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Review

Advancements and the Prospects of Biodegradable Films Fabricated with Biological Macromolecules for Sustainable Food Packaging through Scientometric Analysis: A Review

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ABSTRACT: Food preservation and spoilage reduction are basic components of modern food systems. Plastic packing films have been used for a long time to achieve these goals. However, their rampant use has caused extreme environmental hazards. Biodegradable packaging films, an available solution to the latter problem, are bio-based and renewable. They offer long-term preservation of food with the least unfavorable environmental impacts. They are expected to be optimized for various uses, and their overall performance will be consolidated in terms of mechanical, barrier, and optical qualities. Alongside, the presence of nanoparticles and natural extracts from plant sources can increase the functional ability of these films in aspects such as greater food preservation. Taking into account polymer blending and nanoparticle incorporation along with bioactive compounds, this review focuses on the benefits of biodegradable films for packaging and inquires into packaging solutions that satisfy the needs of the food industry with environmental concerns.

KEYWORDS: *Biodegradable, Packaging films, Environmental pollution, Food preservation, Nanoparticles, Plant extract*

1. INTRODUCTION

Plastic packaging plays a crucial role in our habitual activities because of its affordability, durability, and convenience, leading to its widespread global usage.[1] Plastic packaging is crucial to conserve the freshness, safety, and prolong the shelf life of food and beverages. The strong structure of plastic, attributed to its lengthy polymer chains, makes it highly resistant to breakage.[2] To meet their desires for consumption, humans generate more than 400 million tonnes of plastic garbage annually.[3] Millions of tons of plastic debris fall into the ocean annually, or around 0.5% of total plastic garbage. Every day, almost 8 million plastic particles make their way to the marine bodies.[4] India utilized over 15 million tonnes of main plastics in the financial year 2021−2022. India consumed over 21 million tonnes of plastic in total by 2021, a 23-fold increase from 1990.[5] 500 billion single-use plastic bags are used annually, and one truckload of polythene drinking packages is bought globally per minute.[6] The global marketplace for plastic wrapping was valued at around 265 billion US dollars in 2022.[7] Annually, 141 million metric tonnes of plastic packaging are produced worldwide. Because plastic packaging is more affordable and long-lasting, it uses 1.5% less oil and gas, making it the preferred option.[8] High-density polyethylene (HDPE) produces 44.71 million tons. HDPE is widely used in containers and is more easily recyclable than other types. Widely recycled, HDPE and poly(ethylene terephthalate) (PET), these materials have established recycling systems, although they still contribute significantly to waste. Moderately recycled LDPE and LLDPE are often recycled into lower-grade materials due to contamination issues. Limited or Non-Recyclable polystyrene (PS) and polyvinyl chloride (PVC) have limited recycling due to economic or technical challenges, contributing heavily to landfills and pollution [Figure 1]. The largest use of plastic packaging consumed 142.6 million tons in 2019. Conventional packing materials can release micro- and nanoplastics into food and drink, which can be accidentally consumed by humans and have been linked to a number of health hazards, including oxidative stress, inflammation, immunological and endocrine system disturbance.[9] There are significant worries regarding the long-term effects of micro and nanoplastics on human health because new toxicological research indicates that they can penetrate biological barriers such as the blood−brain barrier, placenta, and gut lining. This could result in systemic distribution, genotoxicity, neurotoxicity, and possibly even cancer.[10] Single-use and disposable packaging contribute significantly to waste, with low recycling rates, often ending up in oceans and landfills. Building and construction utilizes 76.89 million tons. Plastics in this sector are generally durable and long-lasting, used for insulation, piping, and window frames. In transportation accounting for 62.17 million tons, plastic is widely used in automotive and aerospace components due to its lightweight properties improve fuel efficiency.

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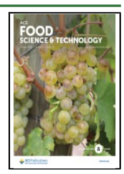

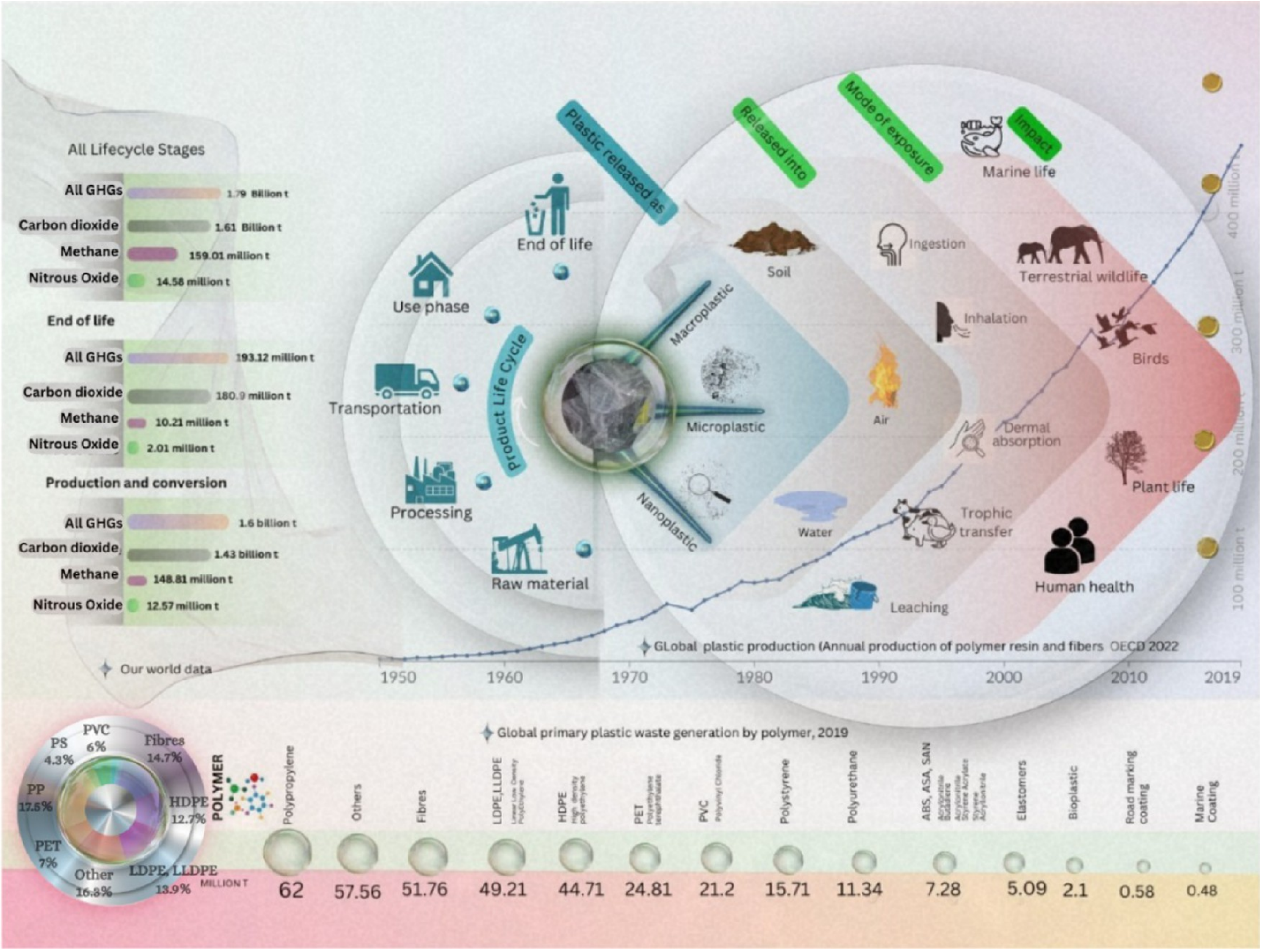

Figure 1. Disadvantages of conventional plastic packaging films.

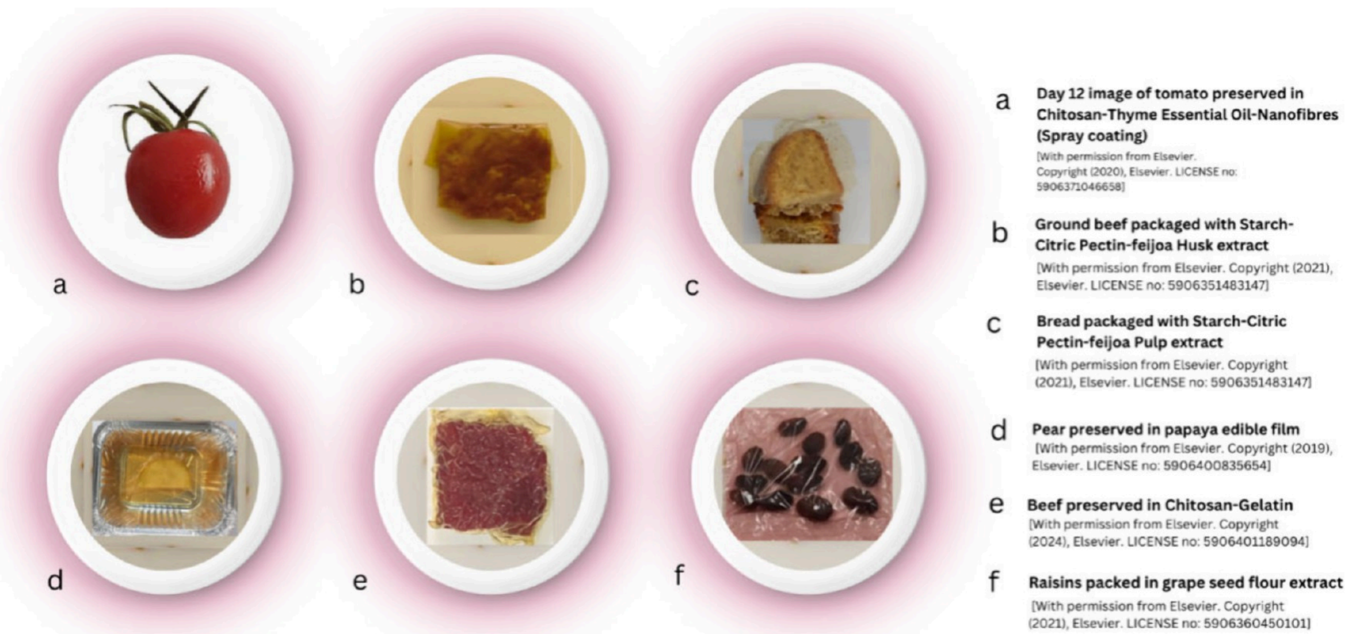

Figure 2. Application of biodegradable packaging films.

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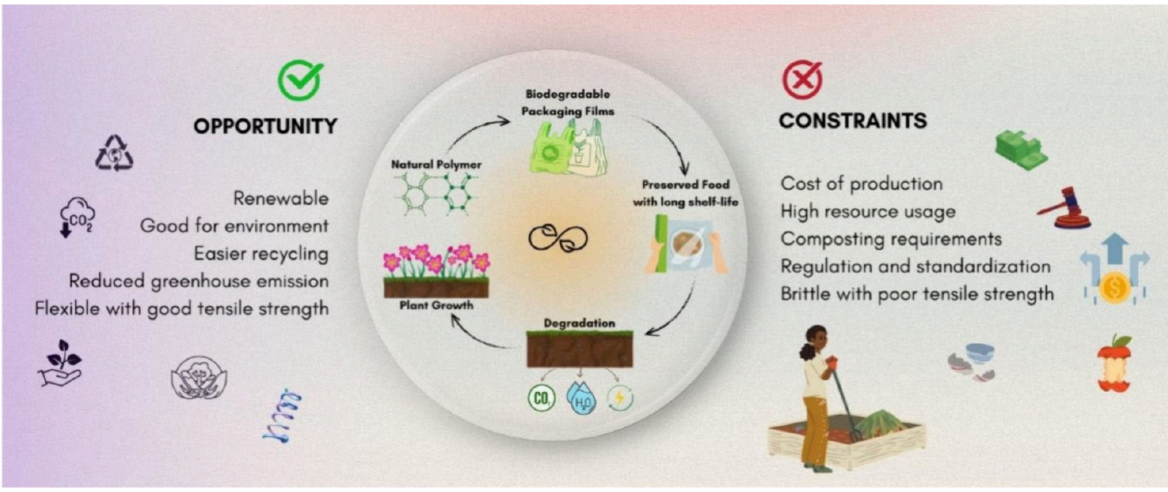

Figure 3. Advantages and disadvantages of biodegradable packaging films.

However, these materials often remain nonrecyclable and accumulate as waste. Factors such as the type and intricacy of the consumable, duration of interaction, system temperature, packaging deposit, along with the characteristics of the migrants, all influence the movement of chemicals from consumable packaging.[11]

Consumable films, as an alternative to plastic packaging films, are crafted from edible components, serving as a protective layer in food packaging [Figure 2], helping to maintain product longevity and prevent microbial invasion.[12] These edible films provide a range of advantages, including controlling gas exchange, regulating moisture, and responding to environmental stimuli [Figure 3]. In addition to providing potential functional benefits, including antibacterial and antioxidant activity, biodegradable packaging films have become a viable substitute for traditional plastic packaging.

These characteristics are crucial for maintaining the quality of food because they stop oxidative deterioration and microbiological contamination while it is being stored. By preventing the growth of harmful and spoiling bacteria on the food's surface, these films' antimicrobial properties help lower the risk of foodborne illnesses and increase shelf life. In order to reduce oxidative events like lipid peroxidation, which can degrade the nutritional value and sensory appeal of packaged foods, antioxidant capabilities are essential. By incorporating these bioactive properties into biodegradable film matrices, active packaging technologies that meet global sustainability goals while improving food safety, waste reduction, and product stability are developed.

