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Vitamin C-infused biopolymer films: a multifunctional approach for active food packaging and preservation

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Vitamin C has a dual functionality as a potent antioxidant and antimicrobial agent, positioning it as a transformative additive in sustainable packaging systems. The review systematically examines the chemical properties of ascorbic acid, highlighting its redox-active enediol structure, which enables oxygen scavenging, inhibits lipid oxidation, and modulates pH to extend shelf life. Advanced fabrication techniques, such as electrospinning, layer-by-layer assembly, and complex coacervation, are analyzed for their ability to stabilize vitamin C within polymer matrices, including chitosan, polyvinyl alcohol, and cellulose derivatives, thereby achieving encapsulation efficiencies. Moreover, the physicochemical, thermal, and functional properties of vitamin C-based films—including water vapor permeability, tensile strength, optical characteristics, and water contact angle — are critically evaluated, demonstrating their capacity to modulate moisture, gas barriers, and light transmission for perishable food protection. Vitamin C-based packaging film demonstrated enhanced physical and mechanical properties, as well as improved morphological and functional properties. However, these properties significantly impact the preservation efficiency of the food product. Moreover, the stability of vitamin C in the film/coating is an essential factor during storage studies. In contrast, the migration of vitamin C from the food packaging material into the food product is a key parameter. Therefore, by bridging material science with food engineering principles, this work establishes vitamin C-infused biopolymers as multifunctional platforms that align with global demands for eco-friendly packaging, nutritional preservation, and circular economy objectives in the food industry.

Sustainability spotlight

This work highlights the transformative potential of vitamin C-infused biopolymer films as a sustainable innovation in active food packaging. Leveraging the natural antioxidant and antimicrobial properties of ascorbic acid, the study explores its integration into biodegradable polymers such as chitosan, PVA, and cellulose derivatives. Through advanced encapsulation techniques like electrospinning, spray drying, and complex coacervation, vitamin C's stability and controlled release are significantly enhanced. These smart packaging materials not only extend the shelf life of perishable foods but also reduce environmental impact by replacing synthetic additives with naturally derived, bioactive compounds. The films exhibit improved physicochemical, mechanical, and barrier properties, contributing to food safety, reduced waste, and circular economy goals. This research bridges food engineering and material science, offering scalable solutions that align with global sustainability targets and consumer demand for eco-friendly packaging.

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1. Introduction

In recent years, the research and development of bioactive substances with inherent preservation properties have been driven by the growing need for sustainable and functional food packaging.[1–3] Among various bioactive compounds, vitamin C (Vit C) has emerged as a potential rival due to its substantial antioxidant and antibacterial properties as well as its role in sustaining human health.[4] Vit C has been renowned for years for its health advantages, and it is regularly used in the food and pharmaceutical sectors to enhance nutritional content and prevent oxidative deterioration. Besides its nutritional advantages, Vit C has been widely investigated for potential uses in food packaging systems.[1] This innovative approach harnesses the inherent characteristics of Vit C to extend the shelf life and maintain the quality of perishable food products. Vit C incorporation into polymer-based films and coatings is an innovative method for developing effective and biodegradable packaging materials that address environmental sustainability issues and food safety.[5] By integrating Vit C into biopolymer substances, these packing processes may safeguard food from oxidation and microbial spoilage while simultaneously being beneficial for human health.

The unique chemistry and strong reducing properties of Vit C make it highly effective in food packaging applications. Although it is susceptible to damage from oxygen, its ability to transfer electrons helps inhibit lipid oxidation and maintain food freshness.[6] Incorporating Vit C into polymer matrices such as starch, chitosan, gelatin, and PVA may improve its stability and bioavailability. Encapsulation methods, such as electrospinning and ionic gelation, enable the precise regulation of film characteristics. These films' physicochemical, mechanical, thermal, and optical characteristics, along with their barrier capabilities, affect moisture and gas transport, allowing controlled Vit C release for enhanced food preservation.[7] The production of Vit C-based films and coatings comprises the integration of Vit C with polymers to create materials demonstrating enhanced barrier, mechanical, optical, thermal, and morphological characteristics. Moreover, these materials might demonstrate enhanced resistance to moisture and oxygen, which are essential in avoiding the deterioration of packed goods.

Because of its nearly neutral pH, Vit C (ascorbic acid) is highly susceptible to environmental factors, including oxygen, light, and temperature. Upon oxidation, it transforms into dehydroascorbic acid (DHAA), which maintains biological activity but has reduced stability. Furthermore, the degradation of Vit C results in irreversible molecules such as 2,3-diketogulonic acid, reducing its functional attributes.[8] Vit C derivatives, such as carboxyl esters and magnesium ascorbyl phosphate, exhibit better stability. These compounds exhibit certain antioxidant activities while providing enhanced stability compared to ascorbic acid.[9] Many techniques, including encapsulation, antioxidant compounds, and regulated storage conditions, are employed to enhance the stability of Vit C. Coatings and films made of polymers can help safeguard Vit C against oxidative stress, improving its shelf-life in food packaging applications alongside retaining its antioxidant capacity. The release kinetics of Vit C through films or coatings into food products are impacted by factors including polymeric structure, film thickness, and atmospheric conditions such as temperature and humidity.[10] The release rate of Vit C from films or coatings into food products might be regulated by various mechanisms, such as diffusion, swelling, and degradation of the film matrix, which check the continuous delivery of Vit C. In edible films, the release of Vit C is typically controlled through dissolution or swelling mechanisms, whereas the bioactive substance is released as the matrix breaks down. Hydrophilic polymers promote rapid release, whereas hydrophobic matrices restrict diffusion. Mathematical techniques, such as Fickian diffusion and Korsmeyer–Peppas models, facilitate the prediction of release characteristics.[11,12] Controlled release ensures prolonged antioxidant capacity, enhancing food preservation and nutritional quality. The release rate can be improved by parameters such as film thickness and production techniques, allowing specific delivery systems that meet particular dietary needs.

The utilization of Vit C-based films and coatings in food preservation has excellent potential for maintaining the safety and quality of packaged food, including fresh fruit, meat, dairy, and baked products.[1] These innovative packaging options can benefit perishable foods, such as fruits, vegetables, and meat products, by minimizing spoilage and preserving their nutritional composition. In addition, the use of biodegradable polymers, such as PVA and cellulose derivatives, in these systems aligns with the growing demand for environmentally friendly packaging alternatives. With current investigations in this field, Vit C-based packaging is expected to become essential to the food sector's efforts to improve product preservation and reduce its environmental footprint.[13] This review aims to comprehensively review an innovative application of Vit C in food packaging systems, exploring its chemistry, physicochemical characteristics, stability, release mechanisms, and practical applications in food preservation. The integration of Vit C into active packaging demonstrates a creative approach to improving food safety and sustainability while meeting customer expectations for organic and health-enhancing options for packaging.

2. Chemistry, structure and properties of Vit C

In 1912, Albert Szent-Györgyi discovered the Vit C (Vit-C).[14] Vit-C ($C_6H_8O_6$), also referred to as ascorbic acid, is a low molecular weight carbohydrate structurally similar to hexose sugars, consisting of a six-carbon symmetric backbone. Chemically, it is classified as an aldono-1,4-lactone of a hexonic acid, featuring an enediol moiety at the C-2 and C-3 positions, which facilitates its electron-donating capability and contributes to its antioxidant properties. Among the stereoisomers of Vit C (Fig. 1), L-ascorbic acid, erythorbic acid (D-araboascorbic acid), and D-ascorbic acid exhibit varying degrees of biological activity in the human body, though L-ascorbic acid remains the most physiologically relevant form. As a crucial micronutrient, ascorbic acid is vital for maintaining normal metabolic functions and homeostasis in the human body.[8] Humans and other primates cannot synthesize this critical water-soluble nutrient due to mutations in the gene that generates L-gulono-γ-lactone oxidase. Vit-C is categorized as a ketolactone and possesses two ionizable hydroxyl groups. Vit-C possesses two pK_a values: pK_{a1} is 4.2 and pK_{a2} is 11.6. At physiological pH (about 7.4), the ascorbate monoanion ($AscH^-$) is predominant, rendering it a potent reducing agent. The acidity of Vit-C is augmented by its

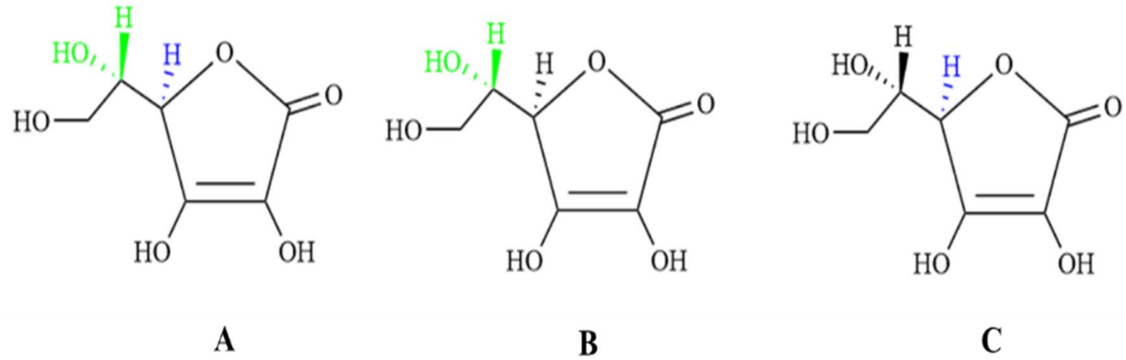

Fig. 1 The optical isomers of vitamin C include (A) L-ascorbic acid, (B) erythorbic acid, and (C) D-ascorbic acid, with distinctions indicated in red and blue.

structural characteristics, notably a nearby enediol group that stabilizes the conjugate base *via* resonance.[15] The molecular weight is approximately 176.12 g mol^{-1}, and the density is 1.694 g cm^{-3}.[16] The compound has a boiling point of 553 °C and a melting point of 190 °C.[17]

Vit-C demonstrates different properties based on dosage and method of delivery (Fig. 2). Numerous diseases, including cancer and coronary artery disease, may result from heightened free radical activity, causing cellular and tissue damage; thus, Vit-C, a potent antioxidant, has been extensively researched for its potential anti-cancer and anti-atherosclerosis effects.[18] Vit C is a powerful antioxidant that effectively prevents oxidative spoilage, particularly in aqueous environments; however, its rapid degradation may restrict its long-term efficacy when

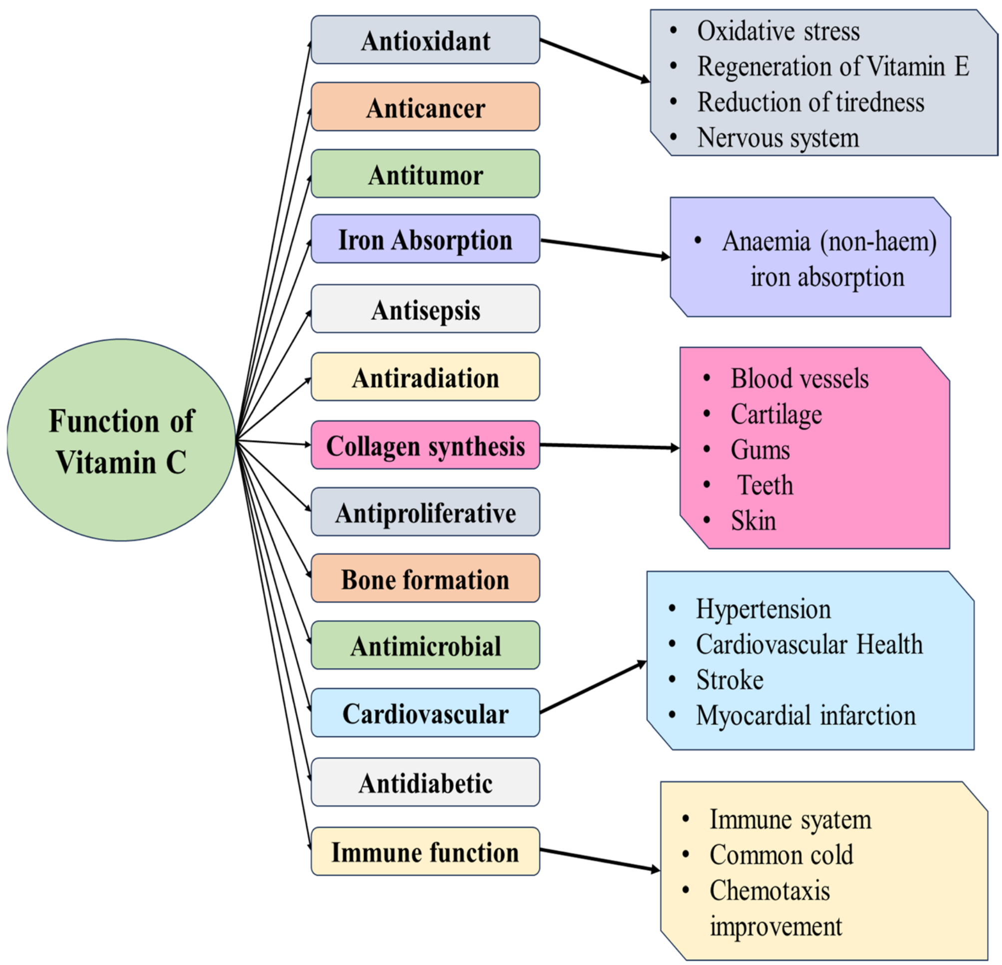

Fig. 2 Functions of vitamin C.

