

REVIEW

New Opportunities and Advances in Catechin-Added Active Packaging: A Review

Christy Sam Sabu¹, Pratap Kalita² and Swarup Roy^{1,3,*}

¹Department of Food Technology and Nutrition, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

²Pratiksha Institute of Pharmaceutical Sciences, Panikhaiti, Guwahati, Assam, India

³Department of Food and Nutrition, Kyung Hee University, Seoul, Republic of Korea

*Corresponding Author: Swarup Roy. Email: swaruproy2013@gmail.com

Received: 11 February 2026; Accepted: 21 April 2026; Published: 30 June 2026

ABSTRACT: Active packaging systems, which react either with the environment or with the food itself, are a new addition to traditional food packaging to improve food preservation. Consumer demand for natural foods with minimal processing has resulted in the integration of natural compounds, including catechins, which are polyphenolic compounds abundant in numerous sources like green tea, cocoa, berries, etc. These compounds are considered bioactive agents due to their high antioxidant, antimicrobial, and anti-inflammatory potential. This review comprehensively analyzes catechin-based active packaging, covering catechin sources, physicochemical and biological properties, and fabrication techniques. It also evaluates the functional properties of these systems and their practical applications in food packaging. The main fabrication techniques, such as solvent casting, electrospinning, and melt processing are used, and each method has specific advantages in incorporating catechins into polymer matrices. The properties of packaging film, such as free radical scavenging, prevention of foodborne pathogens, better UV-blocking activity, and improved thermal stability are discussed extensively. Numerous studies have exhibited that catechin-based active film significantly helps to extend the shelf life of various food products such as meat, seafood, fresh produce, and dairy. Challenges such as the thermal instability of catechins, bitterness after consumption, industrial production, and safety concerns related to migration and toxicity still need to be addressed. The use of encapsulation methods and providing proper regulatory guidelines can create a sustainable and effective solution in catechin-based active packaging.

KEYWORDS: Catechins; sources; active packaging film; functional properties; food preservation

1 Introduction

Traditionally, the notion of packaging implies that it is used as a shield against contaminants and mechanical damage to preserve the packed food [1]. But the development of active packaging has brought an improvement in packaging by not only acting as a barrier but also interacting actively with the food or the surrounding environment to enhance the quality and safety of food products [2]. This innovative approach has brought a significant impact on the concept of food packaging, improving properties such as shelf-life, monitoring the freshness of foods, and increasing convenience to customers [3]. Active packaging operates by adding material capable of releasing or absorbing the causes of spoilage of food products within or outside the packaging. The ability of active packaging to inhibit microbial and oxidative spoilage results in delaying the ripening of items by absorbing ethylene and regulating moisture [4,5]. Also, antimicrobial agents and carbon dioxide emitters are deployed to minimise pathogens and retard the deterioration of packaged foods, respectively, and thus maintain the quality of the product [6]. In combination with the incorporation of

active agents, this has transformed packaging into responsive packaging and given packaged food products a longer shelf life [7].

The recent innovation in active packaging is particularly evident in the incorporation of natural compounds, driven by consumer demand for safer, minimally processed foods with transparent, clean labels [8]. Secondly, there is a rising demand to limit food waste and to reduce the huge amount of food loss globally, which ultimately impacts the environment [9,10]. These trends led to the development of packaging ideas that focus on natural functional elements that provide both preservation and environmental benefits [11]. The global packaging market is now moving away from fossil-driven materials and towards the principles of the circular economy to reduce the great environmental impact of plastic waste. Although high-performance multilayer packaging is essential, it is complex and burdens current recycling systems. The innovations of smart and active packaging systems, which provide real-time monitoring and active preservation of the quality of the product, are increasingly contributing to the growth of the sector in the future. Among natural preservation agents, catechins are a standout as a key compound in the class of naturally occurring polyphenolic compounds, primarily in the flavan-3-ol group, which is abundantly found in green tea, cocoa, and berries [12]. They are known for their antioxidant, antimicrobial, and anti-inflammatory effects [13]. The integration of catechins into packaging as an active material inhibits oxidative degradation and suppresses spoilage bacteria, thereby extending shelf-life while maintaining nutritional and sensory qualities [14,15].

Initial advancements with catechins include the incorporation of green tea catechins into chitosan films, a biopolymer that improves antimicrobial and antioxidant protection, along with water vapour resistance and mechanical properties in packaging [16]. Recent innovations include blending catechins with polylactic acid (PLA), cellulose, and other plant-derived materials to yield biodegradable packaging with enhanced oxidative stability, protection against pathogens, and an improved sensory profile [17,18]. Therefore, these developments have shown that catechins are not just used as additives but are bioactive agents used in modern value-added packaging technology. The growing research activity in this area is also supported by the fact that the number of research publications has steadily increased in the past ten years. A bibliometric search of the Scopus database, which is given in Fig. 1, indicates that the number of publications devoted to catechin-added active packaging has been increasing considerably over the years 2013–2024, indicating that it has become a focus of strategic innovation in preserving food sustainably [19].

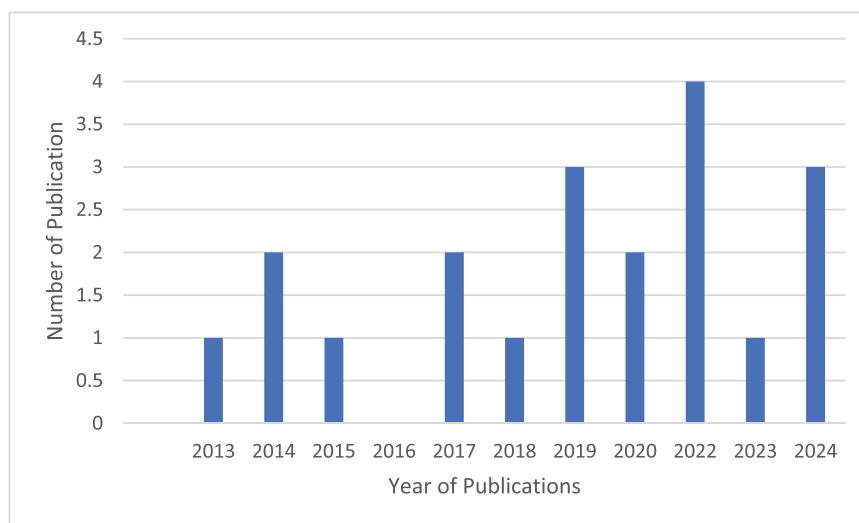


Figure 1: Chronological distribution of scopus publications for catechin-based active packaging.

Due to the increasing focus on health and sustainability, and the current market demand for natural food preservation, catechin-based packaging has great potential as a strategic innovation in active packaging. While the previous studies have often focused on singular aspects such as the biochemistry of catechin, the biopolymer, or the application on single food products, this review aims to provide a comprehensive, source-to-application analysis. It covers the extraction of catechins, their incorporation into polymer matrices through various fabrication processes, and their specific applications in extending the shelf-life of various food products.

2 Catechin and Its Biological Activity

2.1 Sources

Catechins are abundantly available in numerous plants and are widely consumed as part of everyday diets worldwide. Green tea, chocolate, legumes such as faba beans and lentils, and fruits such as grapes, berries, and peaches are major sources of catechins. Beverages such as red wine and black tea also contribute to catechin intake. A description of these major dietary sources, their catechin content, and their biological actions is displayed in [Table 1](#). Several environmental factors influence the catechin level in berries, including the level of ripeness, temperature, water availability, and soil quality.

2.1.1 Green Tea

Green tea (*Camellia sinensis*) is known for its abundant catechins, which make up approximately 15%–27% of its dry weight. The types of catechins present include epigallocatechin gallate (EGCG), which constitutes 40%–69% of total catechins and exhibits potent antioxidant, antimicrobial, and neuroprotective activities. This is followed by epigallocatechin (EGC) at 12%–23%, epicatechin gallate (ECG) at 13%–21%, and epicatechin (EC) at 5%–9% [20–22].

Table 1: The key catechins, their sources, types and their biological activities related to food packaging.

Source	Major Catechins	Key Biological Activities	References
Green Tea	EGCG, EGC, ECG, EC	Antioxidant and antimicrobial properties delay the lipid oxidation and microbial growth in packaged food products, along with radical scavenging, in order to extend shelf life.	[16,23,24]
Chocolate/Cocoa	EC, Catechin, Procyanidins	Antioxidant activity in the films leads to a decrease in oxidation and improves preservation in packaging.	[25–29]
Berries (Strawberry, Raspberry, Blueberry)	Catechin, EC, EGCG	Provides antioxidant and antimicrobial properties along with the enhancement in mechanical strength and barrier properties of edible films, which helps in food preservation and shelf-life extension.	[30–33]
Grapes	Catechin, EC, EGCG, Proanthocyanidins	Potent antioxidant, antimicrobial effects in films; natural preservatives delaying spoilage and oxidation	[34,35]

(Continued)

Table 1 (continued)

Source	Major Catechins	Key Biological Activities	References
Red Wine	Catechin, EC, Proanthocyanidins (oligomers and polymers of flavan-3-ols)	Natural antioxidant and antimicrobial agents that reduce lipid oxidation and inhibit spoilage microorganisms, enhancing shelf life and safety in food packaging.	[36–39]
Black Tea	Theaflavins, Thearubigins (formed from oxidation of catechins like EGCG, EGC, EC, C)	They provide prolonged antimicrobial and antioxidant protection.	[40–42]
White tea/Oolong Tea	EGCG, EGC, EC, theaflavins	They show strong antioxidant, antifungal and antimicrobial properties and upon adding to the films, exhibit improved tensile strength of the films.	[18,43,44]
Peaches	Catechin, Procyanidins, EC	They exhibit radical scavenging properties of metal ions, which reduce the reactive oxygen species in the packaging.	[45–48]
Lentil	Catechin, EC, Procyanidins	Antioxidant activity supports the maintenance of food quality in packaging films.	[49,50]
Faba bean	Catechin, EC	Antioxidant and antimicrobial bioactivity are used in protein-based films to extend shelf life.	[50,51]

The processing method chosen considerably has an impact on the catechin content, since the green tea is minimally manufactured by steaming the freshly collected leaves to avoid enzymatic oxidation and preserve the catechin levels [41]. In contrast, black tea undergoes fermentation, during which the enzyme polyphenol oxidase converts catechins into theaflavins and thearubigins, leading to reduced catechin levels [42]. In packaging, when green tea catechins are incorporated into chitosan films, they significantly enhance the antimicrobial and antioxidant properties, reducing foodborne pathogens and delaying spoilage in fresh foods like minced meat [24]. The addition of catechins improves the film strength and barrier qualities, making them useful for recyclable packaging.

2.1.2 Cocoa Beans

Cocoa beans are an important source of polyphenols, in particular epicatechin and proanthocyanins, which combined contribute roughly 10% of the dry weight [25–27]. However, processing steps such as fermentation, drying, roasting, and alkalisation result in a significant reduction in catechin levels. The process of fermentation itself lowers the level of catechin and epicatechin by 80% via oxidation and polymerisation. Roasting beyond 70°C also causes epimerization of epicatechin into decreased bioactive catechin isomers, while alkalisation reduces the amount by 78.5% [28]. In the packaging system, the catechins present in the cocoa act as antioxidants and antimicrobials, improving the mechanical strength, water barrier, and oxidative

stability of the films. These properties help in the application of active packaging to maintain the quality and shelf life of packaged products [29].

2.1.3 Berries

Berries, such as strawberries, blueberries, and blackberries, are major sources of catechins, proanthocyanidins, and anthocyanins, which are known for their strong antioxidant activity [30–32]. In particular, blueberries are rich in proanthocyanidins, which develop the blue colour and the biological activity [33]. The catechin content in berries is affected by several environmental factors such as ripeness, temperature, water availability, and soil conditions [34]. To take advantage of this rich chemical composition, berry extracts are increasingly being used in edible films and coatings for active food packaging. These systems focus on protecting various food products by inhibiting oxidative degradation and microbial spoilage. The packing material is mechanically active and resistant to moisture and gases, and it exhibits mechanical and barrier properties against gases and moisture that are usually strengthened in the presence of berry extracts, providing it with a direct antioxidant and antibacterial effect [35].

2.1.4 Other Plant Sources

Beyond tea, cocoa, and berries, catechins are also found in other plant-derived foods. Red wine contains a moderate concentration of catechins, epicatechins, and proanthocyanidins, which are associated with cardiovascular effects due to their antioxidant and anti-inflammatory properties [36–39]. The catechins and procyanidins present in legumes, faba beans, and lentils give those foods their antioxidant and anti-inflammatory effects [49,51]. Peaches are a valuable source of catechin, epicatechin, and procyanidin B1, which elevates the level of antioxidants [45–48]. The field of active packaging is also using various plant extracts. Polyphenols are potent antibacterial and antioxidant agents and are present in red wine and legumes. In natural films, they prevent oxidative reactions and microbiological activity [39,50]. In addition, peach polyphenols produce these properties and are employed as food coating functional ingredients to extend the shelf life and freshness of perishable food products [48].

2.2 Major Catechin Derivatives

The catechin family consists of structurally different compounds, and thus generates different biological properties. The non-galloylated compounds are (+)-catechin (C), (–)-EC, (+)-gallocatechin (GC), and (–)-EGC. Their bioavailability, antioxidant activity, and membrane interactions are affected by different stereochemistry and hydroxylation patterns [52,53]. The galloylated compounds are (–)-ECG and (–)-EGCG that contain an esterified gallic acid fragment, which enhances their lipid peroxidation inhibitory, enzyme regulation, and cellular signalling activities [54,55]. The most significant catechin in green tea is EGCG, which is believed to be the most biologically active catechin because of its trihydroxylated B ring and galloyl ester [56]. These structural attributes confer great cardioprotective, anti-inflammatory, and antioxidant properties [54,57]. It can be applied in the packaging of foods, pharmaceutical products, and nutraceuticals since it can react with proteins, transcription factors, and lipid membranes [52,58].

Structural differences may significantly influence the performance of an active packaging system based on catechin derivatives. They have positive antibacterial and antioxidant effects, which increase the shelf life of food packaging by decreasing microbial degradation and retarding lipid breakdown [59]. Also, molecular properties like galloylation determine the stability of catechins and how quickly they release themselves from the packaging, which affects their ability to remain and how readily they preserve [55]. Additionally, combinations of various catechin derivatives can result in combined benefits, which improve the overall

performance of the packaging [53,57]. Fig. 2 shows the structure of the main catechins, with the A, B, and C ring systems that are typical of flavan-3-ols.

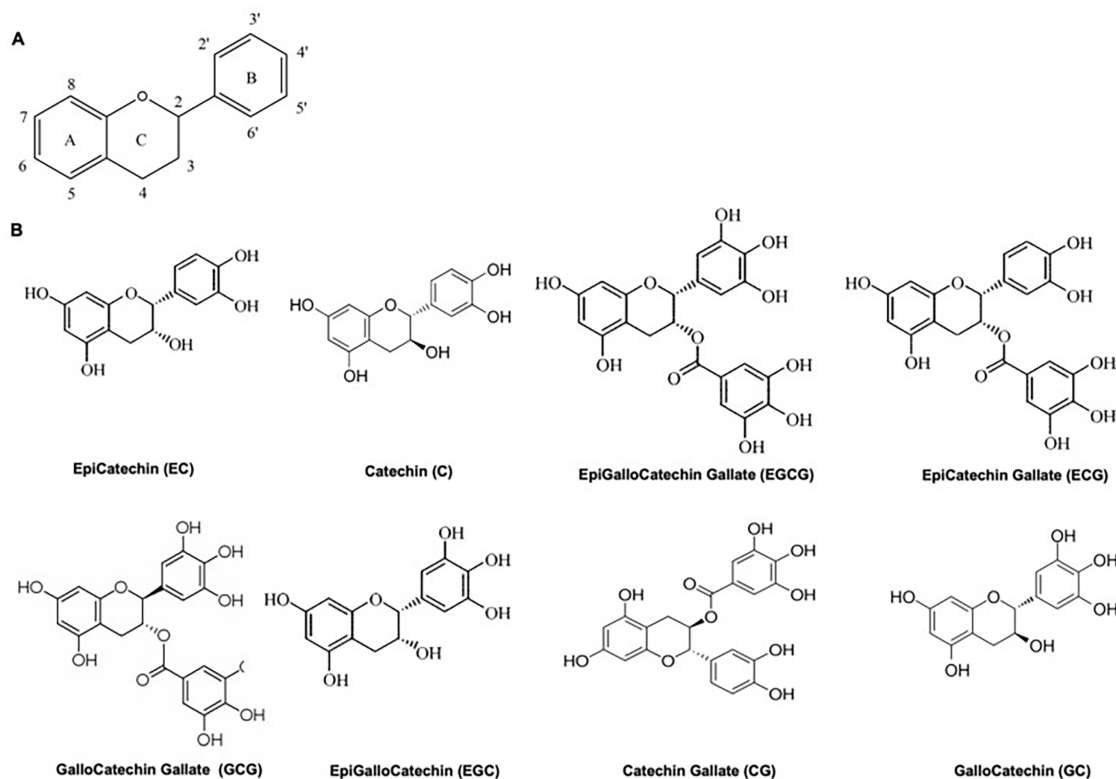


Figure 2: The chemical structures of the major catechins (A) the basic structure of flavonoids (B) the structure of eight catechins [60].