The physicochemical properties of film-forming solutions can be markedly modified through the blending of two distinct biopolymers derived from biological macromolecules, which subsequently influences the functional performance of the resulting films.[13] The structure, pH, hydration behavior, and molecular weight of the two polymers, among other factors, are all affected by their compatibility or incompatibility.[14] On the other hand, blending different polymers enables the production of an entirely new material with distinct physical characteristics.[15] The synergistic effect of the individual polymers contributes to the best characteristics of the resulting blend.[16] By fusing beneficial properties from several polymers into a single substance, polymer blending can streamline production and eliminate the need for intricate manufacturing procedures.[17]

Blending gives designers and developers more flexibility in the creation of films by enabling the modification of material qualities to satisfy certain needs.[18] Biodegradable packaging films have been the subject of a number of review publications, but the majority have focused on specific topics such as natural polymers, polymer blending, or the use of plant-based additives and nanoparticles separately. A thorough assessment that incorporates all of these approaches in order to offer a comprehensive knowledge of their combined influence on film properties is notably lacking in the literature. Furthermore, bibliometric and scientometric analyses are effective methods for charting research patterns and determining future paths. Technical reviews on this subject hardly ever mention them. This review fills that gap by providing a multidisciplinary overview that includes a bibliometric and scientometric assessment of the field in addition to discussing the creation of biodegradable films through polymer blending, the incorporation of plant extracts, and green-synthesized nanoparticles. The study is positioned as a useful tool for promoting research and innovation in sustainable packaging solutions because of its integrated approach, which provides both technical depth and data-driven insight. This review begins by outlining the significance and fundamental requirements of biodegradable packaging films, followed by an in-depth discussion on the role of polymer blending in enhancing film properties. It then explores the incorporation of plant-based bioactive compounds and green-synthesized nanoparticles to impart functional attributes such as antimicrobial and antioxidant activity. This paper also integrates scientometric and bibliometric analyses to map research trends and identify future directions, offering a comprehensive perspective on the development and innovation of biodegradable packaging systems.

2. SCIENTOMETRIC ANALYSIS

Scientometric analyses are the quantitative study of scientific research, focusing on measuring and analyzing the outputs, trends, and impacts of scientific publications and activities. The metrics on information facilitate progress by providing an opportunity for the knowledge seeker to reach the appropriate knowledge provider. The quantitation analysis of research information provides an amicable platform to display the trust area of the research domain. The increasing demand for publications among the academic research community and the

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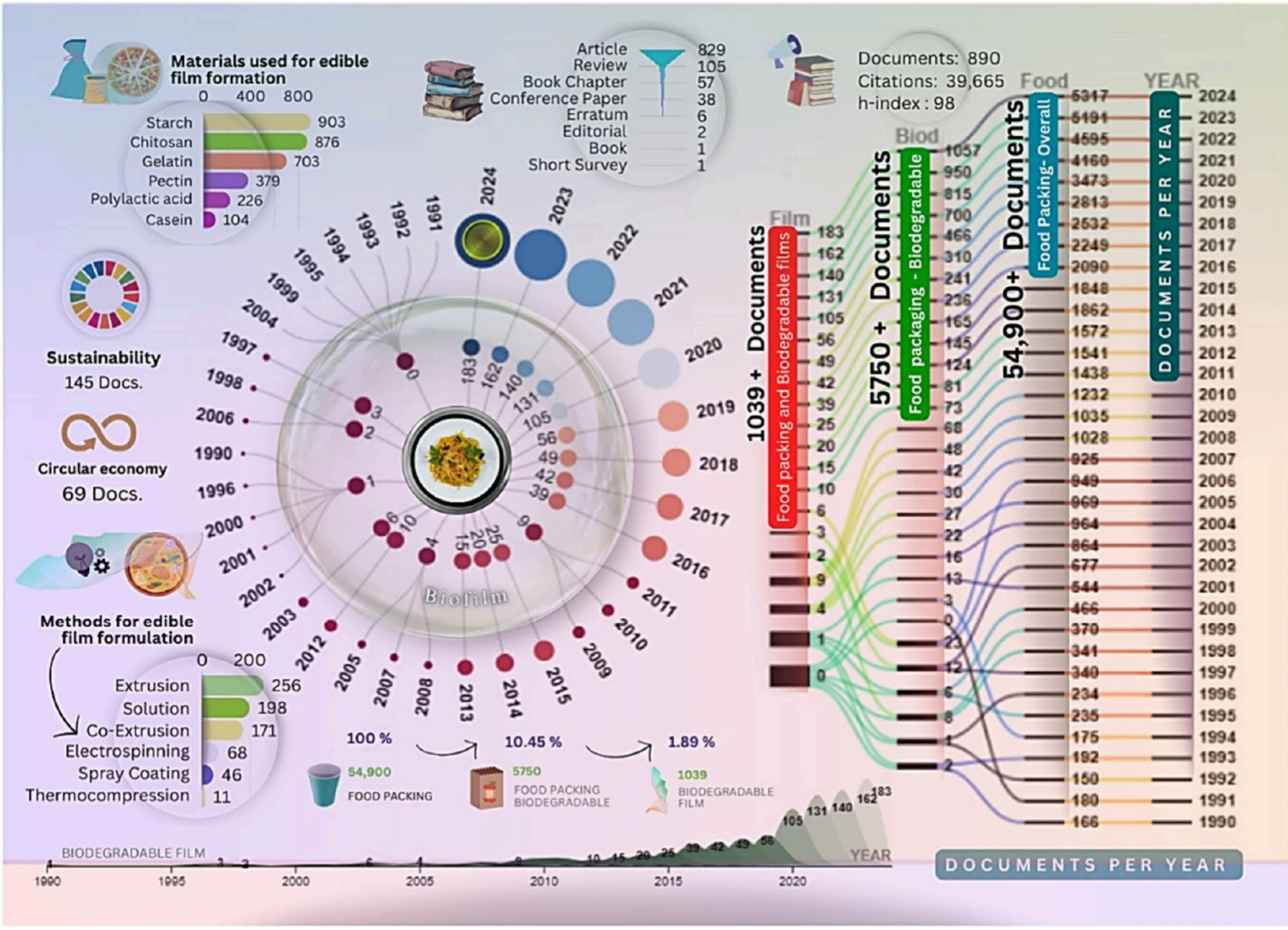

Figure 4. Snapshot summary of biodegradable food packing film publications for the topics used in the study, including “food packing”, “biodegradable”, “film”, “sustainability”, and “circular economy”.

increasing number of publishing platforms are constantly accelerating the publication numbers of research articles. As the number of articles increases, the quality of the research raises concern. The process of peer review, impact factors assessment, and other quality control measures helps to regulate the quality of the research article. In addition, the information metrics help the reader to identify the source of appropriate information.

The review articles are the gateway for the researcher to learn the current state of knowledge in any research domain. The recent trend of reviews is to provide complete information about the research, which includes the metric of the information. Information science crossed the core library education and spread to various other domains. According to the Scopus database, the “scientometric” term wittiness nearly 6740 documents covering social science, computer science, medicine and engineering, and environmental science. Among the 6740 documents, 20% of the documents are comprised of review articles. Interestingly, 70% of the scientometric articles were published in the last 6 years (2019–November 2024). This significant number hints at the importance of scientometric studies.[19] Sudalai and Prabhakar used scientometric analysis to study the biodiesel from *Madhuca indica* and *Azolla* trends. With its versatility, the scientometric analysis supports the researchers and policymakers by providing science and a source of scientific information.

The present study provides the reader with a broad perspective of biopolymers. The scientometric analysis in this study begins with the broad spectrum of food packages, and biodegradable food packages, and finally, the biodegradable film food packages.

Accordingly, the basic keywords “food packing”, “biodegradable”, “film”, “sustainability”, and “circular economy” were chosen, and the Scopus database was used to collect the information. The data for food packages accounts for 54,900 documents, and biodegradable food packaging covers 5750 among the 54,900 documents, representing close to 10%. The individual topics and the corresponding published articles are highlighted with a flag icon in Figure 4. Figure 4 shows the research trend of food packages and the potential to explore further to align with sustainable packages and utilize biodegradable packaging. The further biodegradable film comprises 1029 documents, which represent 1.84% of food packaging documents. The publication details from the year 1977 to October 30, 2024 were presented. From 1977 to 2009, only 10 articles were published per year. Later data indicates a 74% increase in overall publications from the year 2020 to 2024. This shows the significant demand for biodegradable film in food packages. The VOS viewer and Biblioshiny (R studio) tools were used to analyze the data, and Canva and mathematical tools were used to summarize the results [Figure 5].[6,7]

2.1. Bibliometrics Snapshot Study. The entire study is illustrated in two parts. The first part explains the details of contributors, their affiliations, country, and sources. The year-wise article publication of biodegradable food packing film is

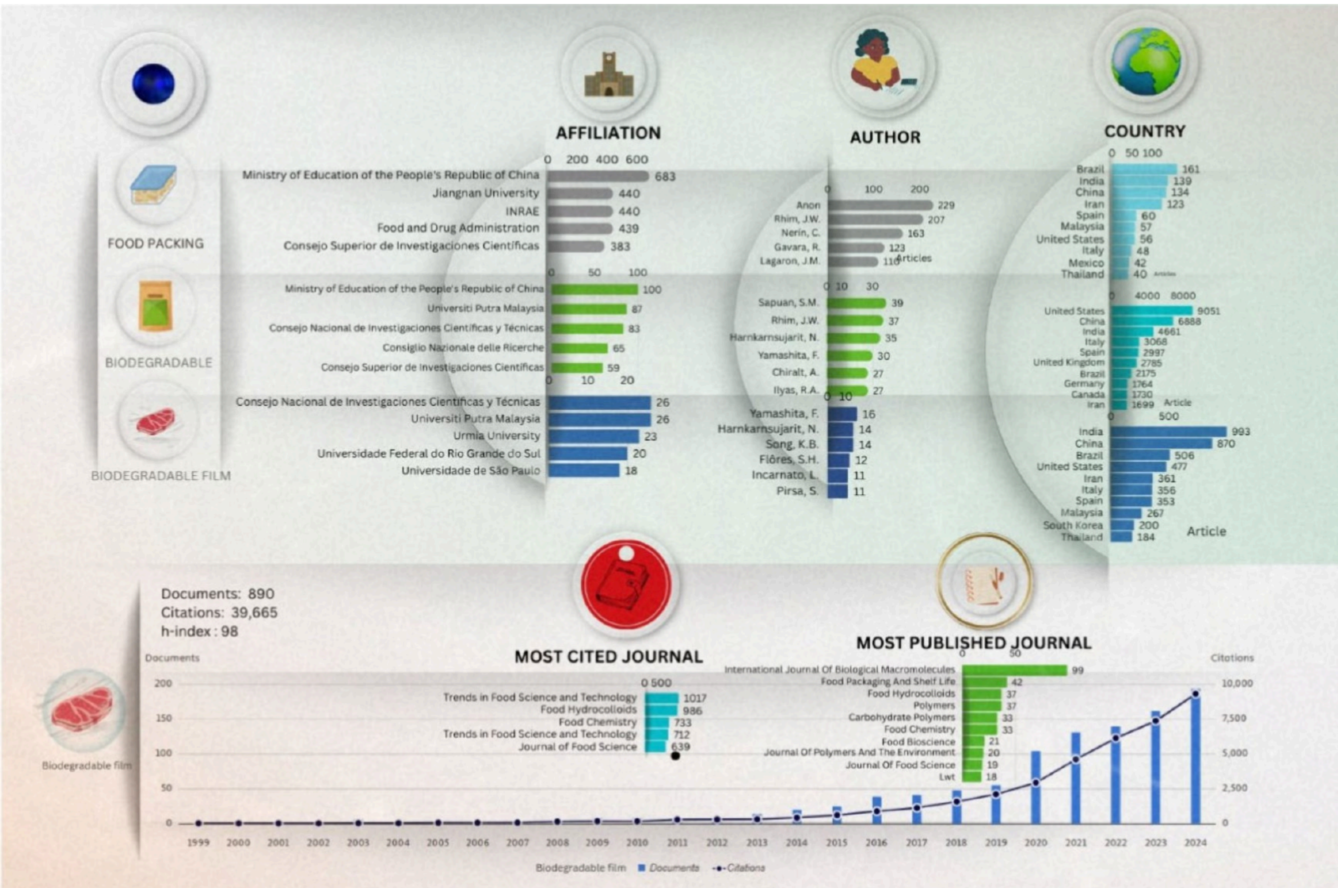

Figure 5. (A) Trends of food packing film publications include affiliation, authors, and country for the topics of food packing, biodegradable, and biodegradable film. (B) The most cited and published journal on biodegradable film is displayed.

compared with food packing articles and biodegradable food packing-related documents. The same data was illustrated with circular and Sankey diagrams for better illustration. The document numbers were used to understand the significance of biopolymer preparation materials and methods. The extrusion methods were covered in 256 documents, followed by the solution casting method with 198 documents and further, the number of publications for other methods was plotted as shown in Figure 4. The materials required for the biopolymer production are also plotted to indicate the significance; accordingly, starch with 903 documents and chitosan with 876 documents cover 86% and 84% of the total biodegradable film-related documents. The citations based on the journal sources were also pictured as shown in Figure 5. The trends in food science and technology and Food hydrocolloids published the most cited articles with 1017 and 986 citations, respectively. The international journal of biological macromolecules and food packaging and shelf life contributes a greater number of articles, with 99 and 42 articles. India leads the published documents on the food packaging biodegradable films. It also secured within three ranks upon broad topics such as food packaging and biodegradable food packaging. The circular economy accounts for 69 documents, and sustainability represents 145 documents in the biodegradable food packaging films. The topic covers 829 research articles and 105 review articles.

