Indian J Anim Health (2024), 63(2)- Special Issue: 62- 72
DOI: https://doi.org/10.36062/ijah.2024.spl.00324

Invited Review Article

Biodegradable packaging of food: An alternative to synthetic polymers for sustainable development

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Abstract

The drive towards sustainable packaging solutions is essential to address the environmental impacts of conventional synthetic polymers. This review explores the potential of biodegradable packaging materials derived from natural polymers, such as cellulose, starch, chitosan, alginate, carrageenan, collagen, and gelatin, as viable alternatives to traditional plastics. These biopolymers, sourced from renewable resources, exhibit significant technological and biological properties suitable for food packaging applications. Certain difficulties have been noticed in the development of biopolymer-based packaging materials, such as brittleness, low barrier properties, and mechanical strength. Advancements in blending techniques, hydrophobic substance incorporation and nanotechnology are progressively overcoming these commonly observed challenges. The historical evolution of food packaging highlights a shift from natural materials to synthetic polymers, with a recent resurgence in biobased materials due to their environmental benefits. Biodegradable packaging materials now play a critical role in extending the shelf life and enhancing the quality of food products. Innovations in active and smart packaging, including antimicrobial and antioxidant agents and real-time quality indicators, are transforming the food industry. However, the widespread adoption of biopolymers faces challenges such as cost, scalability, and market acceptance. Addressing these hurdles through ongoing research, regulatory support, and innovative processing techniques is crucial. Developing economically viable methods for large-scale production and establishing composting systems for proper disposal are essential steps towards mainstream integration. In conclusion, biopolymer-based packaging materials represent a significant advancement towards sustainable development. Continued progress in this field promises to establish biopolymers as foundational elements in food packaging, driving a global transition towards more sustainable practices.

Keywords: Biodegradable packaging, Biopolymers, Food packaging, Sustainable

Highlights

- Synthetic polymer is a challenge to sustainable development.
- Natural polymers have the potential to be utilised as a food packaging material.
- Innovations in packaging are transforming the food industry.

INTRODUCTION

Food packaging is a system specially designed for food, and it constitutes one of the most important parts of the industry involved in food handling. It was developed to protect against physical, chemical, and biological changes. The primary aim of food packaging is to provide a practical means of protecting and delivering food at an economical cost. However, current trends like sustainability and environmental impact reduction have gradually become the most important features in designing a packaging system. Sustainable packaging is designed, developed, and utilized to reduce harmful environmental impact. This approach involves using the minimum amount of materials, lowering energy consumption, and generating the least amount of waste (Escursell *et al.*, 2021). The

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India Packaging Market was valued at USD 128.91 billion in 2023 and is expected to reach USD 204.81 billion by 2025, with a CAGR of 26.7 percent from 2020-2025 (GlobeNewswire, 2020). Packaging consumption in India has surged by 200 percent over the last decade, growing from 4.3 kilograms per person per annum (pppa) to 8.6 kg pppa, according to the Indian Institute of Packaging (IIP) (TOI, 2023). India is adopting a comprehensive approach to packaging sustainability, covering multiple product categories beyond single-focus areas like beverages. The country is proposing regulatory measures for secondary and tertiary packaging, aiming for a holistic regulatory framework (McKinsey and Company, 2022).

Natural polymeric materials, including plant- or marine-based polysaccharides and proteins, are inherently biodegradable, meaning they can be decomposed by local microorganisms and reintegrated into nature. These natural polymers possess significant technological and biological properties, making them suitable for food packaging. Generally, these materials exhibit good film-forming and gelling properties, making them ideal for creating edible films and coatings. However, biopolymeric films often face processing challenges such as brittleness, low barrier properties against water and gases, and subpar mechanical strength inherent to their nature (Mohamed *et al*., 2020). To address these issues, incorporating hydrophobic substances or blending multiple biopolymers to create composites are viable solutions (Petkoska *et al*., 2021).