After discussing the structural variation of the individual catechin derivatives and the individual roles of galloylation and hydroxylation in their bioactivity, the following section will consider how these structural characteristics are applied to the overall physicochemical properties of catechins that determine their stability and performance in packaging matrices.

2.3 Physicochemical Properties

Most catechins are commonly soluble in water and other polar solvents, including dimethylformamide (DMF), dimethyl sulfoxide (DMSO), and ethanol. This characteristic of being dissolved in organic solvents allows for easy extraction and addition to various formulation matrices [52,61]. As an illustration, catechins are easily broken down when subjected to factors such as oxidation, heat, light, and alkaline pH conditions [62]. Catechins are sensitive to pH, with stability being better in weakly acidic conditions (pH 3–4) [63]. Studies demonstrate that the degradation of catechins increases with high pH and temperature [64]. When thermal degradation takes place, it usually follows first-order kinetics, and the half-life values decrease significantly as the temperature rises; the products formed from this breakdown are phloroglucinol carboxylic acid and protocatechuic acid [62,65]. Heat treatment also causes chemical changes, such as epimerization, which changes stereoisomers like (–)-epicatechin to (–)-catechin, and hydrolysis, both of which lower the number of polyphenols in storage [66].

Catechins are sensitive to light, which causes photodegradation, which can be prevented by using packaging materials that protect against light and limit the penetration of ultraviolet and visible light to make the product more stable [61,67]. Under normal processing and storage conditions, catechins suffer from plenty of challenges that lead to decreases in bioactivity and cause undesirable taste changes, like bitterness and color changes, that make customers less likely to purchase them [68]. These challenges have been addressed by developing encapsulation techniques, such as liposomes, nanoemulsions, and cyclodextrin inclusion complexes, to prevent catechin degradation during processing and storage. Such techniques allow for sustained release applications and make it possible to maintain antioxidant activity and reduce sensory degradation [69]. The degradation mechanisms of oxidation, epimerization, and hydrolysis are well known and require consideration of several factors, such as pH, temperature, and light exposure, to ensure the most effective protective methods are used [61]. Besides, studies reveal that catechins are more stable in acidic environments, suggesting that preservation can be enhanced by packaging formulations and matrices that ensure the stability of catechin for a long time in a slightly acidic pH [63]. The reduced oxygen levels of controlled atmosphere packaging and temperature control also contribute to the integrity of catechin [56]. Together with these protective approaches, the biological activities of catechins can be made into practical, effective active packaging solutions that retain functionality throughout processing, storage, and consumer use.

2.4 Biological Properties

The incorporation of catechin into packaging materials imparts different biological properties that significantly improve food preservation. As detailed in Fig. 3, these key functions include antioxidant, antimicrobial, UV-blocking, enzyme inhibition, and anti-biofilm formation, which protect food products from various forms of spoilage and extend their shelf life.

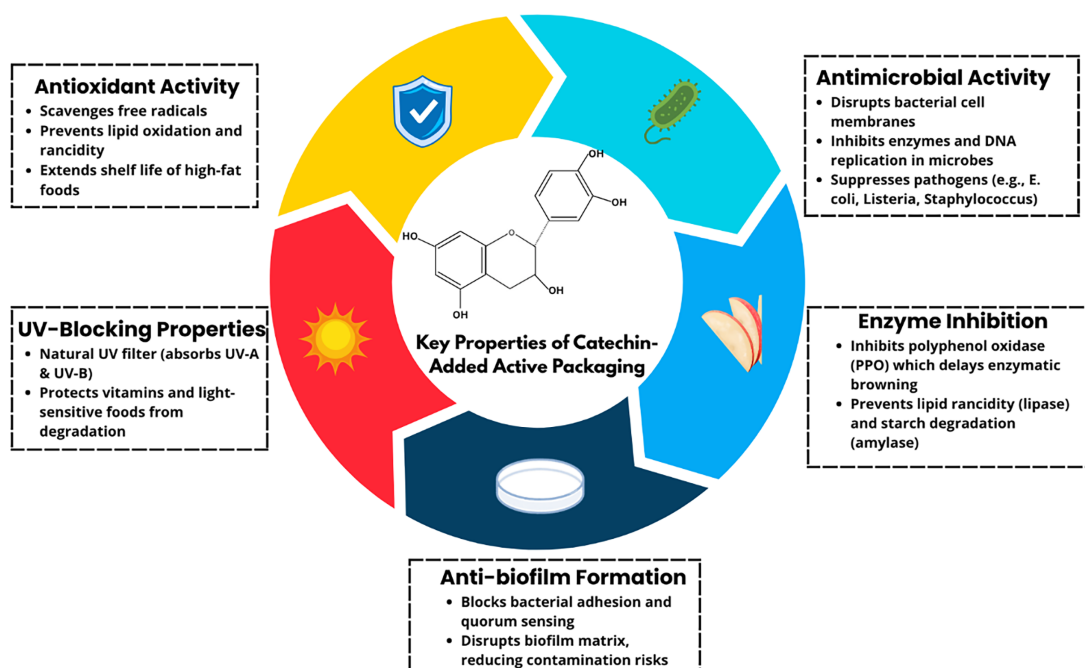


Figure 3: The key functional properties of catechin-added active packaging.

2.4.1 Antioxidant Activity

The antioxidant effect of catechins is associated with the high antioxidant potential of the B-ring phenol rings, particularly the presence of hydroxyl (–OH) groups. These compounds not only readily donate hydrogen atoms but also chelate and bind metal ions such as iron (Fe^{2+}) and copper (Cu^{2+}), preventing catalytic activity [70]. Structural changes affect antioxidant activity, with epigallocatechin gallate (EGCG) commonly being the most effective catechin derivative [56]. These two antioxidant processes play a vital role in active packaging by inhibiting lipid oxidation in high-fat food. Thiobarbituric acid reactive substances (TBARS), the major rancidity indicators, are prevented by incorporating catechins into films and aid the preservation of flavor, color, and nutritional value [71]. Indicatively, gelatin films fortified with catechins have significantly lowered the levels of TBARS in pork patties, and equally fortified films exhibit antioxidant properties in edible oils and dairy products, resulting in superior shelf life and product quality [72].

2.4.2 Antimicrobial Activity

Catechins exhibit a wide range of antimicrobial effects through a variety of pathways. Among the main mechanisms of action of EGCG, there is cell membrane disruption which is linked to the lipid bilayer of bacterial membranes, increasing permeability and releasing vital intracellular components, leading to cell death [73,74]. Besides, catechins suppress vital microorganism enzymes, including fatty acid synthase and DNA gyrase, which are involved in replication [75]. Catechins have been demonstrated to have antimicrobial activity against both Gram-positive and Gram-negative bacteria and pathogenic fungi, the effectiveness of catechins depending on their type and concentration [76]. In packaging, films with catechins produce an active antimicrobial surface that prevents spoilage organisms like *Listeria monocytogenes* and *Escherichia coli*. Chitosan-catechin composite coatings have shown that they can prevent fungi from growing on fruit surfaces, like strawberries, which makes food safer and reduces the need for synthetic preservatives [24,77].

2.4.3 Enzyme Inhibition

Catechins are also enzyme inhibitors of various enzymes that break down food matrices, which produce the possible risk of unsuitability for consumption. Polyphenol oxidase (PPO) is a major enzyme in the oxidation of fruits and vegetables, resulting in fast browning. Catechins are non-competitive inhibitors and they come into contact with copper ions located at the active site of PPO, thus inactivating the enzyme [78]. This type of inhibition can be beneficial to use in the preservation of fresh-cut produce, and recently electrospun nanofibers containing catechin have shown a significant browning inhibition on sliced apples [79]. Also, catechins inhibit lipases and amylases involved in lipid rancidity and starch hydrolysis, respectively [80]. Catechin-based packaging solutions have the potential to reduce the enzymatic activities of numerous food items, such as seafood and baked goods, to maintain their texture, visual and functional characteristics, nutritional specifications, and the total quality of the product [81].

2.4.4 Anti-Biofilm Formation

The formation of biofilms by bacteria is considered a serious food safety issue because of their resistance capability to sanitization. Catechins block the growth of biofilm by interfering with various phases of its growth. They disrupt early adherence of bacteria to surfaces and inhibit quorum sensing (QS), which is a cell-to-cell communication involved in biofilm formation. EGCG inhibits QS by reducing the formation of signalling molecules, which inhibits the full growth of biofilm [82]. Also, catechins dismantle the extracellular polymeric substance (EPS) within the biofilms, which makes them susceptible to disinfectants [83].

The successful reduction of pathogen colonization by adding catechins to packing films to promote the improvement of food hygiene and reduce cross-contamination risks (*Staphylococcus aureus* and *Salmonella* spp.) has been observed [84].

2.4.5 UV-Blocking Properties

Catechins absorb UV-A (315–400 nm) and UV-B (280–315 nm) electromagnetic radiation with their conjugated double bonds and aromatic rings, respectively. When catechin is added to packaging films, it acts as a biological UV filter that inhibits the photooxidation of light-sensitive products [85]. Such protection is required to preserve lipids and all the necessary vitamins (e.g., riboflavin, vitamin A) in milk, cheese, and edible oils [86]. Films made with catechin do not require any artificial UV-blockers to maintain product color, flavor, and nutrient content; catechin also enhances the properties of biopolymer-based packaging, along with its environmental impact and effectiveness [87].

Following the knowledge of the biological activity of catechins, which include antioxidant, antimicrobial, enzyme-inhibitory, anti-biofilm, and UV-blocking activities, the following section discusses effective ways of incorporating the active ingredients into packaging material through certain fabrication processes, characterisation methods, and functional properties.

3 Catechin-Added Active Packaging and Its Properties

Active agents, including catechins, are effectively emulated in different methods to fabricate an active packaging system that has a better functional property. The choice of production technique is determined by the specific features of the catechin extract, release profile, as well as the composition of the polymer matrix. Common thermoplastic materials such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are still used as the primary barriers against contaminants and mechanical damage. Nevertheless, in order to surpass the low physical and mechanical characteristics of biocomposite films, the incorporation of nanoclays as a reinforcing filler has emerged as an effective approach in increasing mechanical strength, thermal stability, and gas barrier properties. These nanofillers enable a more organized film structure and maintain the biodegradability necessary to meet the modern environmental requirements [88]. Table 2 discusses the fabrication methods along with the advantages and disadvantages of each method. Table 3 denotes how these methods are used in incorporating catechins in various polymers and how the functional properties are increased in various packaging films or coatings.

3.1 Fabrication Processes

3.1.1 Solvent Casting

One popular method of preparing films containing catechin is solvent casting due to the minimal effort needed to fabricate and the ability to interact with hydrophilic biopolymers. Under this technique, the polymer and catechin are combined with the appropriate solvents, such as water, ethanol, or acetic acid, followed by pouring onto flat surfaces. Subsequently, the control of drying is performed, ensuring catechins are incorporated into the polymer matrix, and drying can be more readily controlled in terms of film thickness, uniformity, and distribution [89]. The principal benefit of solvent casting is that it is very easy, and no special or expensive materials are needed. Solvent casting has become the standard technique of early optimization studies because it is easy to use. This enables researchers to thoroughly investigate the interaction of catechin with polymers, determine the optimal dose size of the formulations, evaluate the characteristics of the films, and proceed with more complex production stages [90].

Regarding particular procedure steps, the polymer is initially dissolved in a chosen solvent system (usually water, ethanol, or 1% v/v acetic acid), and catechin is then dispersed in the polymer at a concentration of 0.5% to 5% w/w with constant magnetic stirring. The solution is then degassed, poured onto a flat Teflon or glass plate, and dried under controlled conditions (25°C–40°C, 50%–60% relative humidity) to give uniform films of specified thickness [90,91].

Another necessary benefit is the sensitivity of solvent-casting processing. The process operates at normal or slightly higher temperatures without induction of mechanical strain, hence minimizing the likelihood of catechin breakdown. The heat and pH sensitivity of catechins necessitate the maintenance of bioactivity, and these compounds may become deprived of their antioxidant and antibacterial properties due to high processing conditions. This method allows the proper control of the film thickness and uniform catechin distribution, resulting in a homogenous product quality [90]. Catechin retention rates of 70%–90% have been observed under optimized solvent casting conditions, with increased retention at low drying temperatures and reduced drying times [89,91]. Moreover, polymer compatibilities have been offered under solvent casting to a wide range. This has been found to work with hydrophilic polymers, which includes chitosan, gelatin, polyvinyl alcohol, and other biopolymer mixtures. The formulation is easily adapted with adjustment of polymer ratios, additives, or adjustment of solvent systems to achieve individual optimums. This allows the accurate filtering of products, eliminating impurities and providing high optical clarity of the final films [16].

Nevertheless, there are major drawbacks that limit its use in industries. Continuous production is not feasible because drying times of 12–24 h and solvent residual can affect the film safety and biocompatibility [89,90]. Scale-up is also limited by the batch nature of the process, and solvent recovery and disposal are also of environmental and economic concern [91]. Solvent casting is thus most appropriate in the fabrication of edible films, transparent packaging of fresh produce and dairy products, and laboratory scale investigations to optimize catechin-polymer interactions before scaling up.

3.1.2 Electrospinning

Electrospinning is a procedure in which high-voltage electric fields are used to apply a solution, and the solvent evaporates, forming ultrafine fibers to achieve a polymer-catechin film [92]. The most important process parameters are applied voltage (10–30 kV), feed rate (0.1–2.0 mL/h), tip-collector distance (10–20 cm), polymer concentration, and humidity, which should be optimized systematically in every polymer-catechin system [93–95]. The most effective method of increasing bioavailability and stability of catechins is stabilization of catechins in the form of nanofibers [96,97]. Nanofibers produced through electrospinning have a number of distinct advantages for catechin use and delivery. The extensive specific surface area contributes to the increased contact of catechins with the surrounding environment and their possible application with improved antimicrobial and antioxidant functionality [98]. Nanofibers are created by the three-dimensional (3D) fibrous structure, which creates a wide variety of micro- and nano-sized pores that can regulate the release dynamics of catechin for a long period. This characteristic of controlled release is particularly useful in active packaging applications where long-term antimicrobial and antioxidant effects are required [97].

Recent studies have demonstrated successful electrospinning of various polymer-catechin systems [94]. In practice, encapsulation efficiencies exceeding 90% have been reported for catechin-loaded zein nanofibers with fiber diameters in the 200–500 nm range, confirming the effectiveness of electrospinning in preserving catechin bioactivity during processing. It was found that processing parameters, including applied voltage, feed rate, and polymer concentration, may have a profound effect on the fiber morphology and catechin retention. Likewise, (catechin) nanofibers made with gelatin have also demonstrated potential antibacterial activity against *Staphylococcus aureus*, confirming that bioactivity is maintained in gelatin-based nanofibers.

Dual-nozzle electrospinning instruments restore the opportunity to process various polymer solutions simultaneously, which makes it possible to distribute catechin more diversely and in a more controlled manner. Through this method, it is easy to generate films of gradient properties whereby special layers can be used to offer certain functionalities like barrier properties, mechanical strength, or a desired release profile [92].

Nevertheless, electrospinning is associated with serious issues restricting its use at an industrial level. This process uses advanced devices such as high-power voltage supplies, accurate pump systems, and regulated atmospheric pressure. The rate of production is usually low when compared to conventional film production techniques, and therefore, the process proves to be economically challenging for large-scale applications. The difficulty of the optimization of the parameters, such as voltage, distance, flow rate, and environmental conditions, requires a high level of knowledge and careful control of the processes [16,95]. Despite these limitations, electrospinning is specifically an ideal process for high-value specialty active packaging uses, including antimicrobial nanofiber mats on fresh produce and active food-contact surfaces, where the controlled-release and high-surface-area properties of the process are justifiable for the extra processing cost.

3.1.3 Melt Processing

Melt processing methods, such as extrusion and compression molding, are industrially employed to create catechin-loaded films. These solvent-free techniques involve heating polymers above their melting temperature, mechanically mixing in catechin, and then forming the film using different shaping techniques. This approach is suitable for thermoplastic polymers like polylactic acid (PLA), polyhydroxybutyrate-co-valerate (PHBV), and thermoplastic blends of starch [99]. The main benefit of melt processing is its economic feasibility and industrial scalability. Extrusion lines can operate continuously, producing extensive amounts of uniform films with identical characteristics. This technique eliminates the need for solvents, avoiding environmental issues related to solvent recovery and disposal, making the process more sustainable and cost-effective. Contemporary extrusion machines allow for controlled temperature profiles, residence time, and shear rate, optimizing catechin incorporation and reducing degradation [100]. Twin-screw extrusion systems are particularly favoured over single-screw systems for preparing catechin-loaded films, as their high shear mixing and reduced residence time more effectively promote catechin dispersion throughout the polymer network and minimize thermal exposure [99,100].