2.2. Bibliometrics Analysis. The analysis part comprises three portions: occurrence analysis, topic dendrogram, and concept structure map. The data from the Scopus database is downloaded in.csv format, and the text from the keyword, abstract, and title was analyzed using Biblioshiny and VOS viewer. The occurrence analysis was built based on the title and abstract fields. Nearly 18834 terms were identified by the VOS viewer tool, of which 670 terms met the threshold that the minimum number of occurrences of terms should be 10; accordingly, 402 terms were selected for the Co-word analysis. Three clusters were formed, with 157 items. Cluster 1 united the environment concerns related terms, cluster 2 was made out of 141 items and mainly discussed product development and methods, and the 3 clusters with 104 items mainly focused on material properties. The result was interpreted with the help of AI tools and confirmed manually. Further, the relevant topics were identified with the relevance value. The terms such as biopolymer, PLA film, solution casting, and extrusion were identified, and the same was confirmed with the number of publications. The basic functional properties, such as antimicrobial and antioxidant properties, were widely discussed. In addition to food safety, material characterization, and sustainability topics were discussed widely, as shown in the figure. The emphasis on the packaging sector using sustainable alternatives, edible coatings, and antimicrobial films shows useful applications in enhancing food storage and cutting down on plastic waste. The important functional properties for practical packaging are addressed by terms like degradability, low water vapor permeability, and oxygen transmission rate.

Methods and analysis of research from clusters reveal that the material investigations are indicated by characterization techniques such as differential scanning calorimetry, FTIR analysis, and scanning electron microscopy. A focus on

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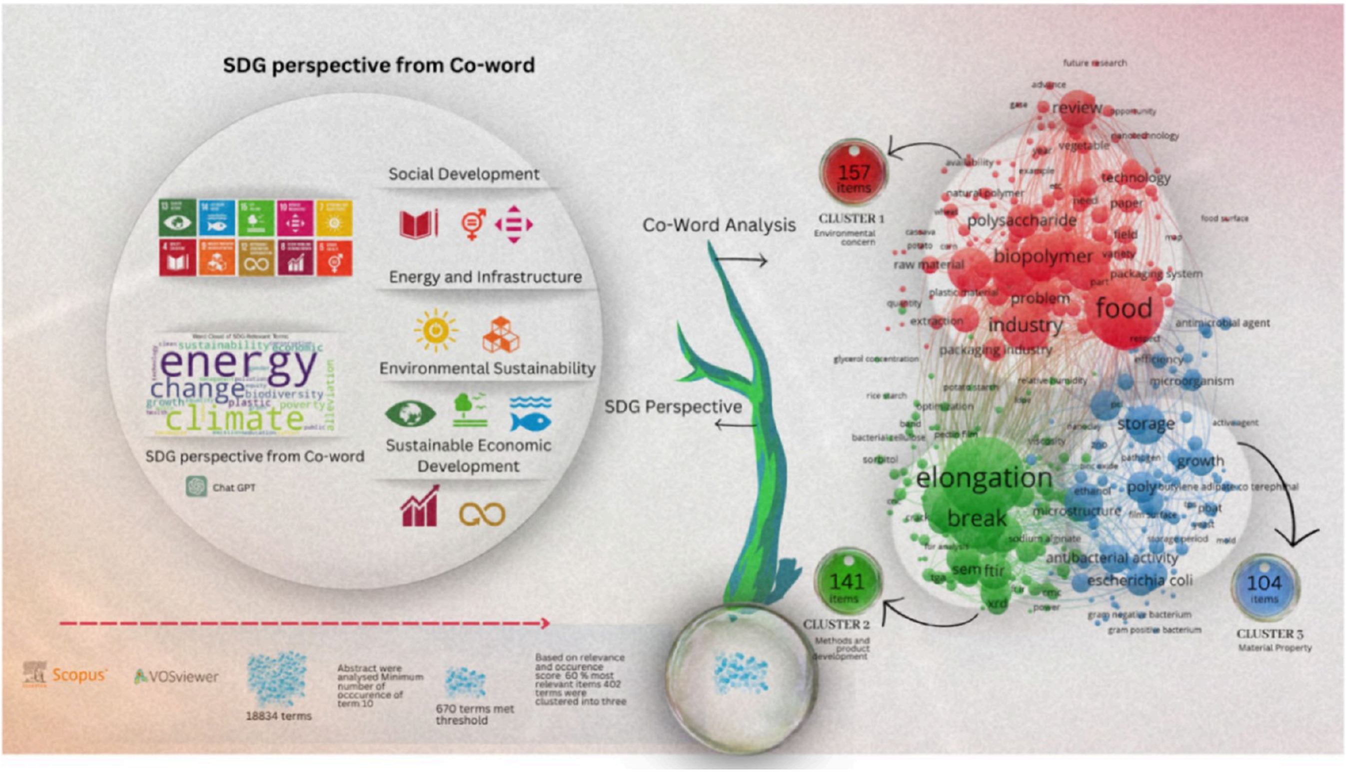

Figure 6. SDG perspectives from Co-word analysis.

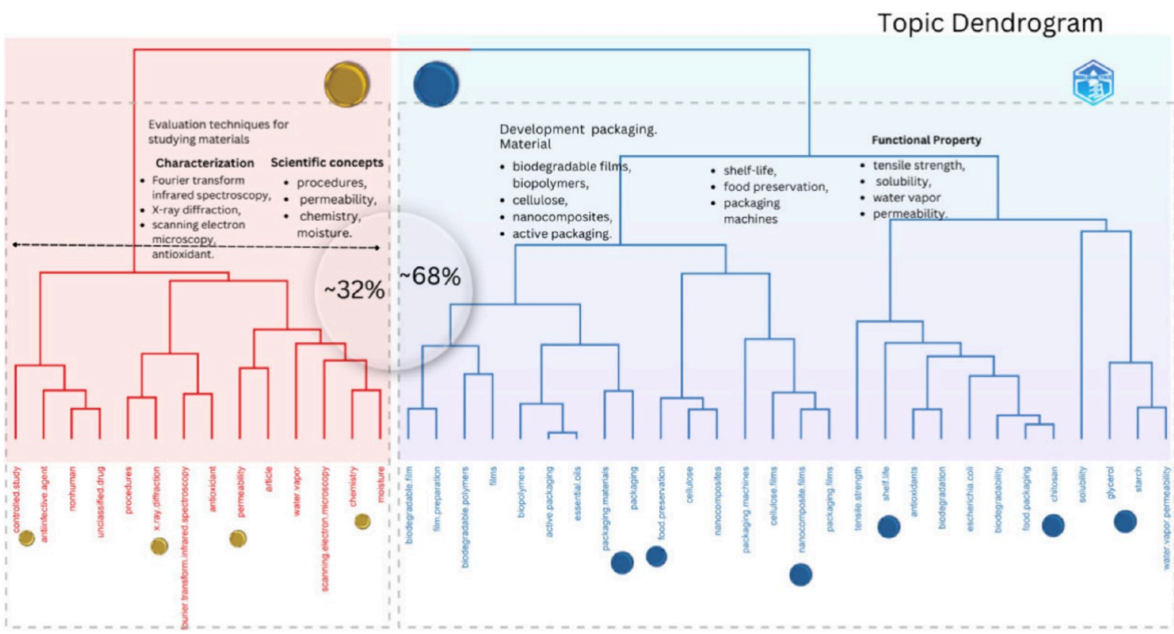

Figure 7. Bibliometric analysis of biodegradable food packaging film.

manufacturing techniques is suggested by keywords such as extrusion and casting methods. Recent developments in biodegradable film packaging, such as the application of natural antioxidants and nanotechnology, show the trend toward creative and environmentally responsible solutions. Apart from clustering, the occurrence and relevance data are further processed with Chat GPT to obtain the relevance of SDGs with the terms that were analyzed and presented as word clouds. The relevant SDGs are mentioned in Figure 6. The exclusive section 11 briefly discusses the sustainability of biodegradable films.

The topic dendrogram was plotted using Biblioshiny; it portrays the similarity of the various clusters of terms. Two groups were identified as red and blue clusters, as shown in Figure 7. Twelve and 26 terms were clustered as red and blue, respectively, divided into further subdivisions. The red cluster explicitly highlights the multidisciplinary potentials of the research and touches on the characterization. The blue cluster dealt with the terms related to the development of packing

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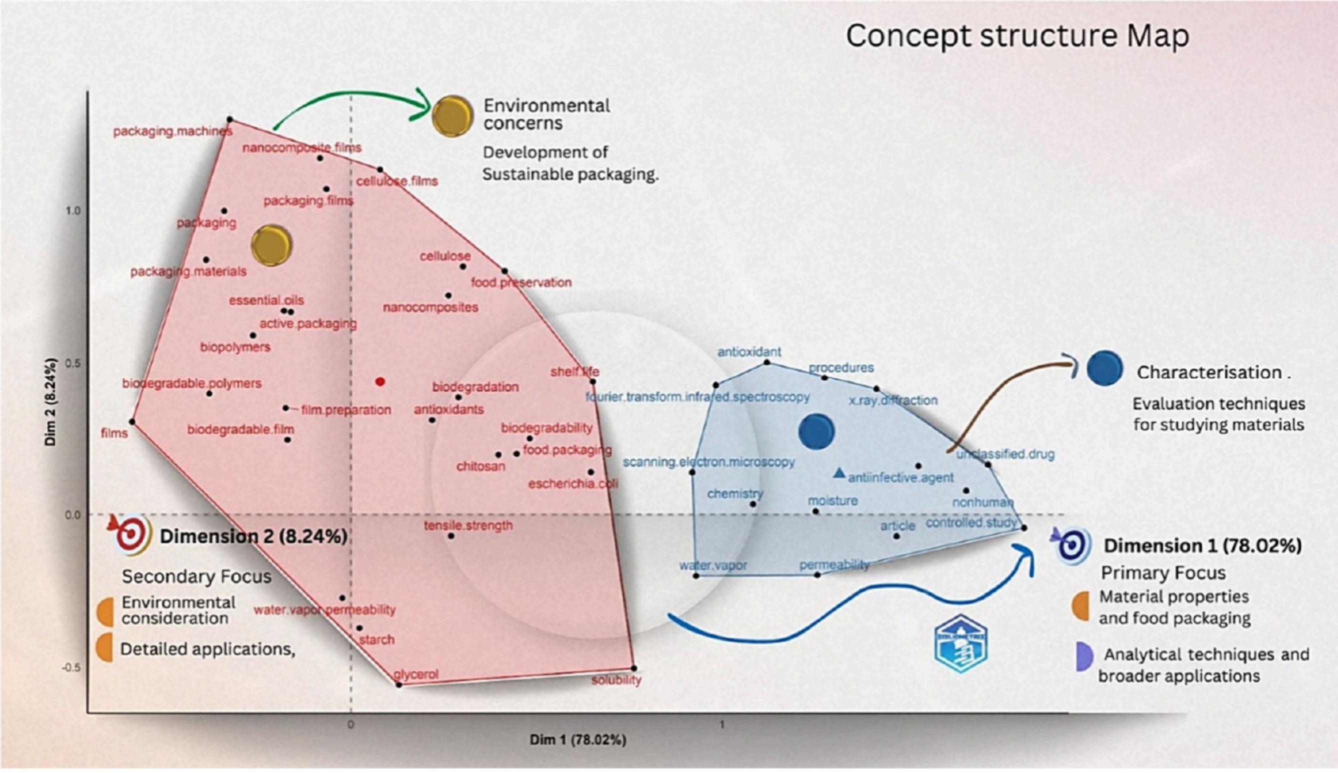

Figure 8. Concept structure map for the food packing film.

materials such as biodegradable films, cellulose, nanocomposites, and functional properties like tensile strength, solubility, water vapor, and permeability. The main observation from the dendogram is that the blue cluster bags approximately 68% cover material development and environmental conservative terms. Whereas the red cluster covers 32% of terms covering the critical parameters, such as characterization and scientific terms. The key observations are focused mainly on material and sustainability, and testing methods. The central terms such as biopolymer, biodegradable film, and FTIR hint at the interdisciplinary potentials. The specific terms such as "food packing", "shelf life", and active packing in the blue cluster, as shown in the figure, significantly connect the research focus on sustainability.

The concept structure mapping (CSM) used multiple correspondence analyses with the keywords used in the published articles. Biblioshiny tools are used to perform the intellectual structure analysis with text mining. The CSM effectively maps the collaborative patterns, research trends, and knowledge dispersion maps. The biodegradable food packaging film-based articles were classified into two dimensions. Dimension 1 consists of 78.02% and dimension 2 consists of 8.02% terms. The keywords in the red cluster, such as biopolymers, biodegradable polymers, nanocomposites, cellulose, starch, food packaging, preservation, shelf life, active packaging, essential oils, tensile strength, water vapor permeability, and solubility, indicate the first-dimension analytical related terms, including the application of biodegradable films and material properties. The second dimension mentions sustainable-related terms and characterization, which covers the keywords such as Fourier transform infrared spectroscopy, scanning electron microscopy, X-ray diffraction, antioxidants, anti-infective agents, and chemical analysis, application studies such as controlled studies, nonhuman analysis. The detailed classification is portrayed in Figure 8.

The scientometric studies concluded that biodegradable food packaging films have recently gained more importance among the scientific community due to the increasing awareness of plastic pollution and global policies toward sustainability. Global Bioplastic production is supported by sustainable principles, which are confirmed by the terms used in the scientific literature. The instrumentation widely associated with biopolymers is SEM, FTIR, XRD, and DSC. The major materials used as per the bibliometrics analysis are glycerol, starch, and chitosan. Methods like extrusion and solution casting are the most common methods been widely used in the scientific literature. The major limitations of the scientometric studies are as follows: the findings based on bibliometrics an indicative, based on the response for the chosen keywords and tools assessment methods. However, this study helps the policy makers and scientists to understand the reach of various aspects of the study parameters. The present scientometric conclusion is that the sustainability-related material science is no longer isolated; innovation and thorough validation must coexist. To scale sustainable biodegradable film packaging solutions, interdisciplinary cooperation between engineering, chemistry, food science, and toxicology is crucial. Scientometrics described the discernible paradigm shift in biodegradable packaging research toward using safe, scalable, and scientifically supported technologies to address actual environmental issues.

