxide, and gold. Bacterial extracts are also used for their antimicrobial properties. n a study by Vasile *et al*. (2017), a composite film of PLA/ZnO/Ag was tested in various food simulants, including distilled water, ethanol 10% (simulant A) and acetic acid 3% (simulant C). The film demonstrated excellent mechanical, thermal, and barrier properties, effectively blocking ultraviolet light, water vapor, oxygen and carbon dioxide. Additionally, it showed antibacterial activity and low migration of nanoparticles into the food simulants. In another study by Meira *et al*. (2016), a starch/halloysite/nisin composite was applied to soft cheese, where halloysite improved mechanical properties, and the material exhibited antimicrobial activity against *L. monocytogenes*, *Clostridium perfringens* and *S. aureus*. In a study low-density polyethylene (LDPE) composite containing Ag and ZnO for packaging orange juice. The material significantly reduced yeast, mold counts, and the growth rate of Lactobacillus plantarum without negatively affecting juice quality attributes.

Results and Discussion

The primary goal of developing alternatives like bionanocomposites is to address the limitations of conventional plastics, while enhancing their functional properties. Packaging materials must protect food from external environmental factors, requiring superior mechanical, thermal, light, water, gas and antimicrobial barrier properties. The performance of bionanocomposites, particularly in terms of mechanical strength, water resistance, electrical conductivity, and thermal stability, depends on the interaction between the polymer matrix and the nanofillers used. The incorporation of nanofillers plays a crucial role in enhancing these properties. A strong interaction between nanofillers and the polymer matrix leads to improved overall performance, enabling bionanocomposites to offer better durability, barrier efficiency, and functionality compared to traditional plastics. This makes them highly suitable for advanced applications such as food packaging, where protection, preservation, and sustainability are essential.

For food packaging applications, the material must exhibit strong mechanical properties, such as tensile strength, Young's modulus, and elongation at break. These properties determine the material's ability to resist breakage during processing, handling, and storage. The efficiency of stress transfer between the polymer and nanofiller plays a critical role in enhancing the strength and modulus of nanocomposites. Numerous studies, including Liu *et al*. (2012) have shown that incorporating nanofillers significantly improves the mechanical properties of bionanocomposites. A variety of natural materials and nanofillers are known to boost these properties, making bionanocomposites more robust for packaging use.

Bionanocomposites offer superior water barrier properties compared to conventional packaging materials (Youssef and El-Sayed, 2018), making them ideal for food products sensitive to moisture. High moisture content in packaging can lead to microbial growth, affect texture, nutrient content, lipid oxidation, and flavor, ultimately reducing the shelf life of food items. Bionanocomposites can effectively prevent moisture loss or gain during packaging, storage, and distribution (Rhim *et al*., 2013). Water barrier properties in bionanocomposites are typically evaluated through tests such as water vapor permeability, swelling, moisture content analysis, water absorption, and film solubility (Noshirvani *et al*., 2018; Rhim, 2013; Yadav *et al*., 2019). Enhancing moisture resistance is achieved by lowering the material's solubility and increasing the water contact angle. Various studies have shown that incorporating nanofillers can significantly improve the water barrier properties of bionanocomposites.

The dispersion of nanofillers within the biopolymer matrix restricts polymer chain mobility, enhancing water barrier properties. Factors such as porosity, crystallinity, humidity and the chemical composition of biopolymers influence water vapor permeability. Strong hydrogen bonding between nanofillers and the polymer matrix also boosts water resistance. Nanoparticles create tortuous pathways that narrow pore channels, increasing the diffusional path and reducing water diffusion (Mathew *et al*., 2019). Gas diffusion can shorten the shelf life of food, particularly fruits and vegetables. A polymer's gas permeability is influenced by factors such as polarity, crystallinity, functional groups, molecular weight, production methods, and crosslinking. Bionanocomposites enhance gas barrier properties largely due to the even distribution of nanofillers within the matrix. These nanofillers form a tortuous pathway that slows the movement of gas molecules through the packaging. Additionally, nanofillers can modify the interfacial regions of the polymer matrix, further restricting gas flow.