Incorporating catechins in melt processing systems requires careful research into thermal management. Although catechins are thermo-reactive, studies have shown that bioactivity can be largely retained under optimal processing conditions. Temperature profiles should be well-regulated to minimize residence time at high temperatures while ensuring sufficient mixing and dispersion. Additives such as stabilizers, antioxidants, or encapsulation systems may be added to further preserve catechins during processing [16]. Co-extrusion and multilayer technologies also enable manufacturers to fabricate complex film structures using melt processing. These methods can produce films in which catechins are placed in a specific layer, optimizing catechin functionality while maintaining the overall integrity of the film. Barrier coatings can protect catechins against environmental degradation, and surface coatings can provide controlled release properties [100,101]. In melt-extruded films, catechin retention rates of 50%–75% have been reported under optimized processing conditions and can be further increased to around 85% when encapsulated catechin systems (e.g., β -cyclodextrin inclusion complexes or maltodextrin-coated catechin powders) are used as the starting material [5,102,103].

These methods can present challenges related to catechin thermal stability and compatibility with hydrophobic polymer matrices. Processing temperatures typically range from 150°C–200°C, and if not properly controlled, these temperatures can lead to significant catechin degradation. Catechins are hydrophilic and may be incompatible with hydrophobic polymers, resulting in poor dispersion and reduced film characteristics. Nevertheless, these issues can be addressed using compatibilizers, surface modification, or encapsulation techniques [101]. Melt processing is the most industrially practical approach for large-scale production of active packaging films containing catechin, especially in biodegradable multilayer barrier films and rigid packaging formats for meat and seafood packaging, due to its demonstrated processing capabilities and solvent-free nature [99–101].

3.1.4 Other Techniques

In addition to basic fabrication methods such as solvent casting, electrospinning, and extrusion, other methods are necessary in order to optimize catechin-packed films. One of the most important preparatory steps is mixing, where the catechins should be uniformly distributed throughout the polymer matrix; uniform distribution is necessary for improving the mechanical strength of the film and its uniform bioactive performance [104]. Once formed, vacuum drying is another important post-processing technique that eliminates residual moisture at low temperature to improve film stability and barrier properties without oxidative destruction of the delicate bioactivity of catechin [105]. Also, the pre-formed films need to be coated and adsorbed, meaning that the catechins are applied directly to the surface, which allows the targeted antimicrobial and antioxidant activity to be attained without changing the bulk polymer properties [106]. Some of the other methods with increasing popularity include layer-by-layer (LbL) assembly, where oppositely charged polyelectrolytes like chitosan and alginate are deposited in alternating layers over a substrate surface over 5–50 cycles, with catechin substituted into one or more layers [107,108]. This method at room temperature allows the thickness of the coatings to be controlled at the nanometer level and provides tunable kinetics of catechin release that can be varied by the number of bilayers, deposition pH, or ionic strength, with coating efficiencies of 80%–95% reported in the literature [109]. Edible coatings LbL is especially well-suited to fresh produce edible coatings and the addition of catechin-activity functional coatings to existing packaging substrates, without affecting their bulk mechanical or barrier properties [107,109,110]. Encapsulation-based pre-treatment methods including nanoemulsions, liposomes, and β -cyclodextrin inclusion complexes represent another critical auxiliary technique used in combination with the primary fabrication methods described above [69,105,111]. Encapsulation enhances catechin thermal stability (to 180°C in maltodextrin systems), encapsulation efficiencies of 85%–98%, effectively masks characteristic bitter catechin taste, and allows controlled, sustained release when the encapsulated particles are embedded in the polymer matrix via solvent casting or melt extrusion [69,112].

These complementary techniques, in combination, mixing, drying, and coating, are essential when it comes to improving the stability and functionality of catechin as well as the overall quality of active packaging films.

As the key fabrication strategies of the catechin-incorporated films are identified, it is also vital to test their structural integrity and distribution of active compounds; the section below examines the characterization methods employed to study these packaging systems.

Table 2: Comprehensive comparison of fabrication methods for catechin-based active packaging films.

Methods	Key Steps	Advantages	Limitations	Best-Suited Polymers	Applicable Scenarios	References
Solvent Casting	<ul style="list-style-type: none"> • Dissolve polymer in solvent (water/ethanol/acetic acid) • Disperse catechin (0.5%–5% w/w) under stirring • Cast onto flat surface; dry at 25°C–40°C for 12–24 h 	<ul style="list-style-type: none"> • Mild temp → minimal catechin degradation • Precise control of thickness & uniformity • Wide biopolymer compatibility (chitosan, gelatin, PVA, starch) • No specialized equipment 	<ul style="list-style-type: none"> • Slow drying (12–24 h); batch only • Residual solvent retention risk • Poor industrial scalability 	<ul style="list-style-type: none"> • Chitosan, gelatin, PVA, starch, whey protein, HPMC 	<ul style="list-style-type: none"> • Lab-scale optimization; edible films • Fresh produce & dairy packaging • Transparent packaging films 	[16,92,113,114]
Electrospinning	<ul style="list-style-type: none"> • Prepare polymer–catechin solution; load into syringe • Apply high voltage (10–30 kV); set feed rate (0.1–2.0 mL/h) • Collect nanofiber mat on grounded collector 	<ul style="list-style-type: none"> • Ultra-high surface area (>100 m²/g) • Encapsulation efficiency >90% • Sustained, controlled catechin release • Maintains catechin bioactivity post-spinning 	<ul style="list-style-type: none"> • Low throughput vs. conventional methods • Complex parameter optimization • Economically challenging at industrial scale 	<ul style="list-style-type: none"> • Zein, gelatin, PLA, PVA, cellulose acetate 	<ul style="list-style-type: none"> • Antimicrobial nanofiber mats for fresh produce • Active food-contact surfaces • High-value specialty packaging 	[92–94,115]
Melt Processing (Extrusion/Compression Moulding)	<ul style="list-style-type: none"> • Dry-blend polymer pellets with catechin/encapsulated catechin • Feed into twin-screw extruder; heat to 150°C–200°C • Shape via film die or blown film head; cool and collect 	<ul style="list-style-type: none"> • Solvent-free; sustainable high-throughput industrial production • 50%–75% catechin retention under optimized conditions • Compatible with multilayer co-extrusion 	<ul style="list-style-type: none"> • High temp (150°C–200°C) risks catechin degradation • Catechin–hydrophobic polymer incompatibility • Requires compatibilizers or encapsulation pre-treatment 	<ul style="list-style-type: none"> • PLA, PHBV, thermoplastic starch, PBS, PCL 	<ul style="list-style-type: none"> • Industrial-scale biodegradable films • Multilayer barrier films for meat & seafood • Rigid trays and containers 	[16,99–101,116]

(Continued)

Table 2 (continued)

Methods	Key Steps	Advantages	Limitations	Best-Suited Polymers	Applicable Scenarios	References
Layer-by-Layer (LbL) Assembly	<ul style="list-style-type: none"> • Alternately dip substrate in polycation/ catechin then polyanion/ catechin solution • Rinse between each deposition; repeat 5–50 bilayer cycles • Dry and characterize coating 	<ul style="list-style-type: none"> • Nanometer-precision thickness control per cycle • Tunable release via number of bilayers • Room-temperature deposition; no thermal stress • Coating efficiency ~80%–95% 	<ul style="list-style-type: none"> • Very time-consuming; batch process • Limited to coatings (not standalone films) • Requires charged polymer pairs 	<ul style="list-style-type: none"> • Chitosan/alginate, gelatin/pectin, cellulose nanocrystals 	<ul style="list-style-type: none"> • Edible coatings on fresh produce • Functional coating on existing packaging substrates • Controlled-release antimicrobial surfaces 	[105,107–109]
Encapsulation (Nanoemulsion/Liposome/Cyclodextrin)	<ul style="list-style-type: none"> • Prepare catechin solution; emulsify with carrier (lecithin, β-CD) • Homogenize/sonicate to form nanoparticles (85%–98% efficiency) <ul style="list-style-type: none"> • Incorporate nanoparticles into polymer matrix for casting/extrusion 	<ul style="list-style-type: none"> • Protects catechin from heat/light/oxidation • Thermal protection up to 180°C (maltodextrin systems) • Masks bitterness; improves sensory acceptability • Enables sustained release in chitosan–PVA matrices 	<ul style="list-style-type: none"> • Added processing complexity and cost <ul style="list-style-type: none"> • Regulatory considerations for nanoparticle systems • Risk of particle aggregation in matrix 	<ul style="list-style-type: none"> • β-cyclodextrin, liposomes, chitosan NPs, zein NPs 	<ul style="list-style-type: none"> • Thermally processed (melt extruded) films • Dairy & high-fat food packaging <ul style="list-style-type: none"> • Long shelf-life applications requiring bitterness masking 	[69,103,111,112,117]

3.2 Characterization Techniques

3.2.1 Structural Analysis

The Fourier transform infrared spectroscopy (FTIR) is applied to interpret the molecular dynamics between catechins and polymer matrices. The method determines the functional groups, hydrogen bonding patterns, and chemical alterations that exist due to the addition of catechins [118]. The spectra are within the 4000–400 cm^{-1} range, the resolution is 4–8 cm^{-1} , and the catechin characterization included the extended band of 3200–3600 cm^{-1} , which is assumed to be the O–H stretching vibrations of the phenolic hydroxyl group. The band at 1600–1650 cm^{-1} corresponds to aromatic C=C stretching vibrations, and the bands at 1000–1300 cm^{-1} are associated with the C–O stretching vibrations. The alterations in the positions of the peaks and intensities, and the emergence of new bands, suggest that the interactions between catechins and the polymer chains on an intermolecular level are yielding information on the process of film formation and stability [107].

The other method of analysis is X-ray diffraction (XRD), which allows for the visualization of the crystal structure and degree of crystallinity of catechin-loaded films. The technique identifies the crystal peaks of catechins, polymers, and other crystalline complexes that were developed during the film-forming process [119]. Changes in the diffraction patterns observed imply the presence of molecular interactions, phase transitions, and structural changes. The XRD patterns in catechin-based films indicate the presence of peaks approximately at 2θ of 20–22 degrees, which is dependent on the polymer matrix and the concentration of catechins. This change or formation of new diffraction peaks, or a change in the existing ones, is a sign that inclusion complexes or crystalline structures are forming. The level of crystallinity can be determined and correlated with mechanical and barrier properties, which can be computed based on the intensities of the various peaks [120].

3.2.2 Morphological Analysis

The instrumental analysis used in the study of the surface morphology and the microstructure of the catechin-loaded films is scanning electron microscopy (SEM). SEM provides high-resolution pictures that may reveal the distribution of catechins throughout the polymer framework, its surface texture, and whether agglomerations or phase separations exist [102]. The samples are typically mounted on carbon sample holders that have been thinly coated with gold and analyzed under accelerating volts of 10–15 kV using magnifications of 1000 \times to 10,000 \times in the instance of the catechin-loaded films [16]. SEM analysis has been able to assess the homogeneity of catechin distribution. The experiments also proved that poorly dispersed catechins will result in aggregates and rough film surfaces, and well-dispersed catechins will result in smooth and uniform film surfaces [118]. The technique has also been adopted to determine the effect of processing parameters on the morphology of the films and also to determine the compatibility of catechins and polymer matrices.

Table 3: The fabrication and functional properties of catechin-added packaging.

Polymer Matrix	Fillers	Method	Properties	Food Application	References
Chitosan	EGCG, EGC, ECG, EC	Solvent casting	Improved DPPH scavenging activity by 20-folds, reduced water vapour permeability by 1.38-folds, increased flexibility by 1.5-folds and tensile strength by 4–8 MPa	Increased the shelf life of the corn oil by 10 days	[16,23,24,121,122]
Poly(ester-urethane)	PU-Cat 1 (1%wt) PU-Cat 2 (2%wt) PU-Cat 5 (5%wt)	Solvent casting	Increased antioxidant activity by 3-fold, increased mechanical strength	–	[102,123]
Chitosan	ECG	Solvent casting	Increased antioxidant activity by 72.57%	–	[107,124]
Soy Protein Isolate	Catechin	Solvent casting	Decreased WVP by 2.4 times and OP by 3.5 times	Increased the shelf life of bean bun by 15 days	[72,125,126]
Zein	Catechin	Solvent casting	Improved the antioxidant activity by 80%	–	[111]
Ethylene Vinyl Alcohol Copolymer	Catechin (Green Tea Extract)	Extrusion	Improved the barrier properties by 2 times and the antioxidant activity by 10 times.	Used in antioxidant active packaging for aqueous to fatty foods	[71,127,128]
Chitosan	Catechin	Vacuum Drying	Increased antifungal activity by 85% and the reduction in rot of <i>Penicillium citrinum</i> and <i>Aspergillus niger</i> by 5 times.	Increased the shelf life of satsuma oranges by 40 days	[105]
Starch	Catechin	Electrospinning	Increased the antioxidant activity by 90%, the antibacterial activity increased by about 52% and the tensile strength increased by 3-fold.	Increased the shelf life of the strawberries by 6 days	[92,93,96,98,115]

(Continued)

Table 3 (continued)

Polymer Matrix	Fillers	Method	Properties	Food Application	References
Fish skin gelatin and guava leaf	Catechin	Solvent Casting	The antioxidant activity was improved by 6.53 times higher than the control and the film shows antimicrobial effect against <i>B. cereus</i> , <i>S. aureus</i> , <i>E. coli</i> , and <i>S. typhimurium</i> .		[72,126,129]

The data provided by atomic force microscopy (AFM) has nanoscale resolution with regard to the surface topography, roughness parameters, and mechanical properties. The technique is effective in characterizing catechin-loaded nanofibers and thin films where surface attributes are significant in functionality. AFM can be used to visualize the surface topography in three dimensions, and it is also possible to measure the values of the root mean square roughness, along with the ratios of the surface areas [130]. In the case of nanostructured catechin delivery systems, transmission electron microscopy (TEM) is employed to provide information on the internal morphology, size distribution, and structural arrangement. The procedure is required in the characterization of catechin-loaded niosomes, liposomes, and other nanoencapsulated systems that are incorporated in the packaging films [118].

3.2.3 Spectroscopic Analysis

The spectroscopic analysis employed is nuclear magnetic resonance (NMR) spectroscopy, which provides a detailed molecular level analysis of catechin-polymer interaction, molecular mobility, and structural change. Both ^1H and ^{13}C NMR are used in studies of the mechanisms and structural changes [131]. The content of catechin, photodegradation, and the development of the release kinetics are also monitored by UV-Visible spectroscopy. The approach is also particularly useful when the light-protective features and photostability of catechin-loaded films are to be investigated. Such tests as DPPH and ABTS are also determined by UV-Vis spectrophotometry, and catechins concentration and antioxidant activity [132]. The microstructure of vacuum-dried chitosan-catechin films has been linked with the antifungal activity in the paper [105].

3.2.4 Electrochemical Analysis

The most sensitive electrochemical methods in quantification of catechin and redox mapping are electrochemical techniques like cyclic voltammetry (CV) and differential pulse voltammetry (DPV). To determine the detection limit of catechin-loaded biosensors using CNT-GNP electrodes [133], it was demonstrated that the biosensing device could allocate a 4.9×10^{-8} M range of catechin, which outperformed the conventional spectrophotometric techniques. This is because such instruments are essential in the real-time determination of catechin stability, dynamics of release, and quality of antioxidants in active packaging systems.

3.2.5 Chromatography

High-performance liquid chromatography (HPLC) analyzes catechins content, identifies degradation products, and release profiles. The technique is required to conduct quality checks and stability tests of catechin-loaded films. HPLC was employed to establish whether catechin retained in ethylene-vinyl alcohol copolymer (EVOH) films, and evaluate whether catechin could migrate to food simulants [127]. Liquid chromatography-mass spectrometry (LC-MS) was one of the tools that were utilized to determine the distribution of the catechins in soy protein films, and to determine that the mechanisms of leaching are minimal as well as the maintenance of the antioxidant activity [125]. The instruments used are important in regulatory compliance and also to ensure that the active compounds are bioavailable during the storage of food.

3.3 Functional Properties

3.3.1 Antioxidant Properties

One of the most crucial functioning features of the films that has been extensively researched and confirmed is the antioxidant value of films containing catechin. The use of antioxidant packaging films

(APFs) is a revolutionary change in food preservation, where naturally derived polyphenols and flavonoids are used to prevent enzymatic and non-enzymatic browning. These bioactive composites actively react with the food or the headspace atmosphere to scavenge free radicals and thus maintain the nutritional value and sensory quality of oxidation-prone products such as oils and meats. Further advancements in encapsulation technology have improved the delivery of these antioxidants, which are stable and can be released at an appropriate rate during the shelf life of the product [134]. The strong free radical scavenging ability of catechins is thought to follow a number of mechanisms, with the major mechanism being the donation of hydrogen atoms through the assistance of phenolic hydroxyl groups to reactive oxygen species (ROS). They are commonly monitored by standard analytical assays, which include DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging, ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) decolorization, and oxygen radical absorbance capacity (ORAC) [70].