3. DIFFERENT MATERIALS USED FOR EDIBLE FILM FORMATION

Innovative and environmentally friendly, edible films can be used as packaging or protective coverings for a variety of food products. Biopolymers, which are mainly divided into different classes of biological macromolecules like proteins, polysacchar-

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ides, lipids, or composite materials, are used to make these films. The structure, barrier qualities, and mechanical strength of the film are influenced by the distinct qualities that each category offers. Because they are cohesive and sticky, proteins like whey and gelatin provide strong film formation. Lipids aid in water resistance, while polysaccharides such as chitosan and starch offer high oxygen barrier properties. These elements are combined in composite films to maximize the advantages, which allows them to be customized for a variety of food safety and preservation applications. The materials used for the development of edible polymers can be broadly categorized into classes of polysaccharides and proteins, along with some biodegradable polymers.

3.1. Polysaccharide Materials. *3.1.1. Chitosan.* Chitosan is a copolymer comprising β-(1−4)-2-acetamido-D-glucose and β-(1−4)-2-amino-D-glucose units, where the latter typically exceeds 60%. It is characterized by its degree of deacetylation and average molecular weight, and is notable for its antimicrobial effects, cationic properties, and capacity to form films.[20] Chitosan, an organic polysaccharide under the class of biological macromolecules, exhibits properties such as water affinity, biological compatibility, environmental degradability, antimicrobial functionality, and selective binding to biomacromolecules. Chitosan-based bioscaffolds are generated through surface modifications combined with lyophilization to achieve stability and porosity. However, the addition of various compounds can alter their biocompatibility. Therefore, the evaluation of biomedical-grade chitosan derivatives is critical to producing high-quality, biocompatible materials for multiple applications. Chitosan derivatives are highly versatile and can be fabricated into multiple forms, such as membranes, nanofibers, nanofibrils, beads, microparticles, nanoparticles, scaffolds, and sponge-like structures.[14]

3.1.2. Starch. Starch serves as a storage polymer in plants, primarily made of two glucose-based polysaccharides: amylose and amylopectin, some of the important biological macromolecules. Amylose forms linear chains with α-(1−4) glycosidic bonds, while amylopectin, although similar in backbone structure, is highly branched with about 5% α-(1−6) linkages. The amylose-to-amylopectin ratio determines the properties of starch, influencing its solubility, gelatinization, and viscosity. For instance, corn starch, which contains 70% amylopectin, forms thicker pastes compared to starches with higher amylose content.[21] Starch-based films are a great option for eco-friendly packaging in different areas, like food and drinks, skincare products, medicines, and everyday items. These films fit specific needs, whether that means changing how thick they are, how strong they need to be, how well they block moisture, or how compatible they are with certain foods.[22]

3.1.3. Pectin. Pectin is a naturally occurring polysaccharide, which is mainly found in the cell walls of fruits, especially in apples, berries, and citrus, among others, such as oranges and lemons.[23] It gives the structure additional strength and keeps the fruit firm. Pectin is a complex carbohydrate, primarily of units of galacturonic acid, joined together to make a long chain, thus giving it the capability to gel in combination with sugar and acid under given conditions. High methoxyl pectin exhibits more than 50% degrees of esterification, requiring the use of high sugar content and acidic conditions, pH below 3.5, to gel, whereas low methoxyl pectin is less than 50% and will gel without the necessity for high sugar levels; it simply forms a gel when calcium ions are present.[24] Pectin is mainly used in food as an agent to gel, thicken, stabilize, and act as an emulsifier. Pectin is nontoxic because it is completely biodegradable. For this reason, efforts have been undertaken toward the development of biodegradable packaging films in which pectin can be blended with other biopolymers to obtain an environmentally friendly alternative to conventional food packaging.[25] It may be prepared like synthetic plastic films for coating or food packaging. Being soluble in water, efforts are normally taken to make it more mechanically strong and resistant to water before packaging.[26]

3.2. Protein Materials. *3.2.1. Gelatin.* Gelatin, characterized by its translucent appearance and varying shades from white to yellow, is a partially hydrolyzed derivative of collagen found in animal connective tissues. Its multifunctional attributes, such as hydrophilic water-binding, gelation properties, and the ability to form protective barriers and stable emulsions, make it invaluable in numerous industries.[27] The gelatin manufacturing process encompasses three principal steps: (i) the extraction of noncollagenous materials from collagenous substrates, (ii) the regulated hydrolysis of collagen into gelatin, and (iii) the recovery and dehydration of the final product. Waste gelatin-based films possess two forms of water-resistant bonding augmented by robust hydrogen bonds between gelatin molecular chains. These bonds in the gelatin matrix function as sacrificial bonds, facilitating multiple energy dissipation, which leads to exceptional mechanical properties and water resistance. Additionally, given that the fabrication process is straightforward, devoid of toxic solvents, cost-effective, and scalable, this strategy markedly enhances the potential for practical applications.[28]

3.2.2. Casein. Casein is a milk protein that makes up the major part of milk and dairy food products. It accounts for 20−45% of human milk proteins and up to 80% of bovine milk proteins.[29] Due to its unique properties, casein is useful for a variety of applications in the food and nonfood industries. Casein is part of a family of related phosphoproteins, meaning proteins containing phosphate groups.[30] Often abbreviated as "galalith" or casein polymers, casein has been applied for the formulation of biodegradable films and plastics.[31] In fact, researchers are currently evaluating the suitability of casein for edible coatings and biodegradable films for the packaging of food products.[32] Casein-based films are edible with food, nontoxic, and form an oxygen barrier for the extended shelf lives of food goods. These films are often blended with other natural polymers, such as pectin or starch, to enhance the mechanical properties as well as water resistance of these films.[33]

3.3. Biodegradable Polymers. *3.3.1. Polylactic Acid.* Polylactic acid (PLA) is a biodegradable and bioactive thermoplastic polymer synthesized from various renewable feedstocks, including corn starch, sugar cane, and cassava.[34] PLA breaks down into its natural components, including water, carbon dioxide, and organic material, when disposed of in industrial quantities and composted over time.[35] Because PLA possesses high mechanical properties, such as strength and rigidity, it finds applications in 3D printing, packaging, and disposable items like cups and cutlery. For these reasons and its transparency and glossy appearance, it looks similar to other commercial polymers like polyethylene terephthalate (PET). PLA is widely found in food packaging for films, trays, and containers because it has many merits like transparency and biodegradability, and it keeps the freshness of products.[36] The ability of PLA to degrade in conventional landfills or in the environment is limited as it requires specific industrial composting conditions to achieve this.

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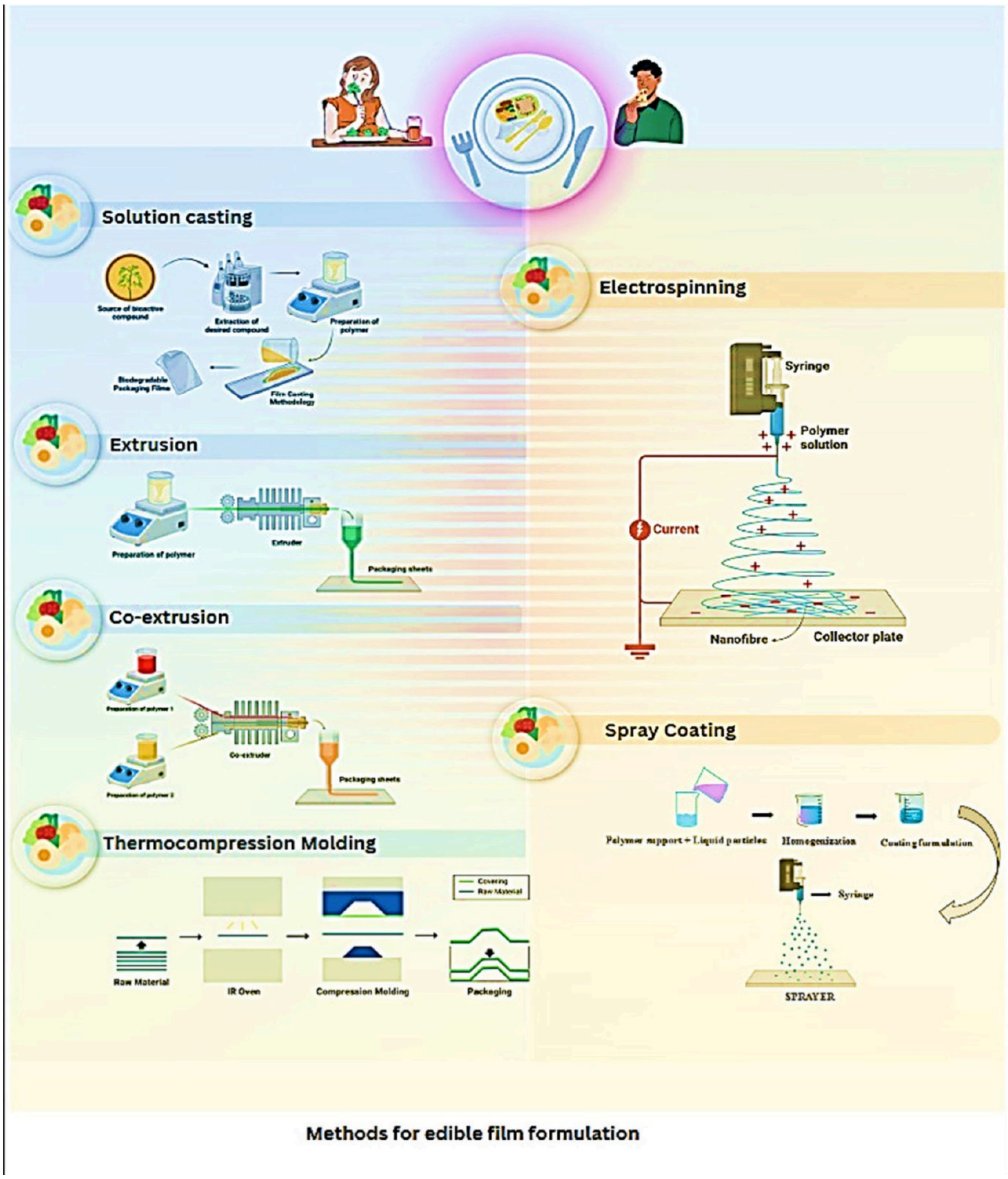

Figure 9. Methods for edible film formation, such as solution casting, extrusion, coextrusion, thermocompression molding, electrospinning, and spray coating.

4. METHODS FOR EDIBLE FILM FORMULATION

A variety of techniques are used in the formation of edible films to produce protective, biodegradable coatings that are appropriate for use in food applications. Casting, extrusion, and solvent evaporation are the main methods. Casting is one of the most often used techniques. Biopolymers are dissolved in water or other appropriate solvents to create a film-forming solution, which is then spread out onto a level surface and allowed to cure. Extrusion, a process frequently employed in large-scale manufacturing, creates a continuous film from biopolymer mixes by applying pressure and heat. By applying a solution to a surface and letting it slowly evaporate, solvent evaporation techniques are used to produce films. The development of films with specific qualities that meet a range of environmental and functional requirements depends on these techniques.

4.1. Solution Casting. The casting technique is an innovative means for fabricating nanocomposite films, achieved by dissolving a biopolymer and integrating plasticizers and additives to yield a film-forming solution [Figure 9]. This methodology is widely applied in the food packaging industry to synthesize gelatin-based composite films. The transition from bench-scale to production-scale film manufacturing is hindered by several process variables, including heating, mixing velocity, and temperature control, all of which may introduce inconsistencies in film formation. To mitigate these challenges, comprehensive optimization of critical parameters such as casting velocity, solvent evaporation rate, and the resulting film thickness must be conducted to ensure reproducibility and quality in commercial-scale outputs.[37] Transitioning from bench-scale to commercial-scale film production presents substantial challenges, as variables such as thermal control, mixing velocity, and temperature regulation may cause fluctuations in film quality. Ensuring consistent film formation at a large scale is not always feasible. Thus, thorough optimization of key parameters, including casting velocity, drying duration, and the final film thickness, is crucial to ensure efficient commercial-scale production.[37]

4.2. Extrusion Method. Melt extrusion is another commonly employed process for fabricating chitosan-based biodegradable active packaging films. It entails (1) preparing a formulation with various compositions; (2) blending and homogenizing the materials; (3) extruding the blended mixture under specified parameters; (4) pelletizing the extrudates using a pelletizer; (5) drying the pellets; and (6) either extruding the pellets into flat sheets with a twin-screw extruder and flat die or producing blown films using a blown film extruder with an annular die [Figure 9]. MCC has been widely used as a filler and binder in the extrusion/spheronization process, but new materials are being looked at to replace it. Chitosan is a great alternative because it is biodegradable, natural, and already used in pharmaceuticals and cosmetics.

