

Review article

Edible biopolymer extraction and characterization for use in food products: Natural biopolymers from agricultural waste

Great Iruoghene Edo^{a,b,*}, Moses Victoria Uwanabasi^c, Karthika Periyasami^d, Kugbere Emumejaye^e, Izuwa Iwanegbe^f, Agatha Ngukuran Jikah^g, Emad Yousif^b, Ephraim Evi Alex Oghrora^a, Joseph Oghe-newogaga Owheruo^h, Patrick Othuke Akpogheli^h, Priscillia Nkem Onyibeⁱ, Arthur Efeoghene Athan Essaghah^j, Dina S. Ahmed^k, Raghda S. Makia^l, Ahmed A. Alamiery^m and Ibiyinka Agboola Fuwape^{n,o}

^a Department of Chemistry, Faculty of Science, Delta State University of Science and Technology, Ozoro, Delta State, Nigeria

^b Department of Chemistry, College of Sciences, Al-Nahrain University, Baghdad, Iraq

^c Department of Microbiology, Faculty of Biological Sciences, University of Uyo, Uyo, Nigeria

^d Department of Food Science and Nutrition, Periyar University Salem, Tamil Nadu, India

^e Department of Physics, Faculty of Science, Delta State University of Science and Technology, Ozoro, Nigeria

^f Department of Food Science and Nutrition, Faculty of Agriculture, University of Benin, Benin City, Nigeria

^g Department of Pharmacy, Faculty of Pharmacy, Near East University, Nicosia, Cyprus

^h Department of Food Science and Technology, Faculty of Science, Delta State University of Science and Technology, Ozoro, Delta State, Nigeria

ⁱ Faculty of Art, Design & Information Technology, Department of Health Informatics, George Brown College, Toronto, Canada

^j Department of Urban and Regional Planning, Faculty of Environmental Sciences, Delta State University of Science and Technology, Ozoro, Delta State, Nigeria

^k Department of Chemical and Petroleum Industries Engineering Techniques, Polytechnic College of Engineering Specializations - Baghdad, Middle Technical University, Baghdad, Iraq

^l Department of Plant Biotechnology, College of Biotechnology, Al-Nahrain University, Baghdad, Iraq

^m Al-Ayen Scientific Research Center, Al-Ayen Iraqi University, AUIQ, An Nasiriyah, P.O. Box: 64004, ThiQar, Iraq

ⁿ Department of Physics, Michael and Cecilia Ibru University, Agbarha-Otor, Ughelli North, Delta State, Nigeria

^o Department of Physics, Federal University of Technology, Akure, Ondo State, Nigeria

* Corresponding author at: greatiruo@gmail.com (G.I. Edo).

Received 3 June 2026; Accepted 29 June 2026; Published

Abstract Agricultural residues such as fruit peels, husks, and tuber wastes are increasingly explored as sustainable sources of edible biopolymers for food applications. This study provides an all inclusive analysis of the extraction and characterization of key biopolymers—pectin, starch, cellulose, and proteins—from underutilized agricultural by-products such as mango peels, cassava peels, rice husks, sugarcane bagasse, and cocoa pod husks. It effectively contrasts conventional acid and alkaline extraction methods with innovative, eco-friendly alternatives like enzymatic hydrolysis, microwave-assisted extraction, and sub-critical water processing, highlighting their potential to improve yield and functional performance. The inclusion of advanced analytical techniques (FTIR, NMR, DSC, TGA, SEM, TEM) provides a robust insight into the formational, thermal, as well as morphological characteristics pertaining the extracted materials. Furthermore, the discussion of rheological and textural evaluations offers valuable insights into their gelling, film-forming, and barrier characteristics—key attributes for industrial and packaging applications. Overall, the study demonstrates both scientific depth and practical relevance, contributing meaningfully to sustainable biomaterial development. Applications focus on edible coatings, biodegradable packaging, and use as thickeners, stabilizers, and nutrient carriers in food systems. Case studies illustrate the processing of agricultural waste to generate high-value products, food-grade materials, underscoring their role in food security and circular bio-economy initiatives. Challenges remain in raw material variability, reproducibility, film performance, and scale-up, pointing to future opportunities in integrated bio-refineries, greener solvents, and composite biopolymer systems.

Keywords: Edible biopolymers, agricultural waste, extraction methods, characterization, edible films, sustainable food packaging

1.0. INTRODUCTION

Biopolymer-based packaging has emerged as a sustainable and biodegradable alternative to conventional synthetic polymer packaging, being derived from renewable resources and natural processes [1]. In the context of food packaging, such materials offer a promising solution to the environmental challenges posed by plastic waste. By employing active packaging approaches, biopolymers can help preserve food products, improving both shelf life and safety in response to the increasing demand for eco-friendly practices [2]. Functional additives, including moisture absorbers, antioxidants, and antimicrobials, can be integrated into these packaging systems to enhance preservation and quality [3]. Despite these advantages, the adoption of biopolymer-based packaging in the food industry remains constrained by several issues, such as high production costs, limited compatibility with industrial manufacturing techniques, insufficient biodegradability, and potential toxicity. These limitations collectively influence the transition from conventional plastics toward more sustainable packaging solutions [4].

Assessing the environmental impact and applicability of biopolymers in food-related uses necessitates a thorough examination of their degradation behavior under both natural conditions and controlled *in vitro* digestion studies [5]. Understanding how biopolymers decompose in soil, the human digestive tract, and marine environments enables product developers to create degradation products that are both safe and effective. It is also essential to investigate the ecological consequences of these degradation products and any potential risks they may pose to human health. Comprehensive knowledge of these processes is critical for designing biopolymer-based packaging systems that are both sustainable and consumer-friendly [6]. Furthermore, the possible toxicity of biopolymers and their breakdown products remains a significant concern, as certain biopolymers or additives used for performance optimization may generate harmful substances over time. Given the direct and prolonged exposure of humans to food-contact materials, rigorous testing and regulatory oversight are required to ensure safety standards are met [7].

Another key challenge is the processability of biopolymer-based packaging. Limitations in mechanical strength, flexibility, and thermal stability can render these materials unsuitable for industrial manufacturing techniques such as extrusion, molding, and printing [8]. Addressing these technological constraints is necessary to enable large-scale production that meets industry standards. Enhancing processability can be achieved by developing composites or incorporating appropriate additives, which allows for improved manufacturability while preserving the sustainability attributes of these advanced materials [1].

Biopolymers are natural, biodegradable compounds composed of recurring structural units and produced via plants, animals, bacteria, and fungi. They include a wide range of materials such as polysaccharides-cellulose, starch, proteins, and microbially produced biodegradable polyesters-exhibit diverse functional properties [9]. Unlike conventional synthetic polymers, which are primarily fossil fuel-derived, biopolymers are predominantly obtained from renewable resources, highlighting their potential for sustainable applications. However, being renewable does not automatically make them biodegradable—their breakdown depends on their chemical

composition and the environmental conditions to which they are exposed to [10]. This distinction is important, as the sustainability of biopolymers relates both to how they are sourced and how they degrade. Because of this versatility, biopolymer are increasingly used in sustainable postharvest practices, particularly as edible coatings that can protect perishable plant based foods [11].

Natural polymer as the name implies are polymers that occur naturally or are produced through biological processes. They are both biodegradable and often biocompatible, breaking down under microbial activity into harmless end products such as carbon dioxide, water, and biomass [12]. According to their origin and chemical composition, so Biopolymers are conventionally classified into three major categories. The first comprises polysaccharide-based biopolymer, including cellulose, starch, and chitosan, which originate from plant and marine biomass. The second category encompasses protein-based materials such as soy protein, whey protein, and gelatin, derived primarily from agricultural and animal sources. The third group consists of microbial-derived polymers, notably polyhydroxyalkanoates and polyactic acid, which are synthesized through microbial fermentation processes [13].

Their capacity to assemble into a wide range of structural forms—such as thin film matrices, fibrous architecture, and gel based structure—provides them with considerable versatility across multiple application domains. Nevertheless, biopolymer obtained directly from agricultural residues typically necessitate further processing, including purification, chemical or physical modification, or strategic blending, to enhance their functional and mechanical performance and render them suitable for industrial implementation [14].

Edible biopolymer coatings are increasingly used to preserve fresh produce by forming thin protective barriers that mitigate oxidative degradation, suppress water vapor loss, and limit microbial contamination while regulating respiration and extending shelf life [11]. Their performance is further enhanced by incorporating active agents such as antioxidants, antimicrobials, and bioactive compounds like essential oils, which provide controlled release and sustained microbial protection [15]. Depending on the biopolymer type, coatings offer different advantages: lipids create hydrophobic barriers that limit water loss, proteins provide strength and flexibility for perishable goods, and polysaccharides supply strong film-forming and gas barrier properties that are suited for high-respiration produce [16]. Together, these properties position bio-based polymer as substitutes for conventional synthetic packaging, aligning with market demand for naturally derived products and eco-friendly strategies for extending food shelf life [17]. In this study, an all inclusive analysis of the extraction and characterization of key biopolymers—pectin, starch, cellulose, and proteins—from underutilized agricultural by-products such as mango peels, cassava peels, rice husks, sugarcane bagasse, and cocoa pod husks is provided. Furthermore, it contrasts conventional acid and alkaline extraction methods with innovative, eco-friendly alternatives like enzymatic hydrolysis, microwave-assisted extraction, and subcritical water processing, highlighting their potential to improve yield and functional performance.

2.0. METHODOLOGY

This review was conducted using a systematic and comprehen-

sive literature survey to identify, evaluate, and synthesize existing knowledge on the extraction and characterization of edible biopolymers obtained from agricultural products. Relevant peer-reviewed articles, review papers, book chapters, and scientific reports were retrieved from major academic databases, including Reseach Gate, PubMed, MDPI, Web of Science, ScienceDirect, and Google Scholar. The literature search primarily focused on studies published between 2015 and 2026 to ensure adequate coverage of recent developments in biopolymer extraction technologies, characterization techniques, and their applications in food systems and sustainable packaging.

A combination of keywords and Boolean operators was employed during the search process. Search terms included “edible biopolymers,” “natural biopolymers,” “agricultural products,” “agricultural waste,” “biopolymer extraction,” “polysaccharides,” “proteins,” “starch,” “cellulose,” “pectin,” “biopolymer characterization,” “biodegradable packaging,” and “food packaging materials.” Additional relevant publications were identified through backward and forward citation tracking of key research articles, review papers, and authoritative reports.

The inclusion criteria comprised original research articles, review papers, and book chapters published in English that addressed the extraction, characterization, properties, and applications of edible biopolymers derived from agricultural products. Studies focusing on agricultural residues and by-products as sources of natural

biopolymers were also included. Publications lacking scientific rigor, duplicate records, conference abstracts without full texts, and studies unrelated to edible biopolymers or agricultural sources were excluded from the review.

The selected literature was critically evaluated based on scientific relevance, methodological quality, novelty, and contribution to the understanding of biopolymer extraction and characterization. Information from eligible studies was systematically organized into thematic areas, including sources of natural biopolymers, extraction methods, physicochemical characterization, functional properties, biodegradability, and applications in food preservation and packaging.

The synthesized findings were subsequently analyzed to provide a comprehensive overview of current advances in the field, identify existing knowledge gaps, compare extraction and characterization approaches reported by different authors, and highlight future prospects for the development and utilization of edible biopolymers from agricultural products as sustainable alternatives to conventional synthetic materials. Table 1 compares between this and other previously published papers to highlight its main contribution to the body of research on this subject.

3.0. AGRICULTURAL WASTE SOURCES FOR EDIBLE BIOPOLYMERS

Agricultural waste (Figure 1) often termed agro-waste, encompasses the residual by-products generated during the cultivation,

Table 1. CONTRIBUTIONS OF VARIOUS PUBLICATIONS

Authors names	Publication title	Central point of discussion	Reference
Elena Hurtado-Fernández, Luis A. Trujillo-Cayado Paloma, Álvarez-Mateos & Jenifer Santos	Extraction, Characterization and Applications of Biopolymers from Sustainable Sources	Explores the potential of sustainable biopolymers as renewable, biodegradable alternatives to conventional plastics, focusing on their sources, properties, processing methods, applications, and commercialization challenges.	[18]
Aashima Salaria, Shubham Singh Patel, Kandi Sridhar, Prince Chawla, Minaxi Sharma	Extraction and characterization of biopolymers from rice bran oil cake: Development of antimicrobial edible coating for extending shelf-life of strawberry fruit	Investigates the sustainable extraction, characterization, and practical application of biopolymers from rice bran oil cake for food preservation and other potential industrial uses	[19]
Mónica Morales-Jiménez, Luisa Gouveia Jorge Yáñez-Fernández, Roberto Castro-Muñoz, Blanca Estela Barragán-Huerta	Preparation and Characterization of Microalgae-Based Biopolymer as a Potential Bioactive Film	Investigates the potential of microalgae-derived biopolymers as sustainable, biodegradable, and functional materials for food-packaging applications	[20]
Evan Moore and Declan Colbert	Ocean Plastics: Extraction, Characterization and Utilization of Macroalgae Biopolymers for Packaging Applications	Examines the potential of seaweed-derived biopolymers as sustainable packaging materials, discussing their extraction, characterization, applications, advantages, and challenges for commercial implementation.	[21]
Athira R. S. Pillai, Ansu Sara Eapen, Wanli Zhang, Swarup Roy	Polysaccharide-Based Edible Biopolymer-Based Coatings for Fruit Preservation: A Review	Focuses on polysaccharide-based edible coatings as sustainable, biodegradable alternatives to synthetic packaging for fruit preservation, aimed at extending shelf life, reducing postharvest losses, and maintaining fruit quality and safety through improved protection against moisture loss, microbial spoilage, and oxidation.	
Anshika Sharma, Arun K	Sodium Alginate: A Green Biopolymer Resource-Based Antimicrobial Edible Coating to Enhance Fruit Shelf-Life: A Review	Explains that sodium alginate-based edible coatings, especially when enhanced with plant extracts and nanoparticles, can effectively improve fruit shelf life by forming protective, antimicrobial, and biodegradable films that reduce spoilage and postharvest losses.	[22]
Niaz Mahmud, Joinul Islam, Reza Tahergorabi,	Marine Biopolymers: Applications in Food Packaging	Highlights marine biopolymers (especially polysaccharides and proteins from seaweed, crustaceans, and fish by-products) as sustainable, biodegradable alternatives to petroleum-based plastics for food packaging, focusing on their extra film/coating applications, and potential to improve food preservation while reducing environmental pollution.	[23]
Ana Perez- Vazquez Paula Barciela Maria Carpena Miguel A. Prieto	Edible Coatings as a Natural Packaging System to Improve Fruit and Vegetable Shelf Life and Quality	Highlights edible biopolymer coatings as a sustainable alternative to synthetic plastic packaging for fruits and vegetables, aimed at extending shelf life, reducing postharvest losses, and improving food safety while addressing environmental concerns such as plastic waste and food spoilage.	[24]