A recent OECD (Organisation for Economic Co-operation and Development) report projects that nearly two-thirds of plastic waste by 2060 will come from single-use and short-lived items, such as packaging, low-cost products, and textiles; without bold new policies, global plastics consumption could rise from 460 million tonnes in 2019 to 1,231 million tonnes in 2060 (OECD, 2022). A clear global strategy with targets, milestones, and structured mechanisms is needed to support sustainable packaging. The Government of India is collaborating with industry experts to maximize the packaging sector's potential. The Packaging Industry Association of India (PIAI) is developing regulations and guidelines to enhance India's export potential in the global market (PIAI, 2024). Adopting sustainable packaging can help brands attract younger generations, such as Millennials and Gen Zs, who are crucial for the future of the planet's resources (Lexicon, 2024).

India launched the India Plastics Pact in September 2021, the first of its kind in Asia, bringing together leading businesses to build a circular system for plastics. The pact aims to achieve several targets by 2030, including addressing unnecessary or problematic plastic packaging through redesign and innovation, making 100 percent of plastic packaging reusable or recyclable, recycling 50 percent of plastic packaging, and incorporating 25 percent recycled content across all plastic packaging (TOI, 2023). Recently, India imposed a ban on single-use plastic items, including straws, cutlery, earbuds, packaging films, and plastic sticks for balloons, candy, ice cream, and cigarette packets. This ban aims to tackle increasing levels of plastic pollution. To align with developed countries, India should introduce taxes on plastic packaging, incentivize the reuse and repair of plastic items, and implement extended producer responsibility (EPR) schemes. The government should also encourage the use of bioplastics, which produce fewer greenhouse gas emissions during manufacturing (Pani and Pathak, 2021).

Historical perspective

Food packaging has undergone significant evolution, beginning with ancient civilizations that used natural materials like wood, bamboo, shells, animal skins, leaves, grasses, jute, glass, and ceramics. Evidence of early pottery and glass for packaging dates back to around 7000 B.C. In the Mediterranean region, ancient ceramic jars called amphoras and glass pottery were used between 1500 B.C. and 500 A.D. for transporting wine, oil, and grains. Latin American indigenous populations used ceramic materials for food preparation and rituals around 1000 B.C. (Barreto and Oliveira, 2016). By 1200 B.C., glass pottery, cups, and bowls were created using limestone, sand, soda, and silica, with the Phoenicians' invention of the blowpipe in 300 B.C. improving glass production. The 17th-18th centuries saw the development of split molding, allowing for irregular shapes and decorations on glass packaging. Glass dominated the packaging market until the 1960s, despite metals being used during the Iron Age (500-332 B.C.) and becoming common in packaging with the advent of tin plating in 1200 A.D. (Welt, 2005). The Industrial Revolution in the 18th-19th centuries marked a significant advancement in packaging with Nicholas Appert's discovery of canning, improving food shelf-life and microbial resistance. This method was widely adopted, especially in the USA by the early 1900s. World War II led to the development of aluminium cans and various polymers, propelling the plastic packaging industry forward (Page, 2012).

Edible materials for food coating have historical roots, such as using animal intestines for sausages by Sumerians and Chinese settlers, and gelatin coatings for meat products patented in the USA in the 19th century. However, the dominance of synthetic plastics post-WWII overshadowed edible resources for packaging until recently (Mkandawire and Aryee, 2018). Post-WWII, plastic materials for food packaging advanced significantly, with the plastic industry expanding profoundly in the 21st century. Plastics improve food preservation and extend product shelf-life with advantages like low cost, solvent resistance, flexibility, lightweight, and moldability. From 1950 to 2015, cumulative plastic production exceeded 7.5 billion metric tons, with global production rising to 360 million tons in 2018. Around 40% of petrochemical-based plastics are used for packaging, with 60% utilized for food and beverages (Groh *et al*., 2019). Major food industries are now committing to reducing plastic waste and practicing a circular economy. Companies like Unilever®, Coca-Cola®, Keurig Dr Pepper®, PepsiCo®, and Mondelez® are making efforts to reduce virgin plastic use and increase recycled materials in packaging (AS YOU SOW, 2021).