Various oxygen scavengers, such as ferrous oxide, catechols, sulfites, ascorbic acid, and enzymes are commonly used to lower oxygen concentration. Addition of calcium carbonate ($CaCO_3$) nanopowder to chitosan-based bionanocomposites enhances their oxygen barrier properties while incorporating zirconium oxide (ZrO_2) nanopowder into starch-based bionanocomposites also reduces oxygen permeability (Brody *et al*., 2008; Swain *et al*., 2014 and Pradhan *et al*., 2014).

Conventional packaging materials have low heat resistance and biopolymer-based packaging also lacks thermal stability, often requiring reinforcement. Key factors affecting thermal properties include decomposition temperature, glass transition, crystallization temperature, and heat deformation. Bionanocomposites, typically evaluated through thermogravimetric analysis, differential scanning calorimetry and dynamic mechanical analysis, exhibit superior thermal stability compared to biopolymers. Their stability depends on chemical composition, compatibility, crosslinking, interactions, and crystallinity (Tomi´c, 2020). Numerous studies have explored the use of nanofillers to enhance the thermal barrier properties of bionanocomposites. Various nanomaterials, such as zinc oxide nanoparticles (Shahvalizadeh *et al*., 2021; Youssef *et al*., 2016), silica nanoparticles (Chrissafis *et al*., 2008), silver-loaded zinc oxide nanoparticles (Murali *et al*., 2019), silver nanoparticles (Mathew *et al*., 2019) and montmorillonite (Khodamoradi *et al*., 2019; Mallakpour and Dinari, 2012) have been shown to significantly improve these properties. The biodegradability of bio-nanocomposites is a key, but debated topic. In biodegradable polymers, it can involve fragmentation, loss of mechanical properties or degradation by microorganisms like bacteria, fungi and algae. This complex process often occurs through enzyme-catalyzed hydrolysis or oxidation. Biopolymers are used in bionanocomposites for their biodegradability, which should be preserved after nanocomposite formation.

Conclusion

As bionanocomposites gain significant attention in research and industry, several challenges need to be addressed. One major issue is the potential for improper mixing and material incompatibility, which can lead to nanoparticle aggregation within the composite matrix. This affects the overall properties of the bionanocomposites, often making them more fragile. Additionally, functional additives may lose their effectiveness during the preparation process, which can compromise the intended performance of the nanocomposites.

Another concern is the widespread use of nanoparticles across various industries. While the incorporation of nanofillers can improve the functional properties of nanocomposites, their potential side effects should be carefully studied before large-scale industrial use. Research has shown that nanoparticles can have toxic effects on the environment and living organisms, largely due to their high surface area, which makes them highly reactive. When inhaled, nanoparticles may interact with cellular components, causing lung inflammation and potentially leading to heart problems. The size of the nanoparticles also plays a crucial role, as smaller particles can penetrate cells more easily than larger ones. Studies have shown that silver nanoparticles with a 20 nm diameter are more toxic to lung tissue than larger particles. However, encapsulating nanoparticles within a polymer matrix can reduce their migration into food. As public awareness of nanotechnology grows, there is an increasing need for government regulation to ensure the safe use of nanomaterials, especially at higher doses. Multidisciplinary research is essential to determine safe practices and address potential health and environmental hazards associated with nanoparticles.

In conclusion, bionanocomposites present a significant step forward in the development of sustainable food packaging solutions. These materials combine biodegradable polymers with nanoscale reinforcements, such as nanoparticles, nanofibers, and nanoclays, to create packaging that not only meets the functional demands of modern food storage but also addresses growing environmental concerns. The incorporation of nanomaterials into biopolymers enhances the mechanical strength, thermal stability, and barrier properties of the packaging, making it more effective at protecting food from factors like moisture, oxygen, and microbial contamination. This results in extended shelf life and better preservation of food quality. Moreover, the use of renewable, biodegradable materials in bionanocomposites helps reduce reliance on petroleum-based plastics, which are a major contributor to environmental pollution. These eco-friendly alternatives decompose more readily, lessening their impact on ecosystems and offering a greener option for industries seeking to minimize their environmental footprint. However, challenges remain in ensuring the optimal performance of bionanocomposites. Issues such as improper mixing and nanoparticle aggregation can affect the structural integrity of the material, leading to reduced effectiveness. Additionally, the potential toxicity of certain nanoparticles, particularly when they migrate into food or interact with biological systems, raises concerns that must be thoroughly investigated before widespread commercial use. Research is actively exploring ways to mitigate these risks through improved nanoparticle encapsulation and by regulating the use of these materials in packaging.