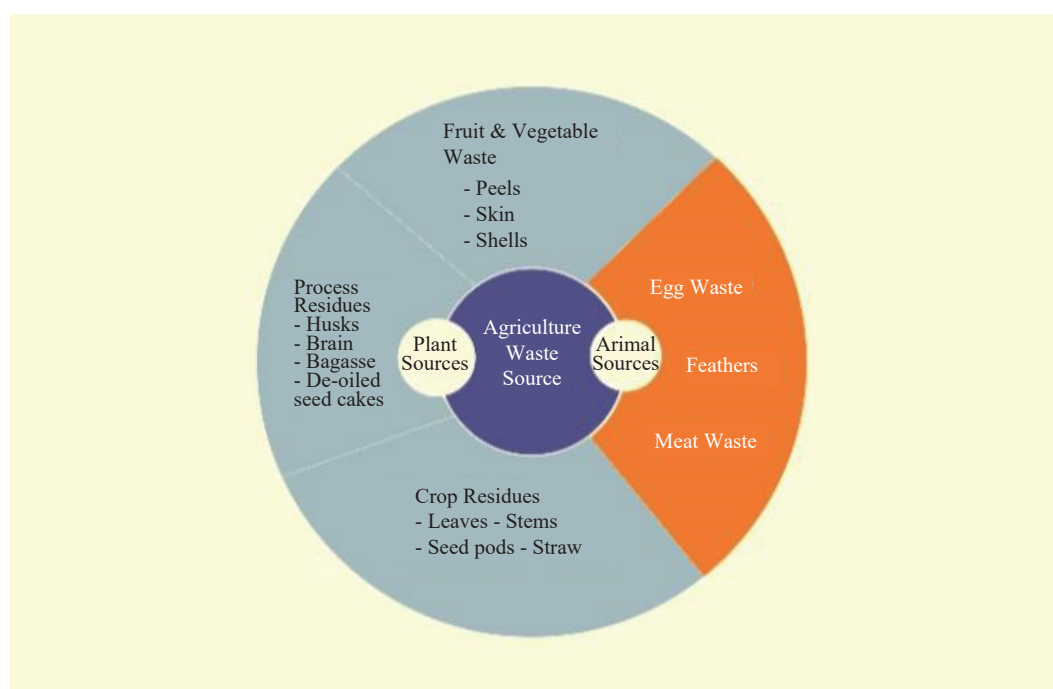


Figure 1. An illustration of the various sources of agricultural waste

processing, and handling of agricultural commodities, including fruits, vegetables, meat, and dairy. These wastes arise from both plant and animal sources and represent a significant biomass stream within the agricultural sector [25].

Agricultural waste, designated as a non-hazardous waste category, encompasses solid residues originating from the cultivation and harvesting of crops, as well as from livestock production. This waste stream includes materials such as animal manures, which are typically reintegrated into the soil to enhance fertility [26]. Extensive recent research on agricultural by-products has yielded a diverse array of high value materials including biofuel, enzymes, essential nutrients, antioxidants, animal feed additives, antibiotics and various chemicals used in industries [27].

Agro-waste-derived biomaterials, such as cellulose, hemicellulose, chitin, lignin, starch, pectin, alginate, and proteins, represent promising resources for sustainable food packaging due to their non-toxicity, biodegradability, abundance, and compatibility with other materials. These solid residues—from crop by-products, processing waste, and animal sources—have been effectively employed as either fillers or primary components, enhancing package performance and extending product shelf life [28].

Food-related agro-waste from diverse origins can be extracted and purified for the production of packaging components. Considerable attention has been given to wastes generated from crop residues, processing by-products, and animal-derived materials [14]. Extraction techniques, processing parameters, and formulation components substantially influence the mechanical, barrier, and thermal characteristics of the resulting composites. For example, cellulose and eggshell powder have been effectively employed as fillers or reinforcing agents in rigid packaging to enhance structural performance, while feather keratin has emerged as a promising novel material [29].

Achieving effective valorization of these waste streams will require supportive policies and innovative packaging strategies ad-

vanced by governmental and regulatory bodies. The agricultural sector produces large quantities of waste throughout production, handling, and processing, and its disposal now poses significant economic and environmental challenges. As a result, the development of recycling and reprocessing pathways has become an important research priority [30].

There is an urgent need for low-cost composite packaging materials with improved functional properties that can support scalable and economically viable manufacturing. Further research is also needed to optimize processing conditions and address safety concerns, particularly regarding the potential migration of constituents from packaging materials. Evidence to date demonstrates that a wide range of agro-waste sources can be transformed into packaging matrices or used as reinforcing and barrier-enhancing additives [31]. However, considerable challenges remain in the collection, storage, preservation, and pre-treatment of agro-waste prior to processing, posing ongoing obstacles for both research and industrial application [32].

4.0. TYPES OF EDIBLE BIOPOLYMERS AND THEIR RELEVANCE IN FOOD PRODUCTS

Biopolymers may be derived directly from natural sources, biosynthesized by living organisms, or chemically produced from biological precursors (Figure 2). Carbohydrate-based materials—such as starch, cellulose, alginates, and pectin—and their composites with animal-derived protein biopolymers (e.g., silk, gelatin, collagen, chitosan/chitin, and gums), as well as plant-based proteins and lipids, present significant potential for advanced technological applications [33]. These materials offer key advantages, including renewable origin, biocompatibility, favorable moisture and gas barrier properties, non-toxicity, environmental sustainability, mechanical robustness, and comparatively low production cost. Moreover, sourcing these biopolymers from non-food plant and animal components helps mitigate competition with food resources [34].

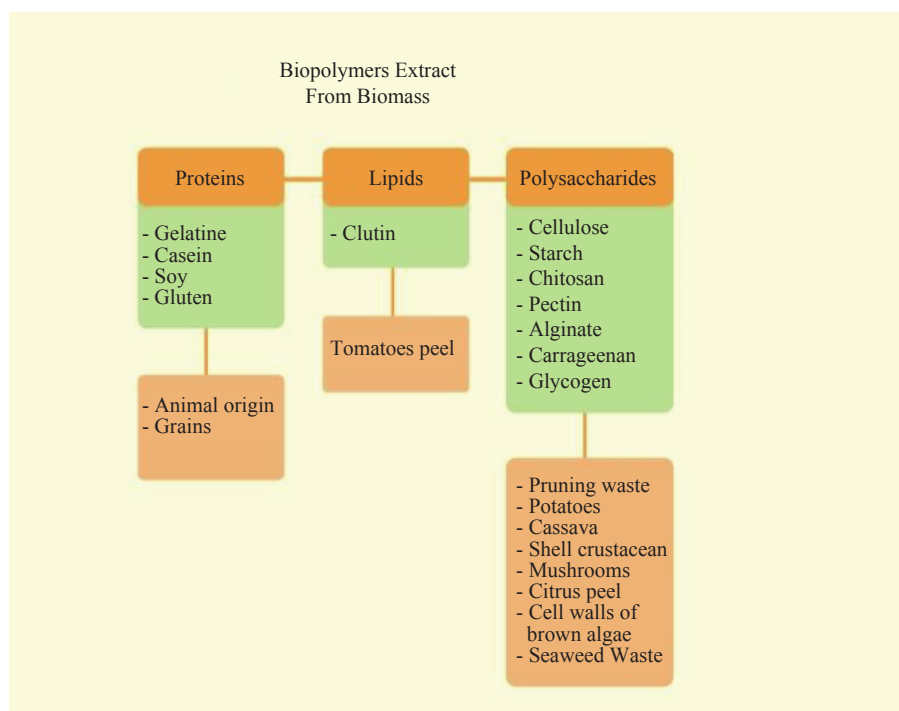


Figure 2. Various edible bio-based polymers derived from plant sources as well as from animal by-products.

4.1. LIPID-BASED BIOPOLYMER

Lipid-derived polymers have recently attracted considerable interest for applications in food packaging and 3D printing due to their tunable functional properties. Efficient extraction from natural sources is essential to isolate fatty acids for downstream esterification reactions [35]. Notably, cutin from tomato by-products and lipids from algae have demonstrated significant potential in producing films with superior water barrier performance, a feature attributed to their inherent low water affinity and molecular architecture. These findings highlight the promise of lipid-based materials as sustainable, high-performance alternatives in advanced material design [36].

4.2. POLYSACCHARIDE-BASED BIOPOLYMERS

Polysaccharide-based polymers, depicted as the final category in Figure 1, are increasingly recognized for their biodegradability, compostability, sustainability, and non-toxic nature, making them highly attractive for food and packaging applications. Unlike other biopolymers such as lipids and proteins, polysaccharides demonstrate superior thermal stability, as they resist irreversible denaturation under heat [37]. Despite these advantages, their practical application is constrained by high moisture sensitivity and inherently low mechanical strength, which can limit durability and performance. To overcome these challenges, two principal strategies have been developed: the reinforcement of polysaccharide matrices with functional additives and the fabrication of blends or multilayer films with complementary polymers. These approaches have substantially enhanced the physicochemical, mechanical, and barrier properties of polysaccharide-based materials, enabling their broader adoption by the food industry in recent years [38]. Ongoing innovations continue to expand their functionality, positioning polysaccharides as a sustainable, high-performance alternative in advanced material design [36]. Polysaccharides form transparent, flexible films with strong mechanical integrity, effectively blocking gases and odors while reducing oxida-

tion and delaying discoloration in fruits and vegetables [39].

4.3. PECTIN BASED BIOPOLYMERS

Pectin, a major structural polysaccharide in higher plant cells, facilitates primary cell wall extension and plant growth. Extractable as a water-soluble anionic polymer, pectin offers clear advantages over conventional polymers, as highlighted in numerous recent studies [40]. Its multifunctionality enables diverse applications in food packaging and processing, including use as a thickening and gelling agent, colloidal stabilizer, texturizer, and emulsifier. Beyond these roles, pectin serves as a coating for fresh and cut fruits or vegetables and functions as a micro- and Nano-encapsulating agent for the controlled release of bioactive compounds with tailored functionalities [41]. Collectively, these attributes underscore pectin's versatility and its growing importance as a sustainable, high-performance biopolymer in both food formulation and packaging [36].

4.4. CHITOSAN BASED BIOPOLYMERS

Chitosan, derived from chitin, forms stable and uniform films with good water and gas barrier properties. When applied to fresh produce, it creates continuous coatings that control thickness, permeability, and protection. Nanoemulsions of chitosan enhance stability, but its weak mechanical strength is usually improved through forming composites with other natural polymers such as starch, alginate, or gelatin [42]. The food industry finds extensive applications in chitosan for its multifunctional properties, including antimicrobial, antioxidant, and film-forming activities. It contributes to the preservation of fruits and vegetables by limiting moisture loss, delaying ripening, and suppressing microbial growth, while simultaneously enhancing the shelf life, preventing oxidation, and maintaining the quality of meat, seafood, and dairy products [43]. Blended with other biopolymers, it is also applied in biodegradable packaging films that block gases and moisture. Additionally, chitosan can act as a func-

tional ingredient, offering health benefits such as cholesterol reduction and antioxidant activity [44].

4.5. ALGINATE BASED BIOPOLYMERS

Alginate, predominantly sourced from brown algae and composed of α -L-guluronate and β -D-mannuronate units, exhibits a negatively charged character that enables its dissolution in water and formation of clear, stable films. These films provide effective barriers to lipids, oxygen, and moisture, thereby reducing oxidation, dehydration, and microbial activity. Consequently, alginate coatings contribute to improved quality retention and extended shelf life in food products [44].

4.6. PROTEIN BASED EDIBLE BIOPOLYMERS

Proteins, whether fibrous or globular, can form edible films after denaturation of their polymer chains through heat, acids, or bases. Denatured chains interact strongly with neighboring molecules, creating compact films stabilized by ionic, covalent, and hydrogen bonds. Protein-based films are regarded for their biodegradable nature, biocompatibility, as well as excellent capacity to form cohesive films [45].

Protein-based biopolymer are utilized in maintaining food quality as a result of their strong barrier together with their structural features. They are applied to plant based food items to minimize moisture depletion and delay spoilage, to meat and seafood to prevent oxidation and microbial growth, and in dairy products to maintain texture and freshness. In packaging, proteins are blended with other biopolymers to create biodegradable films that provide strength, flexibility, and protection, while also enhancing the sustainability of food packaging systems [44].