Biobased packaging materials, derived from renewable resources such as plants, animals, microorganisms, seafood, woods, and agricultural residues, are biodegradable and compostable. These materials decompose into carbon dioxide, methane, water, inorganic compounds, or biomass, returning to nature (Intrado Globe Newswire, 2021). The global production of bioplastics, though still low, reached 2.11 million tons in 2020 and is expected to grow 15% by the end of 2024. The bioplastic market is projected to generate over $4.5 billion in 2019 and exceed $13 billion by 2027, with significant contributions from the Asia-Pacific region and Europe (Halonen *et al*., 2020). Despite high demand for biobased materials, challenges remain, such as improving legislation, revising industrial processes, ensuring product quality and biodegradability, and adjusting waste management systems for biobased plastics collection.

Types of biodegradable packaging materials

Different types of biodegradable packaging materials are presented in Table 1.

Polysaccharides:

Cellulose in food packaging: Cellulose, a linear polymer found in plants and some algae, is a crucial structural element composed of β-D-glucose molecules linked by β-(1-4) glycoside bonds (Hu *et al*., 2018). Abundant in nature, cellulose is present in plant cell walls, fruit and vegetable peels, wood, agricultural residues, and various algae (Liu *et al*., 2020). While indigestible by humans, cellulose is highly valuable in food packaging due to its low density, high durability, non-toxicity, biocompatibility, biodegradability, and excellent film-forming capabilities. Sources of cellulose include wood, sugarcane bagasse, cotton fibrils, and microorganisms, with bacterial cellulose being particularly pure but costly to produce. Plant-based cellulose is more economically viable for food packaging applications (Cazón and Vázquez, 2021). Despite its advantages, cellulose's hydrophilic nature poses commercial challenges. To overcome this, cellulose is often combined with other materials to enhance tensile strength, lipid resistance, and water barrier properties (Azmin and Nor, 2020).

Cellulose derivatives such as acetate, nitrate, sulfate, carboxymethyl, methyl, and ethyl nano-cellulose are used for their edibility, biodegradability, bioavailability, non-toxicity, lightweight, and pleasant organoleptic properties. These derivatives can be easily produced at a low cost and can incorporate active molecules like antimicrobials and antioxidants. Bacterial cellulose, known for its exceptional properties, is used in the food industry as a thickening and gelling agent, stabilizer, water-binding additive, and food packaging material (Cazón and Vázquez, 2021).

Table 1. Types of biodegradable packaging materials

Sl. No.	Class	Material
1	Polysaccharides	Cellulose
		Starch
		Chitosan
		Alginate
		Carrageenan
2	Proteins	Collagen
		Gelatin
3	Bio-based polymers	Polylactic Acid (PLA)
		Polyhydroxyalkanoates (PHAs)
4	Bioplastic composites	Formed from polymers like PLA,
		PCL [poly(ε-caprolactone)], or
		PVDC (polyvinylidene dichloride)

Starch in food packaging: Starch, a polysaccharide found in foods like potatoes, rice, maize, corn, and wheat, consists of two biopolymers: linear amylose and branched amylopectin (Shevkani *et al*., 2017). It is widely used in food packaging due to its excellent gas barrier properties, biodegradability, biocompatibility, edibility, and low cost. Common sources of starch include maize, cassava, wheat, and potatoes (Oyeyinka *et al*., 2021). Despite its benefits, starch is brittle and water-sensitive. These issues can be mitigated by incorporating plasticizers like glycerol and additives such as cellulose, gelatin, and citric acid

(Ni *et al.*, 2018). Advanced processing techniques and blending with synthetic biodegradable polymers like PLA (polylactic acid), PVA (polyvinyl alcohol), and PBAT (polybutylene adipate terephthalate) can further enhance its mechanical properties and moisture resistance. Starch-based films, which can be monolayer or laminated, benefit from the addition of nanomolecules like nano-clay or zinc (Vaezi *et al.*, 2019).