4.3. Co-extrusion. Co-extrusion is a manufacturing process in which more than one layer of film is made by the extrusion of two or more different materials, or polymers, to produce one integrated film with different layers [Figure 9].[38] This is the most commonly used technique in the packaging industry, where films are made while preserving biodegradability along with the benefits of several polymers, including mechanical toughness, flexibility, and barrier qualities. Each layer of the film has a specific purpose in coextrusion. For example, one layer can provide mechanical strength, while another will supply a barrier to moisture or oxygen; a third can improve sealability or adhesion.[39] The end result is one film that serves those multiple purposes. Coextrusion is the simultaneous extrusion of several molten polymers using different extruders. These polymers are then combined into a single film via a multilayer die. In the finished film structure, each polymer maintains its own layer with specific functional benefits. A critical component of coextrusion is the multilayer die.[40] It is designed to make a single uniform film from several polymer melts. To ensure layers remain separated yet connect as one, each polymer feeds into the die by a separate pathway. The polymer layers are then extruded into one film, which is rapidly cooled by water or air to set the film.[41] It can also be stretched both transversely and machine-wise for enhanced mechanical properties like toughness and tensile strength. Co-extrusion enables films to be developed with desired properties.[42] For instance, one layer can be made using PLA as an oxygen barrier while the other layer can be made using PHA or starch, ensuring strength as well as biodegradability. In most cases, in order to prolong the shelf life of food products, the multilayer film often offers enhanced barrier properties to gases (oxygen, carbon dioxide), moisture, and even light. Many biodegradable polymers can be coextruded to form an environmentally friendly final product. For instance, a biodegradable film could contain coextruded layers of PLA, having good barrier properties, and starch-based layers, offering flexibility.[43]

4.4. Elctrospinning. Electrospinning is an electrostatic-based process for forming fibers of incredible thinness from polymers in the nanometre to micrometre scale.[44] Given their promise in such applications as biodegradable packaging, medical devices, tissue engineering, drug delivery, and filtration systems, fibers may be combined into nonwoven mats or thin films [Figure 9] where the fibers, electrospun, possess special qualities such as flexibility, porosity, and an unusually high surface area-to-volume ratio. In electrospinning, a polymer solution or melt is stretched by a high-voltage electric field to produce extremely thin fibers.[45] Most commonly, the setup involves a capillary tube or syringe full of a polymer solution connected to a high-voltage power supply. A tiny droplet of the solution emerges at the tip of the needle or nozzle. When the applied voltage exceeds the surface tension of the droplet, the polymer solution is ejected out of the tip in the form of a jet that stretches as it travels to a grounded collector. The solvent evaporates (in solution electrospinning) or the polymer solidifies (in melt electrospinning) as the fibers collect on the collector as a nonwoven mat or film.[46] Because of their small sizes, the nanofibers prepared by electrospinning have a very large surface area. For these reasons, electrospun materials are ideal for applications such as controlled drug release, filtration, and packaging that require significant surface interactions. Due to its high porosity, electrospun mats can also be used for applications requiring materials or films with gas and moisture permeability or breathable films.[47] This can be particularly useful for the production of biodegradable or active food packaging for the preservation of the product and allowing the exchange of gases. Other examples of natural polymers electrospun into thin, biodegradable films include starch, chitosan, and polylactic acid, or PLA. Films like these are highly useful in food packaging applications where environmental sustainability and biodegradability feature as critical factors. Electrospun films are porous and hence quite useful in breathable packaging applications targeted for fresh produce or goods needing to exchange gases and moisture.[48]

4.5. Thermocompression Molding. The process of thermocompression molding is a very commonly used technique when it comes to the production of biodegradable packaging films and other polymer-based materials.[49] This technique involves heating and compressing a polymer or composite material inside a mold, wherein the substance flows and occupies the shape of the mold as it cools down in solid form [Figure 9]. Biodegradable polymers, such as starch, polylactic acid (PLA), and cellulose-based composites, which can be molded into eco-friendly packaging materials, are particularly suited for this process.[50] Solid forms of biodegradable polymers or composites include granules, pellets, or powders. These materials are filled into a mold cavity. Biopolymer composites, which may consist of natural fibers or fillers such as chitosan, cellulose, or starch, or thermoplastics, the materials soften when heated and set when cooled, often characterize the materials used in thermocompression molding.[51] Because thermocompression molding is a relatively simple process that does not need expensive equipment, it is inexpensive to manufacture a wide range of biodegradable packaging products. This will then enable a significant number of biodegradable polymers and composites, such as PLA, PHA, starch blends, and cellulose-based materials, to be used. It contributes to sustainability packaging solutions and limits plastic waste as it involves renewable and biodegradable materials.[52] It also allows the use of fillers or natural fibers, which reduces the overall environmental load of the material. The process enables the precise regulation of the material thickness that is decisive in packaging films. Variations in mold and production conditions make possible the production of thicker films for trays or containers, and the production of thinner films for wrapping is possible.[53] Compression in the molding step accounts for the development of materials with high mechanical strength and durability. This makes it suitable for applications where biodegradable pack-

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Table 1. Basic Biodegradable Packaging Films

packaging material	applied food	methodology	characterization	physical properties	ref
Chitosan	Strawberry	**Drop-Casting Technique** The formulation contains chitosan at a concentration of 1% w/w along with 0.5% v/v glycerol and 30% w/w acetic acid.	SEM	Excellent bactericidal and fungicidal activity	58
Chitosan	Sweet cherry (*Prunus avium*)	**Dipping Methodology** For every gram of chitosan, use 1.5 mL of glycerol in a 1% acetic acid solution. Yeasts and molds	TMAB TPAB	Improved physicochemical properties and shelf life	59
Chitosan	Apple	Dip coating Choline chloride mixed with urea at a 1:2 ratio and choline chloride combined with acetylsalicylic acid at a 1:1 ratio.	FTIR	Low toxicity and tunability, and maintains stability	60
Gelatin	Bergamot, kaffir lime, lemon, and lime	**Solvent Casting Methodology** Methanesulfonic acid 0.2%, 3.5 M NaOH, 0.2 M citrate buffer, 0.4 mL aliquot	Electrophoretic analysis DSC ATR-FTIR	Improved mechanical properties	61
Starch	Pigeon pea	**Casting Technique** Starch (5, 6.5, 8, 9.5, 11% w/v) + Glycerol (0.5, 0.875, 1.25, 1.625, 2% v/v) + 100 mL distilled water + 1 mL acetic acid.	RSM ANOVA SEM	Enhanced physicochemical property	62
Alginate	Cherry (*Prunus avium*)	**Dipping Methodology** The solution contains 20% glycerol by volume, hot water at 45 °C, and alginate at concentrations of 1%, 3%, and 5% w/v.	Respiration rate, Fruit quality parameters	Enhanced antioxidant property	63
Starch	Mango (*Mangifera indica*)	**Film Casting Technique** 300 mL of modified starch (by extrusion technology) was heated at 80 °C for 10 min, and 25 mL of this gelled solution was then used to develop the film.	Titratable acidity, puncture strength	Maintains chemical and physical properties	64
Gelatin	Citrus fruits	**Solvent casting** The CLCF content was 10 wt %, varying between 10, 20, and 30% based on EG weight. When combined with sodium hypophosphate/citric acid (1/0.25) and gelatin, glycerol (0.4 w/w) acted as a plasticizer and a cross-linker (2.5 w/w).	SEM FTIR	Enhanced antimicrobial and antioxidant properties	65

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aging with strength equivalent to conventional polymers is required. Thermocompression molding is often applied to fabricate thin, flexible biodegradable packaging films that could be used in making biodegradable pouches and bags or in wrapping food items.[54] Thermocompression-molded films are strong and, depending on the materials, may be made to possess some degree of gas or moisture barrier qualities.[55]

4.6. Spray Coating. In this methodology, a liquid solution is applied to food substrates through a spray application [Figure 9]. The act of spraying atomizes the liquid, creating micro-droplets that possess a significantly greater surface area compared to the same volume of liquid. As a result, these droplets can effectively coat a larger area of the food item in air spray atomization. A high-velocity stream of air envelops the fluid emanating from a low-velocity tube during the spraying process. The friction between the fluid and air induces atomization by accelerating and disrupting the liquid flow. This results in the formation of a spray through the nozzle. To convert the cylindrical water jet into fine droplets, a cylindrical air jet is employed as a deflector. This method is primarily used to produce a fine droplet spray for food and food products. The utilization of air for spraying, coupled with the minimized water volume for product coating, renders this technology a cost-effective solution.[56] In the process of air spray atomization, a high-velocity air stream surrounds the fluid exiting from a low-velocity tube. The friction generated between the fluid and air facilitates atomization by enhancing and disrupting the flow of the liquid. Consequently, a spray is generated through the nozzle. To disintegrate the cylindrical water jet into fine droplets, a cylindrical air jet serves as a deflector. This method is chiefly employed for producing fine droplet sprays on food products. Furthermore, the use of air for the spraying process, along with a reduction in the water volumes required for product coating, makes this technology economically advantageous.[57]

5. BASIC BIODEGRADABLE PACKAGING MATERIALS

Biodegradable packaging films are made of materials that naturally deteriorate over time to reduce their effect on the environment. These films are made of renewable materials like cellulose, starch, and polylactic acid, which decompose into elements such as water, carbon dioxide, and biomass, through natural elements like heat, moisture, and microorganisms. The studies that have been carried out to validate the properties of biodegradable packaging films are discussed below and outlined in Table 1.

Chitosan is a natural polymer that has microbe resistance and mold resistance properties. Drop casting method using glycerol, the chitosan films are produced to improve elasticity and hydrophobic character, which can develop a hydrophobic protective layer. The strawberries were coated with chitosan or glycerol of a 30% film that shows protection against fungal attack. Chitosan film protects the strawberry against fungi and acts as an edible coating.[58]

Sweet cherries were coated with 1% chitosan derived from two sources: chitosan-1 and chitosan-2, both obtained from shrimp waste sourced from the Marmara Sea, Turkey. Additionally, commercially produced chitosan-1 and chitosan-2 were also used. The sweet cherries were stored under two different conditions, such as (4 °C) for 25 days or (20 °C) for 15 days. The obtained results show chitosan chitosan-coated cherries have reduced weight loss and maintain the freshness of the cherries. The chitosan produced from shrimp waste exhibits high antimicrobial activity and improves the shelf life of the cherries.[59]

A green solvent, a deep eutectic solvent, is incorporated in the preparation of biodegradable packaging films. The ionic solvent is replaced by a deep eutectic solvent because it has excellent chemical flexibility. Choline chloride-based deep eutectic solvents significantly enhance the mechanical, structural, and barrier properties of films. Serving as a hydrogen bond acceptor, choline chloride in these solvents outperforms traditional plasticizers when natural polymers like chitosan, starch, and cellulose are used in film formation.[60]

The film-forming solution contains 25% glycerol with effects of heat treatments at different temperatures, from 40 to 90 °C. Films produced by heating the solution up to 60−70 °C are firm and have the highest melting point. When the solution was heated at 90 °C showed the greatest elastic limit and also caused breakdown in gelatin. The films are less permeable to water vapor as the temperature increases.[61]

Potato starch was utilized to create biodegradable packaging, with glycerol serving as the plasticizer. Various starch concentrations (5, 6.5, 8, 9.5, and 11% w/v) and glycerol levels (0.5, 0.875, 1.250, 1.625, and 2% v/v) were tested, while 100 mL of distilled water and 1 mL of acetic acid remained constant. This experiment aimed to determine the optimal combination for effective film formation. The films were produced using the casting technique with the prepared film-forming solution. Results of biodegradable films were studied on central composite rotatable design (CCRD) response surface methodology with two factors. Optimized treatment of potato starch film with a response quadratic model. The treatment condition is 7.1 g starch concentration and 0.5 mL glycerol concentration.[62]

Sweet cherries were treated with alginate coatings at varying concentrations of 1%, 3%, or 5% w/v. The alginate coating aids in preserving the fruit's freshness and firmness, while also slowing down the ripening process. Additionally, the coating enhances the antioxidant content and total phenolic levels in the cherries. Without the coating, cherries remain fresh for 8 days at 2 °C plus an additional 2 days at 20 °C, whereas those coated with alginate can stay fresh for 16 days at 2 °C, followed by two more days at 20 °C.[63]

Starch is commonly used in the creation of edible films due to its affordability, wide availability, and biodegradability. However, films made from starch often face challenges like fragility, poor protective barriers, and weak mechanical strength. To overcome these limitations and alter the starch structure, extrusion processing is utilized, particularly through a casting pretreatment technique. Research indicates that starch-based edible films achieved the most favorable functional and barrier properties at an extrusion temperature of 100 °C, with a screw speed of 120 rpm, and a glycerol concentration of 16.73%. When the film was applied to fruit, it helped in preserving quality attributes by minimizing degradation.[64]

Citrus lignocellulosic fibers (CLCF) are abundant with many free radical scavengers, tissue-friendly, and have high safety standards. CLCF is removed from citrus tree trimming waste by fusing the lignocellulosic fibers and extracted gelatin as a low-cost bio-based film. Extracted gelatin is produced from white leather shaving after the hydrolysis process. Both the wastes contain safe and green requirements for the formation of films. The biofilms are produced using Fourier transform infrared (FT-IR) spectroscopy, thermal analysis (TGA and DTGA),

Table 2. Combined Biodegradable Packaging Films

packaging materials	applied food	methodology	characterization	physical properties	ref
Defatted grape seed flour + Polyvinyl alcohol	Raisins	**Casting Methodology** The concentration of grape seed flour is 10% w/v, while the concentration of Polyvinyl Alcohol is 2% w/v, and the concentration of Citric acid is also 2% w/v.	UV–vis WVP SEM	Improved microbiological property.	66
Gelatin + Casein + Starch	Guava	**Surface Coating Methodology** The factorial design included adding different quantities of starch, casein, and gelatin. Level / Starch (g) / Gelatin (g) / Casein (g) −1 / 2 / 2 / 2 0 / 3 / 3 / 3 1 / 4 / 4 / 4 The plasticizer constitutes 30% of the total mass.	WVTR FTIR-ATR WS TA	Increased shelf life is observed.	67
Starch + Chitosan + Thyme	Direct food application	**Solution Casting Method** Using a combination of 0.5 mL of Folin-Ciocalteu reagent, 1.5 mL of Na_2CO_3, 0.1 mL of the sample, and distilled water, a 10 mL solution was obtained.	FFDs	Increased matrix cross-linking to a greater extent.	68
Chitosan + Gelatin	Hibiscus	**Solution Casting Methodology** The CS was eliminated by utilizing a 2% solution of acetic acid. These solutions were swirled at room temperature for 24 h using a magnetic stirrer. It was determined that the suitable solution for creating the film was the 10% w/v GL + 2% w/v CS solution, which was fine-tuned for film production.	FTIR TSM XRD	Enhanced physical, mechanical, and barrier properties	14
Chitosan + Cellulose + Curcumin	Meat and high-fat content food	**Solution Casting Methodology** The solution contains one percent of glacial acetic acid. A uniform chitosan solution at a concentration of 1% w/v. Both glycerin and curcumin are evenly dispersed at a concentration of 0.5% in all groups. There is a presence of a 5% bacterial solution.	EDS FTIR XRD TGA MC WS SEM	Displayed the best antioxidant property.	69
Starch + Chitosan	Apples	**Dipping Methodology** I have 2 g of purple yam flour and need 100 mL of distilled water, as well as 0.5 and 1 g of chitosan. I'll also require 5% v/v acetic acid and 2% w/v glycerol.	SEM WBC IS FTIR	Improved physical property.	70
Polylactic acid + Starch	Capsicum	**Blown Film Extrusion** The composition consists of 80 to 90% polylactic acid, 10 to 20% maize starch, 1.25% benzoyl peroxide, and 1% glycidyl methacrylate.	DSC TGA FTIR SEM XRD	Developed morphological and physiological properties.	71
Strach + Glycerol	Cooled foods	**Solvent Casting Methodology** The mixture contains 1.152% of potato peel starch (PPS) and has an amylose content of 29.49%. Additionally, it consists of 20.5% potato starch and 24% corn and wheat starch.	DSC XRD SEM TGA	Improved thickness, opacity, heterogeneity of surface, and cross-sectional area. Enhanced mechanical properties.	72

scanning electron microscopy (SEM), biodegradability, antioxidant, and antimicrobial.[65]

6. COMBINED BIODEGRADABLE PACKAGING MATERIALS

This process combines different polymers with the concept of attaining better results in mechanical strength, heat stability, and effectiveness of a material barrier. This technique is able to provide dozens of customized materials with balanced properties for a variety of applications. Besides, cost and performance could be optimized. By forming a thick molecular structure that restricts the flow of gases, moisture, and other external factors, polymers serve as efficient barriers in packing films. Permeability is mostly determined by their intermolecular interactions, molecular organization, and crystallinity. Through chain entanglement and molecular weight, polymers simultaneously give the film mechanical strength, which enables it to tolerate stress, hold its shape, and provide flexibility. Because of these combined qualities, polymers are crucial for maintaining the structural integrity and protection of packaging materials. Table 2 depicts various research that has been performed by combining different polymers to develop a sustainable biodegradable packaging material.

