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From concept to shelf: engineering biopolymer-based food packaging for sustainability

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Food packaging plays a crucial role in preventing food spoilage, preserving food quality, minimising food waste, and ensuring food safety. However, the most widely used petroleum-based packaging has environmental and health concerns, which restrict its use. Thus, there is a need for more sustainable options. A viable solution can be the utilization of eco-friendly biopolymers as a substitute for traditional petroleum-based packaging. The primary objective of biopolymer-based food packaging, besides ensuring food safety and quality for consumers, is to address health as well as environmental concerns and reduce negative impacts. However, biopolymer-based materials have certain drawbacks, such as weak mechanical strength and moisture resistance. Thus, it is essential to thoroughly assess the difficulties in employing biopolymers in the food packaging sector and explore strategies to mitigate or eliminate their drawbacks. These challenges can be resolved by the incorporation of some bioactives, functionalization of biopolymers, and using nanotechnological approaches that can upgrade the performance of packaging. New food packaging materials are highly biodegradable and biocompatible, possess appropriate mechanical and thermal strength, and can monitor the real-time freshness of food products. This review provides insightful information about biopolymers that can potentially replace plastic-based packaging in an eco-friendly manner, their origin, functionality, and functionalization using different approaches (blending/composites/edible films/edible coatings/indicators/nanocomposites/nanosensors). The application of biopolymers in various food sectors for enhancing the preservation and packaging is also discussed. Moreover, the integration of SWOT and PESTEL analyses provided here highlights the eco-friendliness and biodegradability of biopolymer packaging as strengths, while their challenges include price, moisture sensitivity and mechanical stability. PESTEL analysis reveals strong political and environmental support for sustainable packaging, but economic scalability and technological roadblocks remain chief obstacles.

Sustainability spotlight

Single-use plastic is globally banned due to its health and environmental concerns. There is a pressing need to utilise natural resources for packaging materials. Biopolymer-based packaging is gaining attention due to its natural, high biocompatibility, biodegradability, non-toxicity, and eco-friendly attributes. Biopolymers (derived from waste) and their active packaging incorporated with natural antimicrobials/antioxidants/plant extracts reduce food spoilage, greenhouse gas emissions and finally play a key role in waste valorization and achieving a circular economy. This review aligns with the BioE3 policy and United Nations Sustainable Development Goals, particularly SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 12 (responsible consumption and production), SDG 13 (addressing climate change), SDG 14 (sustainable use of marine resources), and SDG 15 (protecting terrestrial ecosystems).

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1. Introduction

Annually, approximately one-third of the world's food is either discarded or lost, with its monetary value estimated at $936 billion, excluding the associated social and environmental expenses.[1] Simultaneously, data from 2020 indicate that 811 million individuals face hunger, while 3 billion individuals cannot afford nutritious food around the globe.[1,2] As the global population grows, the demand for food increases accordingly. Reducing food losses could potentially alleviate malnutrition for nearly one-eighth of the world's population, helping to better cope with rising future food needs.[2] Therefore, it is

Table 1 Diverse problems and challenges related to food packaging materials

Type	Problem and challenges	Remarks
Choice of materials	Restricted choices for eco-friendly materials	Sustainable options to plastics, meeting barrier needs and safety standards
	Suitability of components for packaging various food products	Chances of substance migration/chemical seepage impacting food quality and safety
	Biodegradable materials: Price and accessibility	Costly and hardly accessible biodegradable alternatives, particularly for small producers
Environmental concerns	Single-use plastics	Excessive reliance on plastics results in pollution (oceanic habitats)
	Biodegradability concerns	Certain biodegradable substances do not break down efficiently in natural environments or typical landfill sites
	Restrictions of recycling	Difficulties in recycling layered packaging materials and certain types of plastics
	Carbon footprint	Elevated carbon emissions due to production and transportation of conventional packaging materials (plastics and metals)
Food safety	Barrier attributes for preserving food	Ensuring proper barrier attributes (against moisture/light/oxygen) to extend shelf life can be difficult with non-plastic components
	Transfer of dangerous components to food	Preventing packaging components from releasing harmful substances under various storage conditions
	Contamination risk	Physical, biological, or chemical contaminants can infiltrate through packaging
Consumer expectations	Ease *versus* sustainability	Balancing convenient packaging (single use, resealable type) with sustainable practices
	Request for clarity and data	Growing consumer demand for transparency in packaging, ingredients, and sustainability
	Reducing food waste	Ensures that packaging reduces food waste by modifying portion size, enhancing preservation and reducing environmental impact
Customer safety issues	Tamper-evidence and counterfeiting	Packaging with tamper evidence and anti-counterfeit features for a global market
	Existence of chemicals/allergens in packaging	Prevent packaging from unintentionally adding allergens or harmful chemicals to food
Technology and innovation	Expense of advanced packaging technology	Expense of smart packaging (RFID and nanotechnology) limits accessibility for small-medium-sized businesses
	Evaluation and verification of innovative methods	Thorough testing crucial to ensure safety, quality, and effectiveness of new methods
	Restricted advancements in conventional industries	Gradual adoption of sensors, smart packaging, and various novel solutions in conventional food industries
Cost management	Cost of compliance	Costs of meeting packaging tests, certifications, and standards
	Cost of technological integration	Cost of integrating technologies such as RFID/QR codes/smart sensors
	Expensive sustainable packaging options	Increased expenses of environmentally friendly, recyclable, or reusable options over conventional materials
Regulatory compliance	Labeling needs	Labeling compliance (*e.g.*, nutrition, allergen) varies by region and product category
	Compliance with various international standards	Managing diverse packaging rules and standards across countries (*e.g.*, US FDA, EU) on food safety and labeling
	Adapting rules	Regular monitoring and modifications to packaging methods are necessary due to frequent updates
Logistics and storage	Strength during shipping	Ensuring packaging withstands transport without affecting food quality and safety
	Space efficiency	Enhancing packaging design for space efficiency and reduced component use
	Storage durability	Packaging must maintain food stability despite temperature and humidity changes in supply chain

Table 1 (*Contd.*)

Type	Problem and challenges	Remarks
Supply chain issues	Access to eco-friendly resources	Changes in the availability of sustainable or recycled raw materials influence production
	Supply chain disruptions	Global disturbances (*e.g.*, geopolitical issues, natural calamities) impact availability and cost of imported packaging materials
	Tracking capabilities	Challenges in tracking food items throughout the supply chain with conventional packaging
Product integrity	Stopping product interference	Ensuring security against tampering during transit and display
	Prolonging shelf life compared to natural preservatives	Balancing natural preservatives use with shelf life extension by advanced packaging techniques
	Safeguarding the product throughout its shelf life	Packaging needs to shield against biological, physical, chemical threats by keeping product fresh
Waste management	Absence of effective disposal and recycling systems	Lack of disposal and recycling systems for food packaging waste in many areas
	Consumer attitudes about recycling	Challenges in motivating consumer involvement in proper waste disposal and recycling programs
	Handling post-consumer packaging waste	Managing and recycling waste from multi-layered and composite packaging

crucial to lessen food loss and waste to ensure food security worldwide. The most common methods for reducing food loss and waste include the packaging and preservation of food. Packaging plays a vital role and serves as a facilitator in contemporary food systems. The primary objectives of packaging involve ensuring safety, preserving the quality, and prolonging the lifespan of packaged products, shielding them from environmental, microbial, chemical, and physical threats during storage and transit.[1] They offer physical defense and serve as a remarkable barrier, providing the necessary mechanical and optical properties to achieve a satisfactory shelf life by preserving the quality and safety of packaged products.[2] Accordingly, nearly every food item undergoes packaging at least once on its journey from the farm to the consumer. The specifications for a food product are greatly affected by the packaging type, which includes elements such as construction, design, and materials utilized.[3] The widely used packaging materials are paper, glass, plastic, metal, various types of cardboard, and composite substances that contain more than one substance, such as cardboard coated with plastic.[4] However, food packaging face severe issues related to environmental sustainability, production, consumer expectations, regulatory compliance and complexity of balancing food safety, as highlighted in Table 1.[1–5] Therefore, thoroughly assessing the properties of these materials is crucial in creating packaging that fulfils its intended function effectively. These properties include attributes such as barrier against gases (such as water vapor, carbon dioxide, oxygen, *etc.*), aroma, lightness, fat, migration, physical and mechanical strength, along with hygiene, which are greatly influenced by the nature of the material itself.[5]

1.1 Global plastic crisis and food packaging

Plastics can be categorized into two main classes based on their source, petroleum and bio-based plastics. Currently, petroleum-based plastics are frequently used because of their lightweight, low cost, ease of transport, flexibility, wide accessibility, excellent mechanical and barrier properties, and rapid production capability.[6] The most commonly used materials are polyethylene, polyolefins, polyethylene terephthalate, and polypropylene, which have different properties.[6,7] Similarly, the production of bioplastics is expected to increase from 2.11 million tons in 2020 to 2.87 million tons in 2025. Some plastics last less than a year, while others can persist for over 15 years.[8] Consequently, many materials used for packaging are neither biodegradable nor compostable, leading to prolonged environmental pollution in soil and water.[9] Although the suitability of plastics is quite good, their environmental impact, careless handling of raw materials, packaging waste with limited recyclability and biodegradability, microplastics, marine litter, and use of fossil resources are major drawbacks, which have been discussed in public and political debates in recent years.[10] Furthermore, plastics significantly impact global greenhouse gas emissions. In 2019, they accounted for 1.8 billion tons or 3.4% of total emissions. Most of these emissions (90%) originate from fossil fuel-based production and transformation. By 2060, emissions are expected to exceed 4.3 billion tons.[11,12]

The packaging industry is the biggest plastic consumer, accounting for around 40%. In the EU, single-use plastic packaging makes up 60% of plastic waste, but its poor recycling impacts solid waste and the land and marine environments.[13] Between 2009 and 2019, the per capita packaging waste increased from 27 to 35 kg. The EU is addressing these issues through strategies such as circular and bioeconomies to enhance the resource efficiency *via* innovation and research.[14] The circular economy focuses on the 4R concept (reduce, reuse, recycle, recover), asserting that sustainable resource production and consumption should be prioritized when proven more eco-friendly than traditional petrochemical plastics.[15] India, USA, Canada, Taiwan, Belize, and Costa Rica have banned single-use plastics, including plastic cutlery, bags, and straws, to reduce plastic waste.[16] Thus, a big challenge for society is to minimize

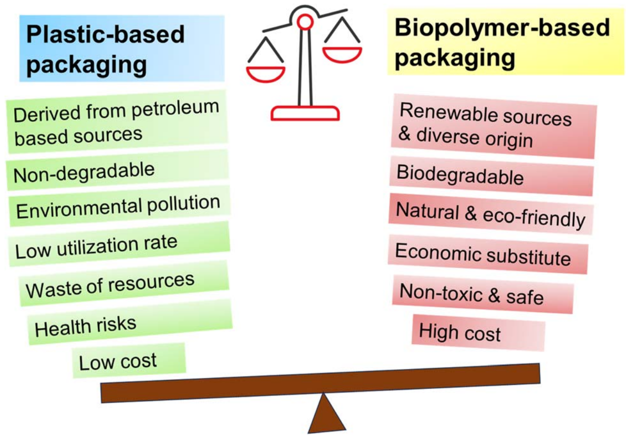

Fig. 1 Comparative analysis of plastic packaging and biopolymer-based packaging.

durable, non-biodegradable packaging materials such as plastics, glass, and metal, and find new alternatives (Fig. 1). Research is ongoing for viable options with suitable packaging characteristics, aiming to reduce waste with eco-friendly systems.[17]

1.2 Biopolymers as a sustainable alternative

Increasing worries about the environmental concerns of plastics have led to studies on alternative materials for food packaging. Biopolymers are excellent renewable and biodegradable materials for packaging, which are derived from agricultural or biomass feedstock.[10] They degrade quickly by natural microorganisms under optimum temperature, oxygen, moisture, and soil conditions, offering enhanced physical and mechanical properties that rival standard plastics.[18] Furthermore, they are biodegradable, biocompatible, renewable, safe, and eco-friendly (Fig. 1). However, despite their advantages, these materials are less commonly used in food packaging due to their higher cost, weaker mechanical properties, and greater gas permeability than traditional polymers.[19] Various approaches, such as altering chemical structures and incorporating inorganic and organic substances, have been investigated to enhance the physicochemical characteristics of biopolymers, which will be addressed subsequently (Section 3).[20]

Food waste and food loss are significant problems that need to be resolved. This review serves as a step forward in the preservation and packaging of food that mitigate food losses with sustainable and green solutions such as biopolymer-based packaging. Here, the data has been collected from different databases (such as Scopus, PubMed, Google Scholar, Web of Science, Science Direct, and Mendeley Databases) by searching various keywords. The keywords used are as follows: food waste, conventional strategies, plastic-based packaging, biodegradable, biodegradable packaging, bio-based packaging, biopolymers, polysaccharides, proteins, lipids, green packaging, sustainable materials, bioactive compounds, active packaging, smart packaging, environmental impact, circular bioeconomy, waste recovery, PESTEL analysis, and food applications, to gather a commendable amount of data, intending to promote the applications of biopolymers for food packaging and preservation in the future.

This review offers a brief, yet critical overview of biopolymers, their origin, advancements, and their functionalization related to food packaging. The novelty associated with this review is that it provides inclusive insight depicting the applications of biopolymers (including natural, synthetic, and microbials), edible films/coatings, antimicrobials, antioxidants, scavengers, nanocomposites, nanoparticles, nanofillers, and nanosensors for preserving and packaging different food products (fruits, vegetables, bakery, confectionary, meat, seafood, dairy, and beverages), typically reported in the last 5 years, in a single frame. A life cycle analysis, SWOT analysis, PESTEL analysis, and the integration of these analyses are also provided herein, which depict the benefits, challenges, and political, economic, social, technological, and legal analysis of biopolymer-based packaging. It should be highlighted here that the formulation of this type of packaging based on biopolymers aligns with the United Nations Sustainable Development Goals (SDGs), particularly focusing on SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), SDG 12 (minimize waste through prevention, reduce, recycle, and reuse), SDG 13 (addressing climate change), SDG 14 (preserving marine life), and SDG 15 (protecting terrestrial ecosystems). This work also aligns with the BioE3 policy and circular economy for fostering high-performance biomanufacturing, promoting food security, and sustainability that improves sustainable cities and responsible consumption.