5.0. EXTRACTION TECHNIQUES FOR EDIBLE BIOPOLYMERS FROM AGRICULTURAL WASTE

The recovery and transformation of biopolymers from agricultural residues utilize diverse chemical, physio-chemical, and bio-based approaches. For example, cellulose is typically obtained through alkali treatment, bleaching, and hydrolysis. In the case of

starch derived from agricultural by-products of corn, cassava, or potato peels, plasticization allows the production of soft, deformable films; however, its natural lack of flexibility and high moisture susceptibility necessitate reinforcement using nanomaterials or polymer blend [46]. Likewise, proteinaceous biopolymers obtained from agricultural or food-processing by-products—such as soy protein isolate or whey—possess good gas impermeability; however their tendency to absorb water requires additional treatments like crosslinking or blending to improve their resistance to moisture and strengthen their mechanical stability [14].

5.1. EXTRACTION METHODS OF CELLULOSE FROM AGRICULTURAL WASTES

Agro-industrial byproducts such as rice husks, remnants of sugarcane, stalk of wheat, banana rinds, and discarded mushroom substrate are primarily composed of cellulose, hemicellulose, and lignin. Among these constituents, cellulose is the most valued for its material utilization attributable to its mechanical integrity, biodegradability, and eco-friendly nature [14]. To isolate it, (Figure 3) the surrounding components—mainly lignin and hemicellulose, which encapsulate cellulose filament within the structural matrix of the plant cell wall—must first be removed. Traditionally, this is achieved through alkaline treatment followed by bleaching, a process that breaks down the complex plant matrix and yields purified cellulose.

5.1.1. Alkaline treatment

The first step in cellulose extraction usually involves treating agricultural waste with a mild alkaline solution, often sodium hydroxide (NaOH). This process removes hemicellulose and part of the lignin by breaking chemical bonds and dissolving unwanted compounds. The treatment also swells the plant fibers, making cellulose easier to access. Afterward, the material is washed until neutral pH is reached, leaving behind cellulose that still contains some lignin, which gives it a light brown color [47].

5.1.2. Bleaching

To obtain white, pure cellulose, the alkali-treated fibers are

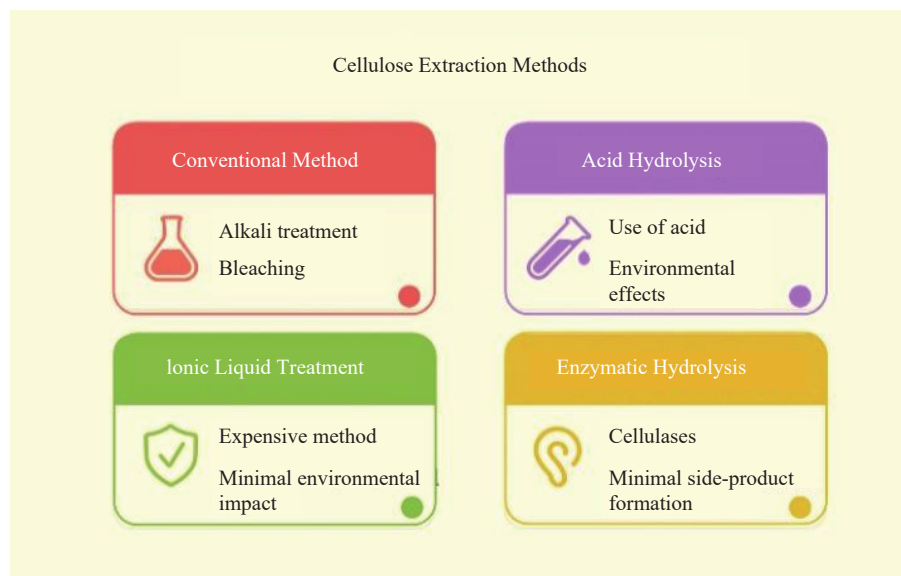


Figure 3. Extraction methods of Cellulose

bleached. Instead of harmful chlorine-based chemicals, safer agents like hydrogen peroxide (H_2O_2) and sodium chlorite (NaClO_2) are commonly used under slightly acidic conditions. These chemicals break down lignin and remove color-causing compounds. The result is a bright, fibrous cellulose suitable for applications where purity and strength are important, such as films and packaging [48]

5.1.3. Acid Hydrolysis

For producing cellulose nanocrystals (CNCs), the purified cellulose is treated with strong acids like sulfuric acid. This step removes the less-ordered (amorphous) parts of the cellulose while preserving the crystalline regions, yielding tiny rod-like nanocrystals with excellent strength and stability. The process requires careful control of acid concentration, temperature, and time to avoid over-degradation. After hydrolysis, the mixture is cleaned thoroughly to remove excess acid [49].

5.1.4. Enzymatic Hydrolysis

An eco-friendly alternative to chemical methods is enzymatic hydrolysis, where cellulase enzymes break down cellulose into smaller molecules or nanostructures. This method is carried out under mild conditions (moderate temperature and near-neutral pH), making it especially suitable for food and biomedical uses. Although slower and more expensive, it avoids harmful residues and produces highly biocompatible cellulose [50].

5.1.5. Ionic Liquid Treatment

Ionic liquids (ILs), which are salts in liquid form, can dissolve cellulose by disrupting its hydrogen bonds. Once dissolved, cellulose can be regenerated into films, fibers, or powders using anti-solvents like water or ethanol. This method is considered greener because ILs can be reused and produce little pollution. However, their high cost, viscosity, and sometimes limited biodegradability are challenges that researchers are still working to overcome [51]. Cellulose can be extracted from agricultural waste using chemical (alkali, acid, or bleaching), biological (enzymes), or advanced “green” methods (ionic liquids). Each technique has strengths and weaknesses, and the choice depends on the desired purity, form (fibers, films, nanocrystals), and end application.

5.2. EXTRACTION TECHNIQUES OF STARCH

Starch, a glucose-based polysaccharide, is abundant, biodegradable, and readily extracted from widely cultivated crops such as corn, potato, cassava, and wheat. Starch-rich agro-residues include rice bran, maize hulls, potato skins, and banana peels [52].

There is no single standard method for starch extraction. The choice of using physical, chemical, or enzymatic techniques depends on factors such as extraction cost, environmental impact, and the required purity of starch. For instance, alkaline extraction is cheaper compared to enzymatic methods but is less eco-friendly. Research also shows that extracting lentil starch at a high pH (around 9.5) can cause more than 1% starch damage. This means that although higher pH levels and temperatures may increase starch yield, they also lead to greater starch degradation. An alternative method involves extraction using 0.45% sodium bisulphite for 6 hours.

The most widely used techniques for isolating starch from cereals, tuber crops, pulses, and other plant sources are water based milling and dry grinding. In water based milling, grains are first steeped in water, after which the kernel components are broken

apart mechanically. The starch granules are then isolated through sieving. By contrast, dry milling reduces grains into refined or whole-grain flour using equipment such as hammer, pin, or disk mills, operated either at room or cryogenic temperatures. These flours can subsequently be used in starch extraction [53].

5.2.1. Water based Milling

Water based milling typically involves immersing grains in a basic solution or a solution containing sulphur dioxide (SO_2). This pretreatment helps to loosen the interactions between grain components while also preventing microbial contamination. The softened grains are then milled, and their components are separated through methods such as screening, centrifugation, hydro cloning, and washing. This process yields starch along with other byproducts. Compared to dry milling, water based milling causes less damage to starch granules, though a fraction of starch is retained in the protein and bran fraction [54].

5.2.2. Dry grinding

The dry grinding method is widely employed for the extraction of starch, particularly from legumes such as peas and beans, and involves mechanical size reduction combined with air classification. Initially, grains are subjected to needle or hammer milling to produce fine, small-particle flours. These flours are then processed using air classification to separate the low-protein starch fraction from the higher-protein components [55]. Despite its utility, the purity of starch obtained through dry grinding is often limited, as air classification alone cannot entirely remove proteins adhering to the starch granules. To address this, a subsequent water-washing step is typically incorporated to eliminate residual proteins and enhance the quality of the starch [56]. Furthermore, starch recovered via dry milling and air classification generally exhibits a higher proportion of damaged starch compared to other extraction techniques, which may influence its functional properties in food and industrial applications. Overall, while dry grinding offers a solvent-free and relatively simple approach for starch isolation, additional processing steps are required to improve purity and minimize starch damage [57].

5.3. Extraction method of Chitin

Chitin is most commonly extracted through chemical methods that involve two main steps. First, demineralization is carried out with strong acids to remove calcium salts such as calcium carbonate and calcium chloride. This is followed by deproteinization, where alkali is used to eliminate the protein content, for example from shrimp shells [58]. After extraction, chitin can be transformed into chitosan through a deacetylation process, typically employing concentrated sodium hydroxide (NaOH). This conventional approach is effective and widely used at an industrial scale, but it relies heavily on harsh chemicals, which pose environmental concerns [59].

To reduce these drawbacks, other strategies, involving enzymatic hydrolysis and microbial fermentation, have been examined. While these approaches are gentler and avoid excessive chemical use, they are not considered economically feasible for large-scale production because of their cost and technical limitations [60].

More recently, biological extraction has been explored as a sustainable alternative. In this method, microbes produce lactic acid, which serves as both the demineralization and deproteinization medium. The chitin obtained through this process can then be deacetylated using enzymes such as chitin deacetylase. This method is environ-

mentally friendly and yields high-quality chitin and chitosan, but it is significantly slower and difficult to scale up to an industrial level [61].

In summary, chemical extraction remains the most practical method for industrial production, while biological extraction shows promise as a greener alternative but requires further development to overcome scalability challenges [62].

5.4. Other Extraction Techniques for Edible Biopolymers from Agricultural Waste

Agricultural by-products such as fruit peels, husks, and tuber residues can be rich sources of edible biopolymers like pectin, starch, cellulose, and proteins. To recover these materials, several modern extraction methods are now used [63]

5.4.1. Ultrasound-Assisted Extraction (UAE):

This method uses sound waves to break open plant tissues, making it easier for compounds to move into the solvent. It works quickly, uses less solvent, and needs lower temperatures, which helps preserve sensitive biopolymers like pectin and starch [64].

5.4.2. Pressurized Liquid Extraction (PLE):

In this technique, water or ethanol is used as the solvent under high pressure and controlled temperature. It is an automated process that gives cleaner extracts and is well suited for compounds like pectin and cellulose. It is also considered environmentally friendly [65].

5.4.3. Enzyme-Assisted Extraction (EAE):

Here, natural enzymes such as cellulase or pectinase are used to break down plant cell walls. This makes it easier to release pectin, proteins, and other useful compounds. EAE is environmentally sustainable, budget-friendly, and capable of producing high amounts of biopolymers [65].

5.4.4. Microwave-Enabled Extraction Technique (MEET):

Microwave-Assisted Extraction utilizes microwave-mediated heating of the solvent–plant matrix to accelerate extraction and enhance yields of starch, cellulose, and proteins. The technique reduces processing duration, uses less solvent, and gives higher yields of starch, cellulose, and proteins compared to traditional methods [65].

Overall, these techniques offer faster, cleaner, and more sustainable ways of extracting edible biopolymers from agricultural waste compared to older chemical methods.

6.0. CHARACTERIZATION OF EDIBLE BIOPOLYMERS

Biopolymers are valued mainly because they are environmentally friendly, but their properties can vary widely depending on their structure and source. These properties can be thought of in three groups: intrinsic (built into the material itself), processing (how the material behaves during manufacturing), and product properties (how it performs once made into something useful) [66].

Intrinsic properties include things like density, crystallinity, solubility, and electrical behavior. For example, crystallinity affects strength, heat resistance, and solubility—highly crystalline biopolymers are usually stronger but less soluble. Some biopolymers, like polyglycolic acid, also have excellent gas barrier properties, often better than conventional plastics, and many are good electrical insulators. Interestingly, polylactic acid (PLA) can even generate small

electric charges when stretched (piezoelectricity) [67].

Processing properties describe how easy or difficult it is to shape and manufacture biopolymers. Some, like PLA and PHAs, are tricky because they don't tolerate high heat or moisture well. They may also need additives—for instance, antistatic agents to stop them from attracting dust, or stabilizers to improve color and surface quality [68].

Product properties are about how they perform in real-world use. This includes strength, resistance to heat and water, how easily they burn, and how long they last. One of their most important advantages is that they break down naturally, thanks to microorganisms like fungi, bacteria, algae, and yeast, making them far more sustainable than synthetic plastics [69].

Biopolymers are also useful in food systems, where they can be used to encapsulate ingredients and improve texture or appearance. To study all these properties, scientists use a range of techniques such as FTIR, SEM, Raman spectroscopy, XRD, and even cell-based tests. In short, understanding these characteristics helps in choosing the right biopolymer for packaging, medical use, or food applications [70].

6.1. Characterization method of starch

Starch is commonly characterized using a range of analytical methods, including electron microscopic imaging (EMI), X-ray diffraction analysis (XRD), and infrared spectroscopic techniques. In addition to chemical analysis, its physical behavior—including functional properties like pasting behavior and viscosity, provides valuable insight into potential applications of isolated starches [71].

While EMI is particularly useful for examining starch morphology, under SEM, starch typically appears as granules. As reported by Sujka and Jamroz how ultrasound treatments affected starches from major staple crops entrained in either aqueous or alcoholic medium. They found that the native starches maintained their characteristic granular structure, though some surface fissures appeared after treatment, FTIR, XRD, NMR, and DSC have also been widely used to explore starch structure. Warren and colleagues examined various starch types (native, modified, amorphous, and extruded) under dry and hydrated conditions [72].

Their FTIR spectra showed characteristic peaks between 1200–1000 cm^{-1} , corresponding to C–O, C–C, and C–OH stretching, along with O–H bending. Differential scanning calorimetry (DSC) revealed enthalpy values ranging from 0 to 17.6 J/g, with an average of 9 J/g across all samples. Solid-state ^{13}C CP/MAS NMR indicated a helix-like order of about 30% on average, ranging from 4% to 49%. XRD confirmed relative crystallinity levels between 0% and 51%, with a mean of 25.8%.