Incorporating antimicrobial agents and natural extracts into starch-based films extends the shelf life of packaged foods by controlling pathogen growth and improving resistance to spoilage. Starch-based films are used to package a variety of products, including fruits, vegetables, meat, and baked goods (Sganzerla *et al.*, 2020). Starch's abundance, low cost, and eco-friendly nature have increased research interest. Processing techniques such as extrusion and baking are used to create starch-based packaging materials with good oxygen barrier properties. These materials can also incorporate essential oils and other additives for extended shelf life. The technological properties of starch, influenced by its amylose/amylopectin ratio and crystallinity, are crucial for film formation and performance. Starch-based films are tasteless, colorless, and odorless, providing a sustainable alternative to conventional plastic packaging.

Chitosan in food packaging: Chitosan, a linear polysaccharide derived from chitin, consists of D-glucosamine and N-acetyl-D-glucosamine linked by β-(1→4) glycoside bonds. It is produced by treating chitin, found in crustacean shells, insect exoskeletons, and fungi cell walls, with sodium hydroxide. Chitosan is known for its antimicrobial and antioxidant properties, making it valuable in food packaging (Roy *et al.*, 2023). Chitosan films exhibit high biodegradability and biocompatibility but have limitations such as low water barrier properties. These can be improved by blending chitosan with other biomaterials, nanometals, and active compounds. For example, chitosan/gelatin films with essential oils show increased mechanical resistance (Roy and Rhim, 2021). Chitosan's ability to bind essential trace metals and stimulate the synthesis of chitinase enzyme enhances its antimicrobial action (Hafsa *et al.*, 2016).

Chitosan-based films are also used in agriculture, medicine, and other industries due to their versatility. In food packaging, they help extend the shelf life of various products, including mangoes and beef fillets, by inhibiting microbial growth and preserving sensory properties (Hiremani *et al.*, 2021). Chitosan's interactions with polyanionic biopolymers allow the formation of complexes used for encapsulating bioactive substances (González-Reza *et al.*, 2021). Recent studies have shown that blending chitosan with other materials, such as white turmeric starch or incorporating extracts like chokeberry pomace, can enhance its barrier properties and biodegradability (Pavinatto *et al.*, 2020). Chitosan films can also be modified to improve their mechanical and UV blocking properties, depending on the solvent and processing conditions used (Qiao *et al.*, 2021). Overall, chitosan's renewable sources, biological properties, and environmental friendliness make it an excellent choice for food packaging and other applications.

Alginate in food packaging: Alginates are salts of alginic acid, a hydrophilic polysaccharide found in brown algae. Common forms include sodium, potassium, and calcium alginate. Alginates form viscous gums capable of entrapping water molecules, making them useful in various industries (Xu *et al.*, 2021). Structurally, alginic acid is a linear copolymer consisting of β-D-mannuronate and α-L-guluronate residues (Chen, 2019). Primarily extracted from brown seaweeds such as *Macrocystis pyrifera*, *Laminaria digitata* and *Ascophyllum nodosum*, alginates are widely used due to their biodegradability, biocompatibility, and nontoxicity. Sodium alginate, in particular, is prevalent in food industries as a thickener and stabilizer.

Alginates' film-forming properties make them suitable for edible coatings, although they have drawbacks such as low UV resistance and sensitivity to microbial growth (Song *et al.*, 2021). Enhancements can be achieved by incorporating substances like aloe vera, frankincense oil, microcrystalline cellulose, silver nanoparticles, and lemongrass essential oil, which improve mechanical properties, moisture barriers, and antimicrobial activity (Juriḋ *et al.*, 2021). Alginate films are used in food packaging to extend the shelf life of products like green capsicum and apple slices by preventing senescence and microbial growth while retaining nutrients and surface color (Chen *et al.*, 2021). The industry of seaweed hydrocolloids, including alginates, has been growing, with significant production in China, Indonesia, the Philippines, Chile, Norway, and France (Günter *et al.*, 2020). Alginate solubility depends on factors such as G and M block distribution, solvent pH, ionic strength, and the presence of gelling ions. They form gels through ionotropic gelation, typically using multivalent ions like calcium, which create an "egg-box" structure by cross-linking with the G blocks (Agüero *et al.*, 2017). Additionally, alginates can form complexes with cationic polyelectrolytes such as chitosan to encapsulate bioactive substances (Juriḋ *et al.*, 2021).