2. Biopolymers for food packaging

2.1 Definition and classification

Biopolymers are naturally degradable through microbial action under appropriate environmental conditions such as oxygen availability, humidity, temperature, and presence of living creatures. Also, their synthesis process is eco-friendly and leaves no harmful residues.[21] They are considered among the most promising materials for applications in food packaging.[22] Nonetheless, they typically show low barrier properties, mechanical properties, processing capabilities, and relatively higher costs than conventional petroleum-based materials.[23] Specifically, their high permeability to gases and vapors, brittleness, low heat-distortion temperature, and limited resistance to extended processing operations significantly restrict their industrial use.[24,25]

Accordingly, various methods have been devised to enhance the attributes of biopolymer-based packaging substances by modifying the chemical structure of polymers and adding inorganic or organic compounds.[26] Modification of the chemical structure of biopolymers can occur through block-copolymerization, which involves the sequential growth of polymers composed of varying segments by post-polymerization modification of functional groups along their backbone.[27] Other approaches for enhancing the biopolymer attributes include the addition of plasticizers, antioxidants, antimicrobials, and nanomaterials, and blending with other biopolymers.[28] Their physical and mechanical attributes can also be improved by employing both natural and synthetic nanofillers. By utilizing polymer matrices and fillers sourced from renewable resources, fully biodegradable nanocomposites can be created.[23]

2.2 Sources of biopolymers

Biopolymers are sourced from animals, plants, marine organisms, food waste, or microbes, including starch, proteins, peptides, DNA, and RNA.[23] Biobased polymers are derived from renewable resources and classified into three main categories based on their origin and synthesis methods including natural (*e.g.*, lipids, polysaccharides, and proteins),[29] synthetic (*e.g.*, aliphatic and aromatic polymer), and microbial biopolymers (*e.g.*, polyesters, carbohydrates, and bacterial cellulose),[29] as shown in Fig. 2. Based on their origin, biopolymers are also divided into two categories, plant-based (starch, cellulose, pectin, *etc.*) and animal-based biopolymers (chitosan, gelatin, *etc.*).[30]

2.2.1 Natural biopolymers. Natural biopolymers are polysaccharides, proteins, and lipids derived from animals or plants. Polysaccharides are prevalent and plentiful types of biopolymers derived from natural resources such as marine plant fibers/crustaceans. They are lengthy chains of monosaccharides linked by glycosidic bonds. They are cost-effective, eco-friendly, non-allergenic, and biodegradable, and due to these properties they have swiftly emerged as the top choice as surface coating agents. Their application as innovative packaging materials has increased due to their widespread availability, ease of access, and non-toxic nature.[31] Packaging materials based on polysaccharides demonstrate superior CO_2 and O_2 barrier attributes, which can efficiently slow down the food respiration rate and potentially prevent the proliferation of bacteria/pathogens/molds inside the packaging.[32] However, one disadvantage is that they poorly block water vapor. The most used polysaccharides are chitosan, cellulose, agar, starch, gum, carrageenan, pullulan, pectin, alginate, *etc.*[31] Chitosan, starch, and cellulose are widely utilized as polymeric substances in food packaging due to their abundant availability and cost-effectiveness.[18] Biopolymers such as starch and cellulose have poor water vapor barrier attributes due to their hydrophilic nature. This element weakens biopolymer films and reduces their durability, exposing them to moisture.[33]

Proteins are crucial for enhancing the rheological characteristics needed for surface coatings and aiding in successful film formation due to their varying functional properties.[7] They are sourced from both animals (collagen, whey, casein, and gelatin) and plants (wheat gluten, soy, and corn zein). Similar to carbohydrate-based biopolymers, they are biodegradable, readily available, and can serve as carriers to integrate other polymers and functional agents (such as antimicrobial agents).[34] They also have outstanding film-forming abilities, and due to their structured and compact network of hydrogen bonds, these films provide effective oxygen barriers attributes. Their potential has sparked increasing attention toward their use as biopolymers in food packaging applications. However, their hydrophilic nature and high susceptibility to moisture result in insufficient resistance to water vapor.[35] The most used proteins are zein, gelatin, whey, casein protein, soya, casein, gluten, peanut, collagen, *etc.* The flexibility of protein-based coatings and films is essential for preserving the quality of food and increasing its shelf life.[34]

Lipid compounds are increasingly appealing as biopolymer materials for edible food packaging. Their commercial application as preservative coatings for fresh produce started in 1930.[36] Compared to biopolymers based on polysaccharides and proteins, lipid compounds offer superior water vapor barrier attributes and environmental stressor defense due to their hydrophobic nature, although they have poor mechanical and oxygen barrier attributes.[17,36] The inherent water-repellent traits of lipids create a robust layer that considerably limits moisture penetration, which aids in decreasing the water loss in perishable foods, and thereby extends their shelf life. Thus, they can be blended with other polymers, such as polysaccharide materials, to boost their mechanical attributes.[37] Additionally, some lipid-based biopolymers play crucial roles as emulsifiers and surface-active agents. Nonetheless, lipid coatings, although beneficial, are susceptible to oxidative rancidity given that they come into contact with atmospheric oxygen, leading to unfavorable sensory traits.[31,38] Additionally, lipids do not possess natural film-forming abilities or adhesive qualities, restricting their direct use on certain food surfaces. These drawbacks can

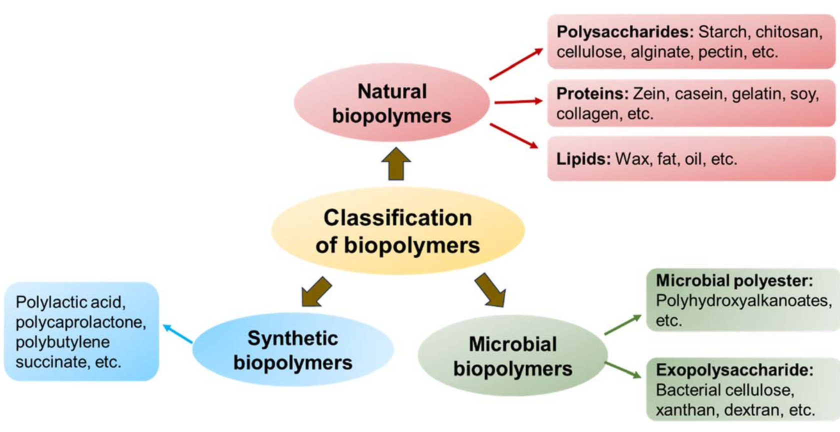

Fig. 2 Major classification of biopolymers.

be addressed by blending lipids with other biopolymers and fillers, which enhance their ability to form films, adhere, and become more flexible. The most used lipids are waxes, vegetable oils, fatty acids, *etc.*[38]

2.2.2 Synthetic biopolymers. Synthetic biopolymers are typically manufactured *via* chemical processes using biological monomers and various condensation or ring-opening polymerization methods. These substances encompass aliphatic-aromatic copolymers (polybutylene adipate-*co*-terephthalate, polyglycolic acid, polyester amides, and polybutylene succinate-*co*-butylene adipate), aliphatic polyesters, polylactides, and aliphatic copolymers, all of which are derived from renewable biobased monomers such as poly lactic acid (PLA), as well as oil-based monomers.[39] PLA is a highly promising biobased polymer due to its accessibility, confirmed ability to be recycled and composted, and potential to substitute traditional plastic materials; however, it exhibits poor mechanical and barrier characteristics.[40]

2.2.3 Microbial biopolymers. Microbial biopolymers are composed of polymers formed by bacteria or microorganisms that have been genetically altered. Microbial polymers are polyesters (polyhydroxybutyrate (PHB), polyhydroxyalkanoates (PHA), and polyhydroxybutyrate-valerate (PHBV)), carbohydrates (curdlan and pullulan), natural polymers (PLA), and bacterial cellulose.[41] An example of polyester, PHA, is created by fermenting sugars and lipids with bacteria. PHA polyester is biodegradable, biocompatible, and derived from renewable sources. Generally, PHA polymers show strong resistance to UV rays, are water-insoluble, somewhat resistant to hydrolytic damage, dissolve in chloroform and chlorinated hydrocarbons, and are non-toxic.[42] Nevertheless, PHAs exhibit limited resistance to acids and bases. These materials are promising given that they could potentially compete with traditional plastics derived from fossil fuels in the food packaging sector, owing to their water-repellent characteristics and the flexibility of their mechanical attributes.[43]

2.3 Key attributes of biopolymers for food packaging

The properties of materials must be assessed before choosing a specific material for packaging. The choice is influenced by barrier, chemical, thermal, mechanical, ecological, and economic criteria (as discussed in Table 1). All these attributes are crucial for extending the quality and shelf life of food products.[44] The major properties of food packaging materials and their benefits are depicted in Fig. 3. Packaging materials should be biodegradable, non-toxic, and suitable for direct contact with food. Also, they should have the ability to bend or stretch without cracking.[12] The main physicochemical and functional properties for food packaging are described below.

2.3.1 Barrier properties. The barrier characteristics of a biopolymer utilized in food packaging are crucial for prolonging the shelf life of the packaged food item.[45] Barrier attributes such as gas, water vapor, organic vapor, and moisture permeability, UV barrier, and liquid barrier are vital for isolating food products from the external environment.[46] Barrier functions against gases are crucial in choosing materials for food packaging. A lack of sufficient barrier in packaging can result in the rapid spoilage of its contents, such as the oxidation of vulnerable fatty foods due to insufficient oxygen protection, or the early wilting of lettuce because of inappropriate water vapor barrier.[47] Thus, it is crucial to prevent oxygen and moisture exchange to ensure effective food packaging, which affects the taste, odor, quality, appearance, marketability, and shelf life of food. The barrier attributes of materials depend on the transmission rate, permeability, permeance, pressure, temperature, relative humidity, and nature of the food product to be packaged.[48]

The oxygen barrier of biopolymers is crucial for enhancing the shelf life of packaged foods. Oxygen permeability is measured *via* the oxygen permeability and oxygen transmission rate. A higher oxygen transmission rate shows poorer barrier properties.[49] Food packaging must also minimize moisture transfer and reduce the water vapor transmission rate. Adding layered nanosilicates and metal oxide nanoparticles such as ZnO, TiO_2, and Al_2O_3 to biopolymers creates nanocomposites that are effective at blocking oxygen.[50] Similarly, the ability to block UV rays is crucial in preserving the nutritional quality and maintaining the color of food.[51] Thus, the packaging should have good barrier properties to reduce microbial growth and preserve food products.

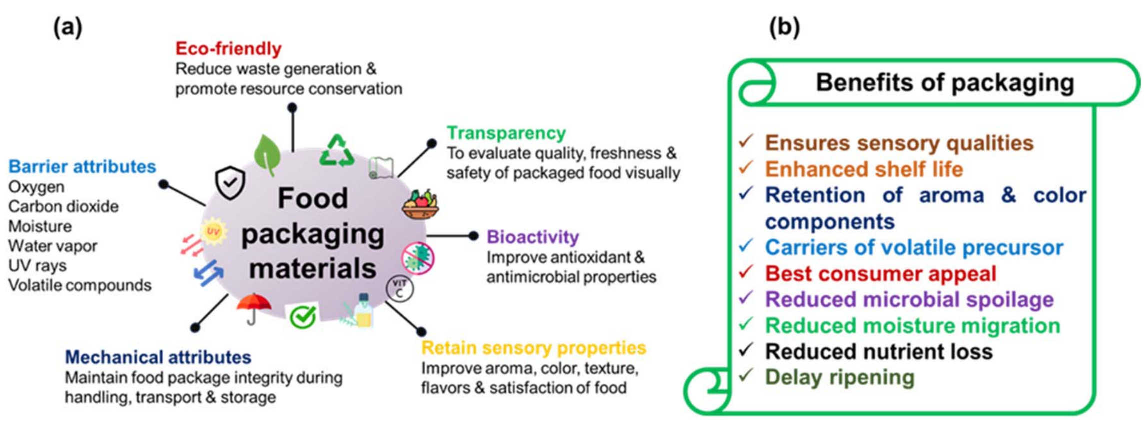

Fig. 3 (a) Major properties of food packaging materials and (b) benefits of food packaging.

2.3.2 Mechanical strength. The main goal of packaging is to protect food from external factors such as cracks and random breaks.[12] The mechanical attributes of a packaging system are crucial for protecting food under challenging conditions such as storage, handling, and processing. The mechanical attributes of biopolymers are mainly influenced by their matrix structure.[22] The key mechanical attributes for packaging include: (a) tensile properties such as elastic modulus, elongation at break, and tensile strength (the force to break a sample), (b) seal strength, the force to separate sealed layers, (c) hot tack strength, peak force at heat seals, (d) impact strength, resistance to impact, and (e) peel strength, force needed to separate adhesive bonds.[39,52] The tenacity, stress, seal strength, resistance to impact, and strain at break of biopolymers can be improved by adding additives to enhance their performance in preserving food. Thus, to enhance characteristics such as strength and stiffness through a reinforcement mechanism, specific nanofillers are distributed or reinforced in polymer matrices.[24] The main factor influencing this reinforcement is the dimensions, form, surface area, concentration, orientation, polydispersity and dispersion state of nanofillers, which can lead to their grafting onto the matrix polymer.[49] The brittleness, odor, gas permeability, and tensile strength are all impacted by crystallinity. Improved cohesion between the polymer matrix and filler materials enhances the Young's modulus, maximum strength, thermal resistance, and stress at break.[36] It also contributes to better shear resistance, reduced exfoliation, and increased corrosion protection. Similarly, interfacial adhesion arises when distinct materials such as particles and polymer matrices are mixed or combined, facilitating enhanced dispersion within the matrix.[53] To achieve the optimal adhesion, the physicochemical characteristics of the components should be compatible, *e.g.*, combining hydrophobic fillers with hydrophobic matrices or hydrophilic fillers with hydrophilic matrices promotes stronger interfacial bonds and improved material integration.[25] Various biodegradable polymers, when reinforced with chitin nanofibers, exhibit greater tensile strength and reduced elongation at break. Thus, all the parameters are interlinked and affect each other's performance.[54]