As public awareness of environmental issues grows and regulatory bodies focus more on sustainable practices, bionanocomposites are positioned to become a key solution in the food packaging industry. By balancing high-performance functionality with environmental sustainability, these materials have the potential to revolutionize packaging, offering a way to meet consumer demand for eco-friendly products without compromising on the quality and safety of food preservation. The ongoing development and refinement of bionanocomposites will be crucial in achieving these goals and driving innovation in the packaging sector.

References

Abral, H., Pratama A.B., Handayani D., Mahardika M., Aminah I., Sandrawati N., Sugiarti E., Muslimin A.N., Sapuan S.M. and Ilyas R.A. (2021). Antimicrobial edible film prepared from bacterial cellulose nanofibers/ starch/chitosan for a food packaging alternative. *Int. J. Polymer Sci.*, 1-11. https://doi.org/10.1155/2021/6641284.

Akpan, E.I., Shen X., Wetzel B. and Friedrich K. (2019). *Design and synthesis of polymer nanocomposites* (pp. 47–83).

Alexandre, E.M.C., Lourenço R.V., Bittante A.M.Q.B., Moraes I.C.F. and Sobral P.J. do A. (2016). Gelatin-based films reinforced with montmorillonite and activated with nanoemulsion of ginger essential oil for food packaging applications. *Food Packag. Shelf Life*, **10**, 87–96.

Bagal-Kestwal, D.R., Pan M.H. and Chiang B.-H. (2019). Bio Monomers Green Polymeric Composite Materials. Wiley and Sons Ltd.; Hoboken, NJ, USA: Processing Methods for Bionanocomposites; pp. 25–55.

Berthet, M., Angellier-coussy H., Machado D., Hilliou L., Staebler A. and Vicente A. (2015) Exploring the potentialities of using lignocellulosic fibres derived from three food by-products as constituents of biocomposites for food packaging. *Ind Crop Prod.*, **69**, 110–22. doi:10.1016/j.indcrop.2015.01.028.

Brody, A.L., Bugusu B., Han J.H., Sand C.K. and McHugh T.H. (2008). Scientific status summary. *J. Food Sci.*, **73(8)**, R107–R116.

Butkus, M.A., Edling L. and Labare M.P. (2003). The efficacy of silver as a bactericidal agent: advantages, limitations and considerations for future use. *J. Water Supply: Res. Technol. e AQUA*, **52 (6)**, 407e416.

Vasile, C., Rapa M., ‘tefan M., Stan M., Macavei S. and Darie-Nita R.N. (2017). New PLA/ZnO:Cu/Ag bionanocomposites for food packaging. *Express Polymer Lett.*, **7 (11)**, 531-544

Choudalakis, G. and Gotsis A.D. (2009). Permeability of polymer/clay nanocomposites: A review. *Eur Polym J.*, **45**, 967-984.

Chrissafis, K., Paraskevopoulos K.M., Papageorgiou G.Z. and Bikiaris D.N. (2008). Thermal and dynamic mechanical behavior of bionanocomposites: Fumed silica nanoparticles dispersed in poly(vinyl pyrrolidone), chitosan and poly(vinyl alcohol). *J. Appl. Polymer Sci.*, **110(3)**, 1739–1749.

Darder, M., Aranda P. and Ruiz-Hitzky E. (2007). Bionanocomposites: A new concept of ecological, bioinspired, and functional hybrid materials. *Advanced Materials*, **19(10)**, 1309–1319.

El Achaby, M., El Miri N., Aboulkas A., Zahouily M., Bilal E., Barakat A. and Solhy A. (2017). Processing and properties of eco-friendly bio-nanocomposite films filled with cellulose nanocrystals from sugarcane bagasse. *Int. J. Biolog. Macromole.*, **96**, 340-352.

Espitia P.J.P., de Fátima Ferreira Soares N., dos Reis Coimbra J.S., de Andrade N.J., Cruz R.S. and Medeiros E.A.A. (2012). Zinc Oxide Nanoparticles: Synthesis, Antimicrobial Activity and Food Packaging Applications. *Food Bioprocess Technol*. **5**, 1447–1464. doi: 10.1007/s11947-012-0797-6.