Kizil and co-workers compared FTIR spectra of irradiated and non-irradiated starches of different sources: potato, waxy, wheat, and corn. The two primary starch components (amylose and amylopectin) exhibited nearly identical infrared and Raman bands, dominated by vibrational stretching. The major absorption regions were below 800 cm^{-1} , between 800–1500 cm^{-1} (the fingerprint region), 2800–3000 cm^{-1} (C–H stretching), and 3000–3600 cm^{-1} (O–H stretching).

The pasting profile of starch is another critical measure, as it reflects the impact of cooking on structure, physicochemical properties, and gelatinization. Rincon-Londoño and colleagues investigated corn starch viscosity between 50–90 °C. At around 66 °C, SEM images showed most granules intact with their polyhedral form, though

some displayed microholes. By 74–75 °C, polymer formation of amylose and amylopectin occurred through β -1,4-glycosidic bonds. Gelatinization was observed within 64–75 °C, a finding supported by DSC analysis [73].

6.2. Physicochemical Characterization of Cellulose

The determination of cellulose and its components is usually carried out using standardized TAPPI methods. Acid-insoluble lignin is measured following method T 222, while alpha-, beta-, and gamma-cellulose contents are determined according to method T 203. These protocols are widely used because they provide consistent and reliable measurements of the main fractions present in wood pulp and isolated cellulose [74].

After isolation, cellulose is typically examined using a range of instrumental techniques to gain deeper insights into its structure and properties. FTIR spectroscopy helps identify functional groups such as hydroxyl bonds and glycosidic linkages, confirming both purity and structural features. X-ray diffraction analysis (XRD) is used to evaluate crystallinity, distinguishing between the ordered and amorphous regions of the material, while electron microscopic imaging (EMI) reveals surface microstructure in detail and fiber morphology [75].

Actual composition of isolated cellulose varies depending on the plant source. Comparative studies, often summarized in tables, report differences in lignin content, the distribution of cellulose fractions, and the overall enrichment of cellulose after processing. These differences are significant because they influence the performance of cellulose in various applications [76].

Beyond chemical composition, the physicochemical characteristics of cellulose are equally important. Crystallinity strongly affects mechanical strength and heat related durability, while thermal analyses including DSC as well as TGA provide information about stability and decomposition behavior. Functional groups identified by FTIR confirm the successful removal of hemicellulose and lignin, and SEM imaging reveals fiber size, shape, and surface characteristics [77].

Taken together, these methods not only establish the purity of isolated cellulose but also link its chemical and structural properties to practical performance. The source of the cellulose and the efficiency of isolation directly influence its crystallinity, morphology, and stability, which in turn determine its suitability for use in biopolymers, composites, and other advanced material utilization [78].

6.3. Characterization of Chitin and Chitosan

Chitin and chitosan are usually characterized with techniques like FTIR, XRD, and SEM, which give information about their chemical bonds, crystal structure, and surface features. Researchers also look at values such as the crystalline index, the degree of acetylation in chitin, and the degree of deacetylation in chitosan, since these directly reflect their quality and performance. Studies comparing different animal shells show that the source and extraction method can significantly influence these properties, which in turn affects how chitin and chitosan can be used in practical uses [79].

6.4. Characterization of Silk fibroin

Silk fibroin is usually studied to understand its structure and appearance using tools like FTIR and SEM. FTIR helps identify the chemical bonds in the protein and shows the different structural patterns that make silk strong and flexible. SEM, on the other hand, lets scientists actually “see” the surface of silk fibroin, where it usually

appears as tiny fibers at the nanometer scale [80].

On a molecular level, silk fibroin is made of two main protein chains: a heavy chain and a light chain, which are connected by a disulfide bond. A third protein, called helper protein (or P25) helps these chains fold and work together properly. These three parts are present in a fixed ratio, which ensures silk fibroin forms correctly and has its unique strength and properties [81].

Together, these characterization methods give scientists a clear picture of silk fibroin’s chemistry, structure, and morphology, which is important for its use in biomedical materials, food coatings, and other advanced practical uses [82].

6.5. Characterization of Keratin

The physicochemical properties of keratins, such as their molecular weight and isoelectric point, are key to understanding their behavior and functions. These properties are usually studied using one- and 2D gel electrophoresis for protein separation by size and charge. Variations in keratin proteins across species arise from differences in genes, RNA processing, protein modifications, and the presence of phosphorylated or glycosylated amino acids. In mammals, keratins generally fall within a certain molecular weight range, and while some keratins from humans and animals share similar sizes and roles, they often differ in fine structural details and amino acid composition [83]. The isoelectric point further distinguishes keratins: type I keratins exhibits acidic properties, whereas type II keratins are basic, each becoming uncharged at characteristic pH values. These differences not only separate keratins by type but also help identify those specific to tissues like hair, nails, or wool [84].

Additional chemical and structural features of keratins are studied using techniques like FTIR for functional groups, XRD for crystallinity, and SEM for morphology. Together, these methods give a complete picture of keratin’s properties and how they vary depending on the biological source [85].

7.0. APPLICATIONS OF EDIBLE BIOPOLYMERS IN PROCESSED FOOD

Edible protective layers are applied on food products based on several key factors such as their barrier properties, their chemical and optical properties, their mechanical strength, structural integrity, and the cost and availability of the coating material. These protective layers are commonly used on various food products and milk based products [86].

The modern food sector is no longer just about producing and distributing food; it must also guarantee safety, quality, and nutrition from the factory to the consumer’s table. With growing end-users need for healthier and environmentally friendly products, there is increasing interest in active and smart biopolymers—materials that not only protect consumables and additionally extend its storage stability as well as maintain quality [87].

Biodegradable natural polymers are widely used in forms such as edible films and protective packaging, and antimicrobial carriers or antioxidant agents. These applications help protect food against spoilage, microbial contamination, oxidation, and moisture loss [88].

Today, food protection is a major concern, especially against factors like temperature, moisture, and rancidity, since these directly affect food quality. Biopolymers, particularly proteins and polysaccharides, play a vital role in this area. They are widely used for incorporation of bioactive compounds, helping to shield sensitive ingredients throughout processing, storage, handling and consumption. Be-

yond protection, they also enhance the functional and physicochemical food characteristics [89].

Natural biopolymers including Polysaccharides and proteins such as casein, whey protein, gelatin, zein, gluten, and chitosan have been successfully applied as nanocarriers and microcarriers in the food industry. Through nano- and microencapsulation techniques, these materials help deliver safe, healthy, sustainable, and high-quality foods. For microencapsulation, the chosen biopolymer must meet several requirements: it should form an effective barrier against oxygen, moisture, and light; control diffusion; be food-grade and legally approved; remain stable and workable during processing; and retain the encapsulated ingredient throughout storage [11].

Different types of biopolymers are used depending on the method of encapsulation. Natural gums (like gum arabic and alginates), carbohydrates (such as maltodextrin and cellulose derivatives), and proteins (soy, whey, gelatin) are common choices. Among these, maltodextrin and gum arabic—alone or in combination—are the most widely used for spray drying, as they provide stability and efficiency. Since no single biopolymer can meet all criteria, combinations with antioxidants, surfactants, chelating agents, or oxygen scavengers are often used [90].

In addition to encapsulation, biopolymers also act as emulsifiers in food systems. Amphiphilic biopolymers (like milk proteins, egg proteins, plant proteins, gum arabic, or modified starch) are especially effective because they contain both hydrophilic and hydrophobic regions [91]. This dual nature allows them to stabilize oil–water interfaces by orienting nonpolar regions toward oil and Polar Regions toward water. The structural arrangement of these molecules also plays a role: globular proteins form compact, rigid films that resist rupture but may suffer from droplet aggregation, while flexible random-coil biopolymers rearrange more quickly, making them less stable but easier to adsorb at interfaces [92].

Overall, biopolymers stand out in the food production industry due to their renewable, cost effective, environmentally friendly, and versatile nature. Their ability to protect, stabilizes, and enhances food products makes them highly competitive as sustainable alternatives for modern use in food.

Food grade films and coatings: Chitosan coatings are coated onto fresh horticultural produce like apples, strawberries, bananas etc. to slow microbial growth and reduce spoilage. Similarly, starch-based or protein-based coatings are used on confectionery to prevent sugar bloom and moisture loss.

Meat and seafood: Gelatin- and alginate-based films are used to protect fresh fish and meat, often enriched with natural antimicrobials (like essential oils) to keep them fresh for longer.

Grains and cereals: Biopolymer coatings help reduce insect infestation and protect quality during storage.

Dairy products: Whey protein films are used as oxygen barriers in cheese packaging, preventing oxidation and mold growth.

For packaging materials, biopolymers such as polylactic acid (PLA) or starch blends are increasingly replacing plastics. These are designed to serve as efficient oxygen- and moisture-resistant barriers while remaining completely biodegradable. Importantly, all packaging substrates for food must conform also to strict non-toxic and legal criterion before being used commercially [93].

By combining biodegradability with protective functions, biopolymers allow the food industry to meet consumer expectations for safe, high-quality, and environmentally friendly products. They represent one of the most promising alternatives to conventional

polymer based packaging, aligning with global efforts with a focus on sustainability [94].

7.1. Edible biopolymer application for Fruits and Vegetables

With increasing health awareness, consumers demand foods rich in vitamins, minerals, and other nutrients that help prevent chronic diseases like heart problems, lung disorders, and neurodegenerative conditions. Fruits and vegetables are the main sources of these nutrients. However, during storage and transportation, they lose moisture and nutritional quality. Research suggests that around 30% of fruits and vegetables are lost due to microbial or insect attacks during harvesting and storage. Once contaminated, they are more prone to browning, spoilage, and a reduced shelf life [95].

Protective edible layers help address the aforementioned issues. They both enhance the storage stability of fruits and vegetables and enrich them with nutrients and protective compounds. Whole fruits are naturally protected by their skin, cuticle, or rind. However, once they are cut or minimally processed, they become more vulnerable to microbial growth, browning, and loss of color, texture, and flavor. Edible coatings act as an additional barrier, reducing microbial contamination, slowing oxidation, and preserving aroma, color, and texture [44].

Over the past years, the demand for lightly processed fruits and vegetables has grown rapidly across the world. In Europe, their market share has risen sharply, while in the United States, products like packaged salads and fresh-cut vegetables are among the most rapidly consumed products in supermarkets. Similarly, in Asia, ready-to-eat fresh produce makes up a major portion of retail food sales [96].

The preparation of these products usually involves subjecting fresh-cut produce to postharvest processes such as skin removal, slicing, surface washing, disinfecting, and drying to preserve quality and safety. Unfortunately, such processes reduce the natural protection of fruits and vegetables, making them more vulnerable to spoilage. Microbial spoilage can occur due to the growth of bacteria like *Pseudomonas*, *E. coli*, and *Salmonella*, or fungi and yeasts such as *Candida* and *Penicillium*. Biochemical spoilage, on the other hand, results from changes such as increased respiration, oxidation, enzymatic browning, and texture loss. Together, these spoilage processes can quickly damage the appearance, taste, safety, and nutritional quality of fresh-cut produce [97].

To counter this, packaging plays a crucial role. Traditional petroleum-based packaging has long been used, but it has two major drawbacks: it creates environmental waste and may transfer harmful chemicals into food. As a result, the focus has shifted toward biopolymer-based and biodegradable packaging, which is safer and eco-friendly. Biodegradable films provides protection against moisture, gases, and aroma, and can also be enhanced with additives such as antimicrobials, preservatives, and flavoring agents to prolong product longevity [98].

Two primary forms of biodegradable packaging are edible films and coatings.

Edible films are thin layers placed over or between food items and can be consumed along with the food. Common materials used include polysaccharides (cellulose, starch, carrageenan, pectin, chitosan) and proteins (whey, soy, corn zein).

Fruits and vegetables are coated with edible layers using techniques including dipping, spraying, or brushing. They provide resistance to oxygen, moisture, and solute permeation while maintaining freshness and quality. A good coating both prolongs storage stability

and enhances antioxidants, vitamins, or flavor compounds directly to the product [99]. Depending on their composition, coatings may be made from polysaccharides, proteins, lipids, or blends of these materials. For example, polysaccharides like alginates and chitosan are common choices, while proteins (soy, gelatin, casein) are less common due to their sensitivity to moisture. Lipid-based coatings, such as beeswax or paraffin wax, are excellent water barriers but are often mixed with proteins or cellulose derivatives to improve strength [100].

These coatings are widely applied to both fresh-cut and whole produce. Examples include fresh-cut apples, pears, peaches, carrots, lettuce, tomatoes, muskmelon, and onions, as well as whole fruits and vegetables like oranges, cucumbers, avocados, lemons, and peppers. Research has shown that such biopolymer-based films and coatings significantly extend shelf life and retain quality, making them a promising solution for the food sector [73].

7.2. Edible biopolymer application for Meat, fish and poultry Industry

Meat products are highly perishable due to enzymatic changes and microbial contamination, which can cause spoilage, discoloration, off-flavors, and loss of texture. In seafood, contamination by pathogenic microbes is especially common, increasing the risk of foodborne illnesses. Since meat has a short freshness period, food safe coating layer holds an important function in preservation [101]. For example, chitosan-based coatings with clove essential oil have been used on frozen tambaqui fillets to prevent microbial growth and chemical spoilage. Similarly, sodium alginate films combined with leaf material from the olive tree and hazelnut seed coat were shown to safeguard oxidative degradation of lipids in breaded chicken portions, thereby extending their shelf life [44].

Meat, poultry, and fish are some of the most nutrient-rich foods, providing high-quality proteins, essential amino acids, and easily absorbed vitamins and minerals. However, this same richness also makes them highly vulnerable to spoilage. Microbial contamination can lead to slime formation, unpleasant odors, structural breakdown, and even toxin production. On top of that, fats and protein oxidation during preservation causes discoloration, off-flavors, and texture loss, reducing both safety and consumer appeal [102].