compared to tocopherols, which are better suited for lipid environments, and polyphenols, which provide both antioxidant and antimicrobial advantages along with enhanced stability across various applications.[19] The degraded product exhibits bioactivity comparable to Vit-C, although it demonstrates reduced susceptibility to oxidation. Because of its hydrophilicity and low molecular weight, Vit-C is oxidized to ascorbyl radical, which then undergoes dismutation to provide Vit-C and dehydroascorbic acid. It is intracellularly converted back to Vit C.[8] The antiviral characteristics of Vit-C are notably advantageous in the treatment of COVID-19. Vit C suppresses viral proliferation and enhances interferon synthesis. Moreover, Vit C amplifies the antiviral efficacy of pulmonary epithelial cells. Vit C participates in the manufacture of catecholamine hormones and amidated peptides, including vasopressin, by serving as a cofactor for hydroxylase enzymes. These hormones are essential for the cardiovascular response to severe illness.[20] Vit C is typically more economical than other bioactive compounds, including tocopherols and certain polyphenols, rendering it a favoured option for extensive uses in food and packaging.[21] However, it is exceedingly unstable and prone to deterioration in adverse conditions, including heat, light, oxygen, and low pH settings. Instability during manufacturing, transportation, and storage can adversely affect the quality of the food product.[22] Encapsulation and antioxidants such as citric acid can enhance its longevity of Vit C.[23]

3. The function of Vit C in a food packaging system

Packaging has been found to extend shelf life by reducing the growth of spoilage organisms.[24] In response to the urgent need for eco-friendly packaging materials, Vit-C is willingly incorporated into packaging based on biodegradable polymers. Vit-C functions as a potent preservative in food packaging systems by safeguarding against oxidation, maintaining nutritional quality, prolonging shelf life, and positively interacting with diverse packaging materials. Vit C (ascorbic acid), tocopherols (vitamin E), and polyphenols comprise the three principal categories of antioxidants commonly incorporated into biopolymer matrices for active food packaging and material stabilization. However, their effectiveness significantly fluctuates based on their chemical composition and the surrounding environment.[25] Comparative analyses consistently demonstrate that polyphenols surpass both tocopherols and ascorbic acid in antioxidant evaluations; however, tocopherols are superior in lipid protection, while Vit C is more efficacious in short-term aqueous environments where rapid release is advantageous.[26] Vit C, however, experiences quick breakdown and migration, diminishing its longevity, whereas tocopherols and polyphenols exhibit greater stability and offer prolonged protection. Moreover, synergistic benefits frequently occur when Vit C is paired with tocopherols, as ascorbic acid can restore oxidized tocopherol, while polyphenols can enhance lipid-phase protection. Consequently, the selection of these antioxidants should be determined by the system's polarity, the specific food or polymer, the preferred release kinetics, and the processing circumstances, with mixtures frequently providing the most efficacious strategy.[21] However, Vit C plays a multifunctional role in active packaging by acting as:

(a) An antioxidant: ascorbic acid functions as an antioxidant in packaging by donating hydrogen or electrons from its enediol structure, thereby neutralising free radicals and reactive oxygen species (ROS). This action interrupts the propagation steps of lipid peroxidation by stabilizing lipid peroxyl radicals, thereby reducing the formation of hydroperoxides and subsequent oxidative deterioration.

(b) An antibacterial agent: although ascorbic acid is a potent antioxidant, it also exhibits prooxidant behavior. This prooxidant behavior is influenced by three factors: the presence of metal ions, the concentration of ascorbic acid in matrix environments and its redox potential.[27] In the presence of transition metal ions, ascorbic acid reduces Fe^{3+} to Fe^{2+} and Cu^{2+} to Cu^{+}. In turn, the transition metal reduces hydrogen peroxide to form reactive hydroxyl radicals or peroxide ions, which induce cell death by exacerbating oxidative stress and damaging microbes' cell membranes, proteins, and DNA.

(c) A moisture regulator: Vit C serves a moisture-regulating role in packaging films due to its hygroscopic characteristics and the multiple hydroxyl groups that can form hydrogen bonds with water molecules. By binding water, it helps regulate moisture retention, thus reducing the amount of free water accessible for microbial growth and effectively lowering water activity. Ascorbic acid can function as a plasticizer within polymeric film matrices, improving flexibility, reducing brittleness associated with dehydration, and limiting excessive water absorption.

(d) A controlled release agent: the release of Vit C can be controlled by encapsulation, which encloses it within protective matrices and prevents degradation by modulating its diffusion. Release occurs gradually as the carrier undergoes swelling, degradation, or reacts to environmental stimuli such as pH or moisture, thereby ensuring sustained delivery and improved bioavailability relative to rapid unprotected release.

Grape packaging plays a crucial role in maintaining freshness, preventing microbial spoilage, and reducing post-harvest losses. Gong *et al.*[28] demonstrated that incorporating Vit-C into PBV films significantly enhanced their antioxidant, antimicrobial, and gas barrier properties, contributing to improved grape preservation. The addition of Vit-C enabled strong DPPH and $ABTS^{+}$ scavenging activity, controlled the packaging atmosphere, and increased nutrient conservation rate by more than 10%, thereby delaying spoilage. Moreover, it exhibited an antibacterial efficiency of above 99.99% against *E. coli*, *S. aureus*, and *B. subtilis*, ensuring food safety and extending shelf life. Hussain *et al.*[29] developed composite films with polyvinyl alcohol and carboxymethyl cellulose, incorporating Vit-C as an antioxidant. The antibacterial efficacy was assessed by measuring the zone of inhibition after 24 h. Films demonstrated significant antibacterial efficacy against Gram-positive *Staphylococcus aureus* (inhibition zone of 21 mm) and Gram-negative *Escherichia coli* (inhibition zone of 15 mm). The control sample exhibited negligible activity due to the absence of Vit-C, indicating that Vit-C serves as an effective antibacterial agent in the formulated films. Another study by Pereira *et al.*[30] aimed to develop biopolymeric films using a cassava starch-gelatin blend (1 : 1) with Vit-C as a natural antioxidant. Vit-C (0–10 g/100 g polymer) and catuaba extract (0–1.5 g/100 g polymer) were incorporated as bioactive ingredients. The highest antioxidant capacity (93.33%) was observed in films containing 10 g of vitamin C per 100 g of polymer.

Etxabide *et al.*[31] found that the addition of Vit-C to whey protein films significantly improved their UV-vis light absorbance up to 500 nm, enhancing the films' ability to protect food from UV-induced lipid oxidation. It is because ascorbic acid reacts with the amino acids present in the whey protein isolate *via* Maillard reaction to form coloured compounds (browning products, melanoidins) that strongly absorb in the visible region.[32] This increases film opacity and UV-vis absorbance. The incorporation of Vit-C also increased water absorption and elongation at break, due to its role as a plasticizer, while maintaining the film's gloss, water vapor permeability, structure, and thermal properties. These improvements make ascorbic acid-enriched whey protein films a promising alternative for food packaging, offering better protection and potential environmental benefits. Babar *et al.*[13] studied the effect of the incorporation of Vit-C at 1% and 1.5% into chitosan-based film. The incorporation of 1% and 1.5% Vit-C improved the DPPH radical scavenging activity, with the 1.5% concentration showing the highest antioxidant activity.

Additionally, the films demonstrated good biodegradability, with complete degradation observed after 60 days, indicating their potential as an environmentally friendly option for active food packaging. Rodríguez *et al.*[33] investigated the effect of Vit-C and moringa leaf extract incorporation into papaya-based edible films to prevent browning in minimally processed pears. The films with Vit-C exhibited the highest antioxidant activity, enhancing the shelf-life of minimally processed pears. The addition of Vit-C preserved the physicochemical properties of the pears and improved sensory acceptance under refrigeration. These findings suggest that ascorbic acid enhances the antioxidant capacity of the films, making them effective for food preservation by preventing oxidation.

Sartori & Menegalli,[32] showed that the incorporation of lipid microparticles containing Vit-C into plantain banana starch films effectively enhanced the films' properties. The encapsulation of ascorbic acid preserved its antioxidant activity during film production, maintaining 84% of its original activity after the drying process. The films with encapsulated ascorbic acid exhibited lower water vapor permeability, higher tensile strength, and improved opacity compared to the control films. The presence of the lipid microparticles also reduced light transmittance, further protecting the ascorbic acid from degradation. These findings highlight that the encapsulation of ascorbic acid not only protects its antioxidant properties but also improves the functional characteristics of polysaccharide-based films, making them suitable for food preservation applications. Bajer & Burkowska-But,[34] evaluated the properties of biodegradable film based on starch modified with ascorbic acid, caffeine, and dialdehyde starch. The addition of Vit C promoted the formation of a crystalline structure, enhancing the hydrophilicity and antioxidant activity of the films. In contrast, caffeine has the opposite effect and leads to a decline in orderliness. Furthermore, the film displayed excellent barrier properties and underwent effective biodegradation.

4. Fabrication of Vit C-based film/coating with polymers

Edible films functionalized with vitamins, minerals, and bioactive compounds are increasingly used to enhance the nutritional and preservative qualities of perishable foods. Among these, Vit-C is a critical additive due to its antioxidant properties, which mitigate oxidative degradation in food systems while offering health benefits.[35] However, Vit-C's instability under heat, light, and pH variations limits its practical efficacy in food and pharmaceutical applications.[36,37] Recent advances in encapsulation and polymer-based stabilization have revitalized interest in Vit-C integration, particularly in biodegradable films for sustainable food preservation.[38]

4.1 Materials for Vit-C-based film fabrication

4.1.1 Polymers. • Polyvinyl alcohol (PVA): prized for its water solubility, mechanical strength, and compatibility with hydrophilic additives like Vit-C.[5,39,40] Its film-forming ability makes it a cornerstone material for solution-cast and electrospun active packaging layers.

• Chitosan: enhances antimicrobial activity and film flexibility, with cationic properties that enable electrostatic interactions for nutrient encapsulation.[36] It is widely used in coatings for fresh produce to extend shelf life.[7,41]

• Cellulose derivatives: this category includes a range of materials from soluble polymers to nano-reinforcements. Phosphorylated cellulose nanocrystals (CNCs) improve cross-linking efficiency and Vit-C retention.[42,43] Nanofibrillated cellulose (NFC) and bacterial nanocellulose (BNC) are also gaining traction for creating high-strength, barrier-enhanced composite films. Sodium carboxymethyl cellulose (CMC-Na) is a soluble derivative commonly used as a primary matrix for edible coatings due to its excellent film-forming and gas barrier properties.[44,45]

• Polylactic acid (PLA): a hydrophobic, biodegradable linear aliphatic polyester widely used in food packaging due to its good biocompatibility and processability. It is often blended with other biopolymers to improve the overall functionality of active packaging systems. For instance, Bai *et al.*[46] used PLA blended with K-carrageenan in electrospun nanofiber membranes for blueberry preservation, highlighting its role as a structural polymer in packaging applications.

• Gelatin: a low-cost, biocompatible protein with good film-forming properties, often used as a base for composite films. It frequently requires modification or blending with other polymers to improve its mechanical and water resistance properties for packaging applications.[47]

4.1.2 Active ingredients. Vit-C: incorporated as ascorbic acid or its derivatives (*e.g.*, sodium ascorbate) to enhance

Table 1 Overview of Vit-C encapsulation and film fabrication techniques for packaging

Technique	Key principle	Common polymers used	Packaging application advantages	Reported Vit-C encapsulation efficiency (EE)/key outcome	Reference
Spray drying	Rapid evaporation of solvent from droplets to form dry powder	Chitosan, sodium caseinate, HPMC	Scalable production of stable powders for integration into films/coatings. High process flexibility	91.9% EE in W/O/W emulsion stabilized by chitosan/HPMC	36
Electrospinning	High-voltage electrostatic field to produce polymer nanofibers	PVA, PLA, gelatin, K-carrageenan	High surface-area-to-volume ratio for enhanced activity; controlled release	71.27–81.35% retention in KC/PLA nanofibers after 10 days	46
Solution casting	Evaporation of solvent from a polymer solution to form a solid film	Chitosan, gelatin, alginate, CMC-Na	Simplicity, versatility, and excellent control over film composition and thickness	Effective integration and retention of function (*e.g.*, 93.6% DPPH scavenging for gelatin-LOHB films)	47 and 48
Complex coacervation	Phase separation driven by electrostatic interaction of oppositely charged polymers	Gelatin-pectin, chitosan-gum Arabic	High EE under mild conditions; protects sensitive compounds from thermal degradation	Up to 90.3% EE in gelatin-pectin coacervates	49

antioxidant capacity. Nanoencapsulation improves its stability, achieving greater than 90% encapsulation efficiency in chitosan-CNC matrices.[42]

4.2 Fabrication methods and innovations

The choice of fabrication method is critical for determining the final film's structure, functionality, and suitability for food packaging applications. Techniques range from simple, scalable casting to advanced technologies that enable nanoencapsulation and precise layered structures. The fabrication technique is a critical determinant of encapsulation efficiency and the resulting film's functionality, as clearly compared in Table 1. However, encapsulation techniques used in the food industry, along with their relative cost and throughput, have been tabulated in Table 2.

4.2.1 Spray-drying microencapsulation. Spray drying (SD) is a versatile industrial process that converts liquids or suspensions into dry powders through rapid evaporation, offering scalability, formulation flexibility, and operational efficiency. This method is indispensable in the food industry for producing stable, functional ingredients that can be incorporated into packaging materials, such as active sachets, or as additives in polymer melts and coatings.[57] SD has dominated microencapsulation for decades due to its ability to protect sensitive bioactive compounds. The technique's success hinges on selecting appropriate encapsulating materials such as proteins, polysaccharides, or lipids, which shield core compounds from environmental stressors while preserving their functionality.[58]

Microencapsulation *via* SD has emerged as a viable solution to Vit-C's stability issues. Hu *et al.*[36] optimized a water-in-oil-in-water (W1/O/W2) emulsion system stabilized by chitosan and hydroxypropyl methylcellulose (HPMC), achieving 91.9% encapsulation efficiency and retaining 80.8% of Vit-C over 60 days of storage. Chitosan's cationic nature facilitates electrostatic interactions with anionic Vit-C, enhancing retention and controlled release. These spray-dried powders can be subsequently dispersed into polymer solutions for casting or compounded into masterbatches for extrusion, creating homogeneous active packaging films with sustained antioxidant release profiles.