Feng, Q.L., Wu J., Chen G.Q., Cui F.G., Kim T.N. and Kim J.O. (2000). A mechanistic study of the antibacterial effect of silver ions on *Escherichia coli* and *Staphylococcus aureus*. *J. Biomed. Mater. Res*., **52**, 662e668.

Fernandes, E.M., Pires R.A., Mano J.F. and Reis R.L. (2013). Bionanocomposites from lignocellulosic resources: Properties, applications and future trends for their use in the biomedical field. *Progress in Polymer Sci.*, **38(10–11)**, 1415–1441.

Jayakumar, A., Radoor S., Nair C.I, Siengchin S., Parameswaranpillai J. and E.K. R. (2021). Polyvinyl alcohol -nanocomposite films incorporated with clay nanoparticles and lipopeptides as active food wraps against food spoilage microbes. *Food Packaging and Shelf Life*, **30**, Article 100727.

Khodamoradi, N., Babaeipour V. and Sirousazar M. (2019). Bacterial cellulose/ montmorillonite bionanocomposites prepared by immersion and in-situ methods: Structural, mechanical, thermal, swelling and dehydration properties. *Cellulose*, **26 (13–14)**, 7847–7861.

Kuciel, S. and Liber-Kneæ A. (2011). Biocomposites based on PHB filled with wood or kenaf fibers. *Polimery/Polymers*, **56**, 218–23.

Li, W., Zheng K., Chen H., Feng S., Wang W. and Qin C. (2019). Influence of nano titanium dioxide and clove oil on chitosan-starch film characteristics. *Polymers*, **11**, 1418.

Ma, H. and Joo C.W. (2011). Investigation of jute-lignin-poly (3-hydroxybutyrate) hybrid biodegradable composites with low water absorption. *Fibers Polym*., **12**, 310–315. doi:10.1007/s12221- 011-0310-2.

Macedo, J.D.S., Costa M.F., Tavares M.I.B. and Thiré R.M.S.M. (2010). Preparation and characterization of composites based on polyhydroxybutyrate and waste powder from coconut fibers processing. *Polym Eng Sci*., 50. doi:10.1002/pen.21669.

Mallakpour, S. and Dinari M. (2012). Surface treated montmorillonite: Structural and thermal properties of chiral poly(amide-imide)/organoclay bionanocomposites containing natural amino acids. *J. Inorg. Organomet. Polym. Mater.*, **22(5)**, 929–937.

Marra, A., Silvestre C., Duraccio D. and Cimmino S. (2016). Polylactic acid/zinc oxide biocomposite films for food packaging application. *Int. J. Biol. Macromol*., **88**, 254–262.

Mathew, S., S S., Mathew J. and E.K. R. (2019). Biodegradable and active nanocomposite pouches reinforced with silver nanoparticles for improved packaging of chicken sausages. *Food Packaging and Shelf Life*, **19**, 155–166.

Meira, S.M.M., Zehetmeyer G., Scheibel J.M., Werner J.O. and Brandelli A. (2016). Starch-halloysite nanocomposites containing nisin: Characterization and inhibition of Listeria monocytogenes in soft cheese Lebensmittel-Wissenschaft und -Technologie- *Food Sci. Technol.*, **68**, pp. 226-234.

Mir, S.A., Dar B.N., Wani A.A. and Shah M.A. (2018). Effect of plant extracts on the technofunctional properties of biodegradable packaging films. *Trends Food Sci. Technol.*, **80**, 141–154. doi:10.1016/j.tifs.2018.08.004

Murali, S., Kumar S., Koh J., Seena S., Singh P., Ramalho A. and Sobral A.J.F.N. (2019). Bio-based chitosan/gelatin/ Ag@ZnO bionanocomposites: Synthesis and mechanical and antibacterial properties. *Cellulose*, **26(9)**, 5347–5361.

Noshirvani, N., Hong W., Ghanbarzadeh B., Fasihi H. and Montazami R. (2018). Study of cellulose nanocrystal doped starch-polyvinyl alcohol bionanocomposite films. *Int. J. Biolog. Macromole.*, **107**, 2065–2074.

Nwabor, O.F., Singh S., Ontong J.C., Vongkamjan K. and Voravuthikunchai S.P. (2021). Valorization of Wastepaper Through Antimicrobial Functionalization with Biogenic Silver Nanoparticles.