Carrageenan in food packaging: Carrageenans are natural sulfated polysaccharides extracted from red seaweeds such as *Chondrus crispus*, extensively used in the food industry for their gelling, thickening, stabilizing, protective coating, and fat substitution capabilities. They are classified into three main types based on their chemical composition and properties: kappa-carrageenan forms strong gels with potassium ions, iota-carrageenan forms less rigid gels with calcium ions, and lambda-carrageenan is used for thickening dairy products without forming gels (Dong *et al*., 2021). Carrageenans are highly biocompatible, biodegradable, and non-toxic, making them suitable for food and pharmaceutical applications, with various biological activities like antioxidant and antimicrobial properties (Baghi *et al*., 2022).

Historically used since 400 A.D., carrageenans' first commercial use dates back to 1862 (Tavassoli-Kafrani *et al*., 2016). Their fast-growing nature and abundant availability have made them a sustainable source of food, pharmaceutical, and cosmetic products. Chemically, carrageenans consist of alternating units of 1,3-linked-β-D-galactopyranose and 1,4-linked-β-D-galactopyranose, with kappa- and iota-carrageenan containing 25–30% and 28-30% sulfate content, respectively. These properties make them ideal for film-forming solutions and suitable for edible films and coatings (Jancikova *et al*., 2020). Carrageenan films are used to replace animal casings in sausage making and as coatings for meat, fish, and poultry to prevent dehydration (Song *et al*., 2021). Recent studies have developed composite films with ingredients like sodium alginate and kappa-carrageenan, showing good mechanical properties and low water vapor permeability, making them suitable for food applications.

Proteins:

Collagen in food packaging: Collagen is a hydrophilic fibrous protein made up of amino acids like glycine, hydroxyproline, and proline, which make it highly soluble in polar liquids. This protein is prevalent in skin and connective tissues, constituting about 30% of the total mass of the human body (Nsengiyumva, 2023). Collagen fibrils are formed by collagen molecules that self-assemble in an orderly fashion on the cell surface, providing tensile strength to tissues. Collagen can be broken down by treating it with weak acids or alkalis. Its primary constituents are α and β chains, with molecular weights of 100 and 200 kDa, respectively, differentiated into covalently cross-linked chain pairs α1–α1 and α2–α2 (Thulasisingh *et al*., 2021).

Films made from hydrolyzed collagen at high concentrations produce more uniform surfaces. Collagen sausage casing is a commercially successful edible protein, often used as a substitute for natural gut casings due to its better mechanical properties and flexibility compared to cellophane. Collagen's oxygen permeability increases with relative humidity, but it provides excellent oxygen barrier properties at very low humidity levels (Jones and Whitmore, 1972). Cross-linking agents such as carbodiimide, microbial transglutaminase, or glutaraldehyde are used to improve mechanical properties, reduce solubility, and enhance film stability (Sommer and Kunz, 2012). When collagen film is used to wrap refrigerated beef, it reduces fluid loss without significantly affecting color (Takahashi *et al*., 1999). Collagen-based films are recommended for storing processed meats as they help reduce shrinkage, enhance juiciness, and absorb fluid exudate in baked meats. For producing biocomposite films, collagen fibers and powder are used, with the fibers providing reinforcement (Wolf *et al*., 2009).

Gelatin in food packaging: Gelatin, a peptide obtained from the partial hydrolysis of collagen, is primarily sourced from bovine and porcine bones and skins, as well as the connective tissues of poultry and fish. It is highly valued in the food industry for its gelling, stabilizing, emulsifying, foaming, and micro-encapsulating properties. Gelatin-based films offer high mechanical and functional performance but have poor water barrier properties, which can be enhanced by adding plasticizers, cross-linking agents, and blending with other biopolymers like soy protein, oils, fatty acids, and specific polysaccharides (Roy and Rhim, 2020). Incorporating antioxidant and antimicrobial agents further improves these films' properties (Panou and Karabagias, 2023) as does the addition of functional nanoparticles like quercetin, lactoferrin, and chitosan nanofibers (Tavassoli *et al*., 2021).