Grape seed flour extract was added with poly(vinyl alcohol), and this film was used for packing raisins. Physio-chemical properties (pH, total acidity, total soluble solids and moisture), antioxidant characteristics, and phenolic contents were assessed for 182 days when stored at 20 °C. After this storage period, the material lessened total acidity and soluble solids, improved the pH, and moisture of raisins. The antioxidant activity and total phenolic concentration were higher. Biodegradable packaging films developed from extracts are a possible source to maintain the antioxidant properties of raisins.[66]

Gelatin, casein, and starch from cassava were utilized to construct biodegradable packaging sources with sorbitol as a plasticizer. Films that contained a low amount of gelatin, and a high amount of casein and starch had the desired solubility, opacity, water vapor transmission rate, and thickness. This film

Table 3. Role of Nanoparticles in Advanced Biodegradable Packaging Films

packaging materials	nanoparticles	applied food	methodology	characterization	physical properties	ref
Chitosan + Gelatin	Silver	Carrot pieces	**Solution Casting Methodology** In 100 mL of water, 2% gelatin is dissolved. 100 mL of 1% acetic acid contains 2 g of chitosan. A 10 mM solution of $AgNO_3$ is made by using 10 mL of the $AgNO_3$ solution.	FTIR UV−vis SEM TEM	Reduced water vapor transmission rate, improved mechanical properties.	73
Starch + Polyvinyl alcohol	Titanium dioxide	Cherry tomato	**Solvent Casting Method** A solution containing 0.2% starch combined with 0.003 g of TiO_2 in glycerol and 30 mL of a PVA solution (1.2 g of polyvinyl alcohol in 40 mL of distilled water) is to be prepared.	SEM FTIR XRD	Enhanced water barrier properties and antimicrobial activity against *Staphylococcus aureus*.	74
Chitosan + aqueous polyvinyl alcohol	Silver	Meat packaging	**Electrospinning** Silver nanoparticles, known as AgNPs, are combined with 12% polyvinyl alcohol (PVA), 6% chitosan (CH) in a water-based solution containing 6% water and 2% acetic acid.	UV−vis DLS SEM FTIR XRD	Enhanced antimicrobial property.	75
Chitosan + essential oil	Nano fibers	Strawberry, Tomato	**Coating Methodology** The aqueous gel contains 2.5% w/v of chitosan nanofiber (NF) with an 85% degree of deacetylation. Additionally, it includes a 1% w/w acidic chitosan solution, 54% carvacrol, and 50.3% thymol. The viscosity of the chitosan ranges from 200 to 800 cP, and its acetylation degree falls between 75% and 85%.	UV−vis AIR-FTIR SEM XRD DMTA	Improved barrier and antibacterial properties.	76
Starch	Chitosan Nano particle	Cherry tomato	**Solution Casting Methodology** Mix TPP powder in 50 mL of distilled water. Next, combine it with CH solution (5, 10, 15, 20% w/w of solid starch) and chitosan flakes in 50 mL of aqueous acetic acid solution (1% v/v).	UV−vis TEM Particle sizer	Enhanced protection against gram-positive bacteria.	77
Gelatin	ZnO	Cakes	**Solution Casting Methodology** ZnO (5% in 100 mL water) + 5% Chitin + Gelatin (4 g/100 mL) + 30% Glycerol + 1% Glutaraldehyde.	WVTR and O_2 permeability through ASTM	Lowered gas permeability, insufficient enhancement of barrier properties.	78
Polyvinyl alcohol + Clay nanocomposite	Silver	Chicken sausages	**Solvent Casting Methodology** Polyvinyl alcohol (1.2 g in 40 mL water) + 40 μL of 1 M silver nitrate.	SEM FTIR XRD UV−vis	Enhanced antimicrobial properties against *S. typhimurium* and *S. aureus*.	79
Chitosan + alginate	Nanocellulose	Cauliflower, cucumber, Broccoli	**Methodology** By mixing sodium alginate in ultrapure water and by immersing 1.5% w/w chitosan in a 1% lactic acid and glycerol aqueous solution.	SEM and property determining tests	Excellent mechanical and oxygen barrier properties	80

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was applied onto guava and resulted in an extended durability of 2 days. That is primarily because of the low water vapor transmission rate, decreasing mass load of fruit, and reduction in senescence of the fruit. Therefore, this film could be used as a potential source for fruit coating.[67]

Chitosan and pea starch were blended and added with thyme extract polyphenols. Thyme extract polyphenols imparted remarkable antioxidant activity because of a durable chitosan-polyphenols interaction. The phytochemicals were distributed at a rapid rate and maximum proportion in pure starch films, but had lower antioxidant properties. Chitosan's high solubility led to the release of the maximum quantity of polyphenols into acetic acid solution. Cross-linking effect is brought in by introducing tannic acid. Therefore, polyphenols have the best capacity to expand the antioxidant characteristics of the film[68]

Boric acid was cross-linked with a blended film comprising gelatin and chitosan. The properties of the developed film were analyzed using SEM, optical microscopy, XRD, and transparency studies. The films were consistent and see-through. They also showed good UV-light barrier properties, increased hardness, decreased water vapor penetrability, moisture content, and solubility of water. Adding Polyethylene glycol as a plasticizer made the films flexible. This blended polymer provides a more potent biodegradable packaging film.[14]

Chitosan and bacterial cellulose were mixed together along with curcumin. The composite films were developed using varying concentrations of chitosan. Certain properties like water moisture content, contact angle, molecular weight, mechanical properties, water solubility, antioxidant properties, and barrier properties were investigated by SEM, XRD, and TGA. Greater molecular weight chitosan reduced OTR, WVTR, and moisture content while increasing mechanical properties and contact angle. From here, these composite films present a viable avenue for packaging film development.[69]

Purple yam starch was blended with chitosan and glycerol to obtain a biodegradable packaging film. This developed film had a homogeneous surface. Infrared spectroscopy was utilized to identify the interface flanked by the polymers. Glycerol contributed to thermal stability and was analyzed using a thermogram. The amount of chitosan influenced the thickness of the film. This film was applied to apples, and it was found that the expiration was prolonged. Therefore, this blended film has boundless chances in the consumable packaging commerce to be developed as a decomposable packaging film with good properties.[70]

Polylactic acid and corn starch were added with reagents, namely, benzyl peroxide and glycidyl methacrylate. The extrusion-blown molding method was used to develop the film. Properties like tensile strength, OTR, and WVTR were measured. This film was then applied onto capsicum with LDPE of 60 μm being the control. The packaged capsicums have an extended shelf life of about 12 days (25 °C) and 24 days (8 °C), while the unpackaged capsicums have an extended shelf life of about 4 days (25 °C) and 9 days (8 °C). Therefore, PLA-corn starch films have a potential application to extend the durability of capsicum.[71]

Potato production leads to agricultural wastes that can be transformed into potato peel starch (PPS) to develop films. These potato peel starch films showed reduced vapor permeability, water solubility, swelling power, and improved thickness due to amplified interaction between the molecules. Low starch-containing films showed decent thermal stability, transparency, pliability, mechanical properties, and enhanced soil and seawater biodegradation. The amorphous characteristics were retained even at higher temperatures (>100 °C). This provides a pivotal application of PPS in packaging delicate and refrigerated foods.[72]

7. ADVANCED BIODEGRADABLE PACKAGING MATERIALS

Advanced degradable packing films are a creative way to reduce plastic waste and enhance the sustainability of food packaging. These films are made from natural polymeric materials, and the addition of plant extracts and nanoparticles improves their qualities. In addition to offering antibacterial action, nanoparticles are used to enhance mechanical strength, thermal stability, and barrier qualities. In the meantime, plant extracts that are high in bioactive substances, such as polyphenols or essential oils, improve the films even further by adding antibacterial and antioxidant qualities that prolong the shelf life of packaged foods. Biodegradable films with multipurpose qualities are produced by combining nanotechnology and natural ingredients, providing a sustainable substitute for conventional plastic packaging.

7.1. Role of Nanoparticles in Biodegradable Packaging Films. Nanoparticles improve the mechanical strength, barrier properties, and antibacterial activity of biodegradable packaging sheets. They extend the shelf life and improve the safety of food by reducing gas permeability and retarding microbial growth. Their application further supports the development of readily biodegradable packaging alternatives, hence promoting environmental sustainability. By donating electrons or hydrogen atoms to neutralize reactive oxygen species (ROS), polyphenols function as antioxidants that scavenge free radicals and stop the oxidative deterioration of dietary ingredients. Their capacity to donate protons stabilizes free radicals and halts the chain events that cause lipid peroxidation. Polyphenols change the permeability and dynamicity of microbial cell membranes to produce their antibacterial actions. In the end, they prevent microbial development by rupturing membrane integrity, interfering with the activity of proteins and enzymes, and possibly causing intracellular contents to spill out. Table 3 gives an overview of research that has been carried out to illustrate the role of nanoparticles in advanced biodegradable packaging films.

Chitosan and gelatin were added with different proportions of silver nanoparticles, and the film was developed using solution casting methodology. The characterization was done using FTIR, UV−vis spectroscopy, and SEM. Adding silver nanoparticles enhanced the physicochemical and biological function of the film. Tensile strength also increased due to Ag nanoparticles. This was applied to carrot pieces, and it was found to lower bacterial contamination than traditional polyethylene bags. Therefore, this film becomes an ideal solution to develop biocompatible antibacterial packing composites.[73]

Starch-grounded poly(vinyl alcohol) composites were added with elderberry extract and TiO_2 nanoparticles. This nanocomposite film was developed using a solvent casting methodology. Water barrier, morphological, mechanical, antimicrobial, and functional properties were evaluated. Adding TiO_2 nanoparticles improved antimicrobial, moisture barrier properties, and tensile strength. Elderberry extract made the composite a possible sensor for pH. The film was layered on tomato, and it prevented infection by microbes up to 22 days. Being easily

Table 4. Role of Plant Extract in Advanced Biodegradable Packaging Films

packaging materials	plant utilized	applied food	methodology	characterization	physical properties	ref
Chitosan	Mango (*Mangifera indica*)	Cashew Nut	**Solution Casting Methodology** 1, 3, and 5 wt % Ethanolic leaf extract of mango (3:1 v/w ratio) + 3 wt % Chitosan in 1 wt % acetic acid + 30 wt % glycerol	SEM and property determining tests	Increased tensile strength and antioxidant properties, decreased permeability, and water solubility.	81
Starch + Citric Pectin	Feijoa (*Accasellowiana*(-Berg) Burret)	Meat, Bread, Grapes	**Casting Methodology** The pulp and husk were separated from the fruit. One gram of the pulp and husk was dissolved in deionized water at a ratio of 1:10 w/v. The concentration of the aqueous extract is 25% v/v, and it includes 2% w/w glycerol, 3% w/w citric pectin, and 2% w/w pine seed starch.	Multiple property determining tests	Enhanced antibacterial activity against *Salmonella*, *Shigella*, and *Escherichia coli*.	82
Chitosan	Clove (*Eugenia caryophyllata*)	Apple, strawberries	**Solution Casting Methodology** After completely dissolving 1 g of chitosan in 100 mL of a 1% v/v acetic acid aqueous solution, the solution was stirred at a speed of 400 rpm for 4 h at a temperature of 60 °C. To serve as a hydrophobic agent, 1 mL of oleic acid was added, followed by the introduction of CEO.	SEM AFM BET	Enhanced antibacterial and antioxidant properties.	83
Chitosan + Gelatin	Ziziphoraclinopodioides (ZC) + grape seed extract (GSE)	Fish	**Solution Casting Methodology** The capillary column used is HP-5MS, containing 5% phenyl methylsiloxane, and is operated with helium gas.	GC-MS and other property determining tests	Enhanced antioxidant and antibacterial properties, decreased tensile strength.	84
Chitosan	Pomegranate	Meat	**Solution Casting Methodology** Combining 10% w/v Zein powder with 96% ethanol, 20% glycerol, and 10% chitosan nanoparticles is followed by the addition of 10% w/v pomegranate peel extract.	FTIR Particle size Zeta potential XRD XPS	Enhanced thermal stability and antimicrobial activity against *L. monocytogenes*.	85
Gelatin	Beetroot Peel	Beef meat	**Solution Casting Methodology** The mixture comprises gelatin at a concentration of 4% w/v and three varying levels of beetroot peel extract: 0.25%, 0.5%, and 1%. Additionally, it contains sodium alginate at a concentration of 3% and glycerol at a concentration of 20% w/w.	HPLC and property determining tests	Improved mechanical properties (delayed protein and lipid oxidation).	86
Starch	Pumpkin Residue Extract + Oregano Essential Oil	Meat	**Solution Casting Methodology** The oregano essential oil concentration in the solution is 4% w/v, and it ranges from 0 to 2%. Glycerol content ranges from 0.85% to 2.55%. Additionally, the solution may contain 0−6% starch obtained from pumpkin residual extract.	SEM TGA and other property determining tests	Reduced tensile strength, enhanced antimicrobial properties against *E. coli*, *S. aureus*, and *L. monocytogenes*.	87
Chitosan	Opuntiamutilage	Berries	The makeup consists of 14% glycerol, 1% chitosan, 4% PVA, and 1% mucilage. The composition of the makeup includes 14% glycerol, 1% chitosan, 4% PVA, and 1% mucilage.	Zeta potential SEM and other property determining tests	Desirable mechanical properties.	88