To overcome these challenges, coatings composed of biologically derived polymers are commonly employed in meat packaging. Direct application of edible coatings can be achieved through dipping, spraying, or surface application of the coating onto the meat with a biopolymer solution, while standalone films are often used to wrap meat and meat products before storage. Researchers have developed films made by combining multiple materials or layers—such as chitosan-starch, gelatin-alginate, or fish protein isolate with gelatin—sometimes mixed with natural lipids like sunflower oil. These composites not only act as physical barriers but also help retain moisture and delay spoilage [103].

The most studied biopolymer for meat packaging is chitosan, recognized for its outstanding antimicrobial and ability to form a continuous film. Other frequently used biopolymers include alginate, gelatin, whey protein, cellulose derivatives, soy protein, starch, pectin, and carrageenan. Less commonly used options include collagen, zein, agar, casein, gum arabic, and gluten. For effective protection, packaging materials must balance gas exchange and moisture retention. Some coatings act as “sacrificial layers,” losing their own moisture before the meat dries out, thereby reducing weight loss

during storage [104]. In fact, studies have shown that biopolymer-based coatings can cut moisture loss in packaged meat by nearly 60%.

Recent experiments highlight the effectiveness of these materials. For example, dry beef wrapped in electrospun chitosan fiber films showed a notable increase in shelf life. Similarly, gelatin granules, whey protein coatings, and sodium carboxymethylcellulose films have been used in absorbent pads for meat packaging, helping manage excess fluid and maintain product quality [105].

Overall, biopolymer-based layers provide a biological, biodegradable, together with effective alternative to synthetic packaging aimed at prolonging products longevity and preserving the quality meat, poultry, and fish products [73].

7.3. Edible biopolymer application for dairy products

Milk ranks among the most widely utilized foods across the globe, with more than six billion people relying on it daily. It is not only a rich source of high-quality protein but also provides vital nutrients such as calcium, magnesium, selenium, and vitamins B2, B5, and B12. Because of this exceptional nutritional value, milk and milk-based products are highly perishable and susceptible to environmental influences like light, air, humidity, and microbial contamination [106].

Even a short exposure to light can trigger oxidation, leading to nutrient loss, unpleasant flavors, discoloration, and evaporation of water. These changes not only shorten shelf life but also reduce the overall sensory and nutritional quality of milk. To prevent such spoilage, appropriate packaging plays a crucial role in the dairy industry [107].

When selecting packaging materials for milk and dairy products, several factors must be considered. These include compatibility with the product, safety (non-toxicity), strength, protection from light and odor, chemical stability, weight, cost-effectiveness, and the product specific attributes undergoing containment within protective materials [108].

Over the course of the past decade, experimental investigation and technological innovation have intensified in the field of biodegradable packaging for dairy products. These biopolymer-based alternatives are gaining attention not only for their capacity to prolong product stability and preserve product integrity but also for their eco-friendly nature compared to conventional petroleum-based plastics [109].

Milk and dairy products require packaging that can preserve freshness, inhibit microbial deterioration, and extend product longevity. In recent years, biopolymers have emerged as promising alternatives to traditional petroleum-based plastics for this purpose. Several natural polymers are being studied and applied in the dairy sector:

Casein-based films: Casein, the main milk protein, forms transparent and flexible films that provide an excellent barrier against oxygen, making them useful for protecting dairy products from oxidative spoilage.

Whey protein films: Derived from cheese-making by-products, whey proteins create strong, transparent coatings with good oxygen barrier properties. They are often used for coating cheese or yogurt packaging to extend freshness.

Chitosan coatings: Extracted from crustacean shells, chitosan has antimicrobial properties, making it highly effective in preventing bacterial growth in milk-based products. It is commonly used as a

coating for cheese and other perishable dairy foods.

Starch-based films: Starch is abundant, cheap, and biodegradable. Blended with other biopolymers, it is used to create flexible films for dairy packaging, although it requires modifications to improve water resistance.

Gelatin coatings: Gelatin, obtained from collagen, forms good oxygen barriers and is used in cheese coatings and edible dairy films. However, it is moisture-sensitive and often combined with other polymers or lipids for better performance.

Poly(lactic acid) (PLA): A plant-derived polymer, PLA is widely used for milk bottle packaging and yogurt cups due to its durability and biodegradability.

These biopolymers are often combined with additives like natural antioxidants, antimicrobial agents, or plasticizers to enhance their protective properties. For instance, whey protein films enriched with essential oils can provide both oxygen protection and antibacterial activity, making them excellent for soft cheese preservation.

Overall, biopolymer-based dairy packaging not only improves food safety and shelf life, it also meets the increasing demand for sustainable and environmentally friendly packaging in the food sector [110].

8.0. HEALTH, SAFETY AND REGULATORY CONSIDERATION

Research on the direct effects of edible coatings on human health is still limited, but many coating materials show promising bioactive properties. Chitosan, for example, has been reported to reduce inflammation linked to metabolic syndrome. Fucoidan, another biopolymer, exhibits antioxidant, antimicrobial, antiviral, anti-inflammatory, anticoagulant, immunomodulatory, and even anticancer activities. Bioactive compounds incorporated into coatings, such as phenolics and terpenoids, contribute additional health benefits. Phenolics are known for their antioxidant, anti-inflammatory, and anticancer effects, though their bioactivity depends on bioavailability and interactions with the coating matrix. Terpenoids and plant-derived volatile compound also demonstrate anticancer and antimicrobial potential [111].

Probiotics are increasingly used in food grade coating materials, where polymer matrices can act as transport medium for beneficial bacteria and yeasts. Their incorporation supports food safety while promoting consumer health, provided that sufficient viable cell counts ($\sim 10^9$ CFU/day) are maintained. Strategies such as microencapsulation and the addition of prebiotic fibers further improve probiotic survival and enhance the functional value of edible coatings [112].

9.0. ENVIRONMENTAL IMPACT, SUSTAINABILITY AND FUTURE RECOMMENDATIONS

With growing environmental awareness and demand for healthier lifestyles, consumers prefer food products that are eco-friendly and rich in essential nutrients such as vitamins, minerals, and antimicrobials. Edible biopolymer based layers meet these needs given their capacity for natural degradations, cost-effective, and can be produced from edible biopolymers [113]. Recent research has also focused on enhancing these films by incorporating functional ingredients with antimicrobial and antifungal properties, improving both food safety and nutritional quality [44].

Biopolymer-based packaging represents a sustainable alternative to petroleum-derived plastics, offering biodegradability, renew-

able sourcing, and reduced carbon footprint. Unlike conventional synthetic plastics, which persist in the environment, biopolymers such as polysaccharides, proteins, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) can degrade naturally, mitigating long-term ecological pollution. Production from agricultural residues and renewable feedstocks further supports circular economy strategies by promoting waste valorization and resource efficiency [114].

However, the environmental advantages of biopolymers are context-dependent. Large-scale production may compete with food resources, impacting land use, water demand, and agricultural sustainability. Processing certain biopolymers, notably PLA, remains energy-intensive, and effective biodegradation often requires industrial composting facilities that are not universally accessible [115].

To fully evaluate sustainability, comprehensive life cycle assessments (LCA) are essential, integrating renewable sourcing, processing energy, and end-of-life considerations. Optimizing feedstock use, improving energy efficiency, and expanding composting infrastructure will be critical to translating biodegradability into measurable environmental benefits [116].

In summary, biopolymer packaging holds substantial potential to reduce the ecological footprint of plastics, but its real-world impact depends on careful integration of production practices, material performance, and end-of-life management. Future research should focus on scalable solutions that align environmental sustainability with practical implementation.

Extending past wellness advancement, consumable protective films contribute to environmental sustainability. Their biodegradability makes them a viable alternative to synthetic packaging, an area of increasing interest given global concern for plastic waste. Natural polymers and their blends are well studied, though plasticizers are often needed to improve durability and adhesion [117]. These, however, may affect disintegration. Biodegradability rates vary: starch films can degrade in ~ 10 days under composting conditions or 5–7 weeks at moderate temperatures; gelatin films within ~ 12 days in soil; pullulan, levan, and chitosan within a week; cellulose or guar gum in nearly a month. Lipid-based films, due to their hydrophobic nature, degrade more slowly. Soil microorganisms can further accelerate decomposition. Standardized testing, such as that outlined in European standard EN13432, is essential to better evaluate biodegradability across materials and conditions [118].

Together, these health-promoting and environmentally friendly properties highlight edible biopolymers as promising tools for both food preservation and sustainable packaging, with significant potential for future development in intelligent packaging systems [118].

Sustainability will keep driving interest in biopolymers and natural fibers. Advances in synthetic biology now make it possible to engineer proteins, design biopolymer precursors, and use biological routes to produce fuels, chemicals, and materials. These innovations open the door to stronger, more versatile biopolymers and composites reinforced with natural fibers [119]. Unlike conventional plastics, they are biodegradable and can even serve as carbon storage, helping address climate change. As long as they remain sustainable and practical, biopolymers are likely to play a growing role in replacing traditional materials [120].

From both economic and environmental perspectives, biopolymer-based coatings offer significant benefits. Since they are often produced from renewable sources like agricultural by-products or marine waste, they reduce reliance on petrochemical-based packaging and support the development of circular bio-economies. As op-

posed to plastics that remain largely non-biodegradable in the environment, biopolymer coatings are compostable and naturally degrade without leaving long-lasting waste [121]. A good example is cellulose-based coatings made from crop residues, which decompose safely while still providing effective protection for fresh produce. With ongoing improvements in processing technologies, these coatings are becoming more cost-efficient and scalable, making them an increasingly practical option for commercial food preservation [11].

9.1. FUTURE RECOMMENDATIONS

Based on the findings of this study on the extraction and characterization of edible biopolymers from agricultural products, there is a need for further work on improving how these biopolymers are extracted from agricultural materials so that higher yield and better quality can be achieved without making the process too expensive or complicated. Future studies should also look more closely at different types of agricultural waste to find out which ones give the best results and are most practical for large-scale use.

It would also be helpful for researchers to explore ways of improving the properties of these biopolymers so they can perform better in real applications like food packaging, especially in terms of strength, durability, and resistance to moisture. More work is also needed to confirm their safety and how well they break down in actual food environments.

In addition, future research should consider how these processes can be scaled up beyond the laboratory stage, since most current studies are still limited to small-scale experiments. Looking into possible combinations with other natural materials may also help improve their functionality and make them more suitable for commercial use.

10.0. CONCLUSIONS

The extraction and characterization of edible biopolymers from agricultural sources have emerged as a sustainable approach to address environmental challenges while adding value to agro-waste. Sources including polysaccharides (starch, cellulose, chitin) and structural proteins (silk fibroin, keratin) provide renewable raw materials that can be processed into functional biopolymers. Extraction methods—ranging from chemical and enzymatic treatments to biological processes—enable the isolation of these polymers, though optimization is necessary to balance efficiency, cost, and environmental impact. Characterization techniques, including FTIR, SEM, XRD, DSC, and electrophoresis, provide critical insights into their molecular structure, crystallinity, thermal stability, and physicochemical properties. These analyses establish the suitability of biopolymers for applications such as food encapsulation, coatings, packaging, and functional ingredient delivery. Ultimately, agricultural-source biopolymers represent a promising environmentally sustainable substitute for synthetic plastics derived from fossil fuels, combining biodegradability, safety, and functional versatility. Future advances in extraction and characterization will further enhance their potential in food and bioprocessing industries.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

References

1. R. Venkatesan, M.M. Alrashed, A.A. Vetcher, S.-C. Kim, Next-Generation Food Packaging: Progress and Challenges of Biopolymer-Based Materials, *Polymers (Basel)*. 17 (2025) 2299. doi: [10.3390/polym17172299](https://doi.org/10.3390/polym17172299).