Research shows that the antioxidant property of catechin-impregnated films depends on the content of catechins; the higher the loading, the higher the radical scavenging effect. Catechin-encapsulated films using ethylene-vinyl alcohol copolymer (EVOH) have demonstrated excellent antioxidant potential, and released catechins have retained their reactivity in food systems. EGCG has the most effective antioxidant potential of the catechin derivatives since it has a trihydroxylated B-ring structure and a gallic acid ester bond [127].

In addition, studies have established that catechin bioactivity can be preserved throughout film processing. An example of this is that poly (L-lactic acid) films containing catechin and epicatechin produced about 32.90% and 36.68% of DPPH radical scavenging activity, respectively, following extrusion, which means that proper processing conditions retain the functionality of catechins [128]. The antioxidant property of catechin-containing films is particularly necessary for the preservation of foods. They have also been found to prevent the oxidation of stored food, contributing to lipid oxidation by inhibiting the formation of thiobarbituric acid reactive substances (TBARS). The inclusion of catechins into chitosan films can also be adopted as other modifications, which can prevent the oxidation of maize oil, and although it proves to be nutritionally beneficial, it can be utilized in practice to increase the shelf life of packed food, improving the nutritional value of the product [16].

3.3.2 Antimicrobial Properties

Films with catechin exhibit considerable broad-spectrum antibacterial activity against a variety of foodborne pathogens and food spoilage organisms. Their antimicrobial effects are general, comprising membrane destruction by disrupting lipid bilayers, inhibiting key enzyme systems, causing oxidative stress, and disrupting key cellular activities, resulting in metabolic dysfunction. Their antimicrobial activity is typically tested using widely used microbiological tests, including disk diffusion tests, minimum inhibitory concentration (MIC), and direct contact with target microorganisms to determine their inhibitory and bactericidal activities [6,135]. As demonstrated by [24], chitosan-based films supplemented with green tea extract (GTE) reduce the transmission of murine norovirus (MNV-1) and inhibit the growth of *Escherichia coli* K12 and *Listeria innocua*. The bioactivity of these films is significantly associated with green tea catechins, especially EGCG, which are potent antiviral and antibacterial agents. Although chitosan is not a good antimicrobial agent, its incorporation with GTE enhances the antimicrobial and antiviral properties of the films. This communication demonstrates the potential of chitosan-GTE edible films in reducing food-borne diseases in food packaging. These films have antimicrobial properties, which are important especially in active food packaging systems developed to handle highly perishable food. Films that contain catechin have been found to be very effective in reducing microbial load on meats, dairy products, and fresh produce. The gradual and prolonged release of the catechins from the film matrix gives continuous antibacterial protection in the storage process, therefore, enhancing food safety and increasing the shelf life [121].

3.3.3 Mechanical Properties

Introduction of catechins has greatly affected the mechanical properties of packaging, and the impacts vary based on catechin concentration, type, and processing conditions. The mechanical properties include functional properties such as tensile strength (TS), elongation at break (EAB), elastic modulus, and puncture resistance [125]. Small quantities of catechins act as plasticizers, increasing the flexibility and stretchability of films with a corresponding decrease in strength. This was demonstrated by a study performed by [129] where a 0.5 percent catechin-lysozyme mixture was added into gelatin films. The result was a tremendous increase in elongation (27.82% to 143.17%) and a massive reduction in tensile strength (33.49 to 3.31 MPa). This occurs because the catechins interfere with the internal structure of the polymer, breaking some bonds and forming others.

An anti-plasticizing effect of catechins can be achieved at higher concentrations, making the film stiffer and less extensible. This is due to the development of large hydrogen bonding networks between the polymer chains and catechin molecules, consequently producing more rigid film structures. To achieve the appropriate mechanical properties, the influence of plasticizing and anti-plasticizing should be well adjusted to obtain the most desirable catechin concentration [103]. Crosslinking is a key approach toward addressing the intrinsic mechanical and thermal drawbacks of natural biopolymer films such as starch and chitosan. This method stabilizes the polymer matrix, decreases water solubility, and enhances moisture barrier properties. By employing sustainable crosslinking technologies, these films are capable of being environmentally friendly and having the longevity needed in the commercial environment [136]. According to current studies, catechin-polymer conjugates can improve the mechanical properties of a material without decreasing its bioactivity. These covalent bond systems tend to be more effective in mechanical terms than standard physical blends because the chemical attachments provide more stable interactions at the core of the film [123].

3.3.4 Water Vapor and Gas Barrier Properties

The addition of catechin considerably influences packaging film properties. It affects how the films regulate the mass transfer of water vapor, oxygen, and light. Improving these properties is vital to preserving food quality and extending the shelf life of food products during packaging. Catechins usually improve the water vapor blocking properties of standard polymer matrices. The addition of catechin to the fish myofibrillar protein structure has reduced the water vapor transmission rate (WVTR) due to the ability of catechins to form intermolecular hydrogen bonds, consequently forming a smaller, more orderly structure [72]. This anti-plasticizing action of catechin was directly shown in PLA-PHB melt-blend films, with the addition of catechin raising elastic modulus and hardness due to the hydrogen bonding of catechin with the polymer matrix. The addition of ATBC (Acetyl Tributyl Citrate) as a plasticizer undid this effect to some extent by breaking the catechin-polymer network and affecting the barrier properties [137]. In addition to natural extracts, the use of functionalized fillers in PLA, such as polyethylenimine-functionalized mesoporous silica (PEI-MS), has been demonstrated as an effective method to increase thermal stability and crystallization rates. These biocomposite films have a more torturous route for gas molecules, effectively reducing the rate at which oxygen can be transmitted to better preserve food [138].

3.3.5 UV Barrier Properties

One of the most significant barrier improvements provided by catechin incorporation is enhanced UV protection. Catechins have aromatic rings and conjugated systems that aid in strong absorption of UV radiation in both UV-A (315–400 nm) and UV-B (280–315 nm) ranges [116]. A study done by [87] on catechin extracts incorporated into chitosan films exhibited excellent UV-shielding properties in the packaging. The

UV-blocking effect is important in safeguarding light-sensitive foods like dairy products, oiled edibles, and beverages against photooxidation. Gelatin films containing catechin, as illustrated, had low UV transmission (0.1–14.14) and satisfactory transparency in the visible spectrum (64.6%–84%). This selective UV absorption preserves visual appearance while preventing UV degradation of food ingredients [123].

3.3.6 Thermal and Optical Properties

The thermal encapsulation of catechins by maltodextrin has raised the decomposition temperature from 130°C (free catechin) to 290°C (encapsulated catechin), which has significantly improved their heat stability and maintained their antioxidant properties [103]. Catechin and epicatechin are more susceptible to degradation with increasing temperatures; however, trehalose almost doubled their half-life because of its protective effect against heat degradation [112].

Optical characteristics of catechin-loaded films play a crucial role in the acceptability and functionality of the films in packaging. Transparency, light transmission, and UV absorption characteristics are considered for catechin-based films. Catechin incorporation in films typically results in a color ranging from pale yellow to brown, depending on catechin concentration and type. This is used as a visual indication of the film's bioactivity, and the color development is due to the phenolic nature of catechins [3]. Transparency is maintained in catechin films at moderate catechin levels. Reference [126] showed that gelatin films containing catechin-lysozyme maintained good transparency with retention of optical clarity and product visibility, which is essential for packaging applications.

3.3.7 Release and Migration Properties

The controlled release of catechins is essential in packaging films, as the bioactivity has to be maintained throughout the storage period. The major factors that influence the release behavior of catechins are film matrix composition, catechin-polymer interactions, environmental conditions, and the medium properties [109]. The release kinetics generally follow Fickian diffusion mechanisms, which indicates that the release rates are dependent on the temperature, pH, and polarity of the medium. Iñiguez-Franco et al. [128] showed that catechin from poly (L-lactic acid) films release into ethanol followed Fickian behavior, with diffusion coefficients of 0.5 to 50×10^{-11} cm²/s. The extent of catechin release varies significantly with the type of food simulant, reflecting the importance of catechin-medium interactions. Jiang et al. [111] observed that catechins released in aqueous and alcoholic food media rather than in fatty food media, which indicates the hydrophilic nature of catechins and their solubility.

4 Applications of Catechin-Incorporated Packaging in Food Systems

The intention to use catechins in various studies has proven that their application is essential to increase shelf-life, food safety, and sensory characteristics. To prevent senescence in fresh produce, Wang et al. [139] applied a composite aloe vera and tea polyphenol coating on passion fruit to inhibit post-harvest senescence and maintain fruit quality. Research integrating blanching and vacuum impregnation with green tea extract on carrots enhanced antioxidant properties, texture, and color during frozen storage [140]. The use of catechin-loaded gelatin films in the preservation of minced pork has been studied in processed meat products [141]. By working in combination with nisin, the active film minimized lipid oxidation and microbial growth within a given duration, which increased shelf life and quality. In the dairy industry, Ref. [142] utilized whey protein isolate films with catechins to lower the number of microbes of *Pseudomonas* spp. and *Lactobacillus* in order to eliminate microbes during 14 days of storage. Research on the action of catechin and ferulic acid on Pacific white shrimp revealed that it inhibits melanosis and maintains quality when placed under refrigerated conditions [143].

Catechins are employed in liquid foods since, when included in apple juice, microbial growth and enzymatic browning have been inhibited, and antioxidant activity has been enhanced [144]. These case studies have demonstrated the use of catechins in fresh and processed food. Table 4 highlights the role of catechin in reducing major spoilage issues and the observed effects in foods. Fig. 4 shows an overview of catechin-based active packaging sources, the fabrication processes by which it is incorporated into various polymer matrices, and the various food applications.

Table 4: Applications of catechin-based packaging in food preservation.

Food Product	Main Spoilage Issues	Role of Catechin Packaging	Observed Effect	References
Meat and poultry (Frankfurter-type Sausage)	Lipid oxidation, microbial growth, and discoloration	Antioxidant, Antimicrobial	Reduced TBARS, lower microbial load, and delayed spoilage for 45 days.	[141,145]
Sea Food (Yellowfin tuna slices)	Amine formation, texture degradation, melanosis (black spot)	Enzyme inhibition, bacterial suppression, and antioxidant	Reduced total volatile basic nitrogen levels, preserved texture and elasticity, inhibited melanosis, and maintained fresh odour and appearance by 12 days.	[143,146]
Fresh Produces (Cut Apples and Strawberries)	Enzymatic browning, moisture loss, microbial spoilage	Polyphenol oxidase inhibition, antioxidant barrier, antimicrobial	Less browning, maintained colour and firmness, reduced weight loss, extended freshness, and inhibited mould growth by 7 days.	[139,140,147]
Bakery items (Muffins)	Enhancing nutritional value, improving quality attributes, and replacing synthetic leavening agents	Incorporated as a component in baking powders to provide antioxidant and rheological benefits.	Increased total phenolic content (TPC) and total antioxidant capacity (TAC) in muffins. Improved sensory profiles (appearance, olfactory, taste, texture). Enhanced dough rheology and mechanical properties of muffins. Potential to serve as a health-promoting ingredient and alternative to phosphate-based leavening agents.	[69,148]
Dairy Products (Full Fat Cheese)	Yeast/mold contamination, oxidative rancidity, flavor deterioration	Antimicrobial layer on film surface, antioxidant diffusion	Fewer spoilage organisms (yeasts and molds), reduced lipid oxidation, retained sensory quality (flavor, appearance), and extended storage life by 90 days.	[131,142,149]
Edible oil (Corn oil)	Lipid oxidation, Rancidity	Strong antioxidant properties	Significant reduction in peroxide value (PV) and thiobarbituric acid reactive substances (TBARS), extended induction period, and maintained oxidative stability by 10 days.	[16,23,71]
Ready to eat (Food simulant)	Microbial spoilage, oxidative degradation, and quality deterioration	Combined antioxidant and antimicrobial barrier	Improved the thermal stability during microwaving, which prolonged the freshness of the food.	[135,144,150]

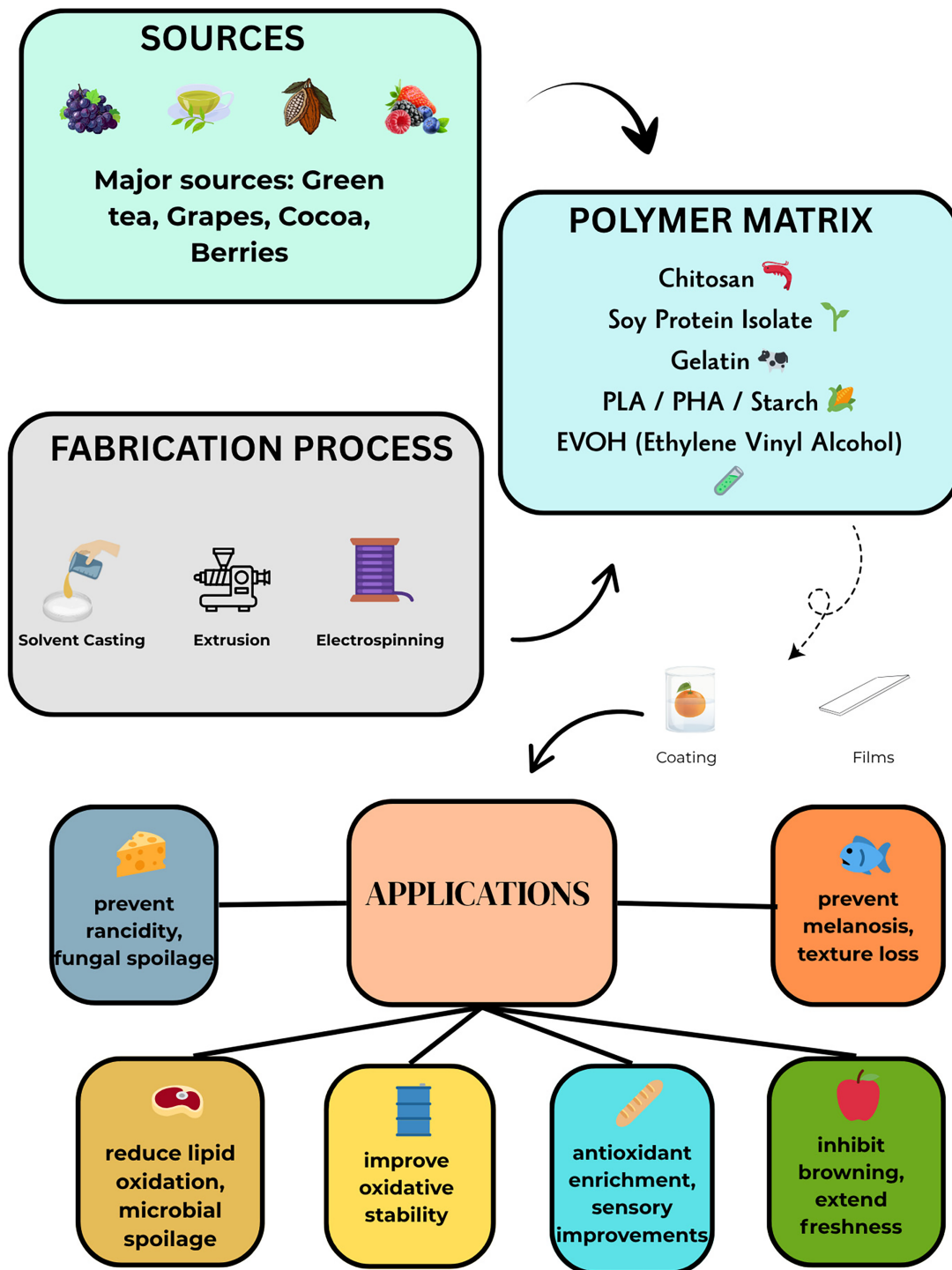


Figure 4: An overview of the sources, fabrication processes, and food preservation applications of active packaging films.

Representative Case Studies of Catechin-Based Active Packaging in Food Systems

To further give evidence of the effectiveness of catechin-based active packaging, five typical representative studies will be examined in detail. Each case has its experimental design, control group set-up, specific

quantitative results, and conclusions. The studies cover processed meat, seafood, dairy, fresh produce, and liquid food systems, which all illustrate the versatility of catechin applicability to various food systems, as shown in [Tables 5–9](#).

Table 5: Comparison of control and catechin-treated groups of minced pork [141].