2.3.3 Optical properties. The optical features of biopolymer-based packaging materials refer to their interaction with light, including absorbance, transmittance, color, transparency, gloss, opacity, and UV light blocking capacity.[17] These characteristics are critical in food packaging because they affect consumer perception, product presentation, and facilitate inspection of the packaged contents.[25] These properties can exhibit significant variation depending on the material composition, thickness, and manufacturing techniques. Transparency, often measured as a key optical attribute, is especially important for biopolymer-based films given that it directly impacts the look of the packaged product.[12] Thus, a clear film is found to be suitable for dry snacks, but an opaque or UV-blocking film is found to be more suitable for oil-rich or protein-rich foods. Chitosan-based films are slightly yellow, transparent, and have good UV barrier properties, while zein-based films are brittle, transparent, and have good UV-blocking attributes.[55] Thus, different biopolymers have been used for packaging different food products. High color or opacity can reduce the water vapor and gas permeability.[44] For example, The incorporation of grape seed extract in gelatin films enhances their oxygen barrier attributes but reduces their light transmittance attributes.[56] Enhanced light resistance contributes to greater thermal stability by reducing photo-thermal degradation. Additionally, films with increased crystallinity tend to exhibit improved heat resistance. Thus, the optical properties of biopolymer-based packaging influences consumer safety, shelf life, and packaging performance.[56]

2.3.4 Chemical resistance. Chemical resistance is vital because the food inside the packaging might be acidic, basic, oils or alcohols and could react with the packaging material.[57] For safety, it is important to identify the chemical composition of the food before its packaging. These chemicals can integrate and migrate into food, degrade the packaging or absorbed by the biopolymer matrix, which can change the barrier and mechanical properties.[57] Thus, there should be enough resistance in packaging to limit the migration of chemicals from the packaging materials to food, and finally the human body, which can overall preserve human health and food products.[22] This property can ensure the shelf life, quality and safety of food products. Chemical resistance property is also interlinked with other properties such as mechanical, thermal, and barrier properties.[35] Biopolymers that withstand breakdown in acidic or oily conditions generally offer enhanced barrier capabilities, especially against gases, moisture, and organic substances. This is due to the robust structural composition needed to resist chemical reactions, which also tends to limit permeability, an important factor for preserving food freshness.[32,41] Additionally, chemical durability often correlates with mechanical resilience, and biopolymers featuring high levels of crystallinity or cross-linking ability not only endure exposure to solvents and pH variations, but also demonstrate superior flexibility and strength. Similarly, the thermal behavior of a biopolymer is also influenced by its chemical resilience.[50] Materials that resist chemical degradation often exhibit greater thermal stability, enabling them to maintain their form and function during manufacturing and storage.[50] However, strengthening one characteristic can sometimes compromise others; for instance, additives that enhance chemical resistance may diminish flexibility or improve brittleness. Therefore, carefully balancing all functional properties is crucial for developing high-performance biopolymer food packaging.[58]

2.3.5 Thermal properties. Thermal properties describe how a biopolymer reacts when exposed to heat, encompassing factors such as its thermal degradation temperature, melting point, glass transition temperature, thermal stability, thermal insulation, and overall heat resistance.[7] These characteristics are vital in the context of food packaging, given that they influence how the material performs during manufacturing processes such as extrusion, sealing, and molding, as well as during storage and thermal treatments such as refrigeration, pasteurization, and microwave heating.[51] Thus, these properties must be considered during the formulation of packaging materials. The thermal attributes of the packaging components are evaluated *via* the thermogravimetric and differential scanning calorimetry methods.[44] Therefore, understanding these thermal characteristics enables the storage and transportation of food packaging at the temperatures necessary for food products.[46] The thermal behavior of biopolymers is intricately connected to their barrier, mechanical, and chemical resistance properties. Generally, improved thermal stability is associated with higher crystallinity, which helps reduce molecular motion and lowers the permeability to gases and moisture, thereby strengthening the barrier performance.[59] Additionally, biopolymers with better heat resistance tend to possess enhanced mechanical durability and chemical resilience, particularly when interacting with acidic or oily food substances.[59] According to research, applying techniques such as nanoclay integration and cross-linking can effectively boost the thermal, mechanical, and barrier characteristics, while preserving the biodegradable nature of materials. This holistic improvement supports the sustainability objectives of contemporary food packaging solutions.[60]

3. Material engineering and formulation strategies

Biopolymers can be utilized for packaging purposes in various forms.

3.1 Structural components

Biopolymers can serve as single materials, components of polymer mixtures, or part of composite materials. The blending of polymers/composites/multi-layered coatings/films represents a transformative method for preserving food, given that it addresses the drawbacks of using single compounds and leverages their combined advantages.[61] Given that one component cannot provide all the required properties, the functionality and properties can be enhanced by mixing different biopolymers. For example, polysaccharide films exhibit strong mechanical properties, but they are not effective at blocking moisture. Thus, their combination with lipids and nanoparticles has improved their moisture barrier properties.[62] For example, the incorporation of stearic acid in starch-based packaging has increased its moisture barrier attributes. The compatibility and miscibility of biopolymers are crucial for obtaining the desired properties required for specific uses.[62] The combination of lipids and hydrocolloids boosts the moisture retention, enhance the mechanical strength, and prolong the shelf life of perishable food items.

3.2 Edible coatings and films

Edible coatings are uniformly applied, thin layers of edible constituents that can be consumed with the product. They are generally flavorless, colorless, and odorless and maintain the sensory properties of the coated produce (aroma, texture, taste, and appearance).[35] They can shape thin films when they are processed in a specific way. A film/coating is obtained by film casting, extrusion, or spraying methods. These coatings and films are typically composed of environmentally sustainable, naturally derived, and biodegradable polymers including polysaccharides, proteins, and lipids, and their blends.[42] Biopolymers serve as a substrate material, creating a multi-layered structure that improves the processability (sealability or printability) and barrier attributes or functionalizes the product surface.[63] These coatings/films offer excellent barrier properties against gases, water, microbes, and volatile substances over the surface of product.[7] They physically trap carbon dioxide gas within the produce tissues, and the higher levels of internal carbon dioxide reduce the respiration and ethylene production rates, and therefore delay senescence. They also preserve various flavorings and other volatile compounds present in the coated product.[64]

Polysaccharides are the most popular and extensively used materials for formulating coatings/films. Biopolymers such as chitosan, a linear polysaccharide, have been widely used as edible coatings/films due to their high biocompatibility, biodegradability, edible, and Generally Recognized as Safe (GRAS) nature.[19] In the food industry, chitosan films delay phenolic oxidation and prevent browning.[65] Their antimicrobial properties also curb microbial growth. When mango slices are coated with chitosan films, their shelf life is extended, and their quality is maintained.[66] Thus, these coatings/films ensure sensory properties, act as a barrier to free gas exchange, reduce microbial spoilage, moisture migration, and enzymatic browning, delay ripening, act as carriers of volatile compounds, and overall enhance the shelf life by preserving the quality of products.

3.3 Functional additives

The properties of polymers can be improved by incorporating various agents such as polymers, composites, flavonoids, plasticizers, nanoparticles, essential oils, antioxidants, phenolic compounds, antimicrobials, and plant extracts.[67] Biopolymers can be used as functional additives to manage the physical and mechanical characteristics such as stiffness, hardness, strength, and barrier function.[68]

Plasticizers are low molecular weight compounds frequently used to alter the properties of biopolymers for specific applications. They influence the intermolecular bonds among polymer chains, encouraging conformational changes and enhancing deformability.[69] Plasticization serves as a technique to reduce the brittleness of bio-nanocomposite films and improve their processability, chain mobility, and flexibility. The commonly used plasticizer materials include sorbitol, triacetin, polyethylene glycol, tributyl citrate, and glycerol in food packaging polymer matrices.[70] Introducing triacetin as a plasticizer into PLA in appropriate amount can markedly improve its ductility. However, the addition of a plasticizer may weaken the mechanical properties and presents environmental and health concerns. Hence, discovering an optimum plasticizer with low mobility and a higher molecular weight is crucial.[71]

Integrating phenolic compounds such as caffeic acid phenethyl ester and curcumin into packaging can enhance food safety and quality by combatting microbial growth through antioxidant release.[72] Flavonoids, vital natural compounds found in oranges, grapes, onions, and celery, offer antioxidant and antimicrobial benefits and are categorized into flavans, anthoxanthins, anthocyanidins, flavonols, and flavanones. These natural antioxidants are now commonly used to shield foods from oxidative damage and free radicals.[73]

Oxidation is a key factor in food spoilage that affects lipid and protein quality. However, the incorporation of antioxidants can slow this process by reducing the oxygen levels. The main method used today is adding antioxidants to foods, despite their drawbacks such as decreased activity during processing and reduced food quality after consumption.[74] Antioxidants can be integrated into biopolymeric films either physically or chemically through techniques such as surface coating, non-covalent embedding, and covalent attachment.[75] Polymeric matrices can hold active compounds within their structure and release them effectively. The most used antioxidants are tea polyphenols, corn stigma extract, pineapple peel extract, litchi shell extract, and blueberry leaf extract.[76]

Similarly, packaged food products are prone to food-borne pathogens (viruses, parasites, and bacteria), which leads to food-borne diseases, spoilage, or contamination.[77] Various bacteria like *Bacillus cereus*, *Pseudomonas aeruginosa*, *Salmonella*, *Staphylococcus aureus*, *Vibrio cholera*, *Escherichia coli*, *Listeria monocytogenes*, *Enterococcus faecalis*, and *Staphylococcus epidermis* contribute to food spoilage.[78] In addition, yeasts (*Candida* and *Torulopsis*) and molds (*Aspergillus* and *Rhizopus*) contribute to foodborne infections. These infections and spoilage can be prevented using antimicrobial agents.[79] The inclusion of metal and metal oxide nanoparticles (Fe_3O_4, MgO, TiO_2, ZnO, Cu, Ag, Au, *etc.*), synthetic agents (EDTA, ammonium salts, sorbic acids, benzoic, and propionic), nanoclay (MMT and Ag-zeolite), enzymes (peroxidase, lysozyme), biopolymers (chitosan), and bioactive compounds (thymol, nisin, carvacrol, and isothiocyanate) can enhance the optical attributes, resilience, thermal stability, glass transition temperature, tensile strength, and antibacterial characteristics of the polymer matrix.[80,81] Metal nanoparticles such as copper, zinc, and silver, along with metal oxide nanoparticles such as TiO_2, CuO, MgO, and ZnO, have been utilized in bio-nanocomposites to improve the physicochemical attributes of packaging materials.[82] To achieve antiviral properties, the integration of nanoparticles such as silver, copper oxide, and zinc peroxide is recommended. Incorporating these nanoparticles into biopolymers has shown promising outcomes against both human enteric viruses and microbial cells.[83]

The antimicrobial attributes of biopolymers can be improved by the incorporation of essential oils. Essential oils are hydrophobic compounds derived from plants, containing elements such as phenols, aldehydes, ketones, and terpenes.[84] Their hydrophobic nature and phenolic components enable them to efficiently infiltrate bacterial cell membranes, resulting in the leakage of cell contents and ions and disruption in lipid–protein interactions. The most used essential oils are clove, cinnamon, thyme, lavender, peppermint, cumin, oregano, and olive.[85] They show antibacterial effects by targeting microbial cells with precision, leading to cell wall disruption, interference with electron transfer, enzyme activity disturbance, oxidation, ROS formation, destruction of organelles, DNA synthesis inhibition, and cell death.[83,85] Thus, the incorporation of functional additives such as flavonoids, essential oils, antimicrobials, antioxidants, nanoparticles, plasticizers, and plant extracts can enhance the shelf life of food products by preserving the quality parameters.[85]

3.4 Nanotechnology in biopolymer packaging

Nanotechnology is a rapidly growing field focusing on small particles with versatile uses. Their tiny size offers a high surface area-to-volume ratio, enhancing the material properties with minimal defects compared to larger particles.[86] Nanocomposites are engineered solid materials derived from merging the distinct physical and chemical properties of polymers and inorganic solids (clays/oxides) at the nanoscale. Nanocomposites are made by adding nanofillers or nanoparticles to polymer matrices, improving their physical, mechanical, barrier, and antimicrobial attributes.[87] Biopolymer nanocomposites consist of bio-based materials with two phases, a biopolymer matrix (continuous phase) and nanoparticle fillers (discontinuous phase). Matrix materials (such as metals, polymers, and ceramics) maintain the arrangement of the reinforcement materials, while filler materials (such as particles/fibers) introduce new characteristics to the matrix phase.[88,89] Nanocomposites or nanofillers consist of organic (natural fibers, polymer nanofibers, natural clay, *etc.*), inorganic (iron, gold, silver, copper oxide, zinc oxide, iron oxide, *etc.*), and carbon structures (fullerenes, carbon nanotubes, graphene, and nanofibers).[90] These materials can enhance the consistency of edible coatings, thereby increasing their efficiency in reducing food spoilage. Incorporating nano-sensors into these coatings could facilitate the real-time monitoring of food quality, offering valuable insights to both consumers and manufacturers.[91] They can interact with food by emitting active agents such as antimicrobials and antioxidants or eliminating unwanted elements such as oxygen and water vapor.[76] Polymer nanocomposites can be divided based on their nanofiller dimensions (0D, 1D, 2D, and 3D), nanofiller type (silicate, metal, sulfide, metal oxide, and hydroxide), polymer matrix type (thermoplastic, thermoset, elastomer, natural, and biodegradable), and synthesis methods (simultaneous polymerization, *ex situ*, and *in situ*).[48,92] Thus, they enhance the polymer properties by improving the barrier, thermal, and mechanical features and can be formulated by solution casting, melt processing, spraying, *in situ* polymerization, or solution blending and casting methods.[35,63]

Despite the numerous benefits of nanotechnological approaches, there are still certain concerns related to long-term stability, potential migration-related risks, changes in sensory attributes, and implications for consumer health.[23] Although nanomaterials offer excellent barrier capabilities (such as minimizing oxygen and moisture transfer), their sustained performance particularly under fluctuating storage conditions, remains a critical consideration.[93] For instance, some coatings made with nanomaterials may deteriorate or lose their protective qualities when exposed to light or high humidity, potentially reducing their effectiveness.[87] Thus, the long-term stability and reliability of these materials are a major concern with the use of nanotechnology in food coatings. Another key concern involves the possible migration of nanomaterials from coatings into food.[59,94] Due to their small size and large surface area, nanoparticles have a greater likelihood of transferring into the food matrix, potentially leading to health risks. The most frequently used nanoparticles are titanium dioxide nanoparticles owing to their whitening effect in food coatings, which can potentially migrate into food, resulting in their inadvertent ingestion.[95] Nanomaterial-based coatings can affect the sensory attributes of food, including its appearance, taste, and texture.[61] However, the long-term health impacts of nanoparticles such as their buildup within the body remain unclear, prompting concerns about their safety. Therefore, it is crucial to prioritize consumer awareness and implement robust regulatory frameworks to ensure that foods treated with these coatings do not pose health risks. Additionally, the durability of these coatings over time must be weighed against their functional performance and environmental sustainability.[95]