4.2.2 Electrospinning. Electrospinning, which leverages high-voltage electrostatic fields to generate polymer nanofibers, has gained significant traction in food packaging due to its mild processing conditions and the high specific surface area of the resulting nanofibers, which is ideal for enhanced antioxidant activity and controlled release in food preservation applications.[28,46] A study suggested that eugenol is encapsulated into gelatin as the active component in the electrospinning technique to create eugenol-loaded gelatin nanofibers.[59]

A prominent example of its use in packaging is the development of rot-proof bronopol-embedded polyurethane hybrid films (PBV) containing Vit C, which showcased applicability in enhancing food preservation.[28] Bai *et al.*[46] demonstrated a highly effective electrospinning approach for blueberry preservation. They encapsulated a Vit C/hydroxypropyl-beta-cyclodextrin (HP-β-CD) inclusion complex within a K-carrageenan/polylactic acid (KC/PLA) nanofiber membrane. This system demonstrated excellent encapsulation and a very slow-release profile, retaining between 71.27% and 81.35% of the Vit C after 240 h (10 days). The resulting composite membrane significantly enhanced the preservation efficacy of blueberries, reducing weight loss to 7.89% (compared to 67.58% in the control) and improving firmness after 15 days of storage.

Beyond standalone mats, electrospinning is also used to create oral dispersible films (ODFs) for the delivery of nutrients. For instance, κ-carrageenan-based films, produced *via*

Table 2 Encapsulation techniques used in food industries along with its relative cost and throughput

Technique	Scalability	Relative cost	Throughput	Encapsulation efficiency & thermal stress	Industrial readiness	Reference
Spray-drying	High (widely used at industrial scale for food ingredients)	Low to medium	Very high (kg per t per day)	High EE possible; thermal stress can degrade Vit C unless optimized	Mature, cost-effective; easiest route for commercial films using powders/dry blends	50 and 51
Electrospinning/electrospraying	Low to medium (pilot plants exist; capital-intensive)	High	Low to medium (g per kg per day; emerging multi-nozzle increases throughput)	Very high EE & low thermal stress; core–shell possible; Vit C shows improved stability	Promising for active packaging (nanofibers/mats) but limited commercial examples; scale-up in R&D	52 and 53
Complex coacervation (protein–polysaccharide)	Medium (batch processes; scalable with unit operations)	Medium	Medium	Good EE for water-soluble actives; gentle process; pH/ionic sensitive	Good for microcapsules with controlled release; additional drying/stabilization add cost	54 and 55
Nanoemulsions/lipid nanocarriers	Medium to high (industrial homogenizers/microfluidizers common)	Medium	High (can be continuous)	Good EE for lipophilic actives; hydrophilic Vit C requires design; moderate thermal sensitivity	Attractive for wet film formulations; storage stability limiting without antioxidants	56

electrospinning, exhibit high solubility and rapid disintegration times.[60] Interestingly, the electrospinning process itself was observed to increase lipid hydroperoxide formation, a phenomenon mitigated by Vit C, particularly at a 4 : 20 Vit C/gelatin mass ratio, highlighting its dual role as both a nutrient and a potent antioxidant in electrospun nanomaterials (ENMs).[61]

4.2.3 Solution casting. Solution casting is a widely adopted, eco-friendly fabrication method for producing biodegradable edible films, offering versatility in sustainable food packaging applications. Its simplicity, scalability, and adaptability make it a cornerstone technique for developing films that align with global demands for greener alternatives.[62,63]

The process involves dissolving a polymer (*e.g.*, starch, alginate, chitosan, gelatin) and other components in a suitable solvent to form a homogeneous solution. This solution is then cast onto a flat substrate and allowed to dry, resulting in a thin film.[64,65] A key advantage lies in its ability to finely control film composition, thickness, and homogeneity, facilitating the integration of functional additives like Vit-C without compromising structural integrity.[66]

This method allows for the direct incorporation of Vit-C. For example, Tang *et al.*[47] synthesized a chemically modified Vit-C derivative (L-ascorbic acid–salicylic acid ester, LOHB) and directly mixed it into a gelatin/glycerol solution *via* solution casting. The resulting films demonstrated powerful, concentration-dependent antioxidant and UV-blocking activities (93.6% DPPH scavenging at 20% LOHB), confirming the successful integration and stability of Vit-C within the polymer matrix. Similarly, Shah *et al.*[48] employed sequential solution casting to fabricate a multilayer film, incorporating L-ascorbic acid into a sodium alginate (SA) layer sandwiched between a chitosan (CH) inner layer and an ethyl cellulose (EC) outer layer, creating a system with improved barrier and antioxidant properties. Furthermore, simple immersion or dipping—a form of solution casting—is a direct application method for applying Vit-C-functionalized coatings, as demonstrated by Song *et al.*[44] with a CMC-Na-based coating on fresh-cut asparagus lettuce and Ngoc *et al.*[41] with a CS/PVA blend on oranges.

4.2.4 Layer-by-layer (LbL) assembly. Layer-by-layer (LbL) assembly is a versatile and precise technique for engineering composite packaging films with tailored physicochemical properties and enhanced performance. By alternately depositing complementary biopolymers or functional components onto a substrate, LbL enables the design of coatings that address specific preservation challenges, such as oxygen barrier capacity, moisture retention, and antioxidant integration.[7,67]

A prominent application of LbL is the development of bilayer or multilayer coatings for fruit preservation, where alternating hydrophilic and hydrophobic layers synergize to prolong shelf life. This technique can be adapted to incorporate Vit-C directly into hydrophilic layers (*e.g.*, chitosan, alginate) or within nanocapsules that are subsequently deposited as a layer, providing a sustained release of antioxidants to the food surface. For instance, hydrocolloid-based bilayer coatings have demonstrated exceptional efficacy in maintaining the visual appeal, texture, and nutrient content of fruits during storage by controlling the release of bioactive compounds from the layered matrix.[68,69] Beyond preservation, LbL-assembled films can incorporate self-healing properties, enabling automatic repair of microcracks during storage—a breakthrough for extending packaging durability.[70]

4.2.5 Complex coacervation. Complex coacervation is a phase separation process driven by electrostatic interactions between oppositely charged biopolymers, such as proteins and polysaccharides. This method has gained prominence in the food industry due to its simplicity, high encapsulation efficiency (>90%), and ability to protect sensitive compounds under harsh thermal conditions.[61,66]

The process relies on adjusting the pH to enable the formation of coacervate complexes, which create a hydrophobic core–shell structure ideal for encapsulating hydrophobic bioactive compounds like vitamins or lipids.[71] Khuntia *et al.*[49] demonstrated this by encapsulating Vit C within gelatin-pectin coacervates, achieving optimal encapsulation efficiency (EE) at a specific wall-to-core ratio. These stable coacervated microparticles can be directly incorporated into biopolymer matrices *via* solution casting or extrusion to produce active packaging films, as demonstrated by their successful integration into starch-based films for perishable food storage. Furthermore, freeze-dried coacervates offer practical benefits over lipid nanovesicles, including easier transport, storage, and compliance with vegetarian or religious dietary requirements.[72,73] By forming a barrier between encapsulated compounds and external stressors, complex coacervation outperforms other methods in preserving unstable components, making it indispensable for functional food and nutraceutical applications.[74] Among the various techniques, complex coacervation and electrospinning (Table 1) consistently achieve some of the highest encapsulation efficiencies, making them particularly suitable for protecting this highly labile compound. Selecting an appropriate fabrication method is the first step in determining the film's final properties. Table 1 provides an overview of techniques such as electrospinning and solution casting, along with their reported encapsulation efficiencies and key advantages for packaging applications. The choice of method directly influences the morphological properties of the film, which in turn dictates its barrier and mechanical performance, as discussed in the next section.

5. Properties of Vit C-based film/coating

The incorporation of Vit C into polymer matrices significantly alters their functional properties, making them suitable for advanced food packaging applications. Recent research has focused not only on enhancing these properties through Vit-C addition but also on understanding the trade-offs and synergistic effects with other functional additives. The properties of these composite films, ranging from physicochemical to intelligent sensing capabilities, are critical determinants of their preservation efficacy and practical viability. The properties of Vit-C-based films are multifaceted and depend heavily on the polymer matrix and fabrication method. A summary of how Vit-C incorporation influences key property categories is provided in Table 3. Biopolymers and macromolecules possess inherent hydrophilicity, which is a primary limitation for their use in the packaging sector, where water resistance is essential.[75] Furthermore, enhancement of film properties through Vit C incorporation has been displayed in Table 4.

5.1 Physicochemical properties

Minor modifications in adduct composition can significantly enhance the optical and textural properties of polymer composites.[5] The encapsulation efficiency (EE) of Vit-C is highly dependent on wall-to-core material ratios and polymer concentration. Khuntia *et al.*[49] reported an optimal EE (up to 90.3%) at a 1 : 1 : 0.75 ratio with 7.5% gelatin/pectin, though ionic imbalances at higher core ratios reduced the EE. In contrast, Liu *et al.*[61] observed that Vit-C inclusion in fish oil-loaded gelatin nanofibers reduced loading capacity but maintained encapsulation efficiency. Ferreira Dantas *et al.*[80] highlighted the importance of accurate quantification, developing a direct colorimetric method that revealed EE for Vit-C in pluronic/chitosan–alginate nanoparticles was between 10–27%, lower than values often reported by indirect methods that mistake degradation for encapsulation.

Composite films integrating Vit-C with additives like methylene blue or nanoparticles further enhance functionality. Sadeghi *et al.*[43] demonstrated that Vit-C and methylene blue increase film thickness by filling cellulose nanofiber pores and coating fibers, improving mechanical resistance. Innovations such as Vit-C adduct-conjugated zinc oxide nanoparticles (ZnO NPs) and magnesium oxide nanoparticles (MgONPs@VCA) have improved photocatalytic degradation and redox activity.[77,83] For instance, pullulan-based coatings with Vit-C and tea polyphenols (TP) at 75.6 mPa s viscosity minimized grape weight loss to 12.27%.[76]

5.2 Barrier properties

Barrier properties, including oxygen (OTR) and water vapor transmission rates (WVTR), are critical for food preservation.[84] Vit-C's impact is matrix-dependent. Pullulan-based papers with Vit-C and TP exhibited improved oxygen-barrier properties at higher viscosities (lowest OTR at 108.5 mPa s), though additives slightly compromised these benefits.[76] Gong *et al.*[28] reported that Vit-C-enhanced polyurethane hybrid films (PBV) exhibited strong hydrophilicity (water contact angle: 94.22°), high moisture retention, and reduced water vapor transmission rates (WVTR), creating a humid microenvironment that slowed grape respiration and nutrient loss. Conversely, Sadeghi *et al.*[43] noted that Vit-C and methylene blue reduced moisture content and water vapor permeability (WVP) in cellulose films by blocking pores and disrupting hydrogen bonding.

A landmark study by Xu *et al.*[81] demonstrated a revolutionary approach to barrier enhancement. By using ascorbic acid (0.4 wt%) in the coagulation bath during regenerated cellulose film (RCF) production, they promoted orderly polymer rearrangement, resulting in a 51.22% increase in crystallinity. This

Table 3 Key properties of Vit C-based films/coatings

Additives	Polymer/matrix	Product	Salient findings	Fabrication methods	Reference
Physicochemical properties					
Tea polyphenols/Vit-C	Pullulan	Grapes	Less weight loss and improved hardness after 10 days	Multi layers	76
Methylene blue/Vit C (Cel/MB/VC)	Cellulose	Kit to detect hydrogen peroxide in smart packaging	Increase the thickness	Immersed in a solution	43
HPMC/Vit C	Chitosan		Vit C at pH 6.8 decreased after 40 min	Spray-dried microcapsules	36
Polyurethane, Vit-C	PBV hybrid films		Hydrophilicity (WCA: 94.22%), high swelling ratio		28
ZnO NPs, MgONPs, Vit-C adducts	ZnO/MgO nanocomposites		Improved photocatalytic degradation, redox activity		77
Vit-C	Gelatin-pectin		Optimal EE at 1 : 1 0.75 wall: core ratio – ionic imbalance at high Vit-C ratios		49
Vit-C	κ-Carrageenan		↑ Solubility- rapid disintegration ↑ tensile strength		60
Barrier properties					
Tea polyphenols/Vit-C	Pullulan	Grapes	Improved the oxygen transmission rate, water vapor transmission rate	Multi layers	76
HPMC/Vit C	Chitosan		Higher permeability and faster dissolution rate	Spray-dried microcapsules	36
Methylene blue/Vit C (Cel/MB/VC)	Cellulose	Kit to detect hydrogen peroxide in smart packaging	Reduced the moisture content and reduced the WVP	Immersed in a solution	43
Sodium caseinate, chitosan, Vit-C	Chitosan-caseinate microcapsules		Degradation at neutral pH due to dissolved oxygen		36
Mechanical properties					
Lemon juice (Vit-C)	PVA		↑ mechanical stability (green cross-linking)-long-term stability		39
Tea polyphenols/Vit-C	Pullulan	Grapes	The tensile strength and tearing properties increased, and the elongation at break was also improved. The addition of Vit-C slightly enhanced elongation	Multi layers	76
Vit C	PBV	Grapes	The mechanical properties of PBV films significantly declined	Electrospinning	28
Methylene blue/Vit C (Cel/MB/VC)	Cellulose	Kit to detect hydrogen peroxide in smart packaging	Reduced the tensile strength and have increased the EAB and flexibility	Immersed in a solution	43
Optical properties					
Vit-C/sulfonamide	PVA	Optical devices	The refractive index (n) and dielectric loss (ε_i) values are elevated notably, whereas the optical band gap energy (E_g) declined	Solution casting	40
Vit-C adducts (dopant 3b)	Gelatin		↑ refractive index (n) ↓ Bandgap (E_g) Enhanced polarization		5