Gelatin is a translucent, water-soluble protein, and its properties are influenced by the initial collagen source and the extraction process, which involves breaking down collagen using heat, acid, or alkali. Gelatin is categorized as Type-A or Type-B based on the extraction method, with Type-A derived from acid-treated collagen and Type-B from alkali-treated collagen (Gómez-Guillén *et al*., 2011). The quality of gelatin is determined by its physicochemical characteristics, including solubility, transparency, and composition, as well as its liquidity and solidity. Gelatin films are used to preserve food by preventing oxygen exposure and spoilage during transportation, thereby enhancing shelf life. The addition of materials like plasticizers, crosslinkers, and antioxidants can further enhance their functional properties (Ortiz Zarama *et al*., 2016). Antimicrobial agents such as essential oils, organic acids, and bacteriocins are also incorporated into gelatin films to extend the shelf life of food. These films are effective in reducing microbial growth and improving food quality, as demonstrated in studies involving chicken, pork, and fish products (Lee *et al*., 2016). Gelatin coatings are also used to preserve fruits and vegetables, enhancing their mechanical properties and shelf life. For example, a mixture of starch, gelatin, and glycerol coated over grapes improves mechanical strength, while sunflower oil packaged in gelatin film without artificial antioxidants can be stored for up to 35 days at 35°C (Kanmani and Rhim, 2014). Researchers continue to explore new materials and techniques to enhance the properties of gelatin-based films for food packaging applications.

Bio-based polymers:

Polylactic acid (PLA) in food packaging: Polylactic acid (PLA) is a notable biopolymer made from renewable resources such as sugar feedstock and corn through the fermentation process that produces lactic acid monomers. These monomers are polymerized to create PLA, which is used in film packaging due to its high molecular weight, transparency, resistance to water solubility, and excellent processing capabilities. PLA is a copolymer of poly-L-lactic acid and poly-D-lactic acid. Enhancements in PLA properties are achieved by blending it with organoclays through processes like hot chloroform dissolution in dimethyl distearylammonium, resulting in nanocomposites. For instance, PLA layered silicate nanocomposite membranes (PLSNM) exhibit decreased gas permeability and improved oxygen barrier properties, especially when combined with Cloisite30B (Koh *et al*., 2008).

PLA's biodegradability is a key focus, breaking down through steps such as water uptake, ester bond hydrolysis, and eventual decomposition into CO2 and H2O (De Jong *et al*., 2001). Nanocomposites degrade faster than pure PLA due to the hydrophilic filler content, as demonstrated by studies measuring lactic acid release or mass change during hydrolytic degradation (Nieddu *et al*., 2009). Commonly used in packaging for beverages and various foods, PLA's advantages include high mechanical resistance, non-toxicity, biodegradability, renewability, high sealability at low temperatures, and low energy consumption and carbon emissions. However, PLA faces challenges such as high brittleness, weak gas barrier properties, low heat resistance, and high cost (Jabeen *et al*., 2015). These issues can be mitigated by blending PLA with cellulose or adding nanofillers like talc, silica, plasticizers, nanoclays, carbon nanotubes, and starch (Balla *et al*., 2021). Additionally, incorporating essential oils like thyme, rosemary, and oregano into PLA-based packaging materials can extend the shelf life of fresh products like rainbow trout from 4 to 6 days (Zeid *et al*., 2019).