3.5 Formulation strategies for food packaging

Different types of packaging products (such as blends/composites/coatings/films/bio-nanocomposites) are prepared using various techniques based on the type of nanosized fillers, the polymer matrix they are dispersed in, and their intended application.[55] The common methods include solution casting, spraying, melt extrusion, and inkjet printing. Melt-blown extrusion techniques are applied in the fabrication of packaging films using biopolymer-based methods such as solvent casting, melt extrusion, and thermal compression.[80] The blown film process is preferred for large-scale film production, whereas the solution casting and extrusion melting methods are primarily employed at the laboratory scale.[15]

Solution casting is the predominantly utilized method for the synthesis of polymer nanocomposites within the laboratory. An appropriate solvent is selected to dissolve the polymer, facilitating the uniform distribution of nanoparticles. To ensure the homogeneous integration of nanostructure additives into the biopolymer matrix, mechanical agitation coupled with ultrasonication is typically employed.[44] The prepared mixture is then cast onto a plate and kept in an oven, enabling solvent evaporation for drying purpose. This process occurs at room temperature and is widely used for proteins, polysaccharides, essential oils, natural extracts or volatile-based films.[22] Extrusion, as another prevalent and scalable method, is an eco-friendly and cost-effective for making bio-nanocomposites and integrating natural additives into appropriate biopolymer matrices. In this process, the active compound is blended with a biopolymer within an extruder.[72] The resulting bioactive films can then be manufactured through compression molding, film blowing, or melt casting methods. For example, the incorporation of nanoparticles in polymer granules in the molten state ensures their uniform dispersion, while the polymer endures shear stress and temperature to prevent degradation.[88] Spraying involves applying a molten bio-nanocomposite onto a substrate to form a protective coating, which is well-suited for enhancing corrosion resistance, minimizing wear, enabling abradable sealing, and providing thermal insulation. This technique is characterized by high deposition efficiency, cost-effectiveness, operational simplicity, and the use of portable equipment.[90] Inkjet printing in solid freeform fabrication has recently been developed for several biopolymers, utilizing inkjet deposition to integrate nanostructures into a low viscosity matrix for rapid processing. This technique effectively incorporates nanosized particles or fibers into a photocurable thermoset matrix to develop functional nanocomposites.[93] Inkjet printing offers benefits such as affordability, simplicity, and high efficiency. For example, the spoilage of seafood and meat results from autolytic reactions and microbial breakdown of proteins, glycogen, fats, and micronutrients. This process gradually produces various metabolites such as sulfur dioxide, volatile amines, biogenic amines, and organic acids such as alcohols, aldehydes, esters, propionic, acetic, butyric acids, and short-chain fatty acids.[76] For predicting the freshness of fish, inkjet-printed indicators have been potentially used to detect pH changes. For example, edible coatings and flexible films were formulated from *Butea monosperma* flower extract and guar gum for preserving and prolonging the shelf life and freshness of tomatoes.[96]

4. Biopolymer-based packaging technologies

Biopolymer-based packaging technologies are broadly classified into active and intelligent packaging based on their interaction with food and function.[46] Their classification is shown in Fig. 4.

4.1 Active packaging

Active packaging materials are engineered compounds designed to enhance the sensory characteristics and maintain the quality of products. These systems incorporate agents that actively interact with both the food and its surrounding environment, thereby ensuring its safety, preserving its quality, and extending its shelf life through functional additives or intrinsic properties.[97] They provide a barrier against the external environment and control the internal atmosphere. These materials fall into two categories, emitters (releasing systems) such as

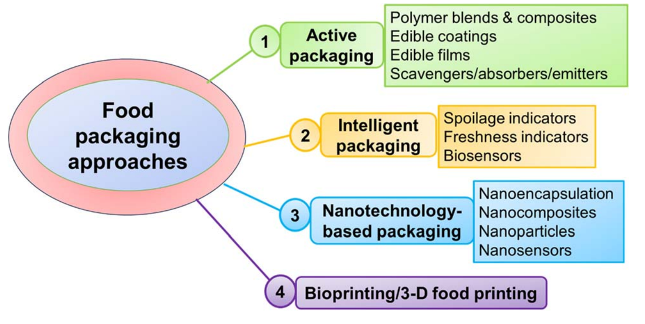

Fig. 4 Biopolymer-based food packaging technologies.

carbon dioxide emitters, and absorbers (scavengers) such as carbon dioxide, oxygen, ethylene, and moisture absorbers.[98,99] Active packaging does not react to particular stimuli, in contrast to intelligent (responsive) packaging.[100]

4.1.1 Ethylene absorbers. Ethylene, even at low levels, can speed up ripening, softening, or aging, reducing the shelf life of food products by increasing their respiration rate during storage and transport. To counter this, ethylene absorbers can be used, which work through chemical reactions or physical adsorption within a closed space.[55,101] Ethylene absorbers are often categorized into three classes, as follows: (a) metal oxides and metals, (b) nanostructured carbon materials, and (c) silicates and zeolites such as vermiculite, clays, and zeolites.[102] Potassium permanganate ($KMnO_4$), in either its pure form or combined with nanosilicates, nanoclays, or nanozeolites, is a well-known ethylene absorber. $KMnO_4$ interacts with oxygen and generates water and carbon dioxide, effectively slowing down the ripening process, and thus preserving food and extending its shelf life.[103]

4.1.2 Carbon dioxide absorbers. CO_2 is useful for maintaining food freshness by suppressing microbial growth and oxidation. However, its concentration in packaging must be controlled given that excess CO_2 can negatively impact the product quality, including changes in flavor and texture, especially in dairy products.[104] A carbon dioxide absorber can curb microbial growth (such as yeast, mold, and bacteria), eliminate excess CO_2, and reduce the environmental impact, preventing the rupture of the package during storage.[105] CO_2 absorbent materials fall into two types, as follows: (a) physical scavengers such as activated carbon, silica gel, zeolite, and silica gel and (b) chemical scavengers such as sodium carbonate, sodium hydroxide, calcium hydroxide, and calcium oxide.[106]

4.1.3 Oxygen absorbers. Typically, food products are susceptible to the presence of oxygen, which can instigate oxidative reactions or microbial degradation, thereby diminishing nutrients, causing discoloration, degrading vitamins, and facilitating oxidation, which result in a reduced shelf life.[33,107] Oxygen absorbers are employed to regulate the oxygen levels and prevent oxygen infiltration through packaging materials during storage. Additionally, these absorbers can enhance the barrier properties of packaging, prevent rancidity, lower the rate of deterioration, and minimize excessive oxygen within active packaging systems.[107] Oxygen absorber agents are systematically categorized into four distinct groups, as follows: (a) inorganic scavengers, such as sulfite and titanium dioxide, (b) metallic scavengers, such as iron and ferrous oxide powder, (c) organic scavengers, such as catechol, ascorbic acid, and lignin, and (d) enzymatic agents.[108] These oxygen absorbers are engineered in various structural configurations such as films, sachets, cards, pads, and labels to effectively absorb or diminish the residual oxygen surrounding food products.[106]

4.1.4 Moisture absorbers. Too much moisture in a sealed package can lead to microbial growth, alter its texture, decrease its transparency, and shorten its shelf life.[108] Thus, to enhance food sensory qualities, moisture absorbers or desiccants are used to manage humidity inside a package, using hygroscopic materials such as calcium oxide, silica gel, and bentonite clays. These materials are utilized as films, pads, and sachets to protect sensitive foods from moisture that preserve the overall quality of food.[108,109]

4.1.5 Carbon dioxide emitter. A CO_2 emitter system maintains the CO_2 levels to preserve the sensory properties, reduce the package volume to control microbes, and extend the shelf life in food products. CO_2 emitters are usually pads or sachets in packaging.[110] These emitters are composed of active ingredients such as citric acid, ascorbic acid, ferrous carbonate, and sodium bicarbonate. The appropriate amount of CO_2 emitter will maintain an appropriate CO_2 level, enhancing the physicochemical properties of packaged products.[111] Additionally, elevated CO_2 levels in certain products such as poultry and meat are necessary to curb microbial growth and minimize waste.[104]

4.2 Intelligent packaging

Packaged product deterioration involves the nature of food (such as pH, water activity, microbial presence, redox potential, respiration, and antimicrobial components), and environmental factors (such as humidity, temperature, and gas composition).[112] Intelligent packaging, as growing technology, enhances quality and safety by indicating package issues. Intelligent food packaging changes color when it detects spoilage by coming into contact with biomarkers such as ammonia and carbon dioxide, or alterations in pH from decaying food.[113] This biomimetic technology offers a visual, real-time alert mechanism aimed at minimizing food waste and enhancing safety, by translating adaptive traits from nature into effective solutions for modern food systems.[79] They offer responsive features across the food supply chain, including detection, locating, communication, registering, and monitoring with scientific logic. Functions such as spoilage indicators and time–temperature indicators monitor product freshness and safety.[113]

4.2.1 Spoilage indicator. Controlled atmosphere packaging is recommended to inhibit microbial spoilage and growth by regulating oxygen, carbon dioxide, nitrogen, pH, and humidity levels. Carbon dioxide and oxygen sensors act as spoilage indicators, showing the gas concentrations in the package.[114] Oxygen indicators include reversible colorimetric redox indicators, luminescence-based systems, and those activated by UV or visible light. Similarly, excessive humidity promotes microbial growth, speeding up spoilage and safety risks. It also causes food to absorb moisture, softening it and reducing its shelf life.[115] For example, bread molds faster under humid conditions due to the increased moisture absorption. Thus, by integrating different indicators into smart packaging, the system can warn about unfavorable storage conditions, thus enabling proactive actions to preserve the quality and extend the shelf life of food.[116] A pH sensor was formulated using agar and glycerin and used to analyze the change in cherry juice and its spoilage.[117]

4.2.2 Time temperature indicators (TTI). Temperature and time are crucial factors impacting product properties during storage, transit, and distribution, which reduces the control over shelf life prediction. They directly impact the rate of enzymatic reactions in food and influence the survival of

Table 2 The recent application of biopolymers for packaging various food products[a]

Base biopolymer	Active component	Product used	Benefits of packaging	References
Fruits and vegetables				
Alginate/cellulose nanofiber	Pomegranate peel extract	Pomegranate arils	-Enhanced shelf life -Preserved quality attributes -Reduced weight loss -Delayed respiration rate -Maintained firmness, anthocyanin level, and antioxidants content	125
Pectin	Pomegranate seed oil/different microalgae	Cajarana	-Reduced breaking stress and elastic modulus -Preserved quality attributes for 14 days -Maintained transparency and glossiness	126
Sodium alginate/polyvinyl alcohol	Safflower extract	Dates	-Enhanced antioxidant and barrier properties -Extended shelf life -Reduced weight loss -Retain color and firmness	127
Apple pomace pectin/grass peas protein	Propolis extract	Black mulberry	-Extended shelf life -Enhanced antimicrobial and antioxidant properties -Inhibited *Escherichia coli*, *Bacillus cereus*, and *Botrytis cinerea* growth -Reduced weight loss -Retain color and firmness -Increased barrier properties	128
Chitosan	Nano-ZnONPs	Tomato	-Inhibited *Alternaria alternata* growth -Reduced weight loss -Maintained appearance -Reduced lesion diameter	129
Chitosan	ZnONPs	Eggplant	-Improved color, texture, and overall acceptability -Enhanced shelf life to 20 days -Reduced weight and respiration loss	130
Pullulan/carboxymethyl chitosan	Zein/turmeric EO	Mango	-Improved mechanical and barrier properties -Increased antimicrobial properties -Improved oxidative stability -Preserved quality parameters by 12 days	131
Polyvinyl alcohol (PVA)	Deep eutectic solvents (choline chloride and organic acids	Cherry tomato	-Increased tensile strength and elongation break of films -Extends the shelf life by 12 days -Inhibited fungal growth	132
Chitosan	ZnONPs	Strawberry	-Improved quality -Enhanced shelf life by 30 days	133
Chitosan/gelatin	Pomelo peel extract	Grapes	-Enhanced shelf life -Reduced decay -Maintained pH, color and texture	134
Sodium alginate	Fe_2TiO_5/ZnONPs	Cut strawberry	-Preserved shelf life by 3 days -Improved quality parameters	135
Gelatin	ZnONPs/balangu seed mucilage	Sweet cherry	-Reduced weight loss -Maintained firmness, titratable acidity and total soluble solids -Improved ascorbic acid, total phenolic and anthocyanin content	136
Starch	Garlic extract	Fresh-cut carrots	-Inhibited microbial growth -Reduced spoilage -Prevented *S. aureus* and *L. monocytogenes* growth	137
Pectin	Cinnamon EO	Fresh cherries	-Inhibited fungal growth (*Alternaria* sp. and *Penicillium* sp.) -Delayed ripening -Preserved quality -Enhanced shelf life	138
Chitosan/gelatin	*Dracocephalum kotschyi* EO	Grapes	-Improved thickness and opacity -Reduced moisture content and water solubility -Preserved quality parameters	139

Table 2 (*Contd.*)

Base biopolymer	Active component	Product used	Benefits of packaging	References
Vanillin/chitosan/ carboxymethyl cellulose	Cassava starch/ glycerol/Ag NPs	Red grapes	-Increased antibacterial efficacy against *S. aureus* and *B. subtilis* -Improved shelf life -Increased antibacterial efficacy against *S. aureus* and *E. coli*	140
Bakery and confectionary products				
Poly lactic acid/ polybutylene adipate terephthalate	Carvacrol	Bread and butter cake	-Prevented fungal growth and sporulation -Enhanced shelf life by 4 days	141
Corn starch	Raw papaya and citrus peel	Muffins	-Enhanced storage quality -Enhanced antioxidant attributes -Reduced microbial growth -High tensile strength and transparency	142
Chitosan/$AgNO_3$	Sunflower seed oil	Bread	-Inhibited *Aspergillus* and *Rhizopus* growth -Reduced water vapor transmission rate -Preserved bread for 10 days	143
Maltodextrin and cyclodextrin	Proteins from corn flower pollen	Bread	-Improved bread quality -Improved nutritional values -Enhanced antioxidant activities -Reduced yellow crumb color and bitterness -Improved loaf volume	144
Potato starch and pectin	Cashew apple and citric acid	Bread	-Extends shelf life from 7–28 days -Increased water vapor permeability -More tensile strength -Increased antimicrobial properties -Extends microbiological stability (4-fold) -Increased thermal, barrier, physical an chemical properties	145
Carioca bean starches	Orange peel EO	Cake	-Inhibited *Penicillium crustosum* and *Aspergillus flavus* growth -Preserved quality parameters -Reduced water vapor permeability and moisture content	146
Polyvinyl alcohol (PVA)	Deep eutectic solvents (choline chloride and organic acids	Bread	-Inhibited mold growth for 22 days -Increased elongation break and tensile strength of films	147
Chitosan/pectin	Thyme EO	Milk cake	-Extended shelf life by more than 10 days -Delayed microbiological contamination and hardness of milk cake -Enhanced water vapor barrier properties -Improved mechanical properties	148
Corn starch	Clove EO	Bread	-Increased antioxidant and antimicrobial activities -Enhanced shelf life and quality -Increased tensile strength and hydrophobicity -Increased physicochemical properties	149
Triticale flour	Glycerol	Muffins	-Prevented staling process -Decreased crumbs hardness	150
Pectin/alginate/whey protein concentrate	Glycerol/tween20	Mini-buns	-Retarded staling process -Reduced crumb moisture	151
Protein isolate fibrils	Octenyl succinate starch	Angel cake	-Retained moisture -Prevented starch retro gradation in cake -Preserved quality -Improved texture and sensory attributes	152
Cinnamon/clove oil	Soy lecithin	Muffins	-Enhanced antioxidant properties -Reduced weight loss -Maintained firmness	152