Table 3 (*Contd.*)

Additives	Polymer/matrix	Product	Salient findings	Fabrication methods	Reference
Thermal properties					
Vit C	PBV	Grapes	Positive thermal stability PBV films degrade at 318.9 °C (*vs.* PU at 344.2 °C)	Electrospinning	28
High catechins/Vit-C	Sodium alginate polysaccharide		Most stable structures	Solution-casting	78
Morphological properties					
Vit-C	Gelatin-pectin		Smooth surfaces at ≥5% wall material; cracks at 2.5%. Median diameter (D_v (50)) influenced by wall-to-core ratio		23
HPMC/Vit C	Chitosan		Irregular, conglutinated, spherical particles with wrinkled surfaces, and bulges on particle surfaces	Spray-dried microcapsules	36
Vit-C sulfonamide adducts	PVA	Optical devices	↑ Amorphous structure (XRD) ↑ Refractive index ↓ Bandgap	Solution casting	40
Vit C	PBV	Grapes	Average fiber diameter: 278 nm (PU), 262 nm (PBU), 269 nm (PBV). Bead-free, uniform morphology	Electrospinning	28
Fish oil/Vit C	Gelatin		Brittleness at high Vit-C ratios but retained core–shell structure. Stable over 10 days	Electrospinning	61
High catechins/Vit-C	Sodium alginate polysaccharide		Dense matrices from Fe^{2+} coordination; improved encapsulation efficiency	Solution-casting	78
Antioxidant properties					
Tea polyphenols/Vit-C	Pullulan	Grapes	Maximum free radical clearance rate (>87%)	Multi layers	76
Vit C	PBV	Grapes	Antioxidant packaging films	Electrospinning	28
Fish oil/vit C	Gelatin		Antioxidant activity	Electrospinning	61
High catechins/Vit-C	Sodium alginate polysaccharide		Strongest antioxidant activity, with 100% scavenging capacity for DPPH and ABTS	Solution-casting	78
Methylene blue/Vit C (Cel/MB/VC)	Cellulose	Kit to detect hydrogen peroxide in smart packaging	Antioxidant properties	Immersed in a solution	43
Vit-C, catuaba extract	Cassava starch-gelatin films		93.33% antioxidant capacity; suitable for cosmetic applications		30
Vit-C	Zein-PpIX membranes		14.1% singlet oxygen clearance in 8 minutes		79
Antimicrobial properties					
Tea polyphenols/Vit-C	Pullulan	Grapes	Improved the antibacterial resistance	Multi layers	76
Vit C	PBV	Grapes	A sterilization rate of over 99.99% against common bacteria (*E. coli*, *S. aureus*, and *B. subtilis*)	Electrospinning	28
Quaternary ammonium groups and Vit-C	PCNC		MICs of 8–16 μg mL^{-1} for *E. coli* and *S. aureus*		42
Methylene blue/vit C (Cel/MB/VC)	Cellulose	Kit to detect hydrogen peroxide in smart packaging	Strongest antimicrobial qualities	Immersed in a solution	43

Table 4 Enhancement of film properties through Vit C incorporation

Property category	Effect of Vit C incorporation	Key contributing factors	Reference
Physicochemical	Modifies thickness, moisture content, solubility, and encapsulation efficiency. Effects are highly concentration- and matrix-dependent	Filling of polymer pores, disruption or formation of hydrogen bonding networks, ionic interactions with polymer chains	43, 49 and 80
Barrier (WVP/OTR)	Generally, improves water vapor and oxygen barriers by creating a more tortuous path for diffusion; however, can increase permeability in some hydrophilic systems	Reduction of free volume in the polymer matrix, cross-linking, and antioxidant action that protects the polymer structure	28, 43, 76 and 81
Mechanical	Variable impact on tensile strength and elongation; can enhance or reduce properties based on interfacial interactions and plasticizing/anti-plasticizing effects	Intermolecular bonding with the polymer matrix, disruption of polymer crystallinity, and acting as a filler or plasticizer	28, 46, 48 and 76
Optical	Can induce light absorption in specific wavelengths (UV) and significantly alter refractive index and optical band gap	Introduction of chromophores, formation of charge-transfer complexes, and reduction of film crystallinity	5, 40 and 47
Thermal	May slightly reduce thermal degradation onset temperature due to Vit-C's own thermal sensitivity, but cross-linking can mitigate this	Vit-C's low decomposition temperature, but also its ability to form stabilizing interactions (H-bonding, coordination)	28 and 78
Functional (antioxidant)	Imparts significant, dose-dependent radical scavenging activity (DPPH, ABTS), directly protecting the food product from oxidation	Electron-donating capacity of the enediol group in ascorbic acid	30, 46 and 78
Functional (antimicrobial)	Exhibits synergistic antimicrobial effects, particularly when combined with other active agents (*e.g.*, chitosan, essential oils)	Induction of oxidative stress in microbial cells, reduction of pH in the micro-environment, and enhancement of other agents' efficacy	28, 42 and 76
Morphological	Influences surface smoothness, fiber diameter in electrospinning, and induces structural homogeneity or defects based on loading	Uniform dispersion within the matrix, aggregation at high concentrations, and interaction with the polymer during solidification	28, 61 and 49
Intelligent/sensing	Serves as a key component in oxidant-responsive colorimetric sensors, enabling real-time food quality monitoring	Redox reaction with indicators (*e.g.*, methylene blue) and oxidation by spoilage biomarkers (*e.g.*, hydrogen peroxide)	43 and 82

single step reduced the WVTR from ~544.8 g (m^2 d^{-1}) to a minimum of 27.24 g (m^2 d^{-1})—a 20-fold improvement—and the Oxygen Transmission Rate (OTR) from ~530.5 cm^3 (m^2 d^{-1}) to 31.21 cm^3 (m^2 d^{-1})—a 17-fold improvement. This pretreatment, followed by a SiO_2 coating, created a cellulose-based film with ultra-high barrier properties, showcasing Vit-C's role beyond a mere additive to a processing aid that fundamentally improves polymer structure.

Environmental factors like temperature and pH influence Vit-C release and stability. Khuntia *et al.*[49] observed higher Vit-C release at elevated temperatures (20–37 °C) due to increased water solubility, risking degradation. Hu *et al.*[36] found that chitosan-coated sodium caseinate microcapsules slowed Vit-C release at pH 6.8 due to reduced permeability, though oxidative degradation occurred over time. Overall, Vit-C-based coatings extend shelf life by minimizing enzymatic browning and microbial growth, aligning with sustainable food preservation goals.[85]

5.3 Mechanical properties

The mechanical performance of Vit-C-incorporated films varies significantly depending on the polymer matrix and processing methods, often revealing a trade-off between strength and flexibility. Interestingly, the mechanical impact of Vit-C is not universal and can vary dramatically. This trade-off between enhanced strength and flexibility is quantitatively detailed in Table 5. The quantitative data in Table 5 reveal that the most significant mechanical enhancements are often achieved not by Vit-C alone, but through its incorporation into sophisticated composite structures like multilayers or electrospun fibers.

For instance, polyvinyl alcohol (PVA) films reinforced with Vit-C-modified ZrO_2 nanoparticles exhibit enhanced tensile

Table 5 Quantitative improvements in film properties with Vit C incorporation

Film system	Property	Control value	With Vit C	% change	Reference
Pullulan/TP/VC coating on paper	Tensile Strength	Baseline (untreated paper)	—	+32.4% to +57.55%	76
CH/SA-AA/EC multilayer film	Tensile Strength	CH monolayer: ~0.33 MPa	Multilayer: 0.56 MPa	+70% (*vs.* CH)	48
PEC/PVA/Pb 0.25%	Tensile Strength	PEC/PVA: 19.51 MPa	PEC/PVA/Pb: 26.90 MPa	+37.9%	86
Cel/MB/VC (cellulose NF)	Elongation at break	Cel film	Cel/MB/VC film	Increased	43
PBV hybrid film	Tensile Strength	PU film	PBV film	−30%	28
KC/PLA/VC-HPβ-CD NF (6%)	Elastic modulus	—	149.97 MPa	—	46
KC/PLA/VC-HPβ-CD NF (6%)	Elongation at break	80.43% (2% loading)	38.49% (6% loading)	−52.2% (*vs.* 2% load)	
Gelatin/LOHB (10%)	Tensile Strength	Gelatin control	14.5 MPa	Increased (max at 10%)	47

strength and UV-shielding capabilities due to improved interfacial interactions.[60] Similarly, pullulan-based coatings blended with Vit-C and tannic acid (TP) increased paper tensile strength by 32.4–57.55%, with pullulan contributing most to the enhanced mechanical resistance.[76] A CH/SA-AA/EC multilayer film demonstrated a tensile strength of 0.56 MPa, which was approximately 70% higher than its constituent chitosan monolayer film (0.33 MPa), showcasing the mechanical advantage of a composite structure.[48]

However, Vit-C's impact is not universally positive. In polyurethane (PBU) films, Vit-C disrupted hydrogen bonding within the polymer matrix, reducing intermolecular cohesion and leading to a 30% decline in tensile strength.[28] In electrospun KC/PLA nanofibers, increasing the load of the Vit-C/HP-β-CD inclusion complex from 2% to 6% caused the elongation at break (EAB) to decrease from 80.43% to 38.49%, indicating increased brittleness at higher active compound concentrations.[46] This trade-off highlights the critical need for optimizing Vit-C concentration and selecting a compatible polymer matrix to balance flexibility, structural integrity, and functional activity.

5.4 Optical properties

The incorporation of Vit-C and its derivatives can profoundly alter the optical properties of polymer films, enabling applications beyond preservation, such as UV blocking and smart packaging. Ayad Shamsallah & Omer Rashid.[5] reported that incorporating Vit C adducts into gelatin films enhanced their refractive index (n) and reduced the optical band gap energy (E_g), with specific isomer adducts (*e.g.*, dopant 3b) amplifying polarization effects, thereby tuning optical dispersion properties.

Similar improvements were observed in PVA composites doped with sulfonamide-modified Vit-C, where the amorphous structure (confirmed *via* XRD) contributed to a 25% increase in refractive index and reduced E_g, making these films promising for optical device applications.[40] Furthermore, Tang *et al.*[47] demonstrated that a chemically modified Vit-C derivative (LOHB) imparted exceptional UV-blocking properties to gelatin films. Films with just 5% LOHB achieved complete blockage of UV rays in the range of 200–325 nm, while those with 10% LOHB showed even further improved UV-blocking ability. This functionality is crucial for protecting light-sensitive foods and nutrients from degradation during storage.

5.5 Thermal properties

The thermal stability of Vit-C-based films varies significantly depending on their composition and structural design. Gong *et al.*[28] demonstrated that polyurethane (PU) films cross-linked with 1,4-butanediol exhibited superior thermal stability, with an initial decomposition temperature of 344.2 °C, compared to branched polybutylene (PBU) and Vit-C-incorporated polybutylene-Vit C (PBV) films, which degraded at 318.9 °C due to Vit-C's inherent thermal sensitivity. Despite this reduced stability, PBV films met functional requirements for food packaging applications.

Similarly, Kou *et al.*[78] analyzed hydrocolloid matrices containing Vit-C, alginate (SA), citric acid (CA), and Fe^{2+}, observing three distinct mass loss stages *via* thermogravimetric analysis. The first stage (46–87 °C) corresponded to water evaporation, while the second (90–230 °C) reflected polymer decomposition. Notably, SA-CA-VC-Fe composites exhibited enhanced thermal resilience due to hydrogen bonding and Fe^{2+} coordination, resulting in minimized mass loss. These results highlight the role of cross-linking agents and ionic interactions in mitigating vitamin C's thermal limitations.

Environmental conditions and film architecture influence Vit-C release kinetics. Khuntia *et al.*[49] studied starch-based films under varying temperatures and pH levels (4.5 for bananas, 7 for beans), noting that moisture diffusion displaces glycerol from the film matrix, triggering Vit-C release. This process stabilizes once moisture equilibrium is achieved, irrespective of concentration gradients. Elevated temperatures increased film swelling in banana applications, altering thickness and release rates. These findings highlight the interplay between thermal conditions, material erosion, and the delivery of bioactive compounds in Vit-C-functionalized coatings.

5.6 Morphological properties of Vit C-based films/coatings

Surface morphology and structural integrity are critical determinants of film performance.[87] Gong *et al.*[28] reported uniform, bead-free electrospun PU, PBU, and PBV fibers with average diameters of 278 nm, 262 nm, and 269 nm, respectively, confirming consistent processability. In contrast, Khuntia *et al.*[49] observed that gelatin-pectin microparticles exhibited size variability (D_v (50)) influenced by wall-to-core ratios, with smoother surfaces at higher biopolymer concentrations (Fig. 3). Freeze-dried microparticles displayed spherical aggregates and crack-free surfaces at optimal wall material concentrations (≥5%), though lower concentrations (2.5%) led to structural defects. Spray-dried Vit-C-loaded casein particles showed irregular, wrinkled morphologies with intact emulsion recovery upon rehydration, emphasizing their reconstitution potential.[36,88] Vit-C incorporation impacts nanofiber stability and nutrient release. Liu *et al.*[61] found that electrospun fish oil-gelatin-Vit-C nanofibers retained their core–shell structure but became brittle at high Vit-C ratios. These nanofibers partially adhered during storage but maintained structural stability over 10 days, suggesting controlled Vit-C loading preserves integrity. In simulated gastrointestinal conditions, nanofibers disintegrated into self-assembled particles, enabling triphasic nutrient release—a behavior linked to material composition and porosity. Cross-linked SA-CA-VC-Fe hydrocolloids, however, formed dense matrices *via* Fe^{2+} coordination, enhancing encapsulation efficiency and mechanical strength.[78] Additionally, gelatin-ascorbic acid composite films developed by Ayad Shamsallah & Omer Rashid,[5] exhibited amorphous structures and strong intermolecular interactions, as evidenced by FT-IR, further validating Vit-C's role in modulating morphological properties.