2. J. Cheng, R. Gao, Y. Zhu, Q. Lin, Applications of biodegradable materials in food packaging: A review, *Alexandria Eng. J.* 91 (2024) 70–83. doi: [10.1016/j.aej.2024.01.080](https://doi.org/10.1016/j.aej.2024.01.080).
3. K.Y. Perera, A.K. Jaiswal, S. Jaiswal, Biopolymer-Based Sustainable Food Packaging Materials: Challenges, Solutions, and Applications, *Foods* 12 (2023) 2422. doi: [10.3390/foods12122422](https://doi.org/10.3390/foods12122422).
4. M.E. González-López, S. de J. Calva-Estrada, M.S. Gradilla-Hernández, P. Barajas-Álvarez, Current trends in biopolymers for food packaging: a review, *Front. Sustain. Food Syst.* 7 (2023). <https://doi.org/10.3389/fsufs.2023.1225371>.
5. G. Atiwesh, A. Mikhael, C.C. Parrish, J. Banoub, T.-A.T. Le, Environmental impact of bioplastic use: A review, *Heliyon* 7 (2021) e07918. doi: [10.1016/j.heliyon.2021.e07918](https://doi.org/10.1016/j.heliyon.2021.e07918).
6. X. Zhang, Z. Yin, S. Xiang, H. Yan, H. Tian, Degradation of Polymer Materials in the Environment and Its Impact on the Health of Experimental Animals: A Review, *Polymers (Basel)*. 16 (2024) 2807. doi: [10.3390/polym16192807](https://doi.org/10.3390/polym16192807).
7. R. Dallaev, N. Papež, M.M. Allaham, V. Holcman, Biodegradable Polymers: Properties, Applications, and Environmental Impact, *Polymers (Basel)*. 17 (2025) 1981. doi: [10.3390/polym17141981](https://doi.org/10.3390/polym17141981).
8. S. V. Pawde, P. Kaewprachu, P. Kingwascharapong, S. Sai-Ut, T. Karbowiak, Y.H. Jung, S. Rawdkuen, A comprehensive review on plant protein-based food packaging: Beyond petroleum-based polymers, *Curr. Res. Food Sci.* 10 (2025) 101104. doi: [10.1016/j.crfs.2025.101104](https://doi.org/10.1016/j.crfs.2025.101104).
9. G.I. Edo, W. Ndudi, A.M. Ali, E. Yousif, A.N. Jikah, E.F. Isoje, U.A. Igbuku, A.N. Mafe, R.A. Opiti, C.J. Madueke, A.E.A. Essaghah, D.S. Ahmed, H. Umar, Biopolymers: An inclusive review, *Hybrid Adv.* 9 (2025) 100418. doi: [10.1016/j.hybadv.2025.100418](https://doi.org/10.1016/j.hybadv.2025.100418).
10. P.K. Drishya, M.V. Reddy, G. Mohanakrishna, O. Sarkar, Isha, M. V. Rohit, A. Patel, Y.-C. Chang, Advances in Microbial and Plant-Based Biopolymers: Synthesis and Applications in Next-Generation Materials, *Macromol* 5 (2025) 21. doi: [10.3390/macromol5020021](https://doi.org/10.3390/macromol5020021).
11. R.R. Krishnan, A.D. Olasupo, K.H. Patel, I.F. Bolarinwa, M.O. Oke, C. Okafor, C. Nkwonta, I. Ifie, Edible biopolymers with functional additives coatings for postharvest quality preservation in horticultural crops: a review, *Front. Sustain. Food Syst.* 9 (2025). <https://doi.org/10.3389/fsufs.2025.1569458>.
12. D. Dutta, N. Sit, A comprehensive review on types and properties of biopolymers as sustainable bio-based alternatives for packaging, *Food Biomacromolecules* 1 (2024) 58–87. doi: [10.1002/fob2.12019](https://doi.org/10.1002/fob2.12019).
13. R. Phiri, S. Mavinkere Rangappa, S. Siengchin, O.P. Oladijo, H.N. Dhakal, Development of sustainable biopolymer-based composites for lightweight applications from agricultural waste biomass: A review, *Adv. Ind. Eng. Polym. Res.* 6 (2023) 436–450. doi: [10.1016/j.aiepr.2023.04.004](https://doi.org/10.1016/j.aiepr.2023.04.004).
14. T. Selvam, N.M.M.A. Rahman, F. Olivito, Z. Ilham, R. Ahmad, W.A.A.Q.I. Wan-Mohtar, Agricultural Waste-Derived Biopolymers for Sustainable Food Packaging: Challenges and Future Prospects, *Polymers (Basel)*. 17 (2025) 1897. doi: [10.3390/polym17141897](https://doi.org/10.3390/polym17141897).
15. A. Karnwal, G. Kumar, R. Singh, M. Selvaraj, T. Malik, A.R.M. Al Tawaha, Natural biopolymers in edible coatings: Applications in food preservation, *Food Chem. X* 25 (2025) 102171. doi: [10.1016/j.fochx.2025.102171](https://doi.org/10.1016/j.fochx.2025.102171).
16. T.T. Alemu, P. Intipunya, B.A. Gebeyo, A comprehensive review of edible coatings for postharvest management of fruits and vegetables: enhancing food and nutrition security, *Discov. Agric.* 3 (2025) 190. doi: [10.1007/s44279-025-00348-8](https://doi.org/10.1007/s44279-025-00348-8).
17. R. Vanaraj, S.M. Suresh Kumar, G. Mayakrishnan, B. Rathinam, S.C. Kim, A Current Trend in Efficient Biopolymer Coatings for Edible Fruits to Enhance Shelf Life, *Polymers (Basel)*. 16 (2024) 2639. doi: [10.3390/](https://doi.org/10.3390/)

- polym16182639.
18. E. Hurtado-Fernández, L.A. Trujillo-Cayado, P. Álvarez-Mateos, J. Santos, Extraction, Characterization and Applications of Biopolymers from Sustainable Sources, *Polymers (Basel)*. 18 (2026) 581. doi: [10.3390/polym18050581](https://doi.org/10.3390/polym18050581).
 19. A. Salaria, S.S. Patel, K. Sridhar, P. Chawla, M. Sharma, Extraction and characterization of biopolymers from rice bran oil cake: Development of antimicrobial edible coating for extending shelf-life of strawberry fruit, *Food Biosci.* 65 (2025) 106053. doi: [10.1016/j.fbio.2025.106053](https://doi.org/10.1016/j.fbio.2025.106053).
 20. M. Morales-Jiménez, L. Gouveia, J. Yáñez-Fernández, R. Castro-Muñoz, B. Barragán-Huerta, Production, Preparation and Characterization of Microalgae-Based Biopolymer as a Potential Bioactive Film, *Coatings* 10 (2020) 120. doi: [10.3390/coatings10020120](https://doi.org/10.3390/coatings10020120).
 21. E. Moore, D. Colbert, Ocean Plastics: Extraction, Characterization and Utilization of Macroalgae Biopolymers for Packaging Applications, *Sustainability* 16 (2024) 7175. doi: [10.3390/su16167175](https://doi.org/10.3390/su16167175).
 22. A.R.S. Pillai, A.S. Eapen, W. Zhang, S. Roy, Polysaccharide-Based Edible Biopolymer-Based Coatings for Fruit Preservation: A Review, *Foods* 13 (2024) 1529. doi: [10.3390/foods13101529](https://doi.org/10.3390/foods13101529).
 23. A. Sharma, A. Singh, Sodium Alginate: A Green Biopolymer Resource-Based Antimicrobial Edible Coating to Enhance Fruit Shelf-Life: A Review, *Colloids and Interfaces* 9 (2025) 32. doi: [10.3390/colloids9030032](https://doi.org/10.3390/colloids9030032).
 24. A. Perez-Vazquez, P. Barciela, M. Carpena, M. Prieto, Edible Coatings as a Natural Packaging System to Improve Fruit and Vegetable Shelf Life and Quality, *Foods* 12 (2023) 3570. doi: [10.3390/foods12193570](https://doi.org/10.3390/foods12193570).
 25. M. Lackner, M. Besharati, Agricultural Waste: Challenges and Solutions, a Review, *Waste* 3 (2025) 18. doi: [10.3390/waste3020018](https://doi.org/10.3390/waste3020018).
 26. S.A. Varghese, H. Pulikkalparambil, K. Promhuad, A. Srisa, Y. Laorenza, L. Jarupan, T. Nampitch, V. Chonhenchob, N. Harnkarnsujarit, Renovation of Agro-Waste for Sustainable Food Packaging: A Review, *Polymers (Basel)*. 15 (2023) 648. doi: [10.3390/polym15030648](https://doi.org/10.3390/polym15030648).
 27. H.A. Areti, M.D. Muleta, L.D. Abo, A.S. Hamda, A.A. Adugna, I.T. Edae, B.J. Daba, R.L. Gudeta, Innovative uses of agricultural by-products in the food and beverage sector: A review, *Food Chem. Adv.* 5 (2024) 100838. doi: [10.1016/j.focha.2024.100838](https://doi.org/10.1016/j.focha.2024.100838).
 28. M.M. Ahmed, M.H. Bin Nabi, M.S. Mia, I. Ahmad, W. Zzaman, Valorization of plant-based agro-waste into sustainable food packaging materials: Current approaches and functional applications, *Appl. Food Res.* 5 (2025) 101368. doi: [10.1016/j.afres.2025.101368](https://doi.org/10.1016/j.afres.2025.101368).
 29. A. Marotta, A. Borriello, M.R. Khan, S. Cavella, V. Ambrogi, E. Torrieri, Boosting Food Packaging Sustainability Through the Valorization of Agri-Food Waste and By-Products, *Polymers (Basel)*. 17 (2025) 735. doi: [10.3390/polym17060735](https://doi.org/10.3390/polym17060735).
 30. A.K. Pandey, S. Thakur, R. Mehra, R.S.S. Kaler, M. Paul, A. Kumar, Transforming Agri-food waste: Innovative pathways toward a zero-waste circular economy, *Food Chem. X* 28 (2025) 102604. doi: [10.1016/j.fochx.2025.102604](https://doi.org/10.1016/j.fochx.2025.102604).
 31. M. Buntinx, C. Vanheusden, D. Hermans, Processing and Properties of Polyhydroxyalkanoate/ZnO Nanocomposites: A Review of Their Potential as Sustainable Packaging Materials, *Polymers (Basel)*. 16 (2024) 3061. doi: [10.3390/polym16213061](https://doi.org/10.3390/polym16213061).
 32. A. Bianchi, F. Venturi, Enhancing the Shelf Life of Food Products: Strategies, Challenges, and Innovations, *Foods* 14 (2025) 4034. doi: [10.3390/foods14234034](https://doi.org/10.3390/foods14234034).
 33. I. Benalaya, G. Alves, J. Lopes, L.R. Silva, A Review of Natural Polysaccharides: Sources, Characteristics, Properties, Food, and Pharmaceutical Applications, *Int. J. Mol. Sci.* 25 (2024) 1322. doi: [10.3390/ijms25021322](https://doi.org/10.3390/ijms25021322).
 34. C. Mellinas, M. Ramos, A. Jiménez, M.C. Garrigós, Recent Trends in the Use of Pectin from Agro-Waste Residues as a Natural-Based Biopolymer for Food Packaging Applications, *Materials (Basel)*. 13 (2020) 673. doi: [10.3390/ma13030673](https://doi.org/10.3390/ma13030673).
 35. C. Culqui-Arce, D. Mori-Mestanza, A.B. Fernández-Jeri, R.J. Cruzalegui, R.C. Mori Zabarburi, A.J. Vergara, I.S. Cayo-Colca, J.G. da Silva, N.M.P. Araujo, E. M. Castro-Alayo, C.R. Balcázar-Zumaeta, Polymers Derived from Agro-Industrial Waste in the Development of Bioactive Films in Food, *Polymers (Basel)*. 17 (2025) 408. doi: [10.3390/polym17030408](https://doi.org/10.3390/polym17030408).
 36. F. Shahbazi, S. Shahbazi, D. Zare, Losses in Agricultural Produce: Causes and Effects on Food Security, *Food Energy Secur.* 14 (2025). doi: [10.1002/fes3.70086](https://doi.org/10.1002/fes3.70086).
 37. A. Gamage, P. Thiviya, A. Liyanapathirana, M.L.D. Wasana, Y. Jayakodi, A. Bandara, A. Manamperi, R.S. Dassanayake, P. Evon, O. Merah, T. Madhujith, Polysaccharide-Based Bioplastics: Eco-Friendly and Sustainable Solutions for Packaging, *J. Compos. Sci.* 8 (2024) 413. doi: [10.3390/jcs8100413](https://doi.org/10.3390/jcs8100413).
 38. A. Kumar, A. Kumar, S. Wei, S. Chopra, S.G. Rudra, A. Rabbani, Biodegradable and smart packaging films for food quality and safety: A review, *Appl. Food Res.* 5 (2025) 101491. doi: [10.1016/j.afres.2025.101491](https://doi.org/10.1016/j.afres.2025.101491).
 39. M. Walait, H.R. Mir, K. Anees, Edible biofilms and coatings; its characterization and advanced industrial applications, *Nat. Resour. Hum. Heal.* 3 (2022) 28–37. doi: [10.53365/nrfhh/149622](https://doi.org/10.53365/nrfhh/149622).
 40. Riyamol, J. Gada Chengaiyan, S.S. Rana, F. Ahmad, S. Haque, E. Capanoglu, Recent Advances in the Extraction of Pectin from Various Sources and Industrial Applications, *ACS Omega* 8 (2023) 46309–46324. doi: [10.1021/acsomega.3c04010](https://doi.org/10.1021/acsomega.3c04010).
 41. S. Sharma, K.M. Wani, S.M. Mujahid, L.S. Jayan, S.S. Rajan, Review on Pectin: Sources, Properties, Health Benefits and Its Applications in Food Industry, *J. Futur. Foods* 6 (2026) 205–219. doi: [10.1016/j.jfutfo.2024.04.009](https://doi.org/10.1016/j.jfutfo.2024.04.009).
 42. I. Usman, S. Sana, H.M. Jaffar, M. Munir, A. Afzal, S. Sukhera, I.D. Boateng, M. Afzaal, M.M. Urugo, Recent progress in edible films and coatings: Toward green and sustainable food packaging technologies, *Appl. Food Res.* 5 (2025) 101070. doi: [10.1016/j.afres.2025.101070](https://doi.org/10.1016/j.afres.2025.101070).
 43. D.T. Oyekunle, M.H. Nia, L.D. Wilson, Recent Progress on the Application of Chitosan, Starch and Chitosan–Starch Composites for Meat Preservation—A Mini Review, *J. Compos. Sci.* 8 (2024) 302. doi: [10.3390/jcs8080302](https://doi.org/10.3390/jcs8080302).
 44. S.S. Meduri, S. Mudawath, P. Butti, S. Kanneboina, S.D. Tattapalli, S. Thoomati, N.R. Rathod, A. Kuna, K. Lavuri, S.C. Darshanaju, K. Kalaivanan, Turning Waste into Taste: Effective Upcycling of By-Products for Innovative Food Solutions, *Food Technol. Biotechnol.* 63 (2025) 190. doi: [10.17113/ftb.63.02.25.8962](https://doi.org/10.17113/ftb.63.02.25.8962).
 45. M.N. Khin, S. Ahammed, M.M. Kamal, M.N. Saqib, F. Liu, F. Zhong, Investigating next-generation edible packaging: Protein-based films and coatings for delivering active compounds, *Food Hydrocoll. Heal.* 6 (2024) 100182. doi: [10.1016/j.fhfh.2024.100182](https://doi.org/10.1016/j.fhfh.2024.100182).
 46. A.C.F. Carvalho, S. Ghosh, T.G. Hoffmann, E.S. Prudêncio, C.K. de Souza, S. Roy, Valuing agro-industrial waste in the development of sustainable food packaging based on the system of a circular bioeconomy: A review, *Clean. Waste Syst.* 11 (2025) 100275. doi: [10.1016/j.clwas.2025.100275](https://doi.org/10.1016/j.clwas.2025.100275).
 47. R.S. Abolore, S. Jaiswal, A.K. Jaiswal, Green and sustainable pretreatment methods for cellulose extraction from lignocellulosic biomass and its applications: A review, *Carbohydr. Polym. Technol. Appl.* 7 (2024) 100396. doi: [10.1016/j.carpta.2023.100396](https://doi.org/10.1016/j.carpta.2023.100396).
 48. A. Walawska, M. Olak-Kucharczyk, A. Kaczmarek, M.H. Kudzin, Environmentally Friendly Bleaching Process of the Cellulose Fibres Materials Using Ozone and Hydrogen Peroxide in the Gas Phase, *Materials (Basel)*. 17 (2024) 1355. doi: [10.3390/ma17061355](https://doi.org/10.3390/ma17061355).
 49. S.E. Wossine, G. Thothadri, H.B. Tufa, W.M. Tucho, A. Murtaza, A.