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ACS Food Sci. Technol. 2025, 5, 3690−3715

biodegradable, this has a boundless chance to be utilized as a dynamic and intelligent packaging source.[74]

Fibrous amalgamated nanolayers were created by blending poly(vinyl alcohol) with silver nanoparticles obtained through chitosan-mediated synthesis. Characterization was done using scanning electron microscopy, UV−vis spectrophotometry, XRD, FTIR and DLS. Chitosan provided firmness and antimicrobial characteristics counter to *Escherichia coli* and *Listeria monocytogenes* when added with Ag nanoparticles. This film prolonged the durability of meat by 1 week. This nanocomposite can then be used to preserve food from microbial degradation and hence extend its longevity.[75]

Chitosan solution was combined along with thyme essential oil, satureja essential oil, and chitosan nanofibers. Both these essential oils contain carvacrol and thymol, yet they possess different physicochemical properties. Satureja EO decreased the barrier property against water vapor, while thyme EO increased the same. Barrier property is enhanced in the presence of nanofibers. Satureja EO displayed antimicrobial properties against *E. coli.* The fruits and vegetables coated with this film were less perished and therefore stand as a potential system to enhance antibacterial characteristics of the composite.[76]

Starch-based nanocomposites containing different concentrations of chitosan nanoparticles (synthesized using ionic gelation) were used to advance packaging composite films. This film showed good antimicrobial properties against *Bacillus cereus*, *Staphylococcus aureus*, *E. coli.*, and *Salmonella typhimurium*, which was confirmed by the appearance of an inhibitory zone. When a film containing nanoparticles was applied onto cherry tomatoes, the growth of microbes was inhibited greatly than in a film without nanoparticles. Hence, they can be used as packaging films with antimicrobial properties.[77]

The progress of composites can be done in a multilayer sense, and one such way includes adding gelatin emulsion, gelatin nanocomposite, and bovine gelatin along with zinc oxide nanoparticles. The addition of nanomaterials reduced water vapor permeability. Films with gelatin nanoemulsion were found to have better barrier properties and hence were effective in preserving sponge cakes. Addition of nanoparticles imparted antifungal properties to the film. This film was also found to enhance organoleptic quality and texture acceptability, thereby standing as an excellent source of packaging material to preserve cakes.[78]

Silver nanoparticles synthesized from ginger extract were added to poly(vinyl alcohol)-montmorillonite K10 clay nanocomposite to develop a packaging film. FTRI, XRD, and SEM were carried out to characterize Ag nanoparticles generated using sunlight irradiation. This developed film had antimicrobial properties against *S. aureus* and *S. typhimurium*. This also possessed good light barrier properties, mechanical properties, and water resistance. Indoor studies proved that the amount of time needed to degrade was 110 days. This was effective in preventing chicken sausages from microbes.[79]

Chitosan and alginate were added with cellulose nanofibrils, cellulose nanocrystals, and bacterial nanocellulose to develop packaging films. There were 25 distinct formulations created, and their density, morphology, water captivation, contact angle, and water and oxygen resistance characteristics were evaluated. Cellulose nanocrystals were found to be suitable for packaging because of their ability to maintain the function and structure of gelatin and chitosan. Barrier properties were improved, WVTR and OTR were reduced, thereby standing as a good alternative for conventional packaging films to extend shelf life.[80]

7.2. Role of Plant Extracts in Advanced Biodegradable Packaging Films. Inclusion of plant extracts into packaging films as natural colorants, antioxidants, and antimicrobials can enhance product shelf life and safety. They increase the sustainability and biodegradability of packaging films in terms of a decrease in their environmental burden. These extracts can also improve the mechanical and barrier characteristics of the films, thus increasing their efficacy in food preservation. The research that has been carried out, which imparts the importance of plant extract-mediated advanced biodegradable packaging films, is discussed in Table 4.

Mango leaf extract is combined with chitosan to enhance its antioxidant properties. The antioxidant properties were evaluated through several assays, including the determination of total phenolic content, assessment of DPPH free radical scavenging activity, and measurement of ferric ion reducing potential. The films made up of MLE are thicker and show less moisture, which helps in extending the shelf life. Compared with chitosan films, MLE incorporated chitosan films show promising results and advanced durability for food packaging.[81]

Biodegradable packaging films made from chitosan, citric pectin, and functionalized compounds derived from feijoa fruit are designed to preserve various food types. These films demonstrate significant antioxidant and antimicrobial properties against *E. coli*, *Salmonella*, and *Shigella*. They help maintain the freshness of ground beef and extend its shelf life. Additionally, grapes coated with these films showed improved storage longevity. The films also kept bread fresh for up to 30 days, protecting it from yeast and mold. Thus, these films release compounds that prevent food spoilage and serve as promising biodegradable packaging solutions.[82]

Chitosan (CH) is combined with clove essential oil (CEO) to improve the structural properties, chemical stability, and microbial resistance of chitosan films. CH-CEO film shows displayed variation in color parameters, mechanical strength, and water vapor permeability. The obtained result shows that the treatment slows the decline in the quality process of preserved apples in firmness and color. The research indicates that the film demonstrates considerable potential as an antioxidant and antimicrobial substance, particularly for freshly cut fruits and vegetables.[83]

Ziziphoraclinopodioides essential oil (ZEO) was incorporated at concentrations of 0% and 1% v/w, along with ethanolic grape seed extract (GSE) at 0% and 1% v/w, into chitosan and gelatin films to enhance their antioxidant, antibacterial, physical, and mechanical properties. The primary compounds in ZEO are carvacrol (65.22%) and thymol (19.51%). Both ZEO and GSE contributed to a reduction in volume increase, tensile strength, puncture resistance, and impact distortion of the chitosan and gelatin films.[84]

The preparation of zein film combined with pomegranate peel extract (PE) coated with chitosan nanoparticles for food packaging. The method used to prepare zein, CSNPs, and PE was the ionic gelatin method, and incorporated into the zein films. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) studies show that the zein/CSNPs/PE nanocomposite film has better thermal stability as compared to the zein film. Zein, CSNPs, PE nanocomposite film antimicrobial property was tested on pork samples inoculated with *L. monocytogenes*.[85]

Gelatin sodium alginate (NaAlg) combined with beetroot extract (BPE). The combination of NaAlg and BPE (0.25, 0.5, and 1)% on the operational, perceptible, antibacterial, and

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antioxidant properties of the films was examined. The Beetroot peel extract (0.25%, 0.5% and 1%) improved the film strength, physical properties, and preservation against bacterial attack. Films encapsulated meat stored for 14 days in a refrigerator with improved meat color and reduced bacterial growth. The gelatin sodium alginate incorporated with beet peel extract has promising antioxidant properties for meat preservation.[86]

Cassava starch incorporated with pumpkin residue extract (PRE) for 0 to 6% and oregano essential oil for 0 to 2%. Pumpkin residue extract made the films frosted, but not extensively improved the antioxidant property as compared to oregano oil. The compounds for testing are F8, 4.8% pumpkin extract and 1.6% oregano oil, and F12 3% pumpkin extract and 2% oregano oil. Glycerol and oregano essential oil facilitate by reducing the stretch strength and increasing deformability. In vitro test results on films show good antioxidant and antimicrobial properties. The beef was protected up to 3 days from getting tainted due to oxidation.[87]

Films containing mucilage, chitosan, and poly(vinyl alcohol) (PVA) at varied concentrations were prepared using glass plates on casting with glycerol as a plasticizer. Zeta potential and SEM were used to check the suitability of film compounds and the consistency of films. Addition of glycerol and mucilage made the film more hydrophilic. Mixing mucilage with chitosan allows the films to allow more water vapor to pass through them. The Resistance properties of the films made from 100% chitosan were similar to composed films containing PVA up to 40%. So, the observed film is homogeneous, as no components are seen separated; all are mixed together completely.[88]

8. PROPERTIES AND PERFORMANCE OF BIODEGRADABLE PACKAGING FILMS

After conducting the aforementioned tests and studies, we eventually devised a unique method to evaluate the effectiveness of the produced biodegradable packaging materials.[89] This is necessary because preserving the products that biodegradable films encapsulate depends on their strength and flexibility.[90] Products may be contaminated or damaged as a result of packing that fails due to low tensile strength and flexibility.[91] To keep oxygen and moisture out of the preserved food and prolong its durability and value, it must have effective barrier qualities.[92] Overabsorption of moisture can cause the film to expand and deteriorate, which raises the possibility of bacterial and mold growth.[93] Customer decisions may be influenced by the package material's look.[94] Assessing the color and transparency guarantees that the package satisfies aesthetic requirements.[95] Evaluating the films' biodegradability guarantees that, in contrast to traditional plastics, they break down effectively after usage, lowering environmental pollution.[96] The standards for packing vary depending on the food product.[97] Key components in assessing biodegradable films' practicality as feasible alternatives are through understanding of their mechanical, barrier, thermal, and biodegradable characteristics.[98]

8.1. Mechanical Properties. The mechanical properties of a film characterize its behavior under various physical forces and environmental conditions.[99] The highest stress a film can bear when extended or dragged prior to breaking is called its tensile strength.[100] This characteristic is essential to figuring out how durable and tear-resistant the film is.[101] The maximum length a material could stretch prior to breaking is known as tensile elongation.[102] Better flexibility is indicated by higher elongation. The tensile modulus of a film, which serves as an index of its stiffness, is calculated as the ratio of tensile stress to tensile strain. Greater values denote materials that are more rigid.[103] Elongation at break is the strain on a material that indicates its plastic deformation capacity without breaking.[104] In order to defend the packaged goods from harm while handling, storage, and conveyance, the packaging film must have appropriate mechanical qualities.[105] Maintaining product quality requires mechanical properties, such as elasticity and durability, to shield the contents from impacts and mechanical stress.[106] In order for the film to be processed and used in various packing functionalities, like printing and sealing, it must have the right mechanical qualities.[107] Better user experiences can be achieved by films with strong mechanical qualities since they are more likely to satisfy customer expectations for usability, including opening and resealing.[108]

8.2. Barrier Properties. The barrier property of a film refers to its ability to resist the permeation of substances such as gases, water vapor, oils, greases, and microorganisms.[109] Maintaining the quality and life span of packaged goods depends on this feature.[110] Strong barrier qualities shield the contents from deterioration, contamination, taste, and fragrance loss by preventing the exchange of gases and moisture.[111] Because it blocks the flow of carbon dioxide and oxygen, the gas barrier feature is crucial for maintaining the freshness of food goods.[112] In order to avoid drying out or moisture buildup, which can result in spoiling, the moisture barrier feature regulates moisture transmission.[113] The ability to keep oils and greases from penetrating the package is essential for preserving its integrity and aesthetic appeal.[114] Because they guarantee the preservation and protection of the packaged items, barrier qualities are essential for biodegradable packaging films.[115] Properties of an effective barrier stop germs from entering, as this is crucial to protect the hygienic and secure quality of consumables.[116] By limiting the exchange of gases that can lead to rancidity and spoiling, barrier qualities aid in the preservation of the sensory qualities.[117] They prevent moisture and oxygen, which can deteriorate vitamins and other nutrients, from destroying food goods, thereby assisting in preserving their nutritional worth.[118] Biodegradable films may now compete with traditional plastics by adding effective barrier qualities, offering an environmentally responsible substitute without sacrificing the performance needed for food packaging.[119]

8.3. Thermal Properties. The behavior and stability of a film at different temperatures are referred to as its thermal characteristics.[120] These characteristics are essential for the utilization and effectiveness of packaging substances, particularly in the food packaging sector.[120] Thermal stability denotes a film's capacity to preserve its structural integrity and functional efficacy when exposed to elevated temperature conditions.[121] Applications like in-package pasteurization, which extend food goods' shelf lives, require high heat stability.[122] The temperature at which a film converts from a hard, glossy condition to a soft, rubbery condition is called the glass transition temperature.[123] At varying temperatures, it disturbs the mechanical and flexible qualities of the film.[124] The temperature at which a film melts is known as its melting temperature.[125] For processing and application, it is essential to make sure the film can endure particular heat procedures without deteriorating.[126] The decomposition temperature is the point at which a film begins to degrade chemically.[127] In order to evaluate the film's robustness and appropriateness for high-temperature applications, this is crucial.[128] Thermal stability is crucial for operations like in-package pasteurization and sterilization because it