5.7 Functional properties: antioxidant and antimicrobial

Vit C exhibits dual functionality as both an antioxidant and pro-oxidant, with its pro-oxidant effects emerging under specific conditions such as high concentrations or the presence of catalytic metals. Nano formulations of Vit-C enhance its pro-oxidant activity, enabling applications like oxidative stress-induced ferroptosis therapy at physiologically relevant doses.[89] Vit-C's antioxidant efficacy is well-documented in food packaging, where it mitigates oxidative degradation. For instance, gelatin–pullulan films incorporating Vit-C demonstrated 100% scavenging capacity for DPPH and ABTS radicals, outperforming polysaccharide-only matrices.[78] Similarly, cassava starch-gelatin films with Vit-C achieved 93.33% antioxidant capacity, making them viable for eco-friendly cosmetics.[30] The KC/PLA/HP-β-CD-VC electrospun membrane developed by Bai *et al.*[46] showed a DPPH radical scavenging rate of 91.86 ± 1.70% at a 6% loading, a quantitative measure of its potent antioxidant power. Vit-C generally acts as a potent antioxidant, a property attributed to the electron-donating capacity of its enediol group.

In fruit preservation, pullulan-coated papers functionalized with tea polyphenols (TP) and Vit-C improved barrier properties and antioxidant activity. Vit-C synergized with TP to reduce lipid hydroperoxides during electrospinning, preserving grape hardness, acidity, and nutrient content.[28,76] Additionally, zein-based membranes with Vit-C eliminated singlet oxygen, enhancing photodynamic therapy efficacy.[79] These coatings also reduced oxidative stress in fruits, protecting vitamins, polyphenols, and carotenoids.[85,90]

Vit-C enhances antimicrobial activity in coatings through oxidative stress induction and synergistic interactions. Pullulan-Vit-C coatings exhibited superior antibacterial efficacy against *E. coli* and *S. aureus* compared to pullulan-only films.[76]

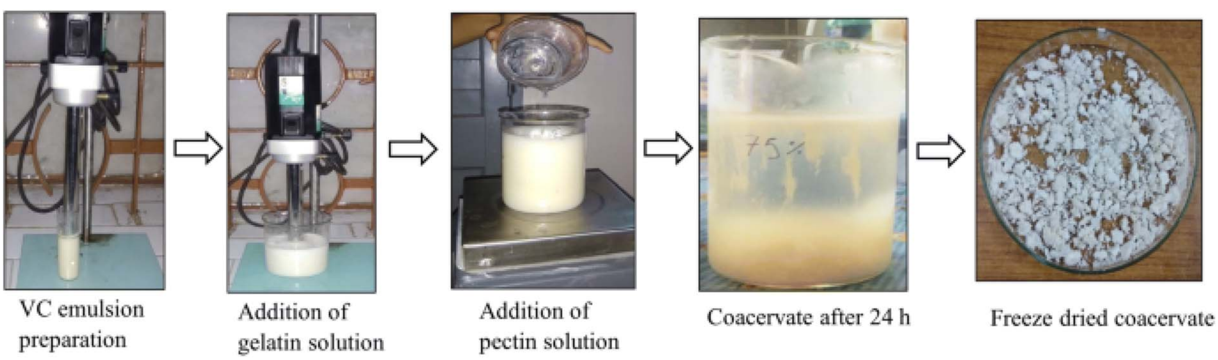

Fig. 3 Process flow for microparticle preparation, reproduced from ref. Khuntia *et al.* with permission from Springer Nature,[49] copyright 2022.

Electrospun PBV films achieved >99.99% sterilization rates against common pathogens, including *B. subtilis*, due to moisture management and rot-proof properties.[28] Nanocapsules with quaternary ammonium groups and Vit-C (VC-GCh-PCNC) showed MICs of 8–16 μg mL^{-1} for *E. coli* and *S. aureus*, extending food shelf life.[42]

A standout example of synergistic functionality is the work of Sadeghi *et al.*,[43] who created a cellulose nanofiber (CNF) film dual-modified with methylene blue (MB) and Vit-C. The pure CNF film showed minimal antioxidant activity (4%), but the Cel/MB/VC film demonstrated a powerful synergistic antioxidant effect of 82%. Furthermore, while the pure CNF had no antimicrobial properties, the composite film exhibited significant inhibition zones against *E. coli* (12.8 mm) and *S. aureus* (14.1 mm). Most innovatively, this film functioned as a colorimetric sensor, changing from white to blue upon exposure to oxidants like hydrogen peroxide, with a high sensitivity and a low detection limit of 1.9 mg/100 mL for H_2O_2.

Lemon juice-derived PVA films cross-linked with Vit-C demonstrated biocompatibility and anti-inflammatory effects, attributed to Vit-C's antioxidant activity.[39] The combination of Vit-C with other agents, as shown in the CNF film, highlights its potential for creating dual-functional active and intelligent packaging systems.

5.8 Intelligent properties: sensing and release

Beyond active preservation, Vit-C is a key component in developing intelligent packaging systems. As demonstrated by Sadeghi *et al.*,[43] Vit-C can act as a reducing agent in a redox-based sensor, providing a visual indicator of oxidation levels within a package—a direct measure of food spoilage. The principle of using Vit-C in sensing is further supported by Kanwal *et al.*,[82] who developed a chitosan-stabilized copper oxide nanozyme sensor whose peroxidase-like activity is inhibited explicitly by Vit-C. This mechanism, resulting in an apparent colorimetric change, provides a blueprint for creating on-package labels that monitor the depletion of antioxidants or the accumulation of oxidative spoilage products in real-time.

Furthermore, the release kinetics of Vit-C itself can be engineered for controlled functionality. The electrospun nanofibers by Bai *et al.*[46] exhibited a sustained release profile, retaining over 71% of Vit-C after 10 days, which is crucial for long-term preservation. The polyelectrolyte complex nanoparticles studied by Ferreira Dantas *et al.*[80] exhibited pH-dependent release, with a much faster release at skin pH (5.5) than at physiological pH (7.4). This principle could be adapted to target specific spoilage environments in food packages.

6. Stability of Vit C and its oxidized derivatives

Humans acquire Vit-C through dietary intake; however, its susceptibility to external factors such as light, heat, and oxygen imposes significant constraints on the processing and storage of Vit C-rich foods. As a potent reducing agent and antioxidant, it offers multiple health benefits. Despite performing numerous

Table 6 Kinetic parameters describing Vit C degradation under different drying methods and heat treatments in food systems[a]

	Kinetic model	Kinetic parameters	Drying method/Storage temperature (°C)				
Product	Techniques		HAD	VD	MVD	FD	Reference
Kiwi fruit slice	Zero order	k	0.3280	0.2943	4.4500	0.0471	91
		R^2	0.9307	0.7604	0.7031	0.5651	
	First order	k	0.0026	0.0045	0.0189	0.0004	
		R^2	0.9898	0.6736	0.618	0.4223	
	Weibull	α	347.7	283.3	9.255	10.400	
		β	0.9600	0.4523	3.877	0.4186	
		R^2	0.9905	0.9827	0.9519	0.8117	
Fruit-based beikost product	First order kinetic model	Temp.	4 °C	25 °C	37 °C	50 °C	92
		k	No degradation	0.0135	0.0550	0.1869	
		R^2		0.9599	0.8834	0.9731	
Fruit juice	First order kinetic model	Temp.	90 °C	105 °C	120 °C		93
		K	0.033	0.244	0.886		
		R^2	0.950	0.975	0.982		
Orange juice	First order		70 °C	75 °C	80 °C	85 °C	94
		k	0.000610	0.000690	0.000790	0.000870	
		R^2	0.9770	0.9447	0.9676	0.9899	
		$t_{0.5}/t_2$ (s)	1136.3	1004.6	877.4	796.7	
		D (s)	3774.7	3337.1	2914.7	2646.6	
Pumpkin slices	First order	Temp.	HAD at 60 °C	HAD at 70 °C	HAD at 80 °C	HAD at 90 °C	95
		K	0.037	0.057	0.080	0.117	
		R^2	0.999	0.996	0.991	0.987	
Crushed tomato	First order	Temp.	70 °C	80 °C	90 °C	100 °C	96
		$k \times 10^{-3}$ (min^{-1})	0.5 ± 0.0	0.9 ± 0.2	1.5 ± 0.1	3.0 ± 0.1	
		$t_{1/2}$ (min)	1494	756	455	231	

[a] HAD – hot air drying; VD – vacuum drying; HA-MVD – hot air microwave assisted vacuum combination drying; FD –freeze drying; (R^2) – coefficient of determination; (k) – reaction rate constant; ($t_{0.5}$) – half life; (t_2) – doubling time; (D) – decimal reduction time.

physiological functions, its inherent instability, resulting from its high reactivity as an antioxidant, presents a significant challenge. The oxidation process occurs because ascorbic acid readily donates electrons to neutralize reactive oxygen species (ROS), free radicals, and other oxidizing agents. This property is beneficial due to its role as an antioxidant, but it also makes it prone to degradation. The dehydration kinetics data of Vit-C under various drying methods or storage at different temperatures have been summarized in Table 6.

The mechanism of ascorbic acid oxidation is depicted in Fig. 4. Initially, the ascorbyl radical is formed. Ascorbyl radical is the one-electron oxidized form of ascorbic acid. It is a semi-stable radical that forms when ascorbic acid donates an electron. When this ascorbyl radical loses its second proton, it oxidizes to dehydroascorbic acid (DHA), which retains biological activity and is stable. This reaction is reversible, but DHA can instead swiftly undergo irreversible hydrolysis further.[8] DHA may be reduced to a non-ionized form or irreversibly hydrolyzed to 2,3-diketogulonic acid in the presence of OH^- as well as H^+.[97] Once DHA is hydrolyzed to 2,3-diketogulonic acid, its activity as Vit-C and as a reducing agent is irreversibly lost.[98] This degradation diminishes the Vitamin's bioavailability and antioxidant efficacy, adversely affecting its functions in collagen formation, immunological response, and iron absorption. Furthermore, the synthesis of DHA can occur in a highly alkaline environment *via* a two-electron oxidation of ascorbate free radical anions. DHA is a neutral compound characterized by a lactone structure and a carbonyl group (3-C=O), rendering it highly susceptible to various reagents, including nucleophiles and oxidants.

Various strategies have been explored to enhance the stability of Vit C under food storage and processing conditions that involve exposure to high temperatures, neutral-to-alkaline pH, oxygen, light, and moisture. The stability of Vit-C can be enhanced through synergistic interactions with other antioxidants, using low-weight stabilizers, and its own derivatives. Flavonoids and Vit-C can regenerate α-tocopherol by reducing the tocopheroxyl radical. *Tert*-butyl hydroquinone (TBHQ), an antioxidant, accelerates the reduction of dehydroascorbic acid back to ascorbic acid. Similarly, glutathione, *via* its free sulfhydryl group, reduces dehydroascorbic acid and shifts the degradation kinetics from first order to zero order with increasing concentration.[99] Ferulic acid also exerts a protective effect through its higher redox potential, indirectly stabilizing ascorbic acid.[8] In addition, derivatives such as glycosylated ascorbic acid, ascorbate derivatives formed by introducing a phosphate group, and lipophilic derivatives exhibit improved thermal or oxidative stability. However, they require an *in vivo* reaction to be converted into Vit-C but are limited by high production cost.[100,101] Other than low-weight stabilizers, antioxidant and derivatives of Vit-C, biomacromolecule-based carriers for the stability of Vit C are used. These processes involve physical and chemical interaction, through encapsulation and adsorption. Different carriers, such as microcapsules,

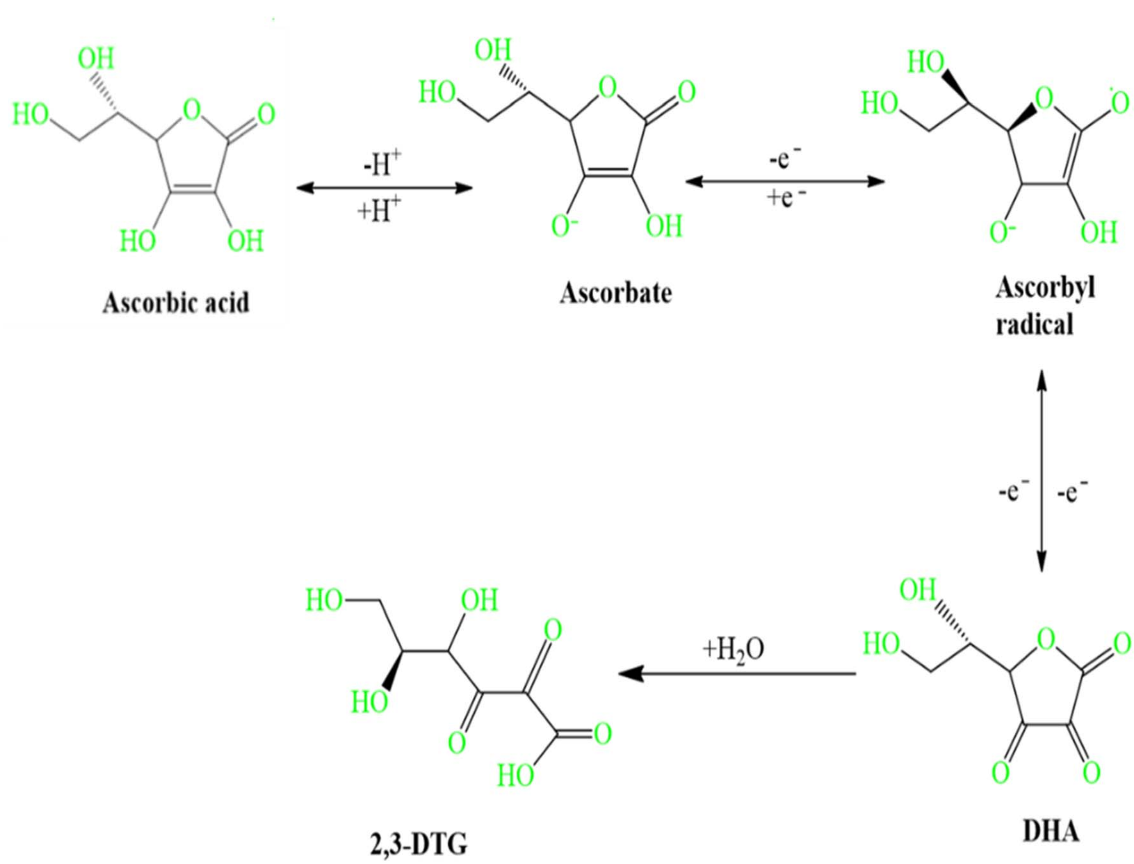

Fig. 4 Degradation of ascorbic acid to dehydroascorbic acid (DHA) and 2,3-diketogulonic acid (2,3-DTG) by photooxidation.