- Edacherian, G.M. Sayeed Ahmed, Isolation and Characterization of Spherical Cellulose Nanocrystals Extracted from the Higher Cellulose Yield of the Jenfokie Plant: Morphological, Structural, and Thermal Properties, *Polymers (Basel)*. 16 (2024) 1629. doi: [10.3390/polym16121629](https://doi.org/10.3390/polym16121629).
50. M. Sarafidou, A. Forys, M. Godzierz, A. Kobylukh, B. Trzebicka, S. Pispas, A. Koutinas, E. Tsouko, Modification of Bacterial Nanocellulose Using Nonthermal Plasma-Assisted Enzymatic Hydrolysis, *Biomacromolecules* 26 (2025) 5657–5669. doi: [10.1021/acs.biomac.5c00397](https://doi.org/10.1021/acs.biomac.5c00397).
51. S. Taokaew, W. Kriangkrai, Recent Progress in Processing Cellulose Using Ionic Liquids as Solvents, *Polysaccharides* 3 (2022) 671–691. doi: [10.3390/polysaccharides3040039](https://doi.org/10.3390/polysaccharides3040039).
52. I. Abulude, S. Wahlen, Food loss analysis in Nigeria: A systematic literature review, *Environ. Challenges* 17 (2024) 101027 doi: [10.1016/j.envc.2024.101027](https://doi.org/10.1016/j.envc.2024.101027).
53. M.-G. Dorantes-Fuertes, M.C. López-Méndez, G. Martínez-Castellanos, R.Á. Meléndez-Armenta, H.-E. Jiménez-Martínez, Starch Extraction Methods in Tubers and Roots: A Systematic Review, *Agronomy* 14 (2024) 865. doi: [10.3390/agronomy14040865](https://doi.org/10.3390/agronomy14040865).
54. M. Li, Y. Tian, S. Dhital, Starch Extraction, in: *Starch Starchy Food Prod.*, CRC Press, Boca Raton, 2022: pp. 17–40. <https://doi.org/10.1201/9781003088929-2>.
55. P. Farshi, S.N. Mirmohammadali, B. Rajpurohit, J.S. Smith, Y. Li, Pea protein and starch: Functional properties and applications in edible films, *J. Agric. Food Res.* 15 (2024) 100927. doi: [10.1016/j.jafr.2023.100927](https://doi.org/10.1016/j.jafr.2023.100927).
56. S. Yu, Y. Wu, Z. Li, C. Wang, D. Zhang, L. Wang, Effect of different milling methods on physicochemical and functional properties of mung bean flour, *Front. Nutr.* 10 (2023). <https://doi.org/10.3389/fnut.2023.1117385>.
57. H.S.O. Darko, L. Ismaiel, B. Fanesi, D. Pacetti, P. Lucci, Current Trends in Food Processing By-Products as Sources of High Value-Added Compounds in Food Fortification, *Foods* 13 (2024) 2658 doi: [10.3390/foods13172658](https://doi.org/10.3390/foods13172658).
58. M.K. Rasweefali, S. Sabu, K.S. Muhammed Azad, M.K. Raseel Rahman, K.V. Sunooj, A. Sasidharan, K.K. Anoop, Influence of deproteinization and demineralization process sequences on the physicochemical and structural characteristics of chitin isolated from Deep-sea mud shrimp (*Solenocera hextii*), *Adv. Biomark. Sci. Technol.* 4 (2022) 12–27. doi: [10.1016/j.abst.2022.03.001](https://doi.org/10.1016/j.abst.2022.03.001).
59. J. Zhang, W.-R. Xu, Y.-C. Zhang, Facile production of chitin from shrimp shells using a deep eutectic solvent and acetic acid, *RSC Adv.* 12 (2022) 22631–22638. doi: [10.1039/D2RA03417D](https://doi.org/10.1039/D2RA03417D).
60. W.Z. Ng, E.-S. Chan, W. Gourich, S.H. Adiiba, M.Y. Liow, C.W. Ooi, B.T. Tey, C. P. Song, Unveiling the role of mechanical process intensifications and chemical additives in boosting lipase-catalyzed hydrolysis of vegetable oil for fatty acid production: A comprehensive review, *Int. J. Biol. Macromol.* 284 (2025) 138144. doi: [10.1016/j.ijbiomac.2024.138144](https://doi.org/10.1016/j.ijbiomac.2024.138144).
61. C. Ghinea, E.-D. Ungureanu-Comăniță, R.M. Tăbuleac, P.S. Oprea, E.D. Coșbuc, M. Gavrilăscu, Cost-Benefit Analysis of Enzymatic Hydrolysis Alternatives for Food Waste Management, *Foods* 14 (2025) 488. doi: [10.3390/foods14030488](https://doi.org/10.3390/foods14030488).
62. J. Jacob, S. Gopi, Isolation and physicochemical characterization of biopolymers, in: *Biopolym. Their Ind. Appl.*, Elsevier, 2021: pp. 45–79. <https://doi.org/10.1016/B978-0-12-819240-5.00003-1>.
63. A. Ait-Kaddour, A. Hassoun, I. Tarchi, M. Loudiyi, O. Boukria, Y. Cahyana, F. Ozogul, K. Khwaldia, Transforming plant-based waste and by-products into valuable products using various “Food Industry 4.0” enabling technologies: A literature review, *Sci. Total Environ.* 955 (2024) 176872. doi: [10.1016/j.scitotenv.2024.176872](https://doi.org/10.1016/j.scitotenv.2024.176872).
64. H. López-Salazar, B.H. Camacho-Díaz, M.L.A. Ocampo, A.R. Jiménez-Aparicio, Microwave-assisted extraction of functional compounds from plants: A Review, *BioResources* 18 (2023). <https://doi.org/10.15376/biores.18.3.Lopez-Salazar>.
65. A.S. Virdi, A. Mahajan, M. Devraj, R. Sanghi, Brewers’ spent grains: Techno-functional challenges and opportunity in the valorization for food products, *LWT* 227 (2025) 117785 doi: [10.1016/j.lwt.2025.117785](https://doi.org/10.1016/j.lwt.2025.117785).
66. S.A. Siddiqui, X. Yang, R.K. Deshmukh, K.K. Gaikwad, N.A. Bahmid, R. Castro-Muñoz, Recent advances in reinforced bioplastics for food packaging – A critical review, *Int. J. Biol. Macromol.* 263 (2024) 130399. doi: [10.1016/j.ijbiomac.2024.130399](https://doi.org/10.1016/j.ijbiomac.2024.130399).
67. K. Latour-Paczka, R. Luciński, Artificial Biopolymers Derived from Transgenic Plants: Applications and Properties—A Review, *Int. J. Mol. Sci.* 25 (2024) 13628. doi: [10.3390/ijms252413628](https://doi.org/10.3390/ijms252413628).
68. M. Flórez, P. Cazón, M. Vázquez, Selected Biopolymers’ Processing and Their Applications: A Review, *Polymers (Basel)*. 15 (2023) 641. doi: [10.3390/polym15030641](https://doi.org/10.3390/polym15030641).
69. N. Tripathi, M. Misra, A.K. Mohanty, Durable Polylactic Acid (PLA)-Based Sustainable Engineered Blends and Biocomposites: Recent Developments, Challenges, and Opportunities, *ACS Eng. Au* 1 (2021) 7–38. doi: [10.1021/acscengineeringau.1c00011](https://doi.org/10.1021/acscengineeringau.1c00011).
70. R. Binaymotlagh, L. Chronopoulou, C. Palocci, An Overview of Biopolymer-Based Graphene Nanocomposites for Biotechnological Applications, *Materials (Basel)*. 18 (2025) 2978. doi: [10.3390/ma18132978](https://doi.org/10.3390/ma18132978).
71. K. Dome, E. Podgorbunskikh, A. Bychkov, O. Lomovsky, Changes in the Crystallinity Degree of Starch Having Different Types of Crystal Structure after Mechanical Pretreatment, *Polymers (Basel)*. 12 (2020) 641. doi: [10.3390/polym12030641](https://doi.org/10.3390/polym12030641).
72. L. Yadav Prakruthi, H. Krishnan, T. Medha, K. Kumarakuru, P.V. Kumari, C. Surekha, H. Alavilli, D. Kaushik, A. Hashem, N.H. Alotaibi, G.D. Avila-Quezada, E.F. Abd_Allah, M. Kumar, C.K. Reddy, Enhancing starch properties through dual modification: Ultrasonication and acetic acid treatment of non-conventional starches, *Ultrason. Sonochem.* 115 (2025) 107301. doi: [10.1016/j.ultsonch.2025.107301](https://doi.org/10.1016/j.ultsonch.2025.107301).
73. C. D’Souza, J.C. Mancuso Tradenta, M. Marimuthu, D. Fleming-Muñoz, S. O’Keefe, The upcycled appetite: exploring intentions behind choosing food waste-based functional products and food neophobia, *Br. Food J.* 127 (2025) 760–780 doi: [10.1108/BFJ-04-2025-0517](https://doi.org/10.1108/BFJ-04-2025-0517).
74. B.K. Chavez, K. Garces-Porras, D.C. Parada, E. Flores, Thermochemical isolation and characterization of nanofibrillated cellulose from *Stipa obtusa* fibers, *Carbohydr. Polym. Technol. Appl.* 6 (2023) 100344. doi: [10.1016/j.carpta.2023.100344](https://doi.org/10.1016/j.carpta.2023.100344).
75. E. Małachowska, M. Dubowik, A. Lipkiewicz, K. Przybysz, P. Przybysz, Analysis of Cellulose Pulp Characteristics and Processing Parameters for Efficient Paper Production, *Sustainability* 12 (2020) 7219. doi: [10.3390/su12177219](https://doi.org/10.3390/su12177219).
76. R. D’Orsi, N. Di Fidio, C. Antonetti, A.M. Raspolli Galletti, A. Operamolla, Isolation of Pure Lignin and Highly Digestible Cellulose from Defatted and Steam-Exploded *Cynara cardunculus*, *ACS Sustain. Chem. Eng.* 11 (2023) 1875–1887. doi: [10.1021/acssuschemeng.2c06356](https://doi.org/10.1021/acssuschemeng.2c06356).
77. S. Mateo, G. Fabbri, A.J. Moya, Lignin from Plant-Based Agro-Industrial Biowastes: From Extraction to Sustainable Applications, *Polymers (Basel)*. 17 (2025) 952. doi: [10.3390/polym17070952](https://doi.org/10.3390/polym17070952).
78. B.-M. Tofanica, A. Mikhailidi, M.E. Fortună, R. Rotaru, O.C. Ungureanu, E. Ungureanu, Cellulose Nanomaterials: Characterization Methods, Isolation Techniques, and Strategies, *Crystals* 15 (2025) 352. doi: [10.3390/cryst15040352](https://doi.org/10.3390/cryst15040352).
79. D. Tapia, J. Quiñones, A. Martinez, E. Millahual, P.C.B. Campagnol, N. Sepúlveda, R. Diaz, The Silent Revolution of Brewer’s Spent Grain: Meat/