Polyhydroxyalkanoates (PHAs) in food packaging: Polyhydroxyalkanoates (PHAs) are biopolymers produced through bacterial fermentation, and some of them are most widely used due to their similarities to traditional plastics (Sathya *et al*., 2018). Short-chain-length PHAs (sCL-PHAs) exhibit less flexibility and elasticity compared to medium-chain-length PHAs (mCL-PHAs), which possess better mechanical properties and crystallinity (Li *et al*., 2016). PHAs are highly biodegradable, making them ideal for packaging perishable foods and medical applications such as implants and bone plates. They are classified based on the number of carbon atoms in their repeating units: sCL-PHAs, mCL-PHAs, and long-chain-length PHAs (lCL-PHAs) (Vandi *et al*., 2018).

PHAs are synthesized from substrates with high carbon content and low nitrogen levels through bacterial fermentation, involving multiple metabolic pathways and enzymes (Costa *et al*., 2019). Despite their biodegradability, PHAs have limitations like brittleness, thermos-sensitivity, and limited malleability (Gumel *et al*., 2014). These issues can be improved by incorporating materials such as carbon nanotubes, nanoclays, cellulose, and metal oxides (Keskin *et al*., 2017). PHB (Polyhydroxybutyrate), commonly used in food packaging and medical fields, effectively controls microbial growth when combined with antimicrobial agents (Solaiman *et al*., 2015). However, PHB tends to become brittle over time, a drawback mitigated by adding co-monomers or plasticizers. Developed in the 1970s, PHBV [Poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate)], a copolymer of PHB, enhances these properties but remains costly and challenging to process due to crystallization kinetics. Adding hydroxyl valerate to PHBV improves its thermoplastic processability and mechanical stability, lowering the melting temperature and broadening its application potential (Narayanan *et al*., 2013).

Bioplastic composites:

Bioplastic composites involve the combination of a matrix binder with reinforcing agents to enhance material properties. Natural fibers, such as glass, carbon, aramid and natural fibers like nylon and polyester, are commonly used due to their biodegradability, renewability, and cost-effectiveness. Coating bioplastics can significantly improve their barrier properties, tensile strength, and elasticity by applying thin layers of polymers like PLA, PCL [poly(ε-caprolactone)], or PVDC (polyvinylidene dichloride). For instance, PLA coatings can enhance the strength and elongation of soy protein isolate films, while reducing water vapor permeability (Peelman *et al*., 2013). Nanocomposites, which incorporate nanoparticles into the matrix, can be classified based on their dimensional structure: polymer layered crystal nanocomposites, nanotubes or whiskers, and isodimensional nanoparticles (Jamshidian *et al*., 2010). These composites, particularly those using nanoclays, can form structures ranging from tactoid to exfoliated, depending on the interaction strength between the matrix and fibers. Methods like melt intercalation and solvent intercalation are used to integrate these nanoparticles into the matrix, enhancing properties like elongation at break, barrier properties, and thermal stability (Peelman *et al*., 2013). Projects like EcoPlast utilize natural fibers and biodegradable polymers to create composites with varying particle sizes and shapes, adapting their dispersion through chemical modifications. Adding cellulose to bioplastics further improves properties like water vapor permeability, Young's modulus, tensile strength, and elongation at break due to its crystalline and hydrophobic nature (Costa *et al*., 2023).

Applications in food packaging and environmental impact

Biodegradable packaging materials are increasingly used in the food industry to extend shelf life and enhance the quality of various products, including meat, seafood, dairy, and fresh produce. These materials control gas flow and prevent color changes in meat products while incorporating antimicrobial and antioxidant agents to slow microbial contamination and oxidation (Sanches *et al*., 2021). Examples include starch/whey protein films with natural antioxidants for meat, whey protein films with essential oils and nanoparticles for lamb and κ-carrageenan films with botanical extracts as spoilage indicators for shrimp (Sani *et al*., 2017). For seafood, temperature-sensitive and smart packaging materials provide quality status indicators, enhancing protection and monitoring during storage (Wu *et al*., 2017).