Parameter	Control Group	Catechin-Treated	Change with Catechin	Shelf-Life Impact
Film type	Plain gelatin film (no active agents)	Gelatin film + catechin (antioxidant) + nisin (antimicrobial), cross-linked with microbial transglutaminase (MTGase)	Active film combines antioxidant and antimicrobial agents in a single cross-linked matrix	Active film substantially delayed microbial spoilage and lipid oxidation in minced pork
Total viable count (TVC) time to reach spoilage limit (10^7 CFU/g)	Reached 10^7 CFU/g in 1 day under aerobic refrigerated storage (5°C)	Reached 10^7 CFU/g threshold on day 4 under the same conditions	$3\times$ extension of the time to reach the microbial spoilage threshold	Acceptable shelf life extended from 1 day to 4 days, a tripling under demanding aerobic storage
Lipid oxidation (TBARS)	Higher TBARS values; faster lipid deterioration throughout storage	Catechin incorporation significantly retarded the increase in TBARS values	Lipid oxidation was measurably reduced by catechin antioxidant activity within the film	Delayed onset of rancidity; maintained sensory quality (odour, colour) for longer
<i>In vitro</i> antibacterial activity of film	Absent with no antimicrobial agent present	Confirmed antibacterial activity (nisin component) against Gram-positive spoilage bacteria	The film surface acquires an active antimicrobial property not present in the control	Microbial load on the meat surface is reduced; slower growth rate throughout the storage period
Film structural integrity (water solubility)	Higher solubility in contact with meat exudate	MTGase cross-linking markedly reduced film solubility	Cross-linked film maintains integrity in a moist meat environment	Sustained active agent retention and delivery throughout the storage period

Table 6: Comparison of control and catechin-treated groups—frankfurter-type sausage [145].

Parameter	Control Group	Catechin-Treated	Change with Catechin	Shelf-Life Impact
Preservation system	Nitrite-free sausage with no natural antioxidants or antimicrobials (negative control); conventional nitrite-containing sausage (positive control)	Nitrite-free sausage with natural antioxidants including catechin incorporated into the formulation	Catechin-based natural preservatives replaced synthetic nitrite as the primary preservation agent	Natural catechin formulation achieved commercially viable shelf life without synthetic additives
Lipid oxidation (TBARS)	Nitrite-free control: highest TBARS; fastest oxidative deterioration throughout 45-day storage	Significantly reduced TBARS compared to nitrite-free control; comparable trend to nitrite-containing sausage	Catechin reduced lipid oxidation by scavenging free radicals and chelating pro-oxidant metal ions	Delayed rancidity onset; maintained acceptable flavour and odour throughout 45-day storage period
Microbial load (TVC)	Nitrite-free control: highest microbial counts; fastest growth throughout storage	Reduced TVC; microbial growth suppressed relative to nitrite-free control across the full 45-day period	Catechin antimicrobial activity (membrane disruption, enzyme inhibition) slowed spoilage organism proliferation	Maintained microbial safety within acceptable limits throughout extended 45-day refrigerated storage
Colour stability (redness, a* value)	Nitrite-free control: most rapid redness loss; fastest colour deterioration	Better redness retention than nitrite-free control; colour maintained at higher a* values throughout storage	Catechin antioxidant activity partially protected myoglobin from oxidation to metmyoglobin	Preserved visual appearance (fresh red colour)—critical for consumer acceptance of fresh sausage
Acceptable shelf life achieved	Nitrite-free control: short acceptable shelf life; spoilage parameters exceeded limits rapidly	45 days of acceptable refrigerated storage achieved with natural catechin-based preservation	Catechin extends shelf life without synthetic preservatives—clean-label alternative validated	45-day shelf life: commercially viable for retail supply chains; matches industry requirements

Table 7: Comparison of control and catechin-treated groups—yellowfin tuna slices [146].

Parameter	Control Group	Catechin-Treated	Change with Catechin	Shelf-Life Impact
Treatment	Distilled water dip—no active agents (control group)	Dip treatment with EGCG (200–400 mg/kg) and/or squid pen chito-oligosaccharide (COS); stored at 4°C for 12 days	Active agents delivered via aqueous dip prior to chilled storage	Active treatment significantly extended microbiologically and chemically acceptable shelf life of tuna slices
Lipid oxidation (TBARS)	Higher TBARS values throughout 12-day storage; progressive lipid deterioration	Both COS and EGCG reduced TBARS vs. control; COS showed stronger inhibition of lipid oxidation	Antioxidant activity of catechin (EGCG) and COS jointly reduced fatty acid oxidation in tuna	Rancidity development delayed; it maintained an acceptable flavour and aroma profile throughout storage
Total volatile basic nitrogen (TVB-N)—freshness indicator	TVB-N exceeded the acceptable limit (30 mg/100 g) within the storage period at 4°C	TVB-N increase was significantly retarded; values remained at lower levels vs. control throughout storage	Catechin (EGCG) and COS inhibited microbial proteolytic activity, reducing volatile amine formation	Freshness maintained for longer; acceptable TVB-N sustained beyond day 6 (the control limit)
Melanosis (black spot formation, score 0–5)	Progressive melanosis development; visible blackening of tuna surface during storage	COS significantly reduced melanosis; EGCG alone had less effect on melanosis (and accelerated metmyoglobin formation at higher concentrations)	COS inhibits polyphenol oxidase (PPO) preventing melanosis; EGCG is more effective for lipid/microbial control than colour	COS preserved visual appearance of tuna (critical for consumer acceptance of raw fish)
Microbial growth (TVC)	TVC increased progressively; microbial spoilage limit (7 log CFU/g) was reached during storage	COS showed higher microbial inhibition than EGCG; COS + EGCG combination was also effective	COS antimicrobial activity (membrane disruption) was the dominant mechanism for TVC suppression	Shelf life extended to 12 days—approximately doubled vs. control under 4°C refrigeration

Table 8: Comparison of control and catechin-treated groups—Latin-style fresh cheese [142].

Parameter	Control Group	Catechin-Treated	Change with Catechin	Shelf-Life Impact
Packaging system	Plain whey protein concentrate (WPC) film—no green tea extract (control)	WPC film incorporating Portuguese green tea extract (GTE, rich in catechins including EGCG and ECG); stored at 5°C	Green tea catechin extract incorporated into food-grade protein film matrix	Active film with catechin extract improved both microbiological and oxidative stability of fresh cheese
Lipid oxidation (TBARS, mg MDA Eq/kg)	4.2 mg MDA Eq/kg—higher oxidative deterioration of cheese fat during storage	3.2 mg MDA Eq/kg—lipid oxidation delayed by catechin antioxidant activity (23.8% lower vs. control)	Catechin radical scavenging and metal chelation within the WPC film delayed cheese fat oxidation	Reduced lipid oxidation extended oxidative shelf life; maintained cheese flavour and aroma quality
<i>E. coli</i> count (CFU/g)	2.2×10^2 CFU/g—higher <i>E. coli</i> contamination during storage	1.5×10^1 CFU/g—approximately 93% reduction in <i>E. coli</i> vs. control film	Catechin antimicrobial activity (membrane disruption, enzyme inhibition) suppressed <i>E. coli</i> proliferation	Improved food safety— <i>E. coli</i> count reduced to near-negligible levels throughout storage at 5°C
Total microorganism count (30°C)	Higher total microbial counts during storage; faster microbial proliferation	Inhibited total microorganism growth relative to plain WPC control film	Catechin antimicrobial properties suppressed broad-spectrum microbial growth on the cheese surface	Extended microbiological shelf life; reduced risk of visible spoilage during refrigerated storage
Film antioxidant capacity (AAC)	Low—plain WPC film has no antioxidant functionality	AAC \approx 595.4—high antioxidant capacity conferred by GTE catechin incorporation	Catechin incorporation transforms passive WPC film into functionally active antioxidant packaging	Active antioxidant film provides continuous protection against oxidative deterioration throughout storage

Table 9: Comparison of control and catechin-treated groups—apple juice [144].

Parameter	Control Group	Catechin-Treated	Change with Catechin	Shelf-Life Impact
Treatment	Plain apple juice with no tea polyphenol addition (control group)	Apple juice supplemented with tea polyphenols (catechin-rich, 0.05% w/v)—direct addition to liquid food matrix; stored at 25°C (accelerated conditions)	Catechin-rich tea polyphenols applied directly to liquid food as functional preservative additive	Tea polyphenols simultaneously inhibited browning, maintained antioxidant capacity, and suppressed microbial growth
Enzymatic browning (visual/ ΔE)	Progressive browning during storage; colour deterioration evident within days at 25°C	Browning significantly inhibited throughout storage; visual appearance maintained at acceptable level	Catechin inhibits polyphenol oxidase (PPO) activity and scavenges quinone intermediates that cause brown discoloration	Maintained visual appeal and consumer acceptability of the juice throughout accelerated storage period
Antioxidant capacity (DPPH scavenging)	Antioxidant capacity declined steadily during storage as phenolic compounds were consumed by oxidation	Antioxidant capacity better maintained and enhanced throughout storage relative to control	Tea polyphenol catechins replenished and supplemented the juice's natural antioxidant pool	Nutritional quality (antioxidant value) preserved for longer—beneficial for health-conscious consumers
Total phenolic content (TPC)	TPC decreased during storage as endogenous phenolics were consumed by oxidation and browning reactions	Higher TPC maintained throughout storage due to catechin supplementation	Catechin addition offset the loss of endogenous phenolics, sustaining total polyphenol levels	Extended period of high nutritional value; catechin supplementation functionally replaced lost phenolics
Microbial growth (log CFU/mL)	Microbial counts increased over time; shelf life limited by both microbial spoilage and browning	Microbial growth inhibited relative to control; slower proliferation throughout storage period	Catechin antimicrobial activity disrupted microbial cell membranes and inhibited key metabolic enzymes	Microbiologically acceptable shelf life approximately doubled—from ~4 days (control) to ~8 days (treated)

Case Study 1: Minced Pork Preservation—Gelatin Film with Catechin and Nisin.

Kaewprachu et al. [141] compared the preservation properties of gelatin-based active films cross-linked with microbial transglutaminase (MTGase) and added catechin as an antioxidant and nisin as an antimicrobial factor. Fresh minced pork was placed in polystyrene trays and overwrapped with plain gelatin film (control group) or the catechin-nisin active film and kept in an aerobic environment at 5°C–10°C. The critical spoilage threshold, a total viable count (TVC) of 107 CFU/g, was reached after only 1 day in the control group, indicating that the minced pork was highly perishable in aerobic conditions. Conversely, pork enclosed in the catechin-nisin gelatin film took 4 days to reach this spoilage level, which is a 3-fold increase of the microbiologically acceptable shelf life. The catechin ingredient provided quantifiable *in vitro* antioxidant ability to the film and inhibited the rise in thiobarbituric acid reactive substances (TBARS) throughout the storage period, postponing lipid oxidation and the formation of rancid flavours. Cross-linking with MTGase greatly decreased the aqueous solubility of the film, which could retain its structural integrity in direct contact with meat exudate and could release the catechin and nisin during storage. These findings indicate that a synergistic combination of catechin (antioxidant) and nisin (antimicrobial) in a cross-linked protein film matrix is much more effective than any single agent used, and that, even in the most rigorous aerobic storage conditions, catechin-based active packaging can provide a noticeable shelf-life extension to fresh processed meat products.

Case Study 2: Nitrite-Free Frankfurter Sausage—Natural Antioxidants Including Catechin.

The purpose of the study by Alirezalu et al. [145] was to explore the possibility of using natural antioxidants such as catechin to replace sodium nitrite as a food preservative in frankfurter-type sausages, as an option to meet the increasing consumer demand for clean-label processed meat products. The experimental design involved testing three groups: a negative control in the absence of nitrite (no preservatives), a positive control (sausage containing nitrite), and a nitrite-free formulation with catechin and complementary natural antioxidants. The quality parameters (TBARS (lipid oxidation), total viable count (TVC), and colour (redness, a^* value)) were tested during 45 days of refrigeration. The nitrite-free control deteriorated quickly, and the TBARS, TVC, and colour degradation exceeded acceptable limits long before the end of the observation period. The catechin-treated group performed significantly better with all three parameters: TBARS values were significantly reduced, the number of microbes was reduced during the entire 45-day storage process, and the redness was better maintained compared to the unsupplemented control. Notably, the catechin-based formulation had 45 days of satisfactory refrigerated shelf life—a commercially significant target that indicates the feasibility of catechin as a clean-label nitrite alternative in processed meat. The results of this study are especially important as they position catechin not only as an adjunct to the current preservation regimes but as an active alternative to synthetic preservatives and provide a pathway toward the introduction of natural, label-friendly sausage products with competitive shelf life.

Case Study 3: Yellowfin Tuna Slices—EGCG and Chito-oligosaccharide Treatment.

Singh et al. [146] compared epigallocatechin gallate (EGCG) and squid pen chito-oligosaccharide (COS), and their combination (1:1, w/w) as an aqueous dip for slices of yellowfin tuna. The control group experienced a quick decline in all parameters, as TVB-N surpassed the freshness limit of 30 mg/100 g and TVC neared the spoilage limit of 7 log CFU/g within the time of observation. The COS and EGCG treatments substantially delayed lipid oxidation (TBARS) and microbial growth in comparison with the control, with COS having better antimicrobial inhibition and melanosis prevention capabilities because of its strong polyphenol oxidase (PPO) inhibitory capacity. An interesting subtlety was found in the case of EGCG: although effective as an antioxidant and antimicrobial agent, at higher concentrations, EGCG alone increased metmyoglobin formation, decreasing tuna redness—a matrix-specific pro-oxidant effect on haem pigments that needs to be taken into consideration in catechin packaging design of high-myoglobin seafoods. By complementing each

other, the combination of COS + EGCG treatment increased the acceptable shelf life of yellowfin tuna slices to 12 days (about twice the shelf life of the controls under the same refrigerated conditions) by concurrently reducing lipid oxidation, microbial growth, and enzymatic browning.

Case Study 4: Latin-Style Fresh Cheese—Whey Protein Film with Green Tea Extract.

The study by Robalo et al. [142] evaluated the effectiveness of whey protein concentrate (WPC) films to preserve Latin-style fresh cheeses (goat cheese and a goat/sheep mixture) stored at 5°C with either no Portuguese green tea extract (GTE) (control) or 2% GTE incorporated. Goat and mixture fresh cheeses were both tested to ensure that they were reproducibly evaluated across cheese matrices. Active film exhibited much better preservation capability on microbiological and oxidative parameters. As a measure of lipid oxidation, TBARS was 4.2 mg MDA Eq/kg in the control group against 3.2 mg MDA Eq/kg in the active film group 23.8 percent less which establishes that catechin radical scavenging activity within the film matrix slowed down the deterioration of cheese fat during storage. Microbiologically, the active film was able to reduce *E. coli* counts (2.2×10^2 vs. 1.5×10^1 CFU/g) and generally inhibit overall microorganism proliferation. These increases in oxidative and microbial stability reflect a significant increase in the fresh cheese shelf life from about 7 days for the control to approximately 14 days for the active film shows a doubling in the shelf life of the marketable fresh cheese. The research also determined that the geographic origin and extraction mode of green tea extract had significant effects on the film efficacy, with Portuguese GTE having a higher antioxidant activity coefficient (AAC = 746.7) in comparison to Asian green tea under study (AAC = 650), with respect to selection of catechin source as an active ingredient in the formulation of active packaging.

Case Study 5: Apple Juice—Tea Polyphenols as a Direct Preservative.

Zhong et al. [144] examined the effects of tea polyphenols consisting of catechins, including EGCG, epicatechin gallate (ECG), and epicatechin (EC) directly added to fresh apple juice (0.05% w/v) at 25°C under accelerated shelf-life conditions. Pure apple juice was prepared and, in each case, divided into a plain control group (no addition) and a tea polyphenol-supplemented group, where quality parameters, including browning index (-dE), DPPH antioxidant scavenging activity, total phenolic content (TPC), and microbial count were measured at regular intervals during the storage process. In the control group, the process of enzymatic browning was rapid at 25°C, and the endogenous polyphenol oxidase (PPO) transformed phenolic substances into brown quinone pigments, antioxidant capacity decreased gradually, TPC reduced with consumption of phenolics, and the number of microbes increased with time. The tea polyphenol-supplemented group was superior to the control in all four parameters at the same time; browning was greatly inhibited by PPO inhibitory and quinone scavenging action, antioxidant capacity was improved and preserved, TPC was maintained at elevated levels during the storage period, and microbial growth was inhibited by catechin antimicrobial activity. This versatile inhibition of enzymatic browning, of oxidative degradation, and of microbial spoilage by distinct but complementary mechanisms in a single natural additive, resulting in a 2-fold increase in the microbiologically and visually acceptable shelf-life of apple juice at the accelerated conditions of 25°C. This case study is of special interest as it introduces the use of catechins to a liquid food matrix for direct applications in solid food packaging films, and shows that catechins are multifunctional natural preservatives and can be utilized in a wide range of food types.

5 Safety Concerns and Challenges

Catechins possess antioxidant and antimicrobial qualities, yet an overall safety assessment must be conducted before they are added to food packaging. The main issue is that excessive concentrations of catechins, especially EGCG, in supplements may alter their antioxidant effect, causing them to act as pro-oxidants and induce oxidative stress and mitochondrial damage, potentially leading to hepatotoxicity [151,152]. This danger is compounded when supplements are taken on an empty stomach, which enhances bioavailability. This is

especially important in active food packaging, since the migration of catechins between the packaging and the food may lead to high-dose exposure, which should be regulated to maintain acceptable daily catechin intake [153].