- Food Innovations Through Circularity, Resource Recovery, and Nutritional Synergy—A Review, *Foods* 14 (2025) 3389 doi: [10.3390/foods14193389](https://doi.org/10.3390/foods14193389).
80. H.D.A. Brough, D. Cheneler, J.G. Hardy, Progress in Multiscale Modeling of Silk Materials, *Biomacromolecules* 25 (2024) 6987–7014. doi: [10.1021/acs.biomac.4c01122](https://doi.org/10.1021/acs.biomac.4c01122).
 81. V. V. Rodin, P.S. Belton, Changes in Natural Silk Fibres by Hydration, Tensile Loading and Heating as Studied by ¹H NMR: Anisotropy in NMR Relaxation Times, *Polymers (Basel)* 14 (2022) 3665. doi: [10.3390/polym14173665](https://doi.org/10.3390/polym14173665).
 82. M. Zhao, Z. Qi, X. Tao, C. Newkirk, X. Hu, S. Lu, Chemical, Thermal, Time, and Enzymatic Stability of Silk Materials with Silk I Structure, *Int. J. Mol. Sci.* 22 (2021) 4136. doi: [10.3390/ijms22084136](https://doi.org/10.3390/ijms22084136).
 83. G.D. Barone, I. Tagliaro, R. Oliver-Simancas, M. Radice, L.M. Kalossaka, M. Mattei, A. Biundo, I. Pisano, A. Jiménez-Quero, Keratinous and corneous-based products towards circular bioeconomy: A research review, *Environ. Sci. Ecotechnology* 22 (2024) 100444. doi: [10.1016/j.ese.2024.100444](https://doi.org/10.1016/j.ese.2024.100444).
 84. E.-M. Nuutinen, J.J. Valle-Delgado, M. Kellock, M. Farooq, M. Österberg, Affinity of Keratin Peptides for Cellulose and Lignin: A Fundamental Study toward Advanced Bio-Based Materials, *Langmuir* 38 (2022) 9917–9927. doi: [10.1021/acs.langmuir.2c01140](https://doi.org/10.1021/acs.langmuir.2c01140).
 85. E.J. Dupree, M. Jayathirtha, H. Yorkey, M. Mihasan, B.A. Petre, C.C. Darie, A Critical Review of Bottom-Up Proteomics: The Good, the Bad, and the Future of This Field, *Proteomes* 8 (2020) 14. doi: [10.3390/proteomes8030014](https://doi.org/10.3390/proteomes8030014).
 86. M. Tasnim, M.N. Islam, Active Edible Coatings for Smart Food Preservation for Sustainability: A Review, *Carbohydr. Polym. Technol. Appl.* (2025) 101061. <https://doi.org/10.1016/j.carpta.2025.101061>.
 87. A.K. V, M. Hasan, S. Mangaraj, P. M, D.K. Verma, P.P. Srivastav, Trends in Edible Packaging Films and its Prospective Future in Food: A Review, *Appl. Food Res.* 2 (2022) 100118. doi: [10.1016/j.afres.2022.100118](https://doi.org/10.1016/j.afres.2022.100118).
 88. L.J.L. Iversen, K. Rovina, J.M. Vonnice, P. Matanjun, K.H. Erna, N.M.N. 'Aqilah, W.X.L. Felicia, A.A. Funk, The Emergence of Edible and Food-Application Coatings for Food Packaging: A Review, *Molecules* 27 (2022) 5604. doi: [10.3390/molecules27175604](https://doi.org/10.3390/molecules27175604).
 89. X. Hu, C. Lu, H. Tang, H. Pouri, E. Joulin, J. Zhang, Active Food Packaging Made of Biopolymer-Based Composites, *Materials (Basel)* 16 (2022) 279. doi: [10.3390/ma16010279](https://doi.org/10.3390/ma16010279).
 90. G.L. Zabet, F. Schaefer Rodrigues, L. Polano Ody, M. Vinícius Tres, E. Herrera, H. Palacin, J.S. Córdova-Ramos, I. Best, L. Olivera-Montenegro, Encapsulation of Bioactive Compounds for Food and Agricultural Applications, *Polymers (Basel)* 14 (2022) 4194. doi: [10.3390/polym14194194](https://doi.org/10.3390/polym14194194).
 91. N. Choudhury, M. Meghwal, K. Das, Microencapsulation: An overview on concepts, methods, properties and applications in foods, *Food Front.* 2 (2021) 426–442. doi: [10.1002/fft2.94](https://doi.org/10.1002/fft2.94).
 92. B.M. Worku, N.T. Shibeshi, T. Zhiyuan, J.-Y. Cho, J.-B. Eun, Encapsulated essential oils in protein-polysaccharide biopolymers: characteristics and applications in the biomedical and food industries, *Food Sci. Biotechnol.* 34 (2025) 851–869. doi: [10.1007/s10068-024-01724-8](https://doi.org/10.1007/s10068-024-01724-8).
 93. F. Versino, F. Ortega, Y. Monroy, S. Rivero, O.V. López, M.A. García, Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations, *Foods* 12 (2023) 1057. doi: [10.3390/foods12051057](https://doi.org/10.3390/foods12051057).
 94. S. Shaikh, M. Yaqoob, P. Aggarwal, An overview of biodegradable packaging in food industry, *Curr. Res. Food Sci.* 4 (2021) 503–520. doi: [10.1016/j.crfs.2021.07.005](https://doi.org/10.1016/j.crfs.2021.07.005).
 95. M. Fekete, A. Lehocski, A. Kryczyk-Poprawa, V. Zábó, J. Varga, M. Bálint, V. Fazekas-Pongor, T. Csipő, E. Rzaşa-Duran, P. Varga, Functional Foods in Modern Nutrition Science: Mechanisms, Evidence, and Public Health Implications, *Nutrients* 17 (2025) 2153. doi: [10.3390/nu17132153](https://doi.org/10.3390/nu17132153).
 96. U. De Corato, Improving the shelf-life and quality of fresh and minimally-processed fruits and vegetables for a modern food industry: A comprehensive critical review from the traditional technologies into the most promising advancements, *Crit. Rev. Food Sci. Nutr.* 60 (2020) 940–975. doi: [10.1080/10408398.2018.1553025](https://doi.org/10.1080/10408398.2018.1553025).
 97. A. Raffo, F. Paoletti, Fresh-Cut Vegetables Processing: Environmental Sustainability and Food Safety Issues in a Comprehensive Perspective, *Front. Sustain. Food Syst.* 5 (2022). <https://doi.org/10.3389/fsufs.2021.681459>.
 98. G.F. Elfawal, A.O. Šišková, A.E. Andicsová, Ecological packaging and creating sustainable solutions for biodegradable cellulose derivatives: A review, *Int. J. Biol. Macromol.* 309 (2025) 142348. doi: [10.1016/j.jbiomac.2025.142348](https://doi.org/10.1016/j.jbiomac.2025.142348).
 99. P.K. Sarangi, P. Pal, A.K. Singh, U.K. Sahoo, P. Prus, Food Waste to Food Security: Transition from Bioresources to Sustainability, *Resources* 13 (2024) 164 doi: [10.3390/resources13120164](https://doi.org/10.3390/resources13120164).
 100. R. Krishnan, M. Misra, J. Subramanian, A. Mohanty, Emerging Trends and Application of Edible Coating as a Sustainable Solution for Postharvest Management in Stone Fruits: A Comprehensive Review, *Compr. Rev. Food Sci. Food Saf.* 24 (2025). <https://doi.org/10.1111/1541-4337.70179>.
 101. A.N. Mafe, G.I. Edo, R.S. Makia, O.A. Joshua, P.O. Akpogheli, T.S. Gaaz, A.N. Jikah, E. Yousif, E.F. Isoje, U.A. Igbuku, D.S. Ahmed, A.E.A. Essaghah, H. Umar, A review on food spoilage mechanisms, food borne diseases and commercial aspects of food preservation and processing, *Food Chem. Adv.* 5 (2024) 100852. doi: [10.1016/j.focha.2024.100852](https://doi.org/10.1016/j.focha.2024.100852).
 102. S. Sheffield, M.L. Fiorotto, T.A. Davis, Nutritional importance of animal-sourced foods in a healthy diet, *Front. Nutr.* 11 (2024). <https://doi.org/10.3389/fnut.2024.1424912>.
 103. L.S. Devi, A.K. Jaiswal, S. Jaiswal, Lipid incorporated biopolymer based edible films and coatings in food packaging: A review, *Curr. Res. Food Sci.* 8 (2024) 100720. doi: [10.1016/j.crfs.2024.100720](https://doi.org/10.1016/j.crfs.2024.100720).
 104. E. Díaz-Montes, R. Castro-Muñoz, Trends in Chitosan as a Primary Biopolymer for Functional Films and Coatings Manufacture for Food and Natural Products, *Polymers (Basel)* 13 (2021) 767. doi: [10.3390/polym13050767](https://doi.org/10.3390/polym13050767).
 105. G.A. Martău, M. Mihai, D.C. Vodnar, The Use of Chitosan, Alginate, and Pectin in the Biomedical and Food Sector—Biocompatibility, Biadhesiveness, and Biodegradability, *Polymers (Basel)* 11 (2019) 1837. doi: [10.3390/polym11111837](https://doi.org/10.3390/polym11111837).
 106. H. Górka-Warszewicz, K. Rejman, W. Laskowski, M. Czaczkotko, Milk and Dairy Products and Their Nutritional Contribution to the Average Polish Diet, *Nutrients* 11 (2019) 1771. doi: [10.3390/nu11081771](https://doi.org/10.3390/nu11081771).
 107. C. Brothersen, D.J. McMahon, J. Legako, S. Martini, Comparison of milk oxidation by exposure to LED and fluorescent light, *J. Dairy Sci.* 99 (2016) 2537–2544. doi: [10.3168/jds.2015-9849](https://doi.org/10.3168/jds.2015-9849).
 108. H.S. Armagan, A. Demirci, Current Status of Pulsed UV Light Technology for Food, Water, and Food Processing Surface Decontamination, *Food Eng. Rev.* 17 (2025) 966–993. doi: [10.1007/s12393-025-09428-3](https://doi.org/10.1007/s12393-025-09428-3).
 109. D.V. Francis, D. Dahiya, S. Kurup, T. Gokhale, P.S. Nigam, Advancing Sustainability Through Circular Economy, Emerging Technologies and Bibliometric Insights Towards Innovative Biodegradable Packaging for Dairy Products, Contributing to Sustainable Development Goal 9, 12, 13, *SCI Sustain.* 1 (2025). <https://doi.org/10.1002/sst2.70005>.
 110. A. Dirpan, A.F. Ainani, M. Djalal, A Review on Biopolymer-Based Biodegradable Film for Food Packaging: Trends over the Last Decade and Future Research, *Polymers (Basel)* 15 (2023) 2781. doi: [10.3390/polym15132781](https://doi.org/10.3390/polym15132781).
 111. S. Mariño-Cortegoso, A. Lestido-Cardama, R. Sendón, A. Rodríguez

- Bernaldo de Quirós, L. Barbosa-Pereira, The State of the Art and Innovations in Active and Edible Coatings and Films for Functional Food Applications, *Polymers (Basel)*. 17 (2025) 2472. doi: [10.3390/polym17182472](https://doi.org/10.3390/polym17182472).
112. M.T. El-Saadony, A.M. Saad, M. Sitohy, S.S. Alkafaas, M. Dladla, S. Ghosh, D. M. Mohammed, T.N. Soliman, E.H. Ibrahim, M.A. Fahmy, J.S. AbuQamar, K. A. El- Tarabily, Chitosan nanoparticles: Green synthesis, biological activities, and sustainable frontiers in targeted drug delivery and cancer nanomedicine – A comprehensive review, *Mater. Today Bio* 35 (2025) 102358. doi: [10.1016/j.mtbio.2025.102358](https://doi.org/10.1016/j.mtbio.2025.102358).
113. L.A. Picos-Corrales, A.M. Morales-Burgos, J.P. Ruelas-Leyva, G. Crini, E. García-Armenta, S.A. Jimenez-Lam, L.E. Ayón-Reyna, F. Rocha-Alonzo, L. Calderón-Zamora, U. Osuna-Martínez, A. Calderón-Castro, G. De-Paz-Arroyo, L.N. Inzunza-Camacho, Chitosan as an Outstanding Polysaccharide Improving Health-Commodities of Humans and Environmental Protection, *Polymers (Basel)*. 15 (2023) 526. doi: [10.3390/polym15030526](https://doi.org/10.3390/polym15030526).
114. G.I. Edo, A.N. Mafe, A.B.M. Ali, I. Iwanegbe, E. Yousif, E.E.A. Oghrro, U.A. Igbuku, K. Zainulabdeen, J.O. Owheru, A.E.A. Essaghah, H. Umar, D.S. Ahmed, A.A. Alamiery, M.R. Aliyu, Evaluating the environmental impact of biopolymer-based packaging compared to conventional plastics in the food industry, *Sustain. Chem. One World* 8 (2025) 100145. doi: [10.1016/j.scowo.2025.100145](https://doi.org/10.1016/j.scowo.2025.100145).
115. M. Stoica, C.I. Bichescu, C.-M. Crețu, M. Dragomir, A.S. Ivan, G.M. Podaru, D. Stoica, M. Stuparu-Crețu, Review of Bio-Based Biodegradable Polymers: Smart Solutions for Sustainable Food Packaging, *Foods* 13 (2024) 3027. doi: [10.3390/foods13193027](https://doi.org/10.3390/foods13193027).
116. M.M. Islam, N. Haque, D. Lau, M. Bhuiyan, B.K. Pramanik, Comparative life cycle assessment of end-of-life strategies for post-consumer polylactic acid waste: Environmental trade-offs and uncertainty analysis, *Chem. Eng. J.* 522 (2025) 167057. doi: [10.1016/j.cej.2025.167057](https://doi.org/10.1016/j.cej.2025.167057).
117. M. Mudersbach, M. Jürgens, M. Pohler, S. Spierling, V. Venkatachalam, H. Endres, L. Barner, Life Cycle Assessment in a Nutshell—Best Practices and Status Quo for the Plastic Sector, *Macromol. Rapid Commun.* 46 (2025). <https://doi.org/10.1002/marc.202300466>.
118. I. Oliveira, T. Pinto, S. Afonso, M. Karaś, U. Szymanowska, B. Gonçalves, A. Vilela, Sustainability in Bio-Based Edible Films, Coatings, and Packaging for Small Fruits, *Appl. Sci.* 15 (2025) 1462. doi: [10.3390/app15031462](https://doi.org/10.3390/app15031462).
119. O. Burgos-Morales, M. Gueye, L. Lacombe, C. Nowak, R. Schmachtenberg, M. Hörner, C. Jerez-Longres, H. Mohsenin, H.J. Wagner, W. Weber, Synthetic biology as driver for the biologization of materials sciences, *Mater. Today Bio* 11 (2021) 100115. doi: [10.1016/j.mtbio.2021.100115](https://doi.org/10.1016/j.mtbio.2021.100115).
120. F. Liu, L. Pan, Y. Liu, G. Zhai, Z. Sha, X. Zhang, Z. Zhang, Q. Liu, S. Yu, L. Zhu, H. Xiang, Z. Zhou, M. Zhu, Biobased fibers from natural to synthetic: Processing, manufacturing, and application, *Matter* 7 (2024) 1977–2010. doi: [10.1016/j.matt.2024.04.006](https://doi.org/10.1016/j.matt.2024.04.006).
121. A. Miserez, J. Yu, P. Mohammadi, Protein-Based Biological Materials: Molecular Design and Artificial Production, *Chem. Rev.* 123 (2023) 2049–2111. doi: [10.1021/acs.chemrev.2c00621](https://doi.org/10.1021/acs.chemrev.2c00621).