Table 2 (*Contd.*)

Base biopolymer	Active component	Product used	Benefits of packaging	References
Dairy products				
Rice husk	*Pinhão* failure	Sliced mozzarella cheese	-Preserved quality -Enhanced antioxidant properties -Increased thermal resistance up to 200 °C -Biopolymer biodegrades within 10–12 days -Acts as a pH sensor	153
Guar gum/chitosan	Orange EO	Mongolian cheese	-Preserved quality and shelf life -Inhibited bacterial growth -Enhanced mechanical attributes -Improved water vapor and oxygen barrier attributes -Reduced moisture content -Delayed lipid oxidation -Prevented weight, pH, and texture loss	154
Beverage products				
Polylactic acid		Water, cold drink and juice bottles	-Better transparency, processability, and composability	155
Polyhydroxyalkanoates		Coatings for juice cartons, milk pouches, and sachet	-Better oxygen barrier properties -High moisture resistance property	156
Starch and cellulose derivatives	Plasticizers	Disposable straws, lids, and pouch linings	-Increased water resistance -Better film forming property	157
Chitosan		Fresh juice and fermented drinks	-Enhanced shelf life -Reduced microbial growth -More antimicrobial properties	158
Snacks and dry food				
PBAT/thermoplastic starch (TPS)	Sorbate and benzoate	Fresh noodles	Reduced microbial growth Enhanced transparency and permeability	159
Sodium alginate	Di-1-*p*-menthene	Pistachios	-Prevented microbial growth -Reduced aflatoxin B1 production -Maintained peroxidase and acid content -Reduced weight loss -Controlled hull color degradation -Maintained kernel firmness	160
Chitosan	ZnO nanocomposite	Pistachios	-Enhanced shelf life by up to 35–40 days -Reduced aflatoxin contamination -Reduced weight loss -Reduced polyphenol oxidase and glutathione-peroxidase activity -Increased oil, carbohydrate and protein amount -Improved flavonoid, firmness, anthocyanin, antioxidant, phenol, and sensory attributes -Inhibited decay	161
Peppermint EO	Green tea extract	Walnut	-Preserved pellicle color and antioxidant attributes for 28 days -Reduced moisture content and peroxide value -Reduced polyphenol oxidase kinetics -Inhibited lipid oxidation	162
Chitosan	*Zataria multiflora* Boiss EO	Pistachio	-Lowered lipid oxidation -Inhibited *Aspergillus flavus* growth -Reduced aflatoxin B1 production	163
Sodium alginate/α-tocopherol	Calcium chloride	Walnut	-Reduced weight loss -Maintained total phenolic content and antioxidant content -Maintained firmness and colour -Improved quality parameters -Reduced microbial growth	162
Chitosan	—	Pecan nuts	-Preserved quality attributes -Maintained hardness and color	164

Table 2 (*Contd.*)

Base biopolymer	Active component	Product used	Benefits of packaging	References
Carboxymethyl cellulose/γ-aminobutyric acid	Calcium oxide	Pistachio	-Increased lightness value, hue index, and color indexes -Increased flavonoids content -Increased lipid content -Reduced H_2O_2 in kernels	165
Chitosan	—	Fresh in-hull pistachio	-Enhanced shelf life -Preserved quality parameters -Reduced weight loss, peroxidase, acid, and aflatoxin B1 production -Inhibited microbial growth -Maintained lightness and firmness	162
Meat and seafood				
Xanthan gum/pectin	Sweet orange peel EO	Chicken meat	-Preserved quality -Reduced weight loss -Reduced water vapor and oxygen permeability -Enhanced UV-protection	166
Polyethylene glycol (PEG)	ZnONPs	Pork sausage	-Reduced *L. monocytogenes* and lactic acid bacteria growth -Enhanced shelf-life	167
Carboxymethyl cellulose	Thyme EO	Fresh chicken breast	-Enhanced shelf life -Reduced pathogen growth -Reduced *Salmonella enterica*, *Campylobacter* sp. growth	168
Vicia villosa protein isolate	ZnONPs	Chicken breast meat	-Reduced microbial growth -Enhanced shelf-life -Decreased chemical deterioration	169
Alginate	Nisin	Turkey slice	-Inhibited *Listeria monocytogenes* growth -Enhanced preservation	170
PLA	Whey protein isolate/ZnONPs	Common carp fillets	-Improved antimicrobial and antioxidant attributes -Enhanced shelf life by 12 days -Maintained quality parameters	171
Pectin	ZnONPs	Poultry meat	-Reduced microbial growth and spoilage -Enhanced shelf life by 15 days -Prevented oxidation and discoloration	172
Cellulose/potato peel	Curcumin	Fresh pork	-Enhanced mechanical properties -Enhanced antioxidant properties -Reduced light transparency, oxygen, and water vapor permeability -Reduced lipid oxidation	173
Chitosan	ZnO nanoparticles	Fresh poultry and minced meat	-Enhanced shelf life -Reduced microbial growth -Reduced oxidation and degradation	174
Poly lactic acid/polybutylene adipate terephthalate	Carvacrol/citral/α-terpineol	Shrimp	-Prevented microorganism growth -Inhibited melanosis -Inhibited loss of shrimp head and drips	175
Agar	Green tea	Hake fillet	-Delayed microbial growth -Decreased spoilage indexes	176
Chitosan	Garlic EO	Chicken fillet	-Enhanced water and mechanical resistance attributes -Prevented microbial growth during refrigeration	177
Chitosan	Monomethyl fumaric acid	Beef	-Reduced lactic-acid bacteria, yeast/mold, and psychotropic bacteria growth - Increased shelf life by 8 days	178
Gelatin	Oregano and rosemary	Cold-smoked sardines	-Reduced oxidation rate -Increased storage life	179
Gelatin/agar	Clove EO/Cu doped ZnO	Pork	-Reduced lipid peroxidation -Reduced microbial count -Enhanced shelf life	180

Table 2 (*Contd.*)

Base biopolymer	Active component	Product used	Benefits of packaging	References
Gelatin/chitosan	*L. nobilis*	Ostrich meat-based hamburgers	-Preserved quality during 28 days of storage -Reduced oxidation -Reduced pH, peroxide, total volatile basic nitrogen and thiobarbituric acid reactive compounds -Inhibited *Staphylococcus aureus, Escherichia coli* and *Salmonella* growth	181
Guar gum/chitosan	Citronellal/ hydroxypropyl-β-cyclodextrin	Harbin red sausage	-Enhanced barrier and mechanical attributes -Enhanced antibacterial properties -Improved thermal properties -Reduced weight loss -Maintained pH, color, and textural stabilities -Retard lipid oxidation and microbial growth	182
Cassava starch/sodium carboxymethyl cellulose	*Litsea cubeba* EO	Chicken meat	-Improved mechanical, textural, and barrier properties -Reduced water solubility and moisture content -Reduced weight loss and color change -Delayed lipid oxidation -Reduced microbial growth -Enhanced shelf life by 12 days	183
Vanillin/chitosan	2-Hydroxypropyl-β-cyclodextrin	Chicken	-Improved hydrophobicity and stability -Enhanced antibacterial properties	184

[a] EO-essential oil and NPs-nanoparticles.

existing microorganisms.[118] Dairy products such as milk and cheese are particularly prone to spoilage at higher temperatures due to increased bacterial activity. TTI offer a solution for packaging systems to maintain food quality, allowing continuous monitoring from production to consumption.[119] Consumers can assess quality changes and choose superior products. For example, a study proposed using a TTI with plasmonic nanocrystals, such as silver and gold nanorods, to control spoilage.[120]

4.3 Antimicrobial packaging

Antimicrobial packaging includes agents that are added to the packaging materials to slow or stop microbial growth, reduce waste, and protect the quality, preserve the appearance, and extend the shelf life of food.[121] These agents are divided as follows: (a) organic materials such as enzymes, organic acids, and polymers, (b) inorganic materials such as metal oxides and metals, (c) essential oils such as thyme, clove, and oregano, (d) plant extracts such as green tea, garlic, rosemary, and ginger, (e) bioactive components such as thymol and carvacrol, and (f) peptides such as lactoferrin and nisin.[80,122] Metal nanoparticles such as zinc, silver, and copper, along with metal oxides such as zinc oxide, titanium oxide, copper oxide, and chitosan biopolymers are commonly used in bio-nanocomposites for antimicrobial purposes in the food industry.[123] Films formulated with chitosan exhibit enhanced antimicrobial efficacy, inhibit microbial proliferation, and extend the preservation period of packaged food products, making them a viable and innovative solution for active food packaging applications.[124]

Table 2 provides a summary of several recent studies exploring antimicrobial packaging compounds, primarily emphasizing biopolymer-derived materials tailored for food packaging applications.

4.4 Antioxidant packaging

Lipid oxidation and microbial growth significantly impact the shelf life and quality of food. Thus, the food industry aims to delay oxidation to prevent lipid degradation, texture loss, off-flavors, and discoloration.[185] Synthetic antioxidants such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and tert-butylhydroquinone (TBHQ) are used to preserve food quality.[186] Concerns over the effects and risks of synthetic antioxidants have prompted research into natural antioxidants as alternatives in food packaging. Natural antioxidants include (a) plant extracts (such as mint, murta, pomegranate peel, rosemary, and oregano), (b) phenolic compounds (such as caffeic acid phenethyl ester, and curcumin), (c) essential oils (such as lemongrass, cinnamon, and bergamot), and (d) flavonoid compounds (such as quercetin and catechin).[187,188] Cellulose films with ascorbyl dipalmitate nanoparticles and curcumin demonstrate antioxidant activity in packaging. Similarly, gelatin-based films incorporated with chitosan nanoparticles and tea polyphenol also show more antioxidant attributes.[189] Antioxidants are divided into primary antioxidants (free radical absorbers) and secondary antioxidants (oxygen and UV absorbers). UV absorbers protect light-sensitive foods such as beverages and oils by blocking UV radiation.[190] Light transmission impacts the nutrition, safety, and quality of packaged foods. Packaging materials can include zinc oxide, titanium dioxide, benzotriazoles, and benzophenones to control food photo-oxidation by enhancing the UV-shielding properties.[191]

4.5 Bioprinting or 3D food printing

3D food printing/bio-printing is revolutionary technology that has potential to transform the food industry significantly. This process includes constructing complex food structures by layering ingredients sequentially, thereby providing precise regulation over the nutritional value, composition, and texture of food.[192] A promising application of 3D food printing involves developing edible coatings, which play a vital role in ensuring the quality, freshness, and safety of food items.[193] Through its ability to tailor surface coatings to specific functional needs, 3D food printing offers advanced solutions beyond the capabilities of traditional coating techniques.[194] This approach employs food-grade substrates, a precision-controlled 3D printer, and a digital management system to deposit components such as pureed fruits, vegetables, and protein matrices in precise, three-dimensional configurations. The flow and viscosity of these ingredients are key for effective printing.[195] Edible inks made from fats, proteins, and carbohydrates ensure safety and consumption. This technology allows the design of custom edible coatings, enabling functionalities such as controlled preservative release and extended shelf life.[196]

5. Applications of biopolymers as food packaging

The escalating global pollution problem has increased the awareness of the environmental effects of plastic waste, emphasizing the urgent need for sustainable alternatives to conventional plastic packaging. In response to the growing societal demand for safer, natural, and eco-conscious alternatives, food preservation technologies are progressively advancing to maintain product integrity, while reducing environmental footprint.[197] These solutions must conserve the nutritional and sensory attributes of food, while minimizing environmental damage. Biopolymers have become promising substitutes that improve the quality and effectiveness of food packaging.[40] The incorporation of bioactive agents in food packaging has received considerable attention because of their availability, low-cost, and ability to function as additives, enhancing the performance of biopolymers.[198] These environmentally friendly sources provide a natural and sustainable method to improve food preservation without sacrificing food safety or worsening the plastic waste problem.[199] The application of biopolymers as packaging for different food products and the major challenges faced by products are described below and shown in Fig. 5.