In the dairy sector, active packaging with antimicrobial substances, such as sodium alginate films with lemon extract for mozzarella, and smart packaging with pH-sensitive indicators for milk, improve product safety and shelf life (Karaman *et al*., 2015). Similarly, for fruits and vegetables, active packaging with nanoparticles and essential oils delays ripening and prevents microbial growth, as seen with tomatoes and apples (Liu *et al*., 2017). Advances in preparation techniques like electrospinning, nanotechnology, and 3D printing further enhance the barrier, mechanical, and antibacterial properties of starch-based biodegradable materials, offering promising prospects for commercial applications. These materials not only extend food shelf life but also introduce intelligent features for freshness monitoring and targeted release of functional ingredients, paving the way for innovative and sustainable food packaging solutions (Sganzerla *et al*., 2021).

Biodegradable bioplastics can decompose into natural materials through microbial mechanisms and blend harmlessly into the soil (Alshehrei, 2017). It has been scientifically established that during the biodegradation of PLA bioplastics, there is no net increase in carbon dioxide gas, this can be justified by the fact that the plants from which they were produced absorbed the same amount of carbon dioxide when they were cultivated as was released during their biodegradation (Elsawy *et al*., 2017). Studies have also reported that substituting traditional plastic with corn-based PLA bioplastics can reduce greenhouse gas emissions by 25% (Sabbah and Porta, 1997).

Challenges and future directions

Biopolymer-based materials offer significant sustainability benefits, being derived from renewable resources and biodegradable through natural processes, thus reducing environmental impact. These materials are gaining attention in the food packaging industries due to their lower carbon footprint and energy efficiency compared to conventional plastics (do ValSiqueira *et al*., 2021). In the food packaging sector, biopolymers are used to extend shelf life, improve food safety, and provide real-time quality indicators. Active and smart packaging materials containing natural antioxidants, antimicrobials, and sensors are being developed to protect perishable items like meat, dairy, fruits, and vegetables, thereby reducing food waste (Sani *et al*., 2021).

Despite their potential, biopolymers face challenges such as balancing biodegradability with durability, achieving cost-effective large-scale production and improving market acceptance. Research is ongoing to improve the mechanical, thermal, and barrier properties of biopolymers, including through the use of nanotechnology and innovative structural designs. Developing economically viable processing methods for mass production and establishing composting systems for proper disposal are critical for the widespread adoption of biopolymers. With continued advancements, biopolymers are poised to become a cornerstone of sustainable practices in food packaging industries

(Panou and Karabagias, 2023). The authors are of the opinion that a continued exploration in the field of biodegradable packaging material will provide a suitable alternative to plastics, and one day, the biggest packaging menace, i.e. plastic, will be replaced with new packaging material derived from renewable sources.

Conclusion

The shift towards sustainable development in food packaging is imperative to mitigate environmental impact and meet growing consumer demands for eco-friendly solutions. Biodegradable packaging materials derived from natural polymers, such as cellulose, starch, chitosan, alginate, carrageenan, collagen and gelatin, offer promising alternatives to synthetic polymers. These biopolymers not only decompose naturally without releasing harmful by-products but also possess significant technological and biological properties suitable for food packaging. The challenges in the development of biopolymers, such as brittleness, low barrier properties and mechanical strength are suitably addressed by advancements in trending packaging technologies. Looking at the current scenario of extensive use of synthetic materials, especially plastics in food packaging, we are in a grave situation to explore the alternative of plastic as it is the biggest challenge to the environment nowadays. In conclusion, biopolymer-based packaging materials represent a pivotal step towards sustainable development, balancing environmental stewardship with functional performance. Continued advancements in this field promise to establish biopolymers as foundational elements in food packaging, driving a global transition towards more sustainable practices.

Conflict of interest: Authors declare that they do not have any conflict of interest.

Author's contributions: PKS, NA, NS: Drafted this manuscript; AS, AKN, SY, RS: Supported in writing the text and referencing; SS, AG: Proof reading and final editing of the manuscript.

Data availability statement: No specific research data was used for the review article and information is compiled from the available literature.

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Received- 26.07.2024, Accepted- 19.11.2024, Published- 01.12.2024 (Print)
Section Editor: Prof. C. Debnath, Editorial Board Member