In addition to direct toxicity, catechins can directly interact with food components, and when consumed, they can interfere with the nutritional value of the food. Catechins have a high affinity for diets and digestive enzymes such as amylase and lipase, which can decrease protein digestibility and nutrient absorption in high-protein diets. This effect may introduce an anti-nutritious property of catechins in the packaging that may affect bioaccessibility and compound the extent of risk [154]. The European Food Safety Authority (EFSA) has reviewed and concluded that catechins from green tea are not dangerous, but supplemental amounts of EGCG of 800 mg/day and above can lead to the risk of hepatotoxicity [155]. Catechins offer excellent bioactive potential; however, safe incorporation into food systems must be ensured, and the dose must be strictly controlled and compliant with applicable regulatory requirements. They could be applied to packaging to retain the quality and shelf life of food.

In order to effectively control catechin migration in active packaging, certain evaluation procedures must be adhered to. Migration testing involves incubating the packaging in a food simulant that resembles the target food under standardised conditions: 10 days at 40°C ambient storage as defined by EU Regulation No. 10/2011 and EN 1186 protocols [156]. Due to the hydrophilic nature of catechins, 10% ethanol is applied as the simulant for aqueous foods like meat and dairy, 3% acetic acid is applied as the simulant for acidic foods like fruits, and 50% ethanol is applied as the simulant for products with moderate fat levels like meat [157]. EGCG, EGC, ECG and EC are then determined in the simulant by reverse-phase HPLC-UV at 278 nm (ISO 14502-2 method), and EDTA and ascorbic acid are added to the sample solution to inhibit EGCG auto-oxidation during analysis [158]. To obtain a more detailed safety profile, with the identification of catechin oxidation products and non-intentionally added substances (NIAS) formed during film fabrication, LC-MS/MS is a complementary analytical technique [157]. Published kinetic data confirm that catechin release from biopolymer films follows Fickian diffusion: chitosan-vanillin-green tea extract films delivered a burst release within 8 h followed by sustained release over 400 h, and starch/PBAT films loaded with tea polyphenols retained above 95% of catechin content initially and above 80% after 12 months of storage [159]. These data indicate that migration doses of realistic packaging formats are significantly lower than the 800 mg/day EGCG limit developed by EFSA, but the cumulative exposure from all sources of catechins in foods needs to be evaluated. EC Regulation No. 450/2009, which regulates the deliberate release of bioactive substances by active packaging, requires that packaging-derived EGCG be assessed as a novel active substance before any product can be commercially marketed [160,161].

Other than safety, the environmental sustainability of catechin-based active packaging should be assessed by means of Life Cycle Assessment (LCA). *Camellia sinensis* is the source of the catechin raw material, and a cradle-to-gate LCA of green tea in a plant in China reported a total carbon emission intensity of 32.90 kg CO₂ eq per kg of dry tea, with processing stages like steaming and drying being the largest hotspots, accounting for 57% of processing-stage emissions [161]. Obtaining catechins by using spent tea leaves, a by-product of approximately 5.8 million tonnes worth of tea processing, can significantly decrease this upstream footprint, as the carbon footprint of cultivation is instead assigned to the main tea product as opposed to the waste-based catechin ingredient [162]. Regarding fabrication, optimised melt extrusion of starch/PBAT films with tea polyphenols has provided retention of catechin levels greater than 95% at processing temperatures, indicating that thermal EGCG degradation can be controlled and extrusion as a fabrication pathway is energy efficient [160]. The greatest environmental advantage of catechin-based packaging is its use phase: reported shelf life increases of 4–15 days on meat, seafood, and dairy products alleviate food spoilage, and in high-carbon foods like beef (ca. 27 kg CO₂eq per kg), even modest decreases

in waste compensate for a significant fraction of the packaging film production footprint. Future research in LCA needs to incorporate a functional unit that incorporates both packaging functions and reduction of food waste to fully encompass this environmental value with an ISO 14040/14044-compliant methodology and established databases like Ecoinvent or AGRIBALYSE [162,163].

Now that the existing safety concerns, regulatory issues, and sustainability concerns of catechin-based active packaging have been identified, the concluding section will consolidate the main findings of this review and give recommendations for possible future research.

6 Conclusion and Future Perspectives

Catechin-based active packaging is another food preservation innovation that has changed the paradigm of packaging from a passive, inert barrier into an active system, protecting and improving food quality. This review has emphasized the application of catechins as natural, sustainable, and bioactive compounds in packaging to address the increased global market demand for safer and clean-labelled products. Catechins exhibit high biological activity, presenting enormous potential for food waste reduction and minimizing the dependence on synthetic preservatives. Their mechanisms are complex: they possess strong antioxidant effects, scavenging free radicals and chelating metals; they have extensive antimicrobial activities, suppressing proliferation of spoilage microorganisms in packaged foods; they may also block UV radiation, as well as enzyme browning, which provides an added security to the sensory and nutritional benefits of packaged foods. They can be incorporated into a wide range of polymer matrices using fabrication techniques like solvent casting, electrospinning, and melt processing, and their characterization using SEM and FTIR has been used to determine catechins' interactivity with polymers.

However, this apparent potential has several hurdles to overcome before it can become a viable practice, even in the commercial environment. Scalability and standardization are among them; experiments at lab scale should be replicable in large-scale production, and would require cost-effective sourcing and uniform fabrication. This has been complicated by the fact that the content of catechins among the different sources is quite variable and cannot be standardized. Moreover, catechins may add undesirable sensory properties, including astringency, bitterness, and color changes, and this has a direct effect on consumer acceptance, particularly as a coating. Another major challenge is stability, since catechins are susceptible to degradation during high-temperature processing or via exposure to light and an adverse pH environment. Lastly, even though catechins are GRAS (Generally Recognized As Safe) in moderate concentrations, their leaching out of the packaging into food presents a regulatory and safety issue. Specifically, the displacement of high doses of ECG leads to concerns about possible hepatotoxicity at levels exceeding threshold limits. Thus, it is important to conduct further research to determine the boundaries of migration and evaluate the toxicological effects of long-term intake of packaged foods.

Future research is aimed at resolving these challenges. Methodologies such as encapsulation in nanocarriers, e.g., lipid-based nanoparticles or biopolymer-hydrogel composites, are promising solutions. These techniques can fix the reactive catechins to resist light, pH, and temperature, besides controlling their diffusion into the food. In addition, the negative sensorial challenges can be alleviated by means of these sophisticated delivery systems, the application of bitterness-masking agents, or catechin-protein complexes. To sum up, catechin-based packaging is a sustainable solution with potential for the future of active packaging. By offering strong answers to the current issues about stability, sensory perception, fabrication cost, and migration, catechins have a chance of being a safer, eco-friendly, and universally acceptable technology in the contemporary food industry.

Acknowledgement: None.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Christy Sam Sabu: Writing—original draft, Methodology, Formal analysis. Pratap Kalita: Writing—review and editing, Visualization, Investigation. Swarup Roy: Writing—original draft, Writing—review and editing, Methodology, Visualization, Conceptualization, Supervision. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: No new data were used in this research.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ahmed MW, Haque MA, Mohibullah M, Khan MSI, Islam MA, Mondal MHT, et al. A review on active packaging for quality and safety of foods: current trends, applications, prospects and challenges. *Food Packag Shelf Life*. 2022;33(1):100913. doi:10.1016/j.fpsl.2022.100913.
2. Ahari H, Soufiani SP. Smart and active food packaging: insights in novel food packaging. *Front Microbiol*. 2021;12:657233. doi:10.3389/fmicb.2021.657233.
3. Fabra MJ, Falcó I, Randazzo W, Sánchez G, López-Rubio A. Antiviral and antioxidant properties of active alginate edible films containing phenolic extracts. *Food Hydrocoll*. 2018;81(2):96–103. doi:10.1016/j.foodhyd.2018.02.026.
4. Gaikwad KK, Singh S, Lee YS. Oxygen scavenging films in food packaging. *Environ Chem Lett*. 2018;16(2):523–38. doi:10.1007/s10311-018-0705-z.
5. Sadeghi K, Lee Y, Seo J. Ethylene scavenging systems in packaging of fresh produce: a review. *Food Rev Int*. 2021;37(2):155–76. doi:10.1080/87559129.2019.1695836.
6. Fadiji T, Rashvand M, Daramola MO, Iwarere SA. A review on antimicrobial packaging for extending the shelf life of food. *Processes*. 2023;11(2):590. doi:10.3390/pr11020590.
7. Biji KB, Ravishankar CN, Mohan CO, Srinivasa Gopal TK. Smart packaging systems for food applications: a review. *J Food Sci Technol*. 2015;52(10):6125–35. doi:10.1007/s13197-015-1766-7.
8. Singh AK, Ramakanth D, Kumar A, Lee YS, Gaikwad KK. Active packaging technologies for clean label food products: a review. *J Food Meas Charact*. 2021;15(5):4314–24. doi:10.1007/s11694-021-01024-3.
9. Cheng J, Gao R, Zhu Y, Lin Q. Applications of biodegradable materials in food packaging: a review. *Alex Eng J*. 2024;91:70–83. doi:10.1016/j.aej.2024.01.080.
10. Deshmukh RK, Hakim L, Gaikwad KK. Active packaging materials. *Curr Food Sci Technol Rep*. 2023;1(2):123–32. doi:10.1007/s43555-023-00004-6.
11. Vanderroost M, Ragaert P, Devlieghere F, De Meulenaer B. Intelligent food packaging: the next generation. *Trends Food Sci Technol*. 2014;39(1):47–62. doi:10.1016/j.tifs.2014.06.009.
12. Gadkari PV, Balaraman M. Catechins: sources, extraction and encapsulation: a review. *Food Bioprod Process*. 2015;93:122–38. doi:10.1016/j.fbp.2013.12.004.
13. Bernatoniene J, Kopustinskiene DM. The role of catechins in cellular responses to oxidative stress. *Molecules*. 2018;23(4):965. doi:10.3390/molecules23040965.
14. Grzesik M, Naparło K, Bartosz G, Sadowska-Bartosz I. Antioxidant properties of catechins: comparison with other antioxidants. *Food Chem*. 2018;241(2):480–92. doi:10.1016/j.foodchem.2017.08.117.
15. Haghighi TM, Mousavi SS, Kohansal Y, Hashemi H, Tavakoli S, Mousavi Khaneghah A. Biopolymer-based edible films and coatings for berry preservation: a systematic review. *Packag Technol Sci*. 2026;39(2):181–99. doi:10.1002/pts.70018.

16. Wang Z, Huang J, Yun D, Yong H, Liu J. Antioxidant packaging films developed based on chitosan grafted with different catechins: characterization and application in retarding corn oil oxidation. *Food Hydrocoll.* 2022;133:107970. doi:10.1016/j.foodhyd.2022.107970.
17. Andrade MA, Barbosa CH, Cerqueira MA, Azevedo AG, Barros C, Machado AV, et al. PLA films loaded with green tea and rosemary polyphenolic extracts as an active packaging for almond and beef. *Food Packag Shelf Life.* 2023;36(suppl 1):101041. doi:10.1016/j.fpsl.2023.101041.
18. Danmatam N, Pearce J, Pattavarakorn D. UV-blocking properties of carboxymethyl cellulose film integrated with oolong tea extracts as eco-friendly packaging film. *Mater Today Proc.* 2023;77(14):1052–8. doi:10.1016/j.matpr.2022.11.387.
19. Lunetta E, Cacciotti I. An overview of the packaging industry. In: *Nanostructured materials for food packaging applications.* Amsterdam, The Netherlands: Elsevier; 2024. p. 1–30. doi:10.1016/b978-0-323-99525-2.00006-2.
20. Pervin M, Unno K, Ohishi T, Tanabe H, Miyoshi N, Nakamura Y. Beneficial effects of green tea catechins on neurodegenerative diseases. *Molecules.* 2018;23(6):1297. doi:10.3390/molecules23061297.
21. Farhan M. Green tea catechins: nature's way of preventing and treating cancer. *Int J Mol Sci.* 2022;23(18):10713. doi:10.3390/ijms231810713.
22. Sivanesan I, Muthu M, Kannan A, Pushparaj SSC, Oh JW, Gopal J. Identification of epigallocatechin-3-gallate (EGCG) from green tea using mass spectrometry. *Separations.* 2022;9(8):209. doi:10.3390/separations9080209.
23. Wrona M, Nerin C, Alfonso MJ, Caballero MÁ. Antioxidant packaging with encapsulated green tea for fresh minced meat. *Innov Food Sci Emerg Technol.* 2017;41(2):307–13. doi:10.1016/j.ifset.2017.04.001.
24. Amankwaah C, Li J, Lee J, Pascall MA. Antimicrobial activity of chitosan-based films enriched with green tea extracts on murine norovirus, *Escherichia coli*, and *Listeria innocua*. *Int J Food Sci.* 2020;2020(3):3941924. doi:10.1155/2020/3941924.
25. González-Barrio R, Nuñez-Gomez V, Cienfuegos-Jovellanos E, García-Alonso FJ, Periago-Castón MJ. Improvement of the flavanol profile and the antioxidant capacity of chocolate using a phenolic rich cocoa powder. *Foods.* 2020;9(2):189. doi:10.3390/foods9020189.
26. García LC, Hernández ANM. Beneficial effects of cocoa and dark chocolate polyphenols on health. *FASEB J.* 2020;34(S1):1. doi:10.1096/fasebj.2020.34.s1.07187.
27. Indiarto R, Subroto E, Sukri N, Djali M. Cocoa (*Theobroma cacao* L.) beans processing technology: a review of flavonoid changes. *Asian J Plant Sci.* 2021;20(4):684–93. doi:10.3923/ajps.2021.684.693.
28. Leong BCC, Sarjadil MS, Mohd Shah R, Abd Majid MH. The effect of processing operations on the polyphenol content of cocoa beans: a review. *Malays J Chem.* 2024;26(2):46–66. doi:10.55373/MJCHEM.V26I2.46.
29. Di Mattia CD, Sacchetti G, Mastrocola D, Serafini M. From cocoa to chocolate: the impact of processing on *in vitro* antioxidant activity and the effects of chocolate on antioxidant markers *in vivo*. *Front Immunol.* 2017;8:1207. doi:10.3389/fimmu.2017.01207.
30. Zam W, Ali A. Evaluation of mechanical, antioxidant and antimicrobial properties of edible film containing myrtle berries extract. *Nat Prod J.* 2019;8(4):323–30. doi:10.2174/2210315508666180723155711.
31. Subash S, Essa MM, Al-Adawi S, Memon MA, Manivasagam T, Akbar M. Neuroprotective effects of berry fruits on neurodegenerative diseases. *Neural Regen Res.* 2014;9(16):1557–66. doi:10.4103/1673-5374.139483.
32. Peña-Sanhueza D, Inostroza-Blancheteau C, Ribera-Fonseca A, Reyes-Díaz M. Anthocyanins in berries and their potential use in human health. In: *Superfood and functional food—the development of superfoods and their roles as medicine.* London, UK: InTechOpen; 2017. doi:10.5772/67104.
33. Sadowska-Bartosz I, Bartosz G. Antioxidant activity of anthocyanins and anthocyanidins: a critical review. *Int J Mol Sci.* 2024;25(22):12001. doi:10.3390/ijms252212001.
34. Qi Q, Chu M, Yu X, Xie Y, Li Y, Du Y, et al. Anthocyanins and proanthocyanidins: chemical structures, food sources, bioactivities, and product development. *Food Rev Int.* 2023;39(7):4581–609. doi:10.1080/87559129.2022.2029479.
35. Dordevic S, Dordevic D, Sedlacek P, Kalina M, Tesikova K, Antonic B, et al. Incorporation of natural blueberry, red grapes and parsley extract by-products into the production of chitosan edible films. *Polymers.* 2021;13(19):3388. doi:10.3390/polym13193388.