5.1 Packaging for fruits and vegetables

Fruits and vegetables are extremely perishable, leaving them susceptible to a significant drop in quality after harvesting. Various elements, such as postharvest handling and processing methods, as well as environmental factors such as temperature, moisture, humidity, and sunlight exposure, affect this deterioration.[200] To tackle these challenges, there is an increasing demand for sophisticated technologies that not only boost production and enhance distribution but also minimize quality loss and extend the shelf life of produce.[201] After harvesting, fruits tend to have a short shelf life primarily due to the presence of microbes, their high respiration rates, and moisture loss. Regulating factors such as moisture, temperature, light, and gases such as carbon dioxide, oxygen, and ethylene (C_2H_2) can decelerate respiration and transpiration, thereby prolonging the storage duration of vegetables and fruits.[202] Biopolymer-based packaging includes antimicrobials and anti-browning and antioxidant compounds, offering a promising means to address these issues by reducing microbial growth, moisture loss, and halting the ripening process.[37]

Salimi *et al.* examined the effect of various concentrations of propolis extract (0, 3%, 6%, and 12% v/w) on edible films formulated by apple pomace pectin (3% w/v) and grass peas protein (5% w/v) on black mulberry. The incorporation of propolis extract enhanced the antioxidant, hydrophobicity, mechanical, and antimicrobial attributes of the films mainly

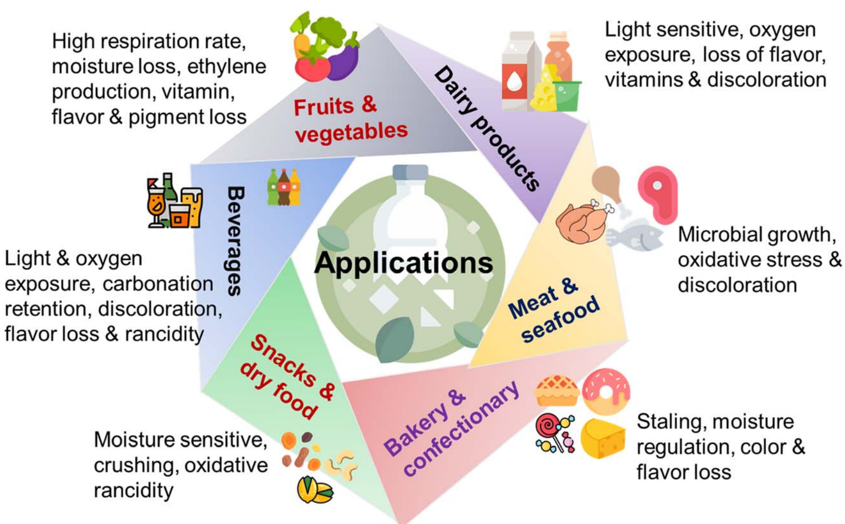

Fig. 5 Applications of biopolymers in packaging various food products and the problems encountered by these products.

against *Escherichia coli*, *Botrytis cinerea*, and *Bacillus cereus*. The propolis extract-enriched coatings reduced the fungal decay and weight loss of the fruits during storage. Specifically, the 12% propolis extract showed 90.22% ABTS radical scavenging activity, 3.11 log CFU g^{-1} total yeast and mold count, and excellent sensory attributes after storage for 18 days. The 12% propolis extract coating was more effective than other combinations and gave better results by preserving the postharvest quality attributes and enhancing the shelf life up to 18 days at 4 °C. Thus, grass pea protein, apple pomace pectin, and propolis extract can be potentially used as a promising natural alternative for food packaging with wide applications for different food products.[128]

Biopolymer-based packaging has been extensively utilized in the preservation of fruits and vegetable by extending their shelf life, as shown in Table 2.

5.2 Packaging for dairy products

Dairy products include processed cheese, ice cream, butter, yogurt, milk, processed milk goods, and cream, providing the human body with diverse nutrients in an easy and effective manner. However, because these products are perishable, humidity, light, oxygen, and bacteria affect their quality and quantity.[203] Therefore, packaging is necessary to prevent harmful effects and improve the stability and quality of these commercial products.[77] Cheese, with its intricate structure and wide variety, is one of the most thoroughly examined and complex dairy products. Edible coatings and films are commonly utilized to prolong the shelf life of certain cheeses due to their biologically and biochemically active properties.[204]

Cai *et al.* examined the effect of edible films of chitosan, guar gum, and orange EO nanoemulsions for Mongolian cheese preservation. Among them, the 4% orange EO nanoemulsion with an even distribution and optimal droplet size (380 ± 44.07 nm) has compatibility with guar gum and chitosan edible films. The films had better oxygen and water vapor barrier characteristics, reduced moisture content (from 96.86% to 34.69%) and water solubility (from 72.27% to 69.76%), and increased water contact angle (from 59.9° to 113.8°). The incorporation of 4% orange EO nanoemulsion improved the mechanical attributes and elongation at break to 135.12%, and reduced the tensile strength of the films. The guar gum/chitosan-orange EO nanoemulsion 3 : 1 edible film maintained the pH, color, weight, and textural changes, inhibited bacterial growth and delayed the lipid oxidation of the cheese samples, thus preserving the safety and quality of cheese.[154]

Biopolymer-based packaging has been extensively utilized in the preservation of dairy products, as shown in Table 2. Materials made from natural biopolymers enhance dairy preservation. Edible films provide benefits such as water interaction, emulsification, stabilization, and gelling, aiding the stability and texture of dairy products.[205]

5.3 Packaging for bakery and confectionary products

Bakery and confectionary products including bread, cookies, biscuits, cake, muffins, pastries, donuts, pasties, pies, wrappers, buns, candies, and sweets are frequently contaminated by yeast and mold, resulting in unwanted odors, taste, and noticeable flaws.[153] These microorganisms impair the safety and sensory qualities of these products. Thus, to address this problem, edible coatings and films are applied using techniques such as wrapping, dipping, and spraying.[154] These protective layers, usually fortified with antimicrobials or antioxidants, form a barrier that inhibits microbial growth and prolongs the shelf life of products.[153]

Pawle *et al.* examined the effect of biodegradable edible films formulated using raw papaya and citrus peel blended with corn starch. The formulated films were used for the preservation of muffins under two distinct conditions of room temperature (25 °C) and refrigerated temperature (7 °C) for 10 days. The biodegradable and plastic films as reference were used for wrapping muffins. Physical parameters were checked every 2nd day. The optimized film had a thickness of 0.26 mm, elongation at break of 11.92%, tensile strength of 5.79 MPa, high transparency, high degradation temperature, and enhanced antimicrobial properties. Thus, raw papaya and citrus peel-based edible films blended with corn starch can be potentially used as innovative food packaging materials for sustainable food preservation, particularly for bakery products.[142]

Biopolymer-based packaging has been widely used for preserving and packaging bakery and confectionary products, as shown in Table 2.

5.4 Packaging for beverage products

Biopolymers are being used more often in beverage packaging as eco-friendly substitutes for conventional petroleum-based plastics.[155] Their ability to degrade naturally, lack of toxicity, and capacity to create films and coatings make them appropriate for many types of beverage products such as water, juices, milk, and carbonated drinks.[156] Polylactic acid, sourced from corn starch or sugarcane, is a widely researched biopolymer for beverage packaging due to its transparency, processability, and composability. It is used for cold beverage bottles such as water and juice.[158]

In a study conducted by Jittanit *et al.*, pineapple juice was sprayed with 15% maltodextrin at 150 °C and the powder yield exhibited 6.2 min solubility and 5.1% moisture. The rehydrated powder showed a pH value of 3.5 with color characteristics measuring 58.8 for lightness, 5.2 for redness, and 25.1 for yellowness. The incorporation of a stabilizer such as agave fructans with maltodextrin can produce low moisture pineapple juice powder (2.74%) with a greater bulk density (0.5913 g mL^{-1}), solubility (97.34%), glass transition temperature (52.68 °C), and superior properties by spray drying.[156]

Biopolymer-based packaging has been extensively utilized in the preservation and packaging of beverage products, as shown in Table 2.

5.5 Packaging for snacks and dry foods

Nuts such as almonds, hazelnuts, walnuts, pecans, chestnuts, and pistachios are significantly profitable and nutrient-rich foods consumed globally.[160] The intake of nuts is increasingly associated with numerous health advantages, including better cardiovascular health and lower risks of chronic illnesses such as coronary heart disease, Type II diabetes, obesity, and various cancers.[163] These nuts have versatile applications, eaten either raw or processed through roasting, and are essential components in different food products such as spreads, baked goods, and sweets.[161] A high unsaturated fatty acids level (46–76%), mainly α-linoleic, oleic, and linoleic acids, is found in temperate nuts, making them more prone to oxidative rancidity, which is a big issue for their long-term storage and quality maintenance.[165]

Hasanshahi *et al.* examined the effect of zinc oxide nanoparticles on the shelf life of fresh pistachios in polyethylene packages in cold storage for 75 days. The variables used were the type and disinfectant concentration (0.5%, 1%, 1.5%, and 2% nano-ZnO and 2% peracetic acid) and storage time (at harvest, 25, 50 and 75 days after harvest). There was no aflatoxin production in the kernels of the disinfectant treatments after storage. The weight, firmness, chlorophyll, phenolics, flavonoids, and carotenoids in the hulls and kernels were reduced with time. In the hulls and kernels, nano-ZnO (2%) prevented this reduction well and enhanced the anthocyanin content. All the combinations of ZnO inhibited ion leakage and limited malondialdehyde and hydrogen peroxide production in hulls. Peracetic acid reduced the polyphenol oxidase activity on the 75th day. All the ZnO treatments (particularly 1.5% and 2%) reduced the quality loss in the shells, taste, aroma, and hulls. Thus, nano-ZnO (2%) has more potential for preserving fresh pistachio preservation in cold storage.[160]

Thus, it is necessary to preserve these products, and biopolymer-based packaging has been widely used in the preservation and packaging of these products, as shown in Table 2.

5.6 Packaging for meat, poultry, and seafood

Meat, fish, and their related products spoil quickly with changes in flavor, texture, oxidation, and appearance when not stored correctly due to their highly perishable nature and biological origin.[167] These alterations may lead to spoilage and potential food safety issues if not properly controlled and stored. To prevent these problems and extend their shelf life, it is essential to package meat (both fresh and frozen), fish, and other animal-derived foods appropriately.[172,181] Meat items, including both fresh and cured varieties, serve as essential protein sources derived from animals for most individuals globally.[174,183] Employing edible films and coatings presents a novel approach for preserving and packaging these goods. These coatings/films act as a barrier that significantly restricts the growth of microorganisms, reduces moisture loss, halts the accumulation of waste products, and prevents the oxidation of lipids, pigments, and proteins.[168,176] As a result, this method improves the sensory appeal of the product for a longer period.

Lotfi *et al.* examined the effect of *Vicia villosa* protein isolate and zinc oxide nanoparticles on the shelf life and quality parameters of rainbow trout fillets under refrigerated conditions (4 °C ± 1 °C). The formulated coating formulations were *Vicia villosa* protein isolate alone, *Vicia villosa* protein isolate + 10 mg ZnO/100 mL, and *Vicia villosa* protein isolate + 20 mg ZnO/100 mL. Rainbow trout fillets were coated with the different formulations, and various parameters such as pH, free fatty acids, peroxide value, thiobarbituric acid-reactive substances, total volatile nitrogen, microbial loads, and sensory attributes were monitored for 12 days on 0, 4, 8, and 12 days. The coatings reduced the lipid oxidation and microbial growth. Among them, 20 mg ZnO/100 mL had the strongest protective effect and delayed rancidity. The coating enhanced the shelf life by four days by preserving quality and sensory attributes. Thus, *Vicia villosa* protein isolate-ZnO NP-based coatings can be used for enhancing the product freshness and acceptability.[169]

Biopolymer-based packaging has been widely used in the preservation and packaging of meat, poultry, and seafood, as shown in Table 2.

6. Sustainability benefits of biopolymer packaging

6.1 Reduction in plastic pollution

It is a fact that plastics, especially single-use plastics are still the most used materials for food packaging but as often reiterated, the non-biodegradable nature of conventional plastics is one of the most important deterrents to their use in food packaging and one of the most important incentives to use biopolymer-based packaging.[47] The gradual transition to bio-packaging will reduce the dependency on conventional plastic packaging materials, thereby easing the environmental load associated with the disposal of these plastic forms into the environment.[206]

The foremost aspect related to the use of conventional plastics *vs.* biopolymers is the environmental concern often associated with the former. Overall, biopolymers have been linked to environmental compatibility but specific considerations need to be made considering that many variables affect the environmental friendliness including existence of appropriate waste management options and robust life cycle assessments (LCAs), along with other conditions.[56] It should be noted that virgin biopolymers do not pose an environmental threat but because they need to be reinforced with specific materials (which may not be environmentally compatible) to achieve properties desirable for use in food packaging, environmental issues emerge.[77] Thus, though, conventional plastics are potentially more serious environmental threats than biopolymer based but the practical use of such biopolymers may also create an environmental nuisance. Their environmental aspect is also closely linked to human health given that materials such as nano-fillers (reinforcing material) may enter the human food chain, and also pose health risks.[91]

Generally, although the use of biopolymers in food packaging has been advocated, these materials have poor strength and barrier properties with high sensitivity to moisture (leading to rapid film deterioration) in comparison to conventional plastic packaging materials. Interestingly, many biopolymers are not found to be fit for packaging food materials owing to their poor strength and chemical structures.[15] This creates a preference for conventional plastic materials in food packaging over many biopolymers given that these issues limit the shelf life of food packaged in these biopolymers.[32,48] The biopolymers used in food packaging need to be reinforced with specific substances to overcome the weaknesses associated with their use in food packaging. As a result of appropriate reinforcement, desirable packaging properties such as effective antimicrobial, barrier, and thermal stability can be improved. Biopolymers are also superior to conventional plastics given that they contribute to less greenhouse emissions than the conventional plastic packaging materials.[101,191]

Currently, the majority of plastic packaging materials are not biodegradable polymers, among which a considerable portion is constituted by single-use plastics, and their use has increased manifolds.[207] The understanding that single-use plastics significantly contribute to the global solid waste issue is increasing. Although biopolymers are environmentally advantageous because they are derived from renewable sources, there is a risk associated with mixing them with non-food packaging plastics, which could lead to toxic residues in food packaging.[208] In evaluating the potential of biopolymers in the food packaging industry, it is crucial to assess the recyclability of various plastics and the financial motivations for recycling them.[82] This is particularly relevant for multi-layer food packaging, where focusing on compostable alternatives is significant due to the difficulties in processing and recycling these intricate materials, especially given their likelihood of contamination as food contact materials.[120,209]

Given that biopolymers are complex structures, their treatment and recycling may also pose issues as well. An important characteristic of biopolymer-based food packaging is the aspect of composability. In reference to this characteristic, the environment is affected in another important way given that compostable packaging such as that made of corn starch can drastically reduce the landfill load.[169] Considering that the nutrients released from these compostable materials gradually return as nutrients to the earth, and landfills are less burdened by waste, a circular economy is established with the efficient re-use of resources and reduced environmental burden.[31] This approach also helps to reduce food wastage given that this type of packaging, such as in the case of active packaging, prolongs the shelf life of food, further leading to less waste being disposed in landfills.[210]