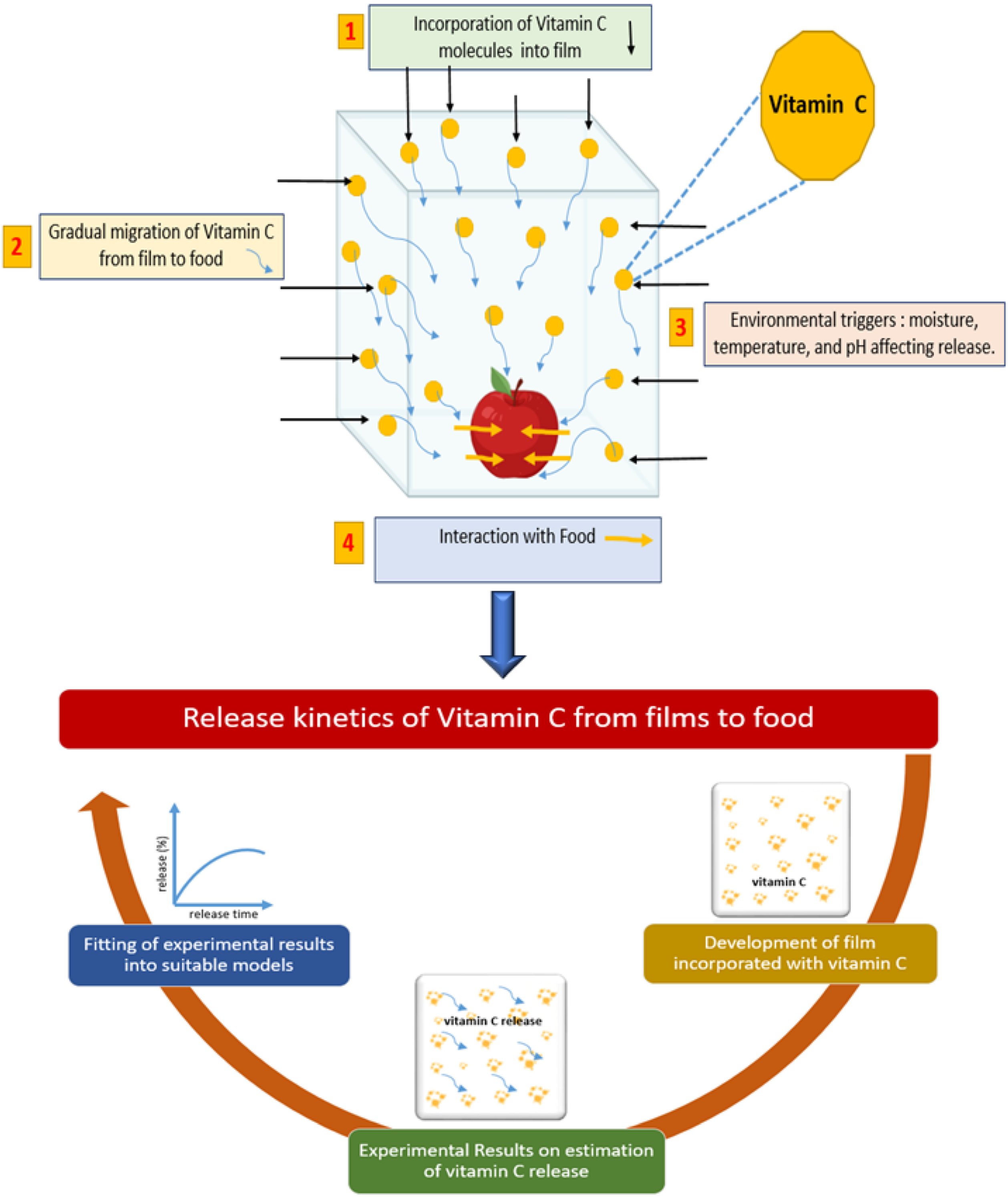

Fig. 5 Schematic of the release mechanism of vitamin C from film to food product and its interpretation of vitamin C release from film to food product.

liposomes, and emulsions, are used in conjunction with wall materials like chitosan, gelatin, gum Arabic, sodium alginate, and many more. Encapsulating Vit C helps in enhancing the stability, controlled release, and improved bioavailability of Vit-C.

7. Release kinetics of Vit C from film/coating to food product

Vit C is a water-soluble vitamin that plays a very prominent role in various physiological functions like antioxidant activity,

Table 7 Different empirical models with equations for controlled release of Vit C[102]

Model name	Parameters	Model equation	Description
Zeroth order	k R^2	$C_t = C_0 - k_0 t$	Constant release rate, independent of concentration
First order	k R^2	$\ln C_t = \ln C_0 - k_1 t$	Release depends on the remaining concentration of the substance
Second order model	k R^2	$\frac{1}{C_t} = \frac{1}{C_0} + k_2 t$	The release rate changes proportionally to the square of the concentration
Higuchi model	k R^2	$Q = k_H t^{1/2}$	Release controlled by diffusion through a solid matrix
Korsemeyar peppas model	k R^2 n	$Q = k_p t^n$	Describes release based on diffusion and matrix erosion, where n determines the mechanism
Hixson crowell model	k R^2	$({C_0}^{1/3} - {C_T}^{1/3}) = k_H C_t$	Accounts for the changing surface area and particle size during dissolution

collagen synthesis, the immune system and cardiovascular health. Hence, integration of Vit C into food packaging films can aid in reducing browning and lipid oxidation, enhancing antimicrobial activity, and controlling release into food products through film coating, prolonging its shelf-life. Furthermore, these films incorporated with Vit C houses various applications for myriad food products such as dairy products, meat products, functional foods and fruits and vegetables as sustainable solutions and innovative packaging materials.[102]

The study of Vit C release kinetics is crucial for optimizing its stability, bioavailability, and functionality in food, pharmaceuticals, and active packaging. However, studies have reported that Vit C is highly unstable. Therefore, delivering potential bioactives such as Vit C through effective delivery systems to improve its performance in various applications requires an understanding of kinetics and its release behaviour. Kinetic study of Vit C release focuses on the AA degradation. AA degradation curves were obtained for each temperature, and the order of reaction was presented graphically by fitting the experimental data to linear models ($y = a - bx$), as shown in Fig. 5. The statistical coefficient of determination (R^2) was employed to evaluate the quality of adjustment. In some instances, the degradation kinetic model suggested a zero-order reaction, which is expressed by eqn (1):

$$C_t = C_0 - kt \tag{1}$$

where C_t is the AA content at a certain time t, C_0 is the AA concentration at time zero, and k is the zero-order kinetic reaction constant. It was observed that AA degradation increased with increased temperature. In some other cases, Vit C loss was represented by an apparent first-order reaction as depicted by eqn (2):

$$C = C_0 \times e^{-kt} \tag{2}$$

where C and C_0 are the concentrations of L-ascorbic acid at time t and zero, respectively, and k is the apparent reaction rate of Vit C loss, estimated by the slope of the linearized plot of $\ln(C/C_0)$ *vs.* t. The temperature dependence of Vit C deterioration was expressed with the Arrhenius equation.[103] AA degradation for headspace oxygen concentrations lower than 0.63% in a model fruit juice was successfully described using zero-order kinetics. Factors associated with degradation include time, moisture content and temperature. Significant differences in AA content (3217.71 μmol L^{-1}) in comparison with those products stored at 25–30 °C (2613.55 μmol L^{-1}) and 40 °C (2105.54 μmol L^{-1}) were observed on storage of fruit-based baby food under refrigeration days. It was reported that high retention of AA was observed until 70 days (3102.86 μmol L^{-1}) and then gradually decreased until the end of the storage period. However, storage at 4 °C reported no losses of AA. The maximum losses of AA after storage of the three types of fruit-based baby foods for 200 days at 5, 25, 30, and 40 °C were 32, 60, 85, and 98%, respectively.

Some of the other kinetic models employed for understanding release mechanisms of Vit C including Zero order (constant release rate, independent of concentration) are Kopcha model, Makoid–Banakar model, Higuchi's model (release rate changes proportionally to the square of the concentration), the First-order model (release depends on the remaining concentration of the substance) and Korsmeyer–Peppas model (describes release based on diffusion and matrix erosion, where it determines the mechanism) as shown in Table 7. These kinetic models employed will aid in understanding the AA release mechanisms, the physics of AA release, and the transport behavior of AA from films to food products. Other techniques to analyze the release of the active substance include the use of a spectrophotometric method. It is based on the colorimetric reaction, where a coloured complex is formed between the released Vit C, ferric chloride ($FeCl_3$), and 1,10-phenanthroline, resulting in accurate quantification of Vit C release.[42] The three main release mechanisms employed for the direct incorporation of bioactives in active packaging systems are driven by diffusion, erosion, and swelling/shrinking.[104] However, Other release mechanisms introduced for the release of bioactives include dissolution and osmosis.

Degradation of Vit C is a significant problem, especially when subjected to increased temperature and light. Studies revealed that no degradation of Vit C was observed till 5 days when Vit C was purged with nitrogen due to the removal of dissolved oxygen in a light-protected environment. However, without nitrogen purging, degradation of Vit C was rapid, and 86% of Vit C degraded within the first 24 h and 100% within 4 days.[42] Moreover, a controlled environment prevented the degradation of Vit C, with the concentration maintained at almost 98% at the end of 5 days. Vit C release studies corresponding to first-order reactions also emphasize sustained-release and matrix diffusion-controlled release. These released vitamins C when entering the food digestive tract observed higher cumulative VC release over 8 h compared to the release at the control pH of 7.4, resulting in a release of approximately 27% at 8 h of digestive simulation.

Khuntia *et al.*[23] developed a starch – Vit C active packaging film and studied the behaviour mechanism for release of Vit C. Starch films were incorporated with optimal VC-loaded nanoliposomes, and the release profiles at different storage temperatures were studied along with kinetics modelling for specific food samples (apple and beans) to simulate different pH effects. Results stated that Vit C loss was lowest in lyophilized SA-free nanoliposomes and the release study showed notable differences in VC release profile with a significant release at 37 °C and neutral pH, effectively replacing sterol-based liposome for food packaging applications.[23] It was concluded that the release was faster at a lower pH (acidic condition) than at pH 7, indicating sustained release. The accelerated VC release rate for apples was reported due to their increased moisture absorption. The release exponent (n) values of 0.26 and 0.19 (less than 0.45) indicated that the VC release mechanism followed Fickian diffusion. In contrast, $n = 0.60$ for apple at 37 °C, indicating anomalous or non-Fickian diffusion, which involves VC diffusion from the lipid core and erosion of the lipid core. Thus, in beans and apples, vitamin release of up to 60% and 26%, respectively, was observed at 37 °C.

Shin *et al.*[105] have studied *in vitro* release characteristics of Vit C disintegrating films loaded with nanoparticles using the Kormeyer–Peppas equation model, where "K" is an experimentally settled parameter that relies on the structural and geometric distinction of the dosage matrix, and "n", the release exponent, relies on the component release mechanism. The component 'n' was interpreted based on the value reported. If value of 'n' was reported in range $0.45 \leq n \leq 0.89$, the diffusion of active substances in the gel and the loss of the gel progress appropriately in the elution of purification whereas if less than 0.45, it indicates that diffusion is dominant among the free mechanisms, and if it is more than 0.89, it indicates that gel loss is dominant. Vit C value observed for DW and saliva was 0.41 and 0.44. Furthermore, Shin & Han,[106] studied release mechanism of active ingredients in orally disintegrating film (ODF) by developing films of varied thickness and number of castings with varied levels of Vit C. Analysing the result of the release pattern of the optimized ODF incorporated with both Vit C and Catechin exhibited rapid release of over 70% within 30 and 20 min, respectively, in all simulated body fluids aiding ODF as potential delivery option. Recommended daily intake (RDI) of Vit C over age 4 is 90 mg; therefore, in the case where catechin levels are zero, two sheets of film per day would be required for adequate intake. Results also concluded that the n values (release component estimated by the Kormeyer–Peppas equation model for the release of Vit C) were 0.41 and 0.44 in DW and saliva, respectively, indicating that diffusion was the dominant mechanism.