36. Viscusi G, Gorrasi G. Polyphenols for packaging application. In: Science and engineering of polyphenols: fundamentals and industrial scale applications. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2024. p. 211–52. doi:10.1002/9781394203932.CH8.
37. Castaldo L, Narváez A, Izzo L, Graziani G, Gaspari A, Di Minno G, et al. Red wine consumption and cardiovascular health. *Molecules*. 2019;24(19):3626. doi:10.3390/molecules24193626.
38. Markoski MM, Garavaglia J, Oliveira A, Olivaes J, Marcadenti A. Molecular properties of red wine compounds and cardiometabolic benefits. *Nutr Metab Insights*. 2016;9(1):51–7. doi:10.4137/NMI.S32909.
39. Buljeta I, Pichler A, Šimunović J, Kopjar M. Beneficial effects of red wine polyphenols on human health: comprehensive review. *Curr Issues Mol Biol*. 2023;45(2):782–98. doi:10.3390/cimb45020052.
40. Silva V, Igrejas G, Falco V, Santos TP, Torres C, Oliveira AMP, et al. Chemical composition, antioxidant and antimicrobial activity of phenolic compounds extracted from wine industry by-products. *Food Control*. 2018;92(46):516–22. doi:10.1016/j.foodcont.2018.05.031.
41. Musial C, Kuban-Jankowska A, Gorska-Ponikowska M. Beneficial properties of green tea catechins. *Int J Mol Sci*. 2020;21(5):1744. doi:10.3390/ijms21051744.
42. Nur S, Aisyah AN, Fadri A, Sharfianty, Sapra A, Sami FJ. Comparative study of catechin levels from green tea, oolong tea and black tea product with various treatments. *GSC Biol and Pharm Sci*. 2021;14(1):1–10. doi:10.30574/gscbps.2021.14.1.0416.
43. Orak H, Yagar H, Isbilir S, Demirci A, Gumus T. Antioxidant and antimicrobial activities of white, green and black tea extracts. *Acta Aliment*. 2013;42(3):379–89. doi:10.1556/aalim.2013.2222.
44. Sun J, Wang L, Chen H, Yin G. Enhancing biodegradable packaging: the role of tea polyphenols in soybean oil body emulsion films. *Coatings*. 2025;15(2):162. doi:10.3390/coatings15020162.
45. Vulić J, Bibovski K, Šeregelj V, Kovačević S, Karadžić Banjac M, Čanadanović-Brunet J, et al. Chemical and biological properties of peach pomace encapsulates: chemometric modeling. *Processes*. 2022;10(4):642. doi:10.3390/pr10040642.
46. Geçer MK. Biochemical content in fruits of peach and nectarine cultivars. *Turk J Agric For*. 2020;44(5):500–5. doi:10.3906/tar-1911-8.
47. Goto T, Obara M, Aoki S, Okazawa K, Konisho K, Osakabe N, et al. Evaluation of polyphenolic content and potential antioxidant activity of Japanese cultivars of peaches, prunes, and plums based on reversed- and normal-phase HPLC and principal component analyses. *ACS Food Sci Technol*. 2021;1(10):2019–29. doi:10.1021/acsfoodscitech.1c00357.
48. Song Y, Zhou L, Zhang D, Wei Y, Jiang S, Chen Y, et al. Stability and release of peach polyphenols encapsulated by Pickering high internal phase emulsions *in vitro* and *in vivo*. *Food Hydrocoll*. 2023;139(1):108593. doi:10.1016/j.foodhyd.2023.108593.
49. Mustafa AM, Abouelenein D, Acquaticci L, Alessandrini L, Angeloni S, Borsetta G, et al. Polyphenols, saponins and phytosterols in lentils and their health benefits: an overview. *Pharmaceuticals*. 2022;15(10):1225. doi:10.3390/ph15101225.
50. Thamarsha AKANWMRK, Kumar N, Pratibha, Mor K, Upadhyay A, Sudhani HPK, et al. A review of functional properties and applications of legume-based edible coatings. *Legume Sci*. 2024;6(4):e70004. doi:10.1002/leg3.70004.
51. Poonia A, Vikranta U, Chaudhary N, Dangi P. Current and potential health claims of faba beans (*Vicia faba*, L.) and its components. In: Faba bean: chemistry, properties and functionality. Cham, Switzerland: Springer International Publishing; 2022. p. 331–55. doi:10.1007/978-3-031-14587-2_13.
52. Bae J, Kim N, Shin Y, Kim SY, Kim YJ. Activity of catechins and their applications. *Biomed Dermatol*. 2020;4(1):8. doi:10.1186/s41702-020-0057-8.
53. Wang J, Tang H, Hou B, Zhang P, Wang Q, Zhang BL, et al. Synthesis, antioxidant activity, and density functional theory study of catechin derivatives. *RSC Adv*. 2017;7(85):54136–41. doi:10.1039/c7ra11496f.
54. Capasso L, De Masi L, Sirignano C, Maresca V, Basile A, Nebbioso A, et al. Epigallocatechin gallate (EGCG): pharmacological properties, biological activities and therapeutic potential. *Molecules*. 2025;30(3):654. doi:10.3390/molecules30030654.

55. Liu Z, Nakamura T, Munemasa S, Murata Y, Nakamura Y. Galloylated catechins as potent inhibitors of angiotensin converting enzyme. *Food Sci Technol Res.* 2016;22(6):847–51. doi:10.3136/fstr.22.847.
56. Bahramian B, Kiani-Salmi N, Abedi-Firoozjah R, Babadi Fathipour R, Tavassoli M, Ghasemi S, et al. Biopolymer-epigallocatechin materials: a sustainable approach material for food packaging. *Qual Assur Saf Crops Foods.* 2025;17(3):24–60. doi:10.15586/qas.v17i3.1547.
57. Sheng Y, Sun Y, Tang Y, Yu Y, Wang J, Zheng F, et al. Catechins: protective mechanism of antioxidant stress in atherosclerosis. *Front Pharmacol.* 2023;14:1144878. doi:10.3389/fphar.2023.1144878.
58. Khanna A, Maurya PK. Role of tea catechins in prevention of aging and age-related disorders. *Tang Humanit Med.* 2012;2(1):2.1–11. doi:10.5667/tang.2011.0016.
59. Dai J, Sameen DE, Zeng Y, Li S, Qin W, Liu Y. An overview of tea polyphenols as bioactive agents for food packaging applications. *LWT.* 2022;167(4):113845. doi:10.1016/j.lwt.2022.113845.
60. Noll C, Kandiah J, Moroy G, Gu Y, Dairou J, Janel N. Catechins as a potential dietary supplementation in prevention of comorbidities linked with down syndrome. *Nutrients.* 2022;14(10):2039. doi:10.3390/nu14102039.
61. Yaneva Z, Ivanova D. Catechins within the biopolymer matrix-design concepts and bioactivity prospects. *Antioxidants.* 2020;9(12):1180. doi:10.3390/antiox9121180.
62. Abudurehman B, Yu X, Fang D, Zhang H. Enzymatic oxidation of tea catechins and its mechanism. *Molecules.* 2022;27(3):942. doi:10.3390/molecules27030942.
63. Li N, Taylor LS, Ferruzzi MG, Mauer LJ. Kinetic study of catechin stability: effects of pH, concentration, and temperature. *J Agric Food Chem.* 2012;60(51):12531–9. doi:10.1021/jf304116s.
64. Yan Z, Zhong Y, Duan Y, Chen Q, Li F. Antioxidant mechanism of tea polyphenols and its impact on health benefits. *Anim Nutr.* 2020;6(2):115–23. doi:10.1016/j.aninu.2020.01.001.
65. Shikha D, Singh A, Rangra NK, Monga V, Bhatia R. Insights to therapeutic potentials, pharmaceutical formulations, chemistry and analytical methods of catechin. *Phytochem Rev.* 2024;23(5):1557–98. doi:10.1007/s11101-024-09929-9.
66. Zhu Y, Zhang J, Chen F, Hu X, Xu D, Cao Y. Epimerisation and hydrolysis of catechins under ultrasonic treatment. *Int J Food Sci Tech.* 2021;56(1):312–20. doi:10.1111/ijfs.14633.
67. McClements DJ. Encapsulation, protection, and delivery of bioactive proteins and peptides using nanoparticle and microparticle systems: a review. *Adv Colloid Interface Sci.* 2018;253(8):1–22. doi:10.1016/j.cis.2018.02.002.
68. Kim JM, Kang JY, Park SK, Han HJ, Lee KY, Kim AN, et al. Effect of storage temperature on the antioxidant activity and catechins stability of Matcha (*Camellia sinensis*). *Food Sci Biotechnol.* 2020;29(9):1261–71. doi:10.1007/s10068-020-00772-0.
69. Bińkowska W, Szpicer A, Stelmasiak A, Wojtasik-Kalinowska I, Póltorak A. Microencapsulation of polyphenols and their application in food technology. *Appl Sci.* 2024;14(24):11954. doi:10.3390/app142411954.
70. Andrés CMC, Pérez de la Lastra JM, Juan CA, Plou FJ, Pérez-Lebeña E. Polyphenols as antioxidant/pro-oxidant compounds and donors of reducing species: relationship with human antioxidant metabolism. *Processes.* 2023;11(9):2771. doi:10.3390/pr11092771.
71. Vilarinho F, Stanzione M, Buonocore GG, Barbosa-Pereira L, Sendón R, Vaz MF, et al. Green tea extract and nanocellulose embedded into polylactic acid film: properties and efficiency on retarding the lipid oxidation of a model fatty food. *Food Packag Shelf Life.* 2021;27(S1):100609. doi:10.1016/j.fpsl.2020.100609.
72. Kaewprachu P, Osako K, Rungraeng N, Rawdkuen S. Characterization of fish myofibrillar protein film incorporated with catechin-Kradon extract. *Int J Biol Macromol.* 2018;107(Pt B):1463–73. doi:10.1016/j.ijbiomac.2017.10.011.
73. Higuchi M, Abiko Y, Washio J, Takahashi N. Antimicrobial effects of epigallocatechin-3-gallate, a catechin abundant in green tea, on periodontal disease-associated bacteria. *Arch Oral Biol.* 2024;167(7 Suppl):106063. doi:10.1016/j.archoralbio.2024.106063.
74. Renzetti A, Betts JW, Fukumoto K, Rutherford RN. Antibacterial green tea catechins from a molecular perspective: mechanisms of action and structure–activity relationships. *Food Funct.* 2020;11(11):9370–96. doi:10.1039/d0fo02054k.
75. Wu M, Brown AC. Applications of catechins in the treatment of bacterial infections. *Pathogens.* 2021;10(5):546. doi:10.3390/pathogens10050546.

76. Gopal J, Muthu M, Paul D, Kim DH, Chun S. Bactericidal activity of green tea extracts: the importance of catechin containing nano particles. *Sci Rep.* 2016;6(1):19710. doi:10.1038/srep19710.
77. Wu X, Liu Z, He S, Liu J, Shao W. Development of an edible food packaging gelatin/zein based nanofiber film for the shelf-life extension of strawberries. *Food Chem.* 2023;426(10):136652. doi:10.1016/j.foodchem.2023.136652.
78. Tilley A, McHenry MP, McHenry JA, Solah V, Bayliss K. Enzymatic browning: the role of substrates in polyphenol oxidase mediated browning. *Curr Res Food Sci.* 2023;7(1):100623. doi:10.1016/j.crfs.2023.100623.
79. Zhou X, Iqbal A, Li J, Liu C, Murtaza A, Xu X, et al. Changes in browning degree and reducibility of polyphenols during autoxidation and enzymatic oxidation. *Antioxidants.* 2021;10(11):1809. doi:10.3390/antiox10111809.
80. Tian X, Lv Y, Zhao L, Wang Y, Liao X. Insight into the mechanism of high hydrostatic pressure effect on inhibitory efficiency of three natural inhibitors on polyphenol oxidase. *Food Chem.* 2024;457(8):140118. doi:10.1016/j.foodchem.2024.140118.
81. Nirmal NP, Benjakul S. Inhibition kinetics of catechin and ferulic acid on polyphenoloxidase from cephalothorax of Pacific white shrimp (*Litopenaeus vannamei*). *Food Chem.* 2012;131(2):569–73. doi:10.1016/j.foodchem.2011.09.025.
82. Hao S, Yang D, Zhao L, Shi F, Ye G, Fu H, et al. EGCG-mediated potential inhibition of biofilm development and quorum sensing in *Pseudomonas aeruginosa*. *Int J Mol Sci.* 2021;22(9):4946. doi:10.3390/ijms22094946.
83. Hengge R. Targeting bacterial biofilms by the green tea polyphenol EGCG. *Molecules.* 2019;24(13):2403. doi:10.3390/molecules24132403.
84. Wu CY, Su TY, Wang MY, Yang SF, Mar K, Hung SL. Inhibitory effects of tea catechin epigallocatechin-3-gallate against biofilms formed from *Streptococcus mutans* and a probiotic *Lactobacillus* strain. *Arch Oral Biol.* 2018;94(9):69–77. doi:10.1016/j.archoralbio.2018.06.019.
85. Kapoor MP, Sugita M, Fukuzawa Y, Timm D, Ozeki M, Okubo T. Green tea catechin association with ultraviolet radiation-induced erythema: a systematic review and meta-analysis. *Molecules.* 2021;26(12):3702. doi:10.3390/molecules26123702.
86. Rashidinejad A, Birch EJ, Everett DW. Effects of (+)-catechin on the composition, phenolic content and antioxidant activity of full-fat cheese during ripening and recovery of (+)-catechin after simulated *in vitro* digestion. *Antioxidants.* 2016;5(3):29. doi:10.3390/antiox5030029.
87. Tripathi S, Kumar P, Gaikwad KK. UV-shielding and antioxidant properties of chitosan film impregnated with *Acacia catechu* modified with calcium carbonate for food packaging. *Int J Biol Macromol.* 2024;257:128790. doi:10.1016/j.ijbiomac.2023.128790.
88. Jacob J, Linson N, Binoj JS, Mansingh BB, Kuriakose S, Thomas S. Polymers and fillers used in the packaging industry. In: *Nanostructured materials for food packaging applications*. Amsterdam, The Netherlands: Elsevier; 2024. p. 31–48. doi:10.1016/b978-0-323-99525-2.00026-8.
89. Borbolla-Jiménez FV, Peña-Corona SI, Farah SJ, Jiménez-Valdés MT, Pineda-Pérez E, Romero-Montero A, et al. Films for wound healing fabricated using a solvent casting technique. *Pharmaceutics.* 2023;15(7):1914. doi:10.3390/pharmaceutics15071914.
90. Das Adhikary N. Recent advances in different fabrication techniques to formulate biodegradable plastic and their effects on functional properties of the film: a mini-review. *Pharma Innov J.* 2023;12(7):1760–6.
91. Prakoso FAH, Indarto R, Utama GL. Edible film casting techniques and materials and their utilization for meat-based product packaging. *Polymers.* 2023;15(13):2800. doi:10.3390/polym15132800.
92. Anu Bhushani J, Anandharamkrishnan C. Electrospinning and electrospaying techniques: potential food based applications. *Trends Food Sci Technol.* 2014;38(1):21–33. doi:10.1016/j.tifs.2014.03.004.
93. Zhang C, Li Y, Wang P, Zhang H. Electrospinning of nanofibers: potentials and perspectives for active food packaging. *Compr Rev Food Sci Food Saf.* 2020;19(2):479–502. doi:10.1111/1541-4337.12536.
94. Rajunaik B, Franklin MEE, Seethu BG, Pushpadass HA, Battula SN, Naik NL. Fabrication and characterization of electrospun catechins-loaded nanofibres for fortification of milk. *J Food Sci Technol.* 2024;61(4):798–811. doi:10.1007/s13197-023-05891-0.
95. Wang Y, Xu H, Wu M, Yu DG. Nanofibers-based food packaging. *ES Food Agrofor.* 2022;7:1–24. doi:10.30919/esfaf598.