6.2 Carbon footprint and life cycle assessment (LCA)

As mentioned earlier, the greenhouse emissions associated with biopolymeric food packaging are less than that from conventional packaging. However, the environmental impact of biopolymer-based food packaging is crucial for determining their true sustainable.[11] Owing to their environmentally friendly properties such as biodegradability, reproducibility, biocompatibility, versatility, renewability, and non-toxicity, biopolymers are known for their low carbon footprint.[211] Important evaluations including biodegradability, compostability and life cycle assessment (LCA) are very important. LCA helps to determine the efficiency of a test material in reference to the environment and evaluates the sustainability related to its use. For example, an LCA was conducted to measure the environmental footprint, in terms of kg CO_2 equivalent, of polylactic acid nanocomposites containing chitin nanocrystals as well as polyethylene terephthalate. The evaluation considered both the manufacturing stages and disposal scenarios.[212] Overall, polylactic acid exhibited a slightly lower carbon footprint compared to polyethylene terephthalate, while the chitin nanocrystal-enhanced polylactic acid nanocomposite showed a significantly higher CO_2 equivalent value. This LCA reveals that this approach minimizes the use of chemicals, integrates biological techniques, and explores different processing strategies such as selecting an appropriate drying method.[212] Biopolymers undergo enzymatic and microbial degradation into carbon and water.[63] In the case of a specific sample, the analysis of released carbon dioxide (CO_2) in comparison to the theoretical CO_2 content is done to study its biodegradability. The biodegradability aspect is investigated in natural settings as well by introducing soil into controlled conditions of a bioreactor, and the rate of biodegradation for a specific time is studied in reference to a control (reference material) according to standard ISO methods.[12,80] The carbon emission involved in different end-of-life scenarios for various biopolymeric packaging materials such as polylactic acid and starch/cellulose-based materials help in LCA evaluations of these materials. The end-of-life scenarios vary given that the environmental impacts of these materials differ for different compositional changes, methods of preparation, end-of-life treatments, *etc.*[18,213]

6.3 Biopolymer-based food packaging and circular economy

The transformation of the food packaging industry by aligning this sector to the principles of a circular economy with the utilization of waste from agro-food industrial sectors is an innovative and rapidly favoured approach, as shown in Fig. 6. By repurposing these waste materials into developing food packaging films, valuable materials of commercial importance are generated, while reducing the bulk of environment disposal of agro-based waste materials.[32,197] Fruit and vegetable seeds, peels, kernels, leaves, *etc.* as raw materials for food packaging materials can be used as bioactive compounds, polymers, active packaging films, coatings, *etc.* after undergoing specific extraction and development steps.[129] This approach well integrates different industrial sectors through the harmonious link of a circular economy, thereby offering sustainable solutions to food packaging, while making waste valorisation possible.[37,214]

One important aspect of using bio-based packaging is that edible packaging may be directly applied as a way to reduce generated waste. Given that consumers can simply consume the packaging the food is packed in, post-consumer waste can be significantly reduced.[65] This approach is valuable and beneficial in multiple ways, from reducing the demand of conventional plastic packaging (especially, single-use plastics), to letting the consumer 'enjoy' an additional food and minimizing the waste generated. Still, even if not consumed by the end users, the edible food packaging, being biodegradable, does not pollute the environment.[90] These applications wonderfully fit into the

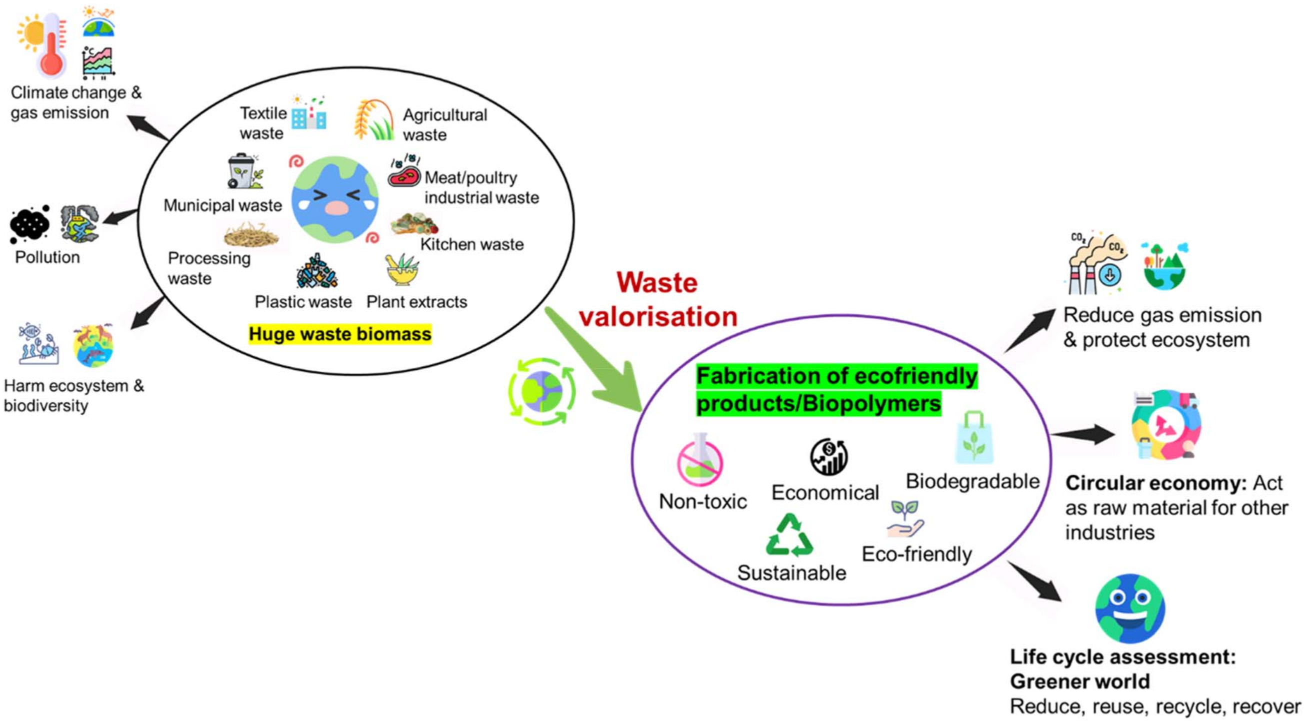

Fig. 6 General representation of waste valorization of different biomass wastes into biopolymers and their interaction with the circular economy and life cycle assessment in a sustainable way.

principles of a circular economy with a closed loop approach to waste generation and are rapidly being explored in the food and beverage industries. These edible films not only offer environmental compatibility but also align with changing consumer perceptions and expectations in light of regulatory guidelines.[215]

6.4 Safety, food contact regulations and labeling

Though food safety and regulations vary from country to country, the basic guiding principles remain the same. Given that safety aspects related to the use of food packaging are important considerations in the concerned regulations, stringent guidelines by appropriate authorities are in place and need to be complied with. The packaging materials need to meet GRAS (Generally Regarded as Safe) and GMP (Good Manufacturing Practices) guided by FDA regulations under the relevant jurisdiction.[37,213] Toxicity and allergenic evaluations are also important assessments for materials, especially those using antimicrobial essential oils given that the efficacy of the materials that do not align well with safety cannot be used with food formulations. The approving guidelines vary by country or export requirements relevant to a country.[12,76] Compulsory disclosure on ingredients is important on labels and information related to any potential allergen, such as that present in coatings, needs to be available. The films and coatings, especially in case of edible ones, are categorized as food ingredients, and need to have GRAS status.[79] Also, the development of edible films may require certain changes that may pose health risks such as in the case of using of cross-linking agents. This also needs to be considered.[216] The European Food Safety Authority (EFSA) evaluates the risks of the leaching of substances from the packaging, and thus crucially evaluates the safety aspects of the films. The panel also looks into any potential risks of contaminant residues left after package material recycling.[121] According to the European Union legislation and EFSA document dossiers on food contact materials, data and information need to be compiled. EFSA also plays crucial role as an advisor to the European Commission and other national authorities on the safety aspects associated with materials that come in contact with food.[122] The ISO standards look into various aspects of biopolymer-based food packaging. The main concerns are safety and environmental issues. Quality management (ISO15593), recycling aspects (ISO 18606), and food safety (ISO 22002-4), are some important aspects that are investigated.[213,214] The standards discuss hygiene and hazards analysis and aid in establishing and maintaining food safety systems through the production cycle. The standards also specify establishing, implementing and maintaining prerequisite programs (PRPs). Standards such as ISO17556 help in determining biodegradability in soil and are important indicators of environmental friendliness of the material tested.[22] Standards are also in place to address guidelines related to the specific type of biopolymer in food packaging. Overall, the standards address various aspects of biopolymer-based food packaging including food safety, mechanical and barrier properties, compostability, texture and appearance, and importantly biodegradability.[217]

Food packaging is a huge market and is rapidly expanding with newer solutions to existing food packaging limitations.

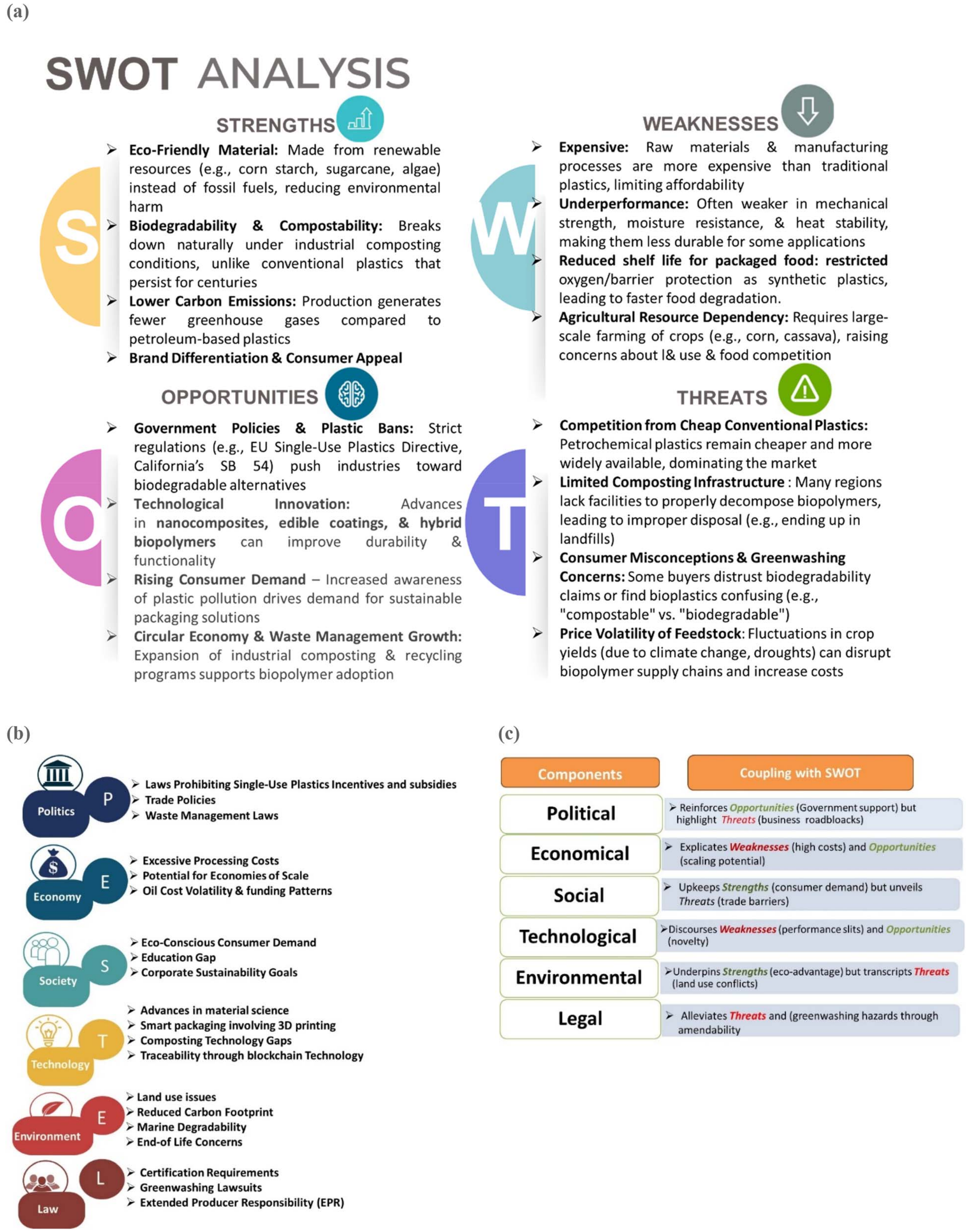

Fig. 7 (a) SWOT assessment; (b) PESTEL assessment; (c) integration of SWOT + PESTEL assessment in relation to biopolymer-based food packaging for sustainability.

The growing concerns about environmental friendliness and the health of individuals have also driven research into better packaging options, further fueling the demand for biopolymers in food packaging, and also bring in important related legislation into play.[173] Many countries have resorted to taxation and the banning of single-use plastics to curb their unscrupulous use in applications such as food packaging. Recycling of plastic packaging also helps in reducing its impact on the environment.[218] A problem commonly encountered with the use biopolymeric packaging is that its recycling may be difficult given that polymers are often mixed with other plastics, making its collection, sorting and subsequent recycling difficult.[219] Hence, legislative requirements and regulations including traceability, prevention of misuse, and separation of food contact materials from non-food contact materials need to be satisfied for the recycling of packaging biopolymers. The inertness of materials is one of the important characteristics that the concerned regulations addresses, and any undesirable interaction with food may endanger human health or change the food properties.[203] Though an important parameter, traceability is often difficult to achieve in a post-consumer scenario. The presence of non-intentionally added compounds should also be considered. Overall, regulations on the use of packaging and its compliance will help in the promotion of biopolymers for food packaging.[219]

7. Challenges and future perspectives

Transitioning to food packaging comprised of biopolymers promises both revolutionary possibilities and formidable challenges. Rapid developments in materials science, processing technologies, and circular system design are progressively eliminating the substantial performance, cost, and infrastructure constraints that currently exist.[80] To completely realize the potential of sustainable biopolymer packaging, it will be essential to strategically integrate technological innovation with market incentives and supportive legislative frameworks. The consideration of resources of biopolymers is crucial for the sustainability of materials. Biopolymers derived from renewable sources are pivotal in research as a strategy towards transitioning to a circular economic model.[121] Thus, conducting a thorough life cycle assessment (LCA) is imperative to ensure the most sustainable material selection. Tools such as the European Commission's "Product Environmental Footprints (PEF)" are employed to evaluate a wide range of criteria, instead of focusing solely on CO_2 footprint to prevent misrepresenting the most sustainable option.[37] The manufacture of biopolymers necessitates resources such as water and land, which may consequently compete with alimentary or fodder production and potentially cause environmental degradation, for instance through eutrophication. This is closely associated with food security and Sustainable Development Goals (SDGs) that must be taken into account. This is especially relevant for food packaging within the Fast-Moving Consumer Goods sector, where low profit margins limit the potential for increased packaging costs due to pricier materials.[211]