Furthermore, Bańkosz,[102] integrated Vit C into microcapsules, hydrogels and hybrid hydrogels to study the physiochemical characterization and kinetic study. Release of Vit C was confirmed by a reaction with ferric chloride and phenanthroline, and a release study was carried out under two conditions such as static and dynamic. Results stated that the polymer systems exhibited the potential to effectively release Vit C and ion exchange with the environment, confirming their potential in controlled release of the active substance. Studies concluded that higher Vit C release was observed for microcapsules in dynamic conditions due to their small structure and continuous mechanical forces promoting swelling of capsules and controlled release when compared to hydrogels. Release of 41.137 mg mL^{-1} of Vit C was observed indicating rapid diffusion of the active ingredient from the microcapsule after 48 h while hydrogels released 34.448 mg mL^{-1} of Vit C. Thus, better understanding of release mechanism was carried out using different models where best fit model for experimental results was found to be Higuchi and Korsmeyer–Peppas models. Though various researchers have attempted to understand the release behaviour of Vit C films through experimentation, fitting of experimental results into models aided in providing better clarity for understanding Vit C release profiles. Development of apps integrated with suitable sensors, artificial intelligence and machine learning can be considered as future takeaway for faster prediction for Vit C release profile in films.

7.1 Controlling factors of Vit C release

Degradation of Vit C in active packaging depends on the diffusion rates of Vit C. Polymer crystallinity is an essential factor that needs to be dealt with while considering Vitamin C-based active packaging. Crystalline regions in a polymer are tightly packed and hence act like barriers, while amorphous regions are loosely packed and allow free diffusion of small Vit C particles. Thus, higher crystallinity can be related to restricted diffusion with slow release of Vit C.

Polymer hydrophobicity is another crucial factor for Vit C-based active packaging. Vitamin-C being highly hydrophilic, a hydrophobic polymer could be the ideal choice for resisting water penetration and limiting the dissolution of Vit C within the matrix. Hence, a more hydrophobic polymer could result in slower release of Vit C. The EHEC-C_{12} derivative, with degrees of substitution ranging from 9.0 to 20.0%, exhibited pronounced hydrophobicity and enhanced surface activity.[106] Other factors affecting Vit C release include environmental factors such as temperature, light, pH, and concentration, as well as chemical interactions within the matrix, physical barriers, controlled release, and encapsulation techniques for controlled release.

7.2 Environmental factors

Light is one such parameter that increases the rate of degradation. In the presence of light for 27 days, an aqueous solution of 1% concentration of ascorbic acid lost around 21% of its initial concentration, while the 10% ascorbic acid system degraded to about 8%.[99,107] Studies also suggested that excessive ascorbic acid (AH_2) is prone to auto-oxidation and thereby produces dehydroascorbic acid anions.[108] Moreover, the pH value of the ascorbic acid solution also plays a prominent role in the degradative study. The pH values change with its degradation process. Ascorbic acid, with an initial pH of alkaline, degraded to about 7.3. This was followed by the formation of degradation products generated from ascorbic acid.[109] In acidic solutions, the degradation products of ascorbic acid are related to oxygen while in aerobic conditions, dehydroascorbic acid is further degraded to form 2-furoic acid and 3-hydroxy-pyrone.

Temperature plays a crucial role in the degradation of food products. When ascorbic acid is heated for 2 h at 100 °C, the degradation or oxidation products formed consist of furfural, 2-furoic acid, 3-hydroxy-2-pyrone and an unknown compound.[110] Among all these compounds, furfural is one of the main degradation products of ascorbic acid, which can polymerize or combine with amino acids to form brown melanoids, causing the browning of ascorbic acid-containing juice products. Oxygen also has a greater effect on ascorbic acid degradation even at temperatures above 100 °C. Therefore, removing all oxygen, including dissolved oxygen, is the best way to preserve ascorbic acid at high temperatures.[111]

7.3 Chemical interactions of matrix

Ascorbic acid is known for its excellent hydrophilicity, and it has the same charge as most proteins (isoelectric point <7) at physiological pH. However, the absence of their interactions, such as hydrophobic interactions, electrostatic interactions, hydrogen bonds, and van der Waals forces, results in low encapsulation efficiency and rapid release of ascorbic acid from protein nanoparticles in aqueous solutions. Hence, Chitosan is a cationic polysaccharide with excellent chelating and cross-linking properties, which can be utilized as a delivery agent in food applications. The formation of chitosan nanoparticles exhibits cross-linking with polyanions, such as tri-polyphosphate (TPP), leading to the formation of a strong hydrogen bond, which captures and retains ascorbic acid on the polysaccharide.[112,113]

The formed chitosan-ascorbic acid complexes exhibit a high singlet oxygen scavenging ability, thereby maintaining the high antioxidant capacity of ascorbic acid. The content of ascorbic acid loaded increased from 30% to 70%, respectively, with an increase in molecular weight of chitosan from 65 kDa to 110 kDa. With the further increase in chitosan molecular weight, the particle size increases, but the overall surface area decreases, resulting in a decrease in the encapsulation efficiency of ascorbic acid.[109] Short fragments of low-molecular-weight chitosan are easier to protonate with free amino groups, thereby complexing with ascorbic acid through electrostatic interactions. The average diameter of 55 kDa chitosan complex particles is 70.6 nm, and the loading efficiency of ascorbic acid is about 66%.[114]

7.4 Physical barriers

The stability of ascorbic acid for food applications is attempted by loading it into biomacromolecule-based delivery vehicles through physical encapsulation and adsorption. Physical barriers, such as microcapsules based on protein and polysaccharide, solid lipids, and liquid-state multiple emulsions, have a better loading capacity of ascorbic acid in the core compared to ascorbic acid nanoparticles chelated with protein and chitosan. Excellent loading capacity of ascorbic acid (more than 90%) was reported for sodium alginate/gum Arabic microcapsules prepared by spray drying. Meanwhile, the thermal stability temperature of ascorbic acid is increased to 188 °C, which is higher than the temperature required for product preparation.[115] Gum Arabic was another material possessing potential to produce spray-dried microcapsules, which can encapsulate around 96% of ascorbic acid. It exhibited vigorous antioxidant activity and inhibited the formation of furan, an ascorbic acid degradation product, during the preheating process of the products. The retention of ascorbic acid in the system remains around 90% even after 60 days of storage at room temperature.[116] The microcapsules prepared with gelatin and pectin as wall materials also improve the thermal stability of ascorbic acid, and exhibited low solubility of the microcapsules.[117] The encapsulation efficiency of ascorbic acid using gelatin and acacia as wall materials was reported to be about 97%.[118]

7.5 Controlled release

Nanoparticles based on chitosan with low molecular weight have a higher delivery rate of ascorbic acid. The mechanisms by which ascorbic acid is released from nanoparticles in the gastric environment and intestinal environment are primarily diffusion and erosion, respectively. Under neutral conditions in the intestine, the ion exchange between chitosan and the release medium results in the erosion of nanoparticles. The release rate of ascorbic acid increased from 30% in the stomach to more than 75% in the intestine.[119] Studies also stated that ascorbic acid in pomegranate juice undergoes 29% degradation during gastric digestion, severely reducing the bioavailability of ascorbic acid.[120] The clinical results have shown that the bioavailability of orally administered liposomal ascorbic acid was 1.77 times higher than that of non-liposomal ascorbic acid, with a higher bioavailability.[121]

The components in gastric juice have a significant effect on the release of ascorbic acid. Gastric juice containing 5% starch slowed the release of bioactive ascorbic acid in the gummies, while other dietary components had no significant effect on its release.[122] The low pH of the gastric environment and the presence of pepsin result in the denaturation and degradation of the protein carrier, leading to the leakage of loaded bioactive compounds into the stomach before they reach the small intestine.[123] Furthermore, gelatin/pectin microcapsules demonstrated a high loading capacity for ascorbic acid. However, studies have reported faster release of ascorbic acid in the gastric environment due to the dissolution of the gelatin coating in the gastric environment.[117]

8. Application of Vit C-based film/coating in food preservation

Food preservation is a vital aspect of modern food industries, aimed at enhancing shelf life, maintaining the nutritional content of food, and minimizing food waste.[124] Among various preservation methods, Vit C-based films and coatings have emerged as a sustainable packaging solution because Vit C imparts the antibacterial, antioxidative, and antimicrobial properties, thus prolonging the food's shelf life (Fig. 6). Dong and Tian,[76] developed a pullulan-based packaging material and investigated its efficacy in fruit preservation. To achieve this, they utilized a blend of tea polyphenol at various viscosities (76.66, 77.8, and 108.5 mPa s) and Vit C (150 : 1), resulting in an enhancement of the oxygen transmission rate (OTR) to 120–160 cm^3 m^{-2} 24 h 0.1 MPa, a reduction of the water vapor transmission rate (WVTR) to below 5.44 g mm^{-1} m^{-2} h kP, a maximum free radical clearance rate exceeding 87%, and improved antibacterial properties of the base packaging paper. Grapes coated in pullulan-based papers exhibited a lesser weight loss (>4.41%) and enhanced hardness (>16.4%) after 10 days of storage compared to control grapes wrapped in untreated/base paper. The coated grapes maintained higher nutritional values, including total soluble solids (greater than 12.6 wt%), ascorbic acid (at least 4.5 mg/100 g), soluble protein (greater than 1.5 mg g^{-1}), and titratable acidity (greater than 0.44 wt%). Thus, this approach provides a sustainable method for extending the storability and nutritional quality of grapes. Popescu *et al.*[125] examined the impact of three different types of chitosan-based edible coatings, derived from medium and high molecular weight chitosan and infused with ascorbic or acetic acid, along with sea buckthorn or grape seed essential oils. Then, the physicochemical and microbiological characteristics of organic strawberries and apple slices were studied during cold storage at 4 °C and 8 °C. In this, three formulations *i.e.*, 2% medium molecular weight chitosan, 1% acetic acid, grape seed essential oil (MMC-AcA-GSEO); 2% medium molecular weight chitosan, 1% acetic acid, sea buckthorn essential oil (MMC-AcA-SBEO) and % high molecular weight chitosan, 2% ascorbic acid, grape seed essential oil (HMC-AsA-GSEO) were coated in apple slices *via* dipping method (20 s), dried (1 h) and then packaged (PET container) and found that coated fruits had higher total phenolic content, antioxidant activity and Vit C levels throughout storage, particularly HMC-AsA-GSEO, which provided better stability. The possible migration of Vitamin C from packaging to apple slices occurs because Vitamin C is water-soluble and can diffuse through the packaging matrix in the presence of moisture. The concentration gradient and the hydrophilic nature of apple tissue facilitate this transfer. Additionally, when strawberries were coated with this film, a reduced microbial load (including yeast and molds) was observed, demonstrating the antimicrobial properties. Moreover, the water activity showed reduced values (0.96–0.98) than the control sample. The results indicate that these developed edible coatings can maintain freshness, thereby increasing shelf life. Another researcher, Gong *et al.*[28] developed a rot-proof bronopol embedded-polyurethane hybrid film (PBV) consisting of Vit C (3

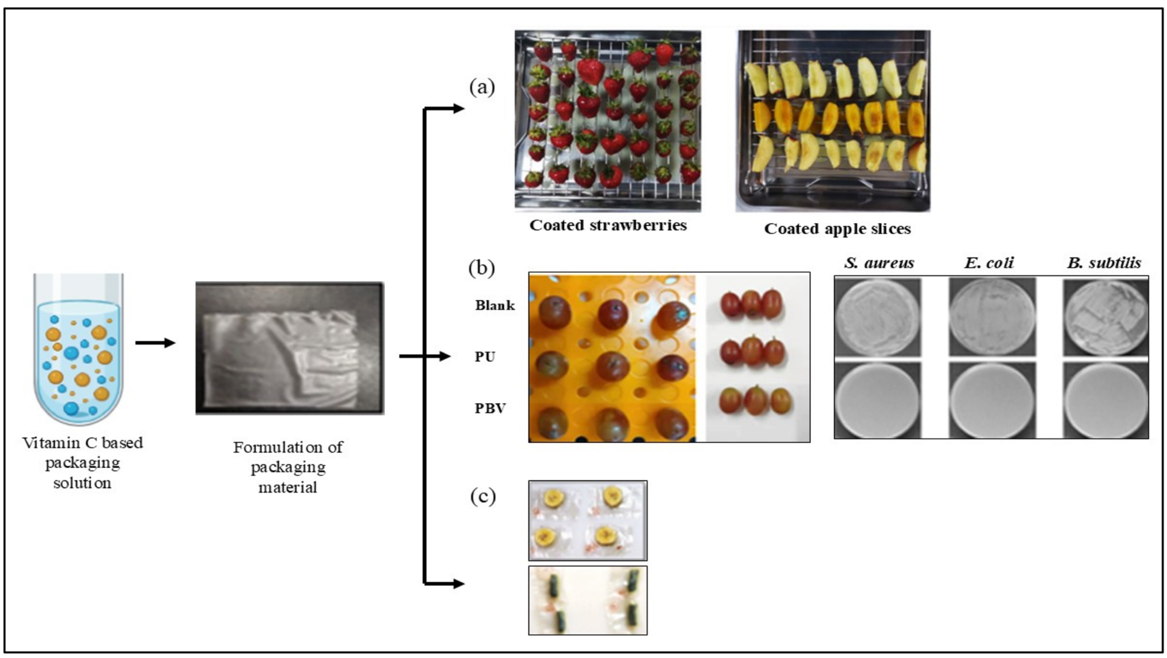

Fig. 6 Application of vitamin C-based packaging film for enhancing the shelf life of (a) strawberries and sliced apples, reproduced from ref. Popescu *et al.* with permission from MDPI,[125] copyright 2022; (b) grapes and showed antimicrobial activity of PBV films, reproduced from ref. Gong *et al.* with permission from Elsevier,[28] copyright 2023; (c) banana and bean sample, reproduced from ref. Khuntia *et al.* with permission from Springer Nature,[49] copyright 2022.

g/100 g) using an electrospinning method for shelf-life enhancement of grapes. They reported that Vit C significantly reduces oxygen permeability, which reduces oxidative degradation. At the same time, the film's water vapor transmission rate remains low (2.57 mg cm^2 h^{-1} at 23 °C, 75%) compared with others. These films exhibit strong antibacterial effects, achieving approximately 99.99% inhibition of *E. coli*, *S. aureus*, and *B. subtilis*. When grapes were coated using this film, it was observed that their organic acid content increased (>10%), and the rate of weight loss lowered by over 50%. Moreover, it effectively controlled respiration and reduced CO_2 production (1.64 ppm g^{-1} h^{-1}), resulting in delayed ripening to at least 7–10 days and spoilage due to transpiration. However, they have not reported the migration of Vit C from the coating into the stored fruits in their study; rather, they have focused on how the coating helps maintain or lose the Vit C already present in the fruit. Thus, these results showcased the potential of Vit C-based films as effective, multifunctional packaging materials that gave good protection against microbes, thus increasing the shelf life of fruit.