96. Wang Y, Khan MA, Chen K, Zhang L, Chen X. Electrospinning of natural biopolymers for innovative food applications: a review. *Food Bioprocess Technol.* 2023;16(4):704–25. doi:10.1007/s11947-022-02896-z.
97. Yu DG, Wang M, Li X, Liu X, Zhu LM, Annie Bligh SW. Multifluid electrospinning for the generation of complex nanostructures. *WIREs Nanomed Nanobiotechnol.* 2020;12(3):e1601. doi:10.1002/wnan.1601.
98. Zhang M, Ahmed A, Xu L. Electrospun nanofibers for functional food packaging application. *Materials.* 2023;16(17):5937. doi:10.3390/ma16175937.
99. Madhu K, Dhal MK, Banerjee A, Katiyar V, Kumar A. Melt-processed cast films of calcite reinforced starch/guar-gum biopolymer composites for packaging applications. *J Mater Sci.* 2025;60(5):2689–708. doi:10.1007/s10853-025-10627-w.
100. Park JH, Kim SK. Expansion injection molding process using clamping force for melt compression. *Polymers.* 2024;16(3):424. doi:10.3390/polym16030424.
101. Sadeghi A, Ali Razavi SM, Shahrampour D. Fabrication and characterization of biodegradable active films with modified morphology based on polycaprolactone-poly(lactic acid)-green tea extract. *Int J Biol Macromol.* 2022;205(1):341–56. doi:10.1016/j.ijbiomac.2022.02.070.
102. Latos-Brozio M, Masek A. The application of (+)-catechin and polydatin as functional additives for biodegradable polyesters. *Int J Mol Sci.* 2020;21(2):414. doi:10.3390/ijms21020414.
103. De La Cruz-Molina AV, Ayala Zavala JF, Bernal Mercado AT, Cruz Valenzuela MR, González-Aguilar GA, Lizardi-Mendoza J, et al. Maltodextrin encapsulation improves thermal and pH stability of green tea extract catechins. *J Food Process Preserv.* 2021;45(9):e15729. doi:10.1111/jfpp.15729.
104. Qi C, Liu G, Ping Y, Yang K, Tan Q, Zhang Y, et al. A comprehensive review of nano-delivery system for tea polyphenols: construction, applications, and challenges. *Food Chem X.* 2023;17(5):100571. doi:10.1016/j.fochx.2023.100571.
105. Cheng H, Mou Z, Wang W, Zhang W, Wang Z, Zhang M, et al. Chitosan-catechin coating as an antifungal and preservable agent for postharvest *satsuma* oranges. *J Food Biochem.* 2019;43(4):e12779. doi:10.1111/jfbc.12779.
106. Kudaibergenova RM, Baibazarova EA, Balpanova DT, Sugurbekova GK, Serikbayeva AM, Kalmakhanova MS, et al. Design and application of superhydrophobic magnetic nanomaterials for efficient oil–water separation: a critical review. *Molecules.* 2025;30(15):3313. doi:10.3390/molecules30153313.
107. Sabaghi M, Maghsoudlou Y, Kashiri M, Shakeri A. Evaluation of release mechanism of catechin from chitosan-polyvinyl alcohol film by exposure to gamma irradiation. *Carbohydr Polym.* 2020;230(5):115589. doi:10.1016/j.carbpol.2019.115589.
108. Peres I, Rocha S, do Carmo Pereira M, Coelho M, Rangel M, Ivanova G. NMR structural analysis of epigallocatechin gallate loaded polysaccharide nanoparticles. *Carbohydr Polym.* 2010;82(3):861–6. doi:10.1016/j.carbpol.2010.06.007.
109. Sabaghi M, Maghsoudlou Y, Kashiri M, Shakeri A. Release kinetics of double entrapped catechin in chitosan nanoparticle matrix and mixing chitosan–polyvinyl alcohol film. *J Packag Technol Res.* 2022;6(2):125–36. doi:10.1007/s41783-022-00136-5.
110. Cheng C, Chen S, Su J, Zhu M, Zhou M, Chen T, et al. Recent advances in carrageenan-based films for food packaging applications. *Front Nutr.* 2022;9:1004588. doi:10.3389/fnut.2022.1004588.
111. Jiang L, Jia F, Han Y, Meng X, Xiao Y, Bai S. Development and characterization of zein edible films incorporated with catechin/ β -cyclodextrin inclusion complex nanoparticles. *Carbohydr Polym.* 2021;261(1526):117877. doi:10.1016/j.carbpol.2021.117877.
112. Lončarić A, Pablo Lamas J, Guerra E, Kopjar M, Lores M. Thermal stability of catechin and epicatechin upon disaccharides addition. *Int J Food Sci Tech.* 2018;53(5):1195–202. doi:10.1111/ijfs.13696.
113. Ponnusamy A, Khan A, Prodpran T, Kim JT, Benjakul S, Rhim JW. Active packaging film based on chitosan/gelatin blend incorporated with mango peel carbon dots: properties and shelf life extension of minced pork. *Int J Biol Macromol.* 2025;288(14):138692. doi:10.1016/j.ijbiomac.2024.138692.

114. Ponnusamy A, Rajasekaran B, Tagrida M, Prodpran T, Kim JT, Benjakul S. Bilayer polylactic acid and chitosan/gelatin film containing epigallocatechin gallate prepared through solvent casting and electrospinning: properties, bioactivities and release kinetics. *J Polym Environ.* 2024;32(1):260–76. doi:10.1007/s10924-023-02998-5.
115. Lv H, Xu H, Xu E, Jin Z, Zhao H, Yuan C, et al. Improving structural and functional properties of starch-catechin-based green nanofiber mats for active food packaging by electrospinning and crosslinking techniques. *Int J Biol Macromol.* 2024;267(3):131460. doi:10.1016/j.ijbiomac.2024.131460.
116. Latos-Brozio M, Masek A, Piotrowska M. Thermally stable and antimicrobial active poly(catechin) obtained by reaction with a cross-linking agent. *Biomolecules.* 2020;11(1):50. doi:10.3390/biom11010050.
117. Gadapa S, Battula SN, Mor S, Pushpadass HA, Naik LN, Emerald ME. Green tea catechin loaded niosomes: formulation and their characterization for food fortification. *J Food Sci Technol.* 2022;59(9):3669–82. doi:10.1007/s13197-022-05384-6.
118. Latos-Brozio M, Masek A. Natural polymeric compound based on high thermal stability catechin from green tea. *Biomolecules.* 2020;10(8):1191. doi:10.3390/biom10081191.
119. Subramani NK. Revisiting powder X-ray diffraction technique: a powerful tool to characterize polymers and their composite films. *Res Rev J Mat Sci.* 2016;4(4):1–5. doi:10.4172/2321-6212.1000158.
120. Uzun İ. Methods of determining the degree of crystallinity of polymers with X-ray diffraction: a review. *J Polym Res.* 2023;30(10):394. doi:10.1007/s10965-023-03744-0.
121. Mittal A, Singh A, Benjakul S, Prodpran T, Nilsuwan K, Huda N, et al. Composite films based on chitosan and epigallocatechin gallate grafted chitosan: characterization, antioxidant and antimicrobial activities. *Food Hydrocoll.* 2021;111(4):106384. doi:10.1016/j.foodhyd.2020.106384.
122. Lei Y, Mao L, Yao J, Zhu H. Improved mechanical, antibacterial and UV barrier properties of catechol-functionalized chitosan/polyvinyl alcohol biodegradable composites for active food packaging. *Carbohydr Polym.* 2021;264(1):117997. doi:10.1016/j.carbpol.2021.117997.
123. Arrieta MP, Sessini V, Peponi L. Biodegradable poly(ester-urethane) incorporated with catechin with shape memory and antioxidant activity for food packaging. *Eur Polym J.* 2017;94(10–11):111–24. doi:10.1016/j.eurpolymj.2017.06.047.
124. Yong H, Wang Z, Huang J, Liu J. Preparation, characterization and application of antioxidant packaging films based on chitosan-epicatechin gallate conjugates with different substitution degrees. *Int J Biol Macromol.* 2024;260:129568. doi:10.1016/j.ijbiomac.2024.129568.
125. Hu X, Zhang H, Wang Y, Wang H, Wang L, Elfalleh W, et al. Effect of soybean protein-isolate-catechin edible film and coating on the storage quality of bean bun. *Food Biosci.* 2024;57(2):103613. doi:10.1016/j.fbio.2024.103613.
126. Rawdkuen S, Suthiluk P, Kamhangwong D, Benjakul S. Mechanical, physico-chemical, and antimicrobial properties of gelatin-based film incorporated with catechin-lysozyme. *Chem Cent J.* 2012;6(1):131. doi:10.1186/1752-153X-6-131.
127. Lopez de Dicastillo C, Nerin C, Alfaro P, Catala R, Gavara R, Hernandez-Munoz P. Development of new antioxidant active packaging films based on ethylene vinyl alcohol copolymer (EVOH) and green tea extract. *J Agric Food Chem.* 2011;59(14):7832–40. doi:10.1021/jf201246g.
128. Iniguez-Franco F, Soto-Valdez H, Peralta E, Ayala-Zavala JF, Auras R, Gámez-Meza N. Antioxidant activity and diffusion of catechin and epicatechin from antioxidant active films made of poly(L-lactic acid). *J Agric Food Chem.* 2012;60(26):6515–23. doi:10.1021/jf300668u.
129. Chou MY, Osako K, Lee TA, Wang MF, Lu WC, Wu WJ, et al. Characterization and antibacterial properties of fish skin gelatin/guava leaf extract bio-composited films incorporated with catechin. *LWT.* 2023;178(4):114568. doi:10.1016/j.lwt.2023.114568.
130. Nguyen-Tri P, Ghassemi P, Carriere P, Nanda S, Assadi AA, Nguyen DD. Recent applications of advanced atomic force microscopy in polymer science: a review. *Polymers.* 2020;12(5):1142. doi:10.3390/polym12051142.
131. Rashidinejad A, Birch EJ, Hindmarsh J, Everett DW. Molecular interactions between green tea catechins and cheese fat studied by solid-state nuclear magnetic resonance spectroscopy. *Food Chem.* 2017;215(10):228–34. doi:10.1016/j.foodchem.2016.07.179.

132. Nain CW, Mignolet E, Herent MF, Quetin-Leclercq J, Debier C, Page MM, et al. The catechins profile of green tea extracts affects the antioxidant activity and degradation of catechins in DHA-rich oil. *Antioxidants*. 2022;11(9):1844. doi:10.3390/antiox11091844.
133. Munteanu IG, Apetrei C. Assessment of the antioxidant activity of catechin in nutraceuticals: comparison between a newly developed electrochemical method and spectrophotometric methods. *Int J Mol Sci*. 2022;23(15):8110. doi:10.3390/ijms23158110.
134. Jacob J, Thomas S, Loganathan S, Valapa RB. Antioxidant incorporated biopolymer composites for active packaging. In: *Processing and development of polysaccharide-based biopolymers for packaging applications*. Amsterdam, The Netherlands: Elsevier; 2020. p. 239–60. doi:10.1016/b978-0-12-818795-1.00010-1.
135. Abdollahzadeh E, Nematollahi A, Hosseini H. Composition of antimicrobial edible films and methods for assessing their antimicrobial activity: a review. *Trends Food Sci Technol*. 2021;110(3):291–303. doi:10.1016/j.tifs.2021.01.084.
136. Garavand F, Rouhi M, Razavi SH, Cacciotti I, Mohammadi R. Improving the integrity of natural biopolymer films used in food packaging by crosslinking approach: a review. *Int J Biol Macromol*. 2017;104(Pt A):687–707. doi:10.1016/j.ijbiomac.2017.06.093.
137. Jacob J, Robert V, Valapa RB, Kuriakose S, Thomas S, Loganathan S. Poly(lactic acid)/polyethylenimine functionalized mesoporous silica biocomposite films for food packaging. *ACS Appl Polym Mater*. 2022;4(7):4632–42. doi:10.1021/acsapm.1c01551.
138. Cacciotti I, Mori S, Cherubini V, Nanni F. Eco-sustainable systems based on poly(lactic acid), diatomite and coffee grounds extract for food packaging. *Int J Biol Macromol*. 2018;112(9):567–75. doi:10.1016/j.ijbiomac.2018.02.018.
139. Wang Y, Muzammal Aslam M, Wang X, Gu H, jia W, Li W, et al. *Aloe vera* and tea polyphenols composite coating delays passion fruit senescence by promoting phenolic and flavonoid accumulation. *Food Res Int*. 2024;190(8):114594. doi:10.1016/j.foodres.2024.114594.
140. Santarelli V, Neri L, Moschetti R, Di Mattia CD, Sacchetti G, Massantini R, et al. Combined use of blanching and vacuum impregnation with trehalose and green tea extract as pre-treatment to improve the quality and stability of frozen carrots. *Food Bioprocess Technol*. 2021;14(7):1326–40. doi:10.1007/s11947-021-02637-8.
141. Kaewprachu P, Ben Amara C, Oulahal N, Gharsallaoui A, Joly C, Tongdeesontorn W, et al. Gelatin films with nisin and catechin for minced pork preservation. *Food Packag Shelf Life*. 2018;18:173–83. doi:10.1016/j.fpsl.2018.10.011.
142. Robalo J, Lopes M, Cardoso O, Sanches Silva A, Ramos F. Efficacy of whey protein film incorporated with Portuguese green tea (*Camellia sinensis* L.) extract for the preservation of Latin-style fresh cheese. *Foods*. 2022;11(8):1158. doi:10.3390/foods11081158.
143. Nirmal NP, Benjakul S. Effect of catechin and ferulic acid on melanosis and quality of Pacific white shrimp subjected to prior freeze–thawing during refrigerated storage. *Food Control*. 2010;21(9):1263–71. doi:10.1016/j.foodcont.2010.02.015.
144. Zhong W, Yuan W, Wang J, Wu Z, Du H, Huang X, et al. Antioxidant and preservation effects of tea polyphenols on apple juice. *Food Biosci*. 2024;60(2):104288. doi:10.1016/j.fbio.2024.104288.
145. Alirezalu K, Hesari J, Nemati Z, Munekata PES, Barba FJ, Lorenzo JM. Combined effect of natural antioxidants and antimicrobial compounds during refrigerated storage of nitrite-free frankfurter-type sausage. *Food Res Int*. 2019;120(5):839–50. doi:10.1016/j.foodres.2018.11.048.
146. Singh A, Benjakul S, Zhou P, Zhang B, Deng S. Effect of squid pen chitooligosaccharide and epigallocatechin gallate on discoloration and shelf-life of yellowfin tuna slices during refrigerated storage. *Food Chem*. 2021;351(2):129296. doi:10.1016/j.foodchem.2021.129296.
147. Popescu PA, Palade LM, Nicolae IC, Popa EE, Miteluț AC, Drăghici MC, et al. Chitosan-based edible coatings containing essential oils to preserve the shelf life and postharvest quality parameters of organic strawberries and apples during cold storage. *Foods*. 2022;11(21):3317. doi:10.3390/foods11213317.
148. Carullo G, Scarpelli F, Belsito EL, Caputo P, Oliviero Rossi C, Mincione A, et al. Formulation of new baking (+)-catechin based leavening agents: effects on rheology, sensory and antioxidant features during muffin preparation. *Foods*. 2020;9(11):1569. doi:10.3390/foods9111569.

149. Alenisan MA, Alqattan HH, Tolbah LS, Shori AB. Antioxidant properties of dairy products fortified with natural additives: a review. *J Assoc Arab Univ Basic Appl Sci.* 2017;24(1):101–6. doi:10.1016/j.jaubas.2017.05.001.
150. Silberbauer A, Schmid M. Packaging concepts for ready-to-eat food: recent progress. *J Packag Technol Res.* 2017;1(3):113–26. doi:10.1007/s41783-017-0019-9.
151. Mazzanti G, Di Sotto A, Vitalone A. Hepatotoxicity of green tea: an update. *Arch Toxicol.* 2015;89(8):1175–91. doi:10.1007/s00204-015-1521-x.
152. Ouyang J, Zhu K, Liu Z, Huang J. Prooxidant effects of epigallocatechin-3-gallate in health benefits and potential adverse effect. *Oxid Med Cell Longev.* 2020;2020(4):9723686. doi:10.1155/2020/9723686.
153. Nwakaudu AA, Nwakaudu MS, Owuamanam CI, Iheaturu NC. The use of natural antioxidant active polymer packaging films for food preservation. *Appl Signals Rep.* 2015;2(4):38–50. doi:10.1007/978-1-4615-2175-4_4.
154. Chen J, Gao Q, Zhou G, Xu X. Interactions between the protein-epigallocatechin gallate complex and nanocrystalline cellulose: a systematic study. *Food Chem.* 2022;387(42):132791. doi:10.1016/j.foodchem.2022.132791.
155. Younes M, Aggett P, Aguilar F, Crebelli R, Dusemund B, Filipič M, et al. Scientific opinion on the safety of green tea catechins. *EFSA J.* 2018;16(4):e05239. doi:10.2903/j.efsa.2018.5239.
156. European Commission. Commission Regulation (EU) No. 10/2011 on plastic materials and articles intended to come into contact with food; Commission Regulation (EC) No 450/2009 on active and intelligent materials intended to come into contact with food. *Official J Eur Union.* 2011 [cited 2026 Jan 1]. Available from: <https://www.chemradar.com/tools/cis/inv/66ed3bbd7b3f24e605ba0684>.
157. Piyasena N, Weerakoon N, Edirisinghe N, Ranatunga M, Abeysinghe S, Siriwardhane U. Extraction of tea polyphenols, catechins and caffeine from different tea cultivars in Sri Lanka. *Probe Food Sci Res.* 2024;6(1):2273. doi:10.18686/fsr2273.
158. Gupta RK, Pipliya S, Karunanithi S, Eswaran UGM, Kumar S, Mandliya S, et al. Migration of chemical compounds from packaging materials into packaged foods: interaction, mechanism, assessment, and regulations. *Foods.* 2024;13(19):3125. doi:10.3390/foods13193125.
159. Westlake JR, Laabei M, Jiang Y, Yew WC, Smith DL, Burrows AD, et al. Vanillin cross-linked chitosan film with controlled release of green tea polyphenols for active food packaging. *ACS Food Sci Technol.* 2023;3(10):1680–93. doi:10.1021/acscfoodscitech.3c00222.
160. Zhai X, Li M, Zhang R, Wang W, Hou H. Extrusion-blown starch/PBAT biodegradable active films incorporated with high retentions of tea polyphenols and the release kinetics into food simulants. *Int J Biol Macromol.* 2023;227:851–62. doi:10.1016/j.ijbiomac.2022.12.194.
161. He M, Li Y, Zong S, Li K, Han X, Zhao M. Life cycle assessment of carbon footprint of green tea produced by smallholder farmers in Shaanxi Province of China. *Agronomy.* 2023;13(2):364. doi:10.3390/agronomy13020364.
162. Thiruvengadam V, Baharuddin NHB, Lim JS. Implementation of life cycle analysis on green tea process. *Heliyon.* 2023;9(5):e15850. doi:10.1016/j.heliyon.2023.e15450.
163. Almeida C, Loubet P, da Costa TP, Quinteiro P, Laso J, Baptista de Sousa D, et al. Packaging environmental impact on seafood supply chains: a review of life cycle assessment studies. *J Ind Ecol.* 2022;26(6):1961–78. doi:10.1111/jiec.13189.