Despite the environmental benefits of biopolymers, several economic and technological bottlenecks hinder their widespread commercialization. The major roadblocks are high production costs, limited scalability, lack of robust processing infrastructure, and the challenges faced by small and medium-sized enterprises (SMEs).[1,9] A significant challenge in the widespread adoption of biopolymers as substitutes for traditional materials is their higher cost (approximately 2–4 times more than petroleum-based plastics), particularly when pricier alternatives fail to meet necessary barrier requirements due to molecular differences.[16,22] This is primarily due to their expensive feedstocks, fermentation requirement, and downstream purification processes. SMEs face steep challenges due to their limited access to large biorefineries, costly infrastructure, and the subsidies that conventional plastics benefit from.[48] In addition to high costs, scalability and infrastructure pose major hurdles, where most biopolymer facilitates operate at pilot or semi-commercial levels, making it difficult to compete with the multi-million-ton annual output of petrochemical plastics.[37,40] Similarly, technological barriers are also a major hurdle, given that processing biopolymers often requires modifications to conventional plastic-processing equipment.[45] For example, PHA is brittle and requires plasticizers and blending, which increases the production costs. Furthermore, inconsistent standards and certification processes for compostability and biodegradability across different regions hinder their effective market entry.[40]

Thus, working together across the value chain from waste managers to brand owners and feedstock producers will be essential to the future success in creating commercially and environmentally sustainable substitutes for traditional plastic packaging systems.[98,213] The SWOT (Strength, Weakness, Opportunities and Threats) and PESTEL (Political, Economic, Social, Technological, Environmental, Legal) assessments presented here will provide stakeholders with a methodical framework for traversing the surroundings, identifying strategic priorities, and expediting the advancement of food packaging technologies that are extremely sustainable and address the demands of both people and the environment.[219]

7.1 SWOT analysis of biopolymers in the food packaging industry

7.1.1 Strengths. Biopolymers represent sustainable alternatives to synthetic packaging substances due to their biodegradable, non-toxic, renewable, and biocompatible properties. These materials facilitate recycling processes and mitigate the environmental pollution typically associated with synthetic polymers. Consequently, biopolymers offer a reduced ecological impact compared to conventional synthetic products.[37] Originating from natural sources such as animals, plants, and microorganisms, biopolymers are readily available. The processes of extraction and synthesis vary according to the specific type of biopolymer. Biopolymers have excellent film-forming capability and unique strengths, as previously discussed. They can be combined with other biopolymers or reinforcements to create lightweight, high-performance packaging materials. As matrices, biopolymers can integrate antioxidants, nanofillers, natural substances, vitamins, minerals, nutrients, and antimicrobial agents, enhancing their functionality as active packaging materials.[44,82]

7.1.2 Weaknesses. Despite being eco-friendly, biopolymers have significant drawbacks such as weak mechanical and barrier attributes, rapid degradation, and high moisture sensitivity. These attributes detract from their performance, making them unsuitable for direct use in food packaging mainly due to their weak chemical and mechanical structures.[12] They are hydrophilic, degrade with moisture, and more expensive and harder to process than synthetic polymers, compromising their ability to preserve the quality and shelf life of food.[47]

7.1.3 Opportunities. There are numerous opportunities for utilizing biopolymers in food packaging, including materials designed to be active and smart. Biopolymers form the fundamental substances for most packaging material combinations, often in conjunction with nanomaterials or other active agents.[180] Adding reinforcement substances into the biopolymer matrix enhances the crucial properties required in packaging materials, such as thermal, barrier, mechanical, antioxidant, and antimicrobial attributes. Most of these food packaging materials are still undergoing research, presenting a chance for their scaled-up and global production as alternatives to synthetic polymers.[11] The industrial production of biopolymers and bioplastics offers the potential to diminish environmental pollution globally and support the circular economy, as highlighted by the European Union.[215]

7.1.4 Threats. Although there is extensive documentation on the environmental issues associated with plastic packaging, evaluating the ecological impact of biopolymers is more complex. Biopolymers may offer environmental benefits, but their specific strengths and weaknesses depend on various factors, including their source, manufacturing processes, waste management systems, and end-of-life considerations.[8] To make well-informed decisions about the ecological effect of a material, one must conduct a comprehensive analysis of its life cycle. Most biopolymers, when left unchanged, do not threaten society or the environment.[33] However, when these biopolymers are combined with nanofillers or other additives to improve the characteristics of packaging, these substances may transfer into food items, and eventually the human body. If the agent is cytotoxic, it may pose a risk to human health.[64] Moreover, during the biodegradation process, active agents can migrate into the soil or water, potentially altering environmental conditions and causing pollution. The transfer of chemical substances is linked not just to biopolymers but may also happen with alternative packaging materials.[71] Thus, it is essential to assess and manage the possible movement of substances from all types of packaging, including biopolymers, to guarantee food safety and compliance with regulations. Ongoing research and development focus on enhancing the safety and efficiency of biopolymers used in food packaging.[213] This involves creating new materials, optimizing processing methods, and conducting thorough evaluation to ensure their appropriateness for food contact, while minimizing the movement of harmful components. Furthermore, the microorganisms used in biopolymer production might be hazardous and contribute to environmental pollution.[181]

7.2 PESTEL analysis of biopolymers in the food packaging industry

7.2.1 Political factors (administrative impact). Through waste management regulations that demand compostable packaging (*e.g.*, in France and Italy), subsidies for bio-based research and development (*e.g.*, USDA BioPreferred Program), and regulatory bans on single-use plastics (*e.g.*, EU SUPD and California's SB 54), governments around the world are propelling the transition to biopolymer-based packaging. Trade constraints on traditional plastics could increase the production of biopolymers locally.[220]

7.2.2 Economic factors (market and financial viability). As their production increases, biopolymers are becoming cost-competitive, even if they are 20–50% more expensive than petroleum plastics. The cost of biopolymers such as PLA decreased by 30% in just ten years. While still 20–50% more expensive than conventional plastics (*e.g.*, PLA at \$2.50–3.00 kg^{-1} *vs.* PET at \$1.00–1.50 kg^{-1}), economies of scale and technological improvements are narrowing this gap.[221] Their appeal is increased by the unpredictability of oil prices, and growing venture capital investments (such as in TIPA and Notpla) indicate promising market prospects. Fossil plastic prices are tightly linked to crude oil, which is subject to geopolitical and economic shocks. For example, oil prices above \$80/barrel make biopolymers more competitive. Biopolymers prevent oil dependency, appealing to industries seeking supply chain stability. Notpla (seaweed-based packaging) raised £20 M (\$25 M) in 2024, targeting the replacement of 100 M single-use plastics annually.[222]

7.2.3 Social factors (consumer and industry trends). Consumer demand for sustainable packaging is high (67% prefer eco-friendly options), but confusion over terms such as "biodegradable" and "compostable" hampers proper disposal. Major corporations (*e.g.*, Nestle and Unilever) are committing to 100% recyclable/compostable packaging by 2025–2030, though some consumers remain wary of food safety risks despite FDA approvals.[223]

7.2.4 Technological factors in biopolymer-based food packaging: innovations and infrastructure challenges

7.2.4.1 Enhancing barrier properties. Recent advancements in biopolymer-based food packaging have focused on enhancing material performance and integrating smart technologies, though infrastructure limitations remain a barrier to full sustainability. Nanocellulose, derived from plant biomass, has emerged as a key material for improving the moisture and heat resistance of biopolymers.[171] Its high surface area, mechanical strength, and tunable hydrophobicity make it ideal for coatings that enhance barrier properties. For instance, nanocellulose-reinforced PLA films have demonstrated 40–60% improvements in oxygen barrier performance, addressing a critical limitation of pure PLA.[224] Similarly, polyhydroxyalkanoates (PHA), produced by microbial fermentation, offer superior marine biodegradability and moisture resistance compared to starch-based biopolymers. PHA degrades 90% in seawater within 6 months, making it a promising alternative for flexible packaging.[225]

7.2.4.2 Smart packaging and IoT integration. Smart packaging systems combine biopolymers with IoT sensors, RFID tags, and NFC chips to monitor food freshness in real time. These systems tracks temperature, humidity, and gas composition (*e.g.*, CO_2 for spoilage detection, real-time monitoring, and environmental regulation) and tampering *via* blockchain-verified digital watermarks.[224] For example, PLA films embedded with pH-sensitive dyes or graphene-based sensors can signal food spoilage visually, reducing waste. However, their scalability is hindered by the high cost of IoT components and the need for standardized protocols.[226]

Self-healing coatings are smart coatings that enhance the shelf life, safety, and preservation of food by autonomously fixing small defects such as cracks and punctures by releasing healing agents from embedded microcapsules when damage occurs.[227] They are engineered to react to environmental factors including temperature, humidity, and gas levels, allowing the real-time monitoring and regulation of storage environments.[227] These coatings hold significant potential for food transport and storage applications, where packaging frequently encounters mechanical strain. Moisture-responsive coatings integrated into packaging systems can regulate the internal humidity, helping to avoid mold formation and preserve freshness in produce such as fruits and vegetables.[228]

Despite material innovations, <5% of global composting facilities can process industrial-compostable biopolymers such as PLA. Key challenges include consumers confusing "home-compostable" and "industrial-compostable" materials, leading to contamination. Industrial composting requires sustained high temperatures (50–60 °C), which many regions lack. Countries such as Italy and Germany are piloting extended producer responsibility (EPR) schemes to fund composting infrastructure, but progress is uneven.[229]

7.2.4.3 Blockchain for supply chain transparency. Blockchain technology is being adopted to verify the sustainability of biopolymer supply chains, addressing greenwashing concerns. Applications include provenance tracking, which aims at certifying renewable feedstocks (*e.g.*, sugarcane for PLA) and carbon footprint validation, which tokenises carbon credits for biopolymer production.[230]

Fig. 7 shows the comprehensive SWOT and PESTEL analysis for biopolymer-based food packaging for sustainability, examining the macro-environmental factors influencing this industry. This complements the SWOT analysis by exploring external drivers and constraints in detail.

Furthermore, the biopolymer market is projected to reach $120.5B by 2033 (10.5% CAGR), driven by packaging (53% market share) and agriculture. With this rapidly growing rate, roadblocks such as high fixed costs and feedstock competition require innovations such as algae- and waste-based feedstocks.[34] Additionally, the scalability of composting depends on infrastructure investment and standardized labeling, resulting in the requirement for unified labeling policies (ISO 18606/EN 13432).[34,37]

The future of edible packaging lies in optimizing coating technologies and integrating them with preservation methods such as modified atmospheric packaging, refrigeration, and UV treatment to boost shelf life through combined effects.[231] They effectively tackle the multifaceted issues of microbial contamination, spoilage, and nutrient loss. This integrated strategy responds to the increasing demand for safe, sustainable, and longer-lasting food products. Thus, combining edible coatings with advanced preservation methods will offer a well-rounded solution to food preservation issues.[232]

8. Conclusions

The food sector is undergoing a radical change toward sustainable solutions with the introduction of food packaging made of biopolymers. These materials, which are made from renewable resources including cellulose, starch, and polylactic acid, have several environmental benefits over traditional plastics, such as biodegradability and a lower carbon footprint. However, to guarantee their success, they must overcome the opportunities and difficulties that come with their transition from laboratory discovery to broad commercial application. One of the primary hurdles is balancing performance with sustainability. Although biopolymers excel in eco-friendliness, their widespread acceptance is currently hampered by their limited mechanical strength, moisture resistance, and thermal stability and high cost (20–50% greater than plastics). Recent advancements in materials science, such as nanotechnology-enhanced coatings and active packaging systems, are bridging this gap. Innovations such as nanocellulose composites and oxygen-scavenging films demonstrate that biopolymers can meet the functional demands of food packaging, while maintaining their environmental benefits. Scalability is still a significant obstacle. Their large-scale adoption is hampered by their high manufacturing costs and inadequate composting infrastructure. However, the market demand is being driven by increasing governmental support, such as prohibition of single-use plastics and incentives for sustainable alternatives. To improve manufacturing procedures, cut expenses, and extend waste management systems for the disposal of biopolymers, cooperation among researchers, business executives, and legislators will be crucial. Education and consumer awareness are also very important. To guarantee correct disposal and optimize environmental advantages, terminology such as "compostable" and "biodegradable" must be clearly labeled and understood by the general public. Biopolymers are positioned to become a common solution as more businesses commit to sustainable packaging goals, limiting ecological harm and lowering the dependence on plastics derived from fossil fuels. An important trade-off between environmental advantages and performance/economic issues is brought to light by the comparison of biopolymer-based food packaging with traditional plastics. The pressing need to lessen plastic pollution and reliance on fossil fuels is achieved using biopolymers, which are made from renewable resources such as corn starch and sugarcane and have a 60–70% lower carbon footprint and biodegradability. Notwithstanding these obstacles, the consumer demand for sustainability and legislative assistance (such as the EU single-use plastics directive) are propelling quick innovation. The performance of biopolymers is being improved by developments in nanocomposites, PHA blends, and active coatings (such as vanillin-enhanced films), while cost reductions may be possible due to economies of scale and feedstocks made from agricultural waste. Conventional plastics are still widely used because they are inexpensive and longlasting, but companies are moving toward alternatives as a result of growing restrictions, ineffective recycling, and reputational hazards. Policy-industry cooperation, infrastructure investment for composting, and consumer education to guarantee appropriate disposal are key to the future of sustainable packaging. Although they are not yet a perfect substitute, biopolymers are a crucial part of the shift from single-use plastics because of their compatibility with the circular economy. To bridge the gap between ecological principles and commercial viability, stakeholders must give priority to R&D investment, supply chain resilience, and unambiguous labeling standards to hasten this transformation. Finally, biopolymer packaging is an essential advancement in food packaging that strikes a balance between economic and technological realities and the health of the world. It can revolutionize sustainability in the global packaging sector with sustained innovation and systemic support.

Author contributions

Chhavi Sharma: writing original draft, review and editing, supervision, conceptualisation. Sapna Kundu: writing original draft, visualisation, validation, investigation, data curation. Shalini Singh: review and editing, data curation, visualisation. Juhi Saxena: visualisation, validation, formal analysis. Sneh Gautam: formal analysis, review and editing. Amit Kumar: visualisation, validation, formal analysis. Puneet Pathak: review and editing, validation, supervision.

Conflicts of interest

There is no conflict of interest to declare.

Data availability

There is no primary research data to declare.

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