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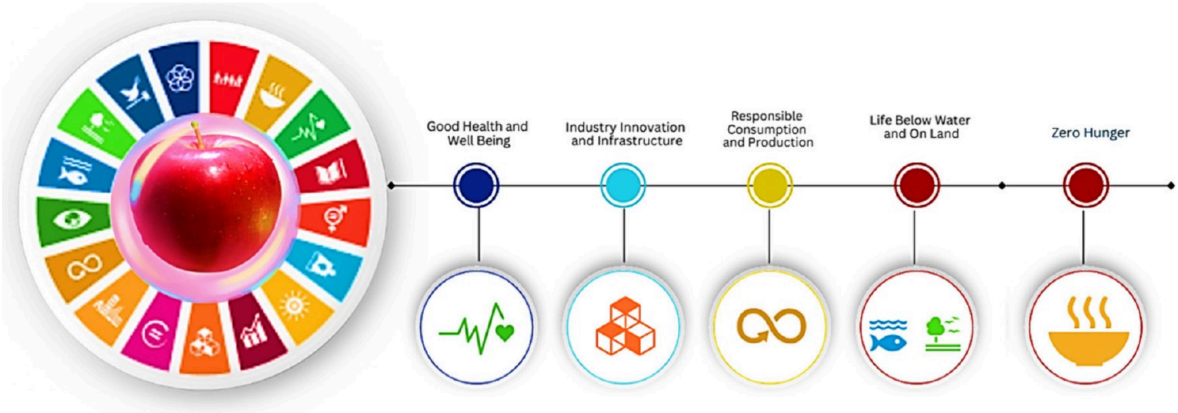

Figure 10. Sustainability of biopolymers.

guarantees that the film will not break down or lose its functionality at high temperatures.[129] This ensures protection and quality of packaged goods, prolonging the life span.[130] Processing the film correctly depends on knowing its melting temperature (T_m) and glass transition temperature (T_g).[131] This is simple to mold, extrude, or thermally process films that have the right thermal characteristics without sacrificing their structural integrity.[132] By minimizing plastic waste, films with the right thermal characteristics can break down or compost at particular temperatures, improving environmental sustainability.[133]

8.4. Biodegradability. The degradability of a film refers to its ability to undergo spontaneous decomposition through the activity of microorganisms such as bacteria, algae, and fungi.[134] The film is degraded by this method into compounds that are found in the environment, like as carbon dioxide, water, and biomass, without polluting the environment or leaving behind hazardous leftovers.[135] The purpose of biodegradable films is to lessen the harmful effects of conventional plastic trash by breaking down into nontoxic materials.[136] Usually derived from natural polymers, these films can sometimes be created from synthetic polymers designed to degrade more quickly in natural environments.[137] Various ecological parameters, such as humidity, temperature, and the presence of microbes, might affect the degrading process.[138] For instance, after a year, tests using soil burial have revealed that certain biodegradable films can reduce body weight by 80% to 90%.[139] The use of decomposable materials helps in reducing landfill waste, conserving resources, and promoting sustainability in packaging and other applications.[140] Biodegradable films break down organically, minimizing the number of microplastic debris that accumulates in oceans, landfills, and other environments.[141] As a result, pollution and the detrimental impacts of the same on wildlife and human well-being are greatly reduced.[142] When related to conventional plastics, the manufacturing and disposal of decomposable polymers typically result in lower carbon emissions, which helps alleviate climate change.[143] Biodegradable films can be composted with organic waste because they decompose more quickly.[144] This increases the effectiveness in managing wastes, thereby lessening the strain on recycling facilities.[145]

9. PRESENT LARGE-SCALE USE OF BIODEGRADABLE PACKAGING MATERIALS

Nonbiodegradable polymers are frequently utilized in food packaging because they help maintain food quality during storage and transportation.[146] The most effective packaging techniques often employ PVA, chitosan, gelatin, or protein-based films.[147] The industry only expects a $6 million expansion for biodegradable polymers by 2023, even though projections suggest that these polymers will become the norm for food packaging.[148] Over the last nine years, there has been a rapid expansion in food packaging research, resulting in the publication of more than papers on bio and active packaging technologies. The advancement has led to growth, but only a small percentage, less than 5%, of these advancements have been commercialized and are currently protected by important patents.[149] Addressing the issue of plastic pollution can be effectively tackled through the development of biodegradable alternatives to traditional plastic. Currently, the primary focus of biodegradable material research revolves around both natural and synthetic polymers.[150] Synthetic polymers find use as biodegradable materials in our everyday lives. Starch-based biodegradable polymers are among the naturally occurring biodegradable materials that have received the greatest research and use.[50] This is attributed to starch's natural abundance, affordability, nontoxicity, renewability, biocompatibility, and its capability to form films. Additionally, the polyhydroxy structure of starch allows for easy modification of its structural and functional properties through enzymatic or chemical processes.[151]

10. PRACTICAL IMPLICATIONS

Despite the observable technological advancements for real-world use, there is a notable lack of research concerning the ability to scale packaging materials crafted from natural polymers.[152] Thus, it is crucial to prove the viability of these characteristics for large-scale production and to continue improving them to boost their mechanical properties and performance.[153] Due to the higher production costs and lower mechanical and barrier properties, the use of biodegradable packaging film materials is limited compared to regular packaging film materials.[154] The use of biopolymers as substitutes for traditional plastics has faced several challenges, including inadequate performance, the absence of incentives or relevant legislation for disposable plastic food packaging, and insufficient education and awareness campaigns for consumers and manufacturers.[155] In addition, many biodegradable packaging materials do not have the necessary barrier properties to maintain the freshness and quality of food.[156] The film's limited mechanical capabilities, lack of resistance to water, and insufficient physical qualities make it unsuitable for many

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ACS Food Sci. Technol. 2025, 5, 3690−3715

culinary uses, despite numerous efforts to enhance it to match those of petroleum-based polymers.[153] Delamination between layers frequently causes the failure of the multilayer approach in producing composite films, and creating the multilayer film requires substantial time, energy, and financial investment.[157] Another important aspect of films is their ability to be heat sealed, but the optimal sealing temperature range for bio-based films is restricted.[158] Consequently, undersealing and charring from overheating are more likely to occur with these coatings, negatively impacting the production of covers and bags.[159] The practical application of edible film technology is hindered by the inability to produce films larger than 25 cm, challenges in controlling thickness, and a lengthy drying period of two to 3 days.[160] The market entry of BCPP faces several obstacles, including the necessity for interventions that alter human behavior alongside technological advancements.[161]

11. SUSTAINABILITY

Biodegradable packaging films offer some hope for a sustainable solution in the light of the mounting ecological problems associated with the conventional plastic packaging [Figure 10]. These films reduce the volume of persistent wastes that accumulate in landfills and the ocean because they are made to organically degrade in the environmental surroundings.[36] In the case of decomposable packaging films, the concept of sustainability includes not only the natural degradability of the material but also renewable resources in the production process that reduce demand for fossil fuels. Any judgment about overall sustainability must account for the energy efficiency of their production and the environmental impact from degradation byproducts.[162] Although the properties positive to the environment in biodegradable films have many advantageous features, one should consider attributes regarding cost-effectiveness, durability, and barrier qualities. Plant-based pigments within biodegradable packaging materials have huge potential for finding sustainable solutions in packaging.[163] These films will bring together the advantages of biodegradability to the environment, with the advantage of natural pigments able to improve the functional qualities while enhancing the visual appearance of the packaging. Plant-based pigments are both nontoxic and biodegradable, thus offering minimal chances of causing harmful outcomes on nature or the well-being of humans during degradation. Most of these pigments are harvested from fruits, vegetables, and flowers.[164] These pigments can also deliver the materials with antioxidant, UV protective, and antibacterial characteristics, which helps in extending of durability of packed goods and decreases the use of artificial additives. These natural pigments further minimize the environmental trail of packing polymers, in addition to following the principles of green chemistry.[165] However, the problems of constantly ensuring pigment quality, stability, and color retention for the whole lifetime of the film are not yet completely solved. Biodegradable packaging films with nanomaterials are an upcoming strategy to bring improved functionality and sustainability into more environmentally benign package designs.[166] Nanomaterials, in the form of metallic nanoparticles, nanocellulose, and nano clays, have greatly improved the durability, barrier properties, and thermostability of biodegradable films, so positioning them alongside traditional plastic packaging concerning protection and life span is advantageous.[167] Such improvement may decrease the total amount of material used as thinner films with more advantageous qualities are required, reducing resource consumption and waste generation. Some of them also provide UV resistance and antibacterial properties to nanomaterials to enhance the durability of unpreserved consumables, which can help decrease wastage of food at the level of primary consumers, which is one of the essentials of sustainable food systems.[168] The lifetime effects of nanomaterials in and of themselves, sources, possible release into the environment, and degradation at the end of their useful life will also influence how sustainable these films are.[169] Although challenging, the route for the incorporation of nanoparticles and pigments from plants into biodegradable films potentially can help in developing more environmentally friendly, multipurpose packaging options.

12. FUTURE TRENDS

Intelligent food packaging offers an intriguing avenue for developing innovative bio-based packaging technologies.[170] These innovative solutions are commonly utilized for perishable items such as meat, fish, and shellfish, providing valuable insights into the product freshness.[171] The development of freshness sensors has predominantly used biopolymers (polysaccharides or proteins) and natural colorants, employing pigments that undergo color changes in response to pH variations.[172] Extensively researched materials for creating bio-based sensors[173] include betalains, curcumin, and anthocyanins derived from vegetables, fruits, plants, and the respective byproducts.[174] These pigments not only have antibacterial and antioxidant properties, but they can also impart some activity to the biopolymer in the packaging, thereby prolonging the life span of packed goods. Consequently, these natural sensors could be a practical possibility for smart consumable packing systems.[175] Development of two-layered and multicomponent films with superior mechanical and barrier qualities that resemble synthetic packaging materials is another opportunity to utilize in the future.[176] Using enzymatic or chemical cross-linking to join the different biomolecules is another useful method for creating composite biodegradable films.[177] Foods can have their shelf lives extended and the conditions of their contents monitored throughout storage and transit with the use of intelligent and active packaging that interacts with its surroundings.[178] The next generation of biodegradable smart packaging will be made possible by sealing efficient adsorption and release systems, such as antimicrobials, liquid and moisture absorbers, and oxygen scavengers, together with indicators detecting freshness and time−temperature into degradable packaging materials.[179] The food sector can gain from improved packaging upstream (preconsumption features like extended shelf life and monitoring) as well as downstream (post-consumption features like biodegradable).[180] Smart biodegradable packaging films that track temperature, humidity, and spoiling indicators in real time can be developed through the integration of Internet of Things technology, improving food safety and preserving environmental sustainability.[181] In the design of biodegradable packaging, universal compostability, particularly home and marine compostability, should be given specific consideration.[182] Industrial compostable plastics typically meet residential and marine compostable plastics, not the other way around. One well-known Bioplastic that is compostable at home, in the sea, and in industry is PHAs.[183] In certain nations, particularly those where commercial composting facilities are currently nonexistent or only partially constructed, home composting offers a means of controlling a portion of the household's biodegradable waste stream.[184] Marine biodegradation exhibits promise in explaining the

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problem of plastic litter in the face of the rising volumes of these wastes, particularly microplastics that are building up in the marine environment.[157] The Food Safety and Standards (Packaging) Regulations, 2018, govern how packaging materials are regulated for food contact by the Food Safety and Standards Authority of India (FSSAI). The development of biodegradable plastics standards, such as IS/ISO 17088:2021 for compostable plastics, is another project being undertaken by the Bureau of Indian Standards (BIS). The U.S. Food and Drug Administration (FDA) oversees packaging materials and their requirements under Title 21 CFR. In the European Union, Regulation (EC) No. 1333/2008 governs edible coatings. For biodegradable packaging, compostability standards such as ASTM D6400 and EN 13432 are becoming the norm.

From the foregoing, it follows that biodegradable packaging sheets offer a sustainable option to conventional plastic packaging in light of serious environmental concerns regarding plastic waste.[185] These films break down naturally through microbial processes, leading to a substantial decrease in the number of pollutants ending up in landfills and the ocean.[186] By providing a compostable solution, biodegradable films help address the environmental impact of plastic waste.[187] This, in turn, alleviates the pressure on waste management systems and helps maintain cleaner environments.[188] Biodegradable films are made from various natural sources, like agar, onion pulp, and milk proteins.[187] These materials guarantee biodegradability and offer extra advantages like edibility and active packaging capabilities.[189] The advancement of technology has led to an intensification of the economic viability of biodegradable materials.[190] They now possess strength, durability, and flexibility that can be compared to traditional plastics, thereby providing a variety of appropriate packing purposes.[191] Despite their advantages, there are also drawbacks, including increased production costs and a lack of infrastructure for composting biodegradable materials.[192] The ongoing research and development aim to strike an equilibrium among environmental impact, performance, and cost to enhance the accessibility and affordability of these films.[193] The important polymeric sources utilized in consumable packing are petroleum-based plastics, and the increase in their production over the last few decades has raised concerns about environmental contamination.[136] There have been recent advancements in research and innovation for bio-based polymers, which have helped reduce our reliance on packaging films made from fossil fuels.[194] When choosing suitable raw materials for synthesizing these polymers, various factors are taken into account, such as the availability of the raw materials, their inherent properties, their capability in producing acceptable polymeric materials, alongside the ecological aids of using them.[195] It is possible to utilize byproducts, waste products, and side streams to develop more sustainable solutions, promote the idea of a circular bioeconomy, and optimize our natural resources.[196] Natural ingredients, such as proteins and polysaccharides, biodegrade rapidly in most cases; as a result, they can be used as helpful fillers, processing aids, or modifiers for biopolyesters.[197] To make them appropriate for certain packaging applications, they can help to improve their mechanical, rheological, and barrier qualities. Some technological and scientific research is necessary to determine how their presence affects the recyclability of biopolyesters.[198] By delaying their ultimate biodegradation and preventing the need to produce equivalent raw materials, biopolyester-based goods may be made more recyclable, which can lessen their environmental effect.[199]

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