Hussain *et al.*[29] studied the development of biodegradable packaging film using poly (vinyl alcohol) (PVA), carboxymethyl cellulose (CMC), and ascorbic acid (AA), which was crosslinked with glutaraldehyde and synthesized at 60 : 40 : 1 and 70 : 30 : 1 concentration ratios of PVA : CMC : AA with AA at an equal concentration. The films demonstrated excellent antimicrobial activity against both Gram-positive (*Staphylococcus aureus*, with an inhibition zone of 21 mm) and Gram-negative (*Escherichia coli*, with an inhibition zone of 15 mm) bacteria, thereby enhancing food safety and shelf life. The 60 : 40 : 1 ratio for the film showed a lower water vapor transmission rate than the 70 : 30 : 1 composition, suggesting better moisture barrier properties. This maintains food freshness and aids in extending shelf life by preventing moisture-induced spoilage. The 60 : 40 : 1 film exhibited higher mechanical strength and better biodegradability (71% at day 15), with a uniform morphology rate than 70 : 30 : 1, having biodegradability at (65% at day 15). These properties, combined with the antimicrobial effects of AA, make these films promising for enhancing shelf life while reducing environmental impact, and could be a potential candidate in the food industry.

However, Vit C is easily degraded in light, moisture, and air. Khuntia *et al.*[49] encapsulated Vit C (using the nanoliposome technique). They incorporated it in a film made of phosphatidylcholine (PC) and stearic acid (SA) at different ratios using a thin-layer dispersion method followed by ultrasonication. Optimal Vit C-loaded nanoliposomes were added to starch films to examine release characteristics at various storage temperatures. Various pH effects were simulated using kinetics modelling on apple and bean samples. They also reported that sonication has significantly impacted the particle size of liposomes. The highest storage stability and encapsulation efficiency of 94.18 ± 1.5% were found for nanoliposomes developed without SA. Similarly, another study was carried out in which Vit C was encapsulated using the complex coacervation method for wrapping the cut fruits and vegetables with biodegradable film, eventually increasing its shelf life. The complex

Table 8 Storage temperature ranges and the composition of coating for perishable food products

Sample	Composition of coating	Storage temperature	Key outcomes	Extended shelf life	Reference
Strawberries	Chitosan (1%) + ascorbic acid (1%)	4 °C for 15 days	Maintained sensory quality throughout; control deteriorated faster	Reduced weight loss, decay, MDA, H_2O_2; higher antioxidant enzyme activity	129
Fresh cut apples	Chitosan (1%) + ascorbic acid (5%)	5 °C for 14 days	Quality maintained over 14 days; control softened earlier	Browning suppressed, firmness retained, phenolics preserved	130
Raw pork meat slices	Sodium alginate coating + ascorbic acid (500–1500 ppm) + MAP	4 ± 2 °C	Shelf life reached 8.9 days (≈60% longer than control)	Sensory quality improved; spoilage microorganisms slowed	131
Abiu fruit	Ascorbic acid dip (5 mM, 10 mM)	Ambient 28 °C, 12 days	Maintenance of quality across 12 days *vs.* control	Firmness, color, browning delay, phenolics, respiration rates monitored	132
Pork meat hamburger	Chitosan (1% w/v), acetic acid (1% w/v), lactic acid (1% w/v) films	5 °C, 8 days	—	Reduction of 0.5–1 log for mesophilic microorganisms; 1 log CFU g^{-1} for coliforms	131

coacervation was performed for gelatin and pectin as wall materials (2.5, 5.0, 7.5%) with different concentrations of Vit C (50, 75, and 100%). They reported that the concentration of wall material and Vit C at 7.5% and 75%, respectively, yielded an optimum encapsulation efficiency of 85.1 ± 2.94% with homogeneous microparticles. Also, at 20 °C, packed beans (pH 7) released more Vit C from the packaging film than packed bananas (pH 4.5) at 25 and 37 °C.[23] Another study focused on extending the shelf life of oxygen-sensitive food, particularly by reducing headspace oxygen and minimizing oxygen permeation through the packaging wall. To achieve this, they developed an edible packaging film based on whey protein isolate (WPI) infused with ascorbic acid (AA) at varying concentrations for scavenging oxygen (O_2). They added different ratios of WPI : glycerol (1.00, 0.80, or 0.67) for film formation (5%, w/w) and maintained a pH of 3.5 to stabilize AA against oxidation. When the pH is adjusted to more than 7, the O_2-scavenging action of the AA-infused film becomes activated. AA-incorporated WPI films were tested for O_2 scavenging by detecting residual O_2 in the headspace of a high-barrier container. Each ratio of WPI : Gly showed reduced tensile strength and oxygen permeability in WPI-AA film. AA-containing films at pH levels greater than 7 demonstrated oxygen (O_2) absorption proportional to the AA content, confirming the predicted O_2-scavenging capacity. Moreover, AA-incorporated film showed properties including O_2-scavenging, O_2 barrier improvement, and good mechanical attributes, making it an appealing packaging in food industry prospects.[126] Table 8 presents some of the storage temperature ranges and the composition of coatings for perishable food products. Although no single company solely manufactures Vit C-infused biodegradable films, companies namely TIPA (Israel), Natureworks (USA), BASF, Kingfa, Debbie Meyer® (USA), Zeomic Co Ltd® (Japan), Sharper Image® (USA), Kinetic Go Green® (USA), InMat® Inc, (USA) *etc.* Focuses on the research and production of biodegradable packaging solutions.[127,128]

9. Commercial viability

(1) Scalability of encapsulation techniques: spray drying is the most widely used technique for encapsulation of Vit C in biopolymers (starch, protein, cellulose, *etc.*). It is cost-effective, compatible with industrial throughput, and has already been used for scaling additive products.[133] However, heat exposure can degrade Vit C, lowering encapsulation efficiency. Furthermore, another study by Jafari *et al.*[50] and Berraquero-García *et al.*[51] reported that electrospaying or electrospinning offers higher encapsulation efficiency and controlled release properties with minimal thermal degradation. However, high equipment costs, low throughput, and challenges in continuous operation hinder industrial feasibility.[52] Coacervation and nanoemulsion also provide reasonable protection against oxidation, but they have stability issues during storage and added processing costs raise scalability concerns.[56] To enhance stability, novel methods (such as ultrasound) were employed.

(2) Regulatory barriers: Vit C-infused biopolymer food packaging faces regulatory barriers, including the need to comply with food contact safety standards from authorities like the FDA and EFSA. The supplemental daily dose for Vit C for humans is 1 g per day. However, habitual intake of 1.5 g per day of Vit C is found to reduce the risk of renal and kidney stones. Higher doses of Vit C (3–4 g per day) may lead to acute gastrointestinal effects.[134] Key concerns are controlled migration of Vit C to avoid toxicity or sensory changes, and ensuring the antimicrobial and antioxidant additives are safe.[135] Uniform production, stability during storage, and reproducibility are required for regulatory approval. Additional scrutiny applies if nanomaterials are involved. Testing for migration, release kinetics, sensory impact, and biodegradability is essential. Regulatory labelling for allergens or additives also matters. Meeting these requirements ensures the safety, efficacy, and environmental sustainability of such packaging solutions.[136]

(3) Consumer acceptance: Vit C is generally acceptable, but nano-encapsulation or synthetic crosslinkers may trigger consumer doubt and stricter labeling/regulatory scrutiny. Transparent labeling, sensory testing (including taste/odor), and clear benefits (such as days gained and reduced waste) are crucial to adoption. Studies often omit sensory trials, a key gap to be filled before market rollout.[137] The following Table 2 shows some of the encapsulation techniques used in food industries, along with their relative cost and throughput.

10. Life cycle analysis, biodegradability of Vit-C incorporated films

Life Cycle Assessments (LCAs) examine the environmental impacts of a product throughout its entire life cycle, from the extraction of raw materials to the final disposal of waste. Without the presence of such assessments, claims regarding biodegradability or decreased carbon footprint lack justification—assertions regarding the sustainability of Vit C-based films need thorough validation through LCAs that assess their environmental effects throughout the manufacturing, utilization, and disposal phases.[138,139] Biodegradable films incorporated with Vit C offers an environmentally friendly alternative to traditional polymer-based food packaging, delivering active food preservation and improved biodegradability at the end of its life cycle. The implications of Vit C in packaging film imparts antibacterial and antioxidant qualities, extending shelf life and minimizing food waste while avoiding the toxicity concerns associated with some metal packaging.

The biodegradability test of Vit C in soil demonstrates higher biodegradation rates for films containing Vit C, with degradation exceeding 65–70% after two weeks, depending upon the film's composition.[29] These films often exhibit optimal mechanical properties and resistance to water vapor, making them suitable for sustainable packaging applications. Moreover, the LCAs of Vit C incorporated packaging film is rare in the literature. Broeren *et al.*[140] found that starch-based films might decrease emissions of greenhouse gases up to 80% compared to conventional plastic films, mainly due to their sustainable sources and biodegradability. The European Starch Industry Association revealed that Starch Europe's Life Cycle Assessment demonstrated that starch products had a 35% lower carbon footprint than fossil-based alternatives when utilizing the mass allocation method.[138] The starch film incorporated.

Biodegradable films infused with Vit C offer an environmentally sustainable solution to traditional plastic-based food packaging, incorporating strong antibacterial and antioxidant capabilities with rapid environmental degradation. Their utilization lowers plastic waste while offering optimal food preservation, hence enhancing sustainability and food safety. These films represent a significant step in the development of active, biodegradable packaging for modern food systems.

11. Conclusion

Vit C-infused biopolymer films represent a transformative advancement in active food packaging, offering a sustainable and multifunctional solution that extends shelf life, preserves nutritional quality, and mitigates food waste. The integration of ascorbic acid (AA) or its derivatives into biodegradable polymers, such as chitosan, polyvinyl alcohol (PVA), cellulose derivatives, and starch, enhances their antioxidant, antimicrobial, and oxygen-scavenging properties, addressing critical challenges in food preservation. Develop pH-responsive films for targeted Vit C release in acidic foods. Encapsulation techniques, including spray drying, electrospinning, and complex coacervation, have proven vital in stabilizing Vit C against environmental degradation while enabling controlled release kinetics. For instance, spray-dried microcapsules achieved an encapsulation efficiency of over 90%, retaining 80% of AA's bioactivity over 60 days, while electrospun nanofibers demonstrated sustained release profiles and reduced lipid oxidation. These methods not only improve the thermal and oxidative stability of AA but also enhance the mechanical and barrier properties of the films, such as tensile strength, water vapor permeability, and UV resistance. The functional efficacy of Vit C-based coatings has been validated across diverse food matrices. Grapes coated with pullulan-Vit C composites exhibited 50% lower weight loss and retained >10% higher nutrient content during storage. In comparison, chitosan–ascorbic acid films inhibited microbial growth by 99.99% against *E. coli* and *S. aureus*. Layer-by-layer (LbL) assemblies further optimized oxygen and moisture barriers, extending the shelf life of apples and guavas by 40% through the delay of enzymatic browning and respiration. However, challenges persist in balancing AA's pro-oxidant effects at high concentrations and its pH-dependent stability, necessitating precise formulation adjustments. Therefore, future research should prioritize scalability and cost-effectiveness of fabrication methods, such as solution casting and LbL techniques, to facilitate industrial adoption. Innovations in innovative packaging, including self-healing films and AI-driven release kinetics models, could further enhance precision in nutrient delivery and environmental adaptability. Additionally, exploring synergies with plant-derived antioxidants (*e.g.*, tea polyphenols) may amplify preservative effects while aligning with consumer demand for natural additives. By addressing these gaps, Vit C-based biopolymer films can revolutionize sustainable packaging, reducing reliance on synthetic preservatives and contributing to global food security initiatives.

Author contributions

Rakesh Kumar Gupta: conceptualization; data curation; formal analysis; methodology; validation; writing – original draft; writing – review & editing; Manisha, ElSayed Ali, Neha Naijo Areekal, Sunil Pipliya and Jyotsana Patel: data curation; formal analysis; methodology; validation; writing – original draft; Prem Prakash Srivastav, Chin-Kun Wang, and Roberto Castro-Muñoz: supervision; validation; visualization; writing – review & editing.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

No primary research results have been included and no new data were generated or analysed in this review.

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