Nwabor, O.F., Singh S., Paosen S., Vongkamjan K. and Voravuthikunchai S.P. (2020). Enhancement of food shelf life with polyvinyl alcohol-chitosan nanocomposite films from bioactive *Eucalyptus* leaf extracts. *Food Biosci*., **36**, 100609. doi: 10.1016/j.fbio.2020.100609.

Oleyaei, S.A., Zahedi Y., Ghanbarzadeh B. and Moayedi A.A. (2016). Modification of physicochemical and thermal properties of starch films by incorporation of TiO_2 nanoparticles. *Int. J. Biol. Macromol.*, **89**, 256–264. doi: 10.1016/j.ijbiomac.2016.04.078.

Orsuwan, A. and Sothornvit R. (2017). Development and characterization of banana flour film incorporated with montmorillonite and banana starch nanoparticles. *Carbohydrate Polymers*, **174**, 235-242.

Phanthong, P., Reubroycharoen P., Hao X., Xu G., Abudula A. and Guan G. (2018). Nanocellulose: Extraction and application. *Carbon Resour. Convers*., **1**, 32–43. doi: 10.1016/j.crcon.2018.05.004.

Pradhan, G.C., Dash S. and Swain S.K. (2014). Effect of zirconium oxide nanopowder on the thermal, chemical and gas barrier properties of starch. *Mater. Sci. Semicond. Processing*, **23**, 115–121.

Puiggalí, J. and Katsarava R. (2017). *Bionanocomposites*, 239–272.

Rhim, J.-W., Park H.-M. and Ha C.-S. (2013). Bio-nanocomposites for food packaging applications. *Progress in Polymer Science*, **38(10–11)**, 1629–1652.

Russell, A.D. and Hugo W.B. (1994). Antimicrobial activity and action of silver. *Prog. Med. Chem.*, **31**, 351e370.

Shahvalizadeh, R., Ahmadi R., Davandeh I., Pezeshki A., Seyed Moslemi S.A., Karimi S. and Mohammadi M. (2021). Antimicrobial bio-nanocomposite films based on gelatin, tragacanth, and zinc oxide nanoparticles-Microstructural, mechanical, thermo-physical, and barrier properties. *Food Chem.*, **354**, Article 129492.

Nwabor, O.F., Singh S., Ontong J.C., Vongkamjan K. and Voravuthikunchai S.P. (2021). Valorization of wastepaper through antimicrobial functionalization with biogenic silver nanoparticles, a sustainable packaging composite. *Waste and Biomass Valorization*, **12**, 3287-3301.

Swain, S.K., Dash S., Kisku S.K. and Singh R.K. (2014). Thermal and oxygen barrier properties of chitosan bionanocomposites by reinforcement of calcium carbonate nanopowder. *J. Mater. Sci. Technol.*, **30(8)**, 791–795.

Tomi´c, N.Z. (2020). Thermal studies of compatibilized polymer blends. *Compatibilization of Polymer Blends*, 489–510.

Wong, S., Shanks R. and Hodzic A. (2021). Properties of poly (3-hydroxybutyric acid) composites with flax fibres modified by plasticiser absorption. *Macromol Mater Eng.*, **287**. doi:10.1002/1439-2054(200211)287:10< 647::AID-MAME647>3.0.CO;2-4.

Yadav, M., Liu Y.-K. and Chiu F.-C. (2019). Fabrication of cellulose nanocrystal/silver/alginate bionanocomposite films with enhanced mechanical and barrier properties for food packaging application. *Nanomaterials*, **9(11)**, 1523.

Youssef, A.M. and El-Sayed S.M. (2018). Bionanocomposites materials for food packaging applications: Concepts and future outlook. *Carbohydr. Polym.*, **193**, 19–27. doi: 10.1016/j.carbpol.2018.03.088.

Youssef, A.M., El-Sayed S.M., El-Sayed H.S., Salama H.H. and Dufresne A. (2016). Enhancement of Egyptian soft white cheese shelf life using a novel chitosan/carboxymethyl cellulose/zinc oxide bionanocomposite film. *Carbohydrate Polymers*, **151**, 9–19.

Zhao, R., Torley P. and Halley P.J. (2008). Emerging biodegradable materials: Starch and protein-based bio-nanocomposites. *J. Mater. Sci.*, **43(9)**, 3058–3071.