

Advances in polyphenol-loaded green nanocarriers for eco-friendly food preservation

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Abstract Growing demand for natural food preservatives has stimulated increasing interest in polyphenolic compounds. However, their application in food systems is constrained by insufficient stability during processing and storage, which can lead to reduced antioxidant and antimicrobial efficacy and, consequently, compromised preservation performance. To address these limitations, green nanocarriers—including chitosan-based particles, liposomes, and nanoemulsions—have been widely explored to enhance polyphenol stability, enable controlled release, and improve compatibility within food matrices. This review systematically summarizes the bioactive properties of polyphenols, the design principles of green nanocarriers, and their applications in the preservation of meat, fruits and vegetables, and dairy products. Current evidence indicates that polysaccharide-, protein-, lipid-, and stimuli-responsive carrier systems can effectively enhance the antioxidant, antimicrobial, and anti-browning functions of polyphenols, extend food shelf life, and reduce health and environmental risks associated with synthetic preservatives. Taken together, the rational design and application of polyphenol-loaded green nanocarriers hold promise as an effective and sustainable strategy for food preservation.

Keywords: Green nanocarriers; polyphenol; food preservation

1 Introduction

In recent years, there has been a growing consumer demand for food safety and natural preservatives, prompting significant advancements in food preservation technologies. Polyphenolic compounds, such as tea polyphenols and grape polyphenols ^[1-2] have attracted attention in the food preservation sector due to their antioxidant

and antimicrobial properties. However, the direct application of polyphenols in food systems is often hindered by their instability under environmental factors such as light and temperature, as well as potential alterations to the food sensory profile ^[3-5].

The integration of green, food-grade delivery systems—such as chitosan, liposomes, and nanoemulsions—has emerged as a promising strategy to enhance the stability, targeted release, and compatibility of polyphenols within food matrices ^[6-8].

This review aims to systematically explore the bioactivity of polyphenols, the characteristics of green nanocarriers, and their synergistic applications in food

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preservation. By examining recent advancements in this field, we seek to provide a theoretical foundation for the development of novel, natural, and efficient food preservation technologies.

2 Mechanisms of polyphenol-based food preservation

Polyphenols, as natural preservatives, exert synergistic effects in food preservation through various mechanisms, including antioxidant activity, antimicrobial properties, inhibition of enzymatic browning, interactions with food components, and the formation of physical barriers (Fig. 1). These mechanisms can be summarized as follows:

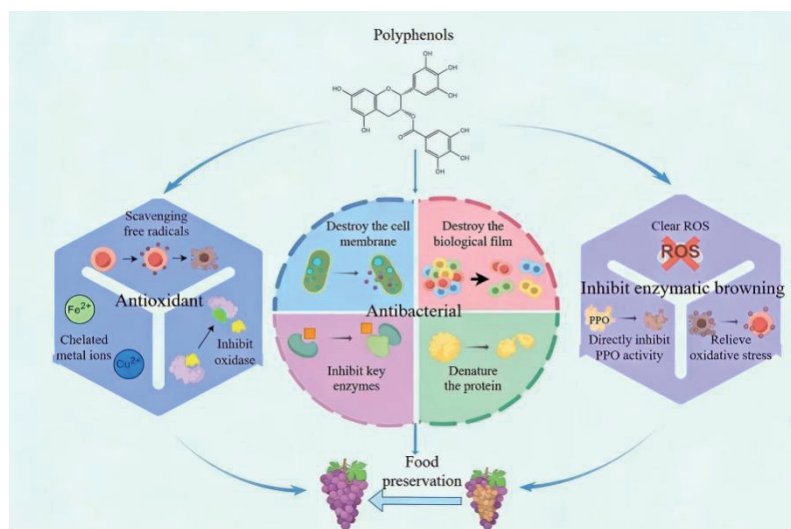


Fig. 1 The food preservation mechanism of polyphenols

2.1 Antioxidant activity

The antioxidant capacity of polyphenols primarily stems from their phenolic hydroxyl moieties and conjugated molecular structures, which enable these compounds to neutralize reactive oxygen species (ROS) through hydrogen atom or electron donation. This redox reaction effectively interrupts radical-mediated chain reactions, such as lipid peroxidation, thereby delaying oxidative deterioration in food systems^[9-10].

In food matrices, this radical scavenging capacity is particularly important for suppressing the initiation and propagation stages of lipid oxidation, which are responsible for the formation of rancid off-flavors and quality deterioration during storage^[11]. Certain polyphenols can inhibit the activity of endogenous oxidase enzymes in food (e.g., lipoxygenases and polyphenol oxidases), thereby reducing the occurrence of enzymatic browning and oxidative reactions. Additionally, polyphenols can chelate pro-

oxidant metal ions (e.g., Fe^{2+} and Cu^{2+}), reducing their catalytic role in oxidative reactions and further enhancing the oxidative stability of food^[12].

For example, flavonoids derived from peanut shells have been shown to significantly reduce the formation of thiobarbituric acid reactive substances (TBARS) and carbonyl compounds in refrigerated pork, indicating a marked preservation of meat quality during storage^[13]. Moreover, polyphenols can interact with myoglobin (Mb) and inhibit its oxidation to metmyoglobin, a mechanism that contributes to the enhanced color stability of red meats and fish products^[14].

2.2 Antimicrobial properties

Polyphenols inhibit spoilage and pathogenic bacteria through mechanisms such as disruption of microbial cell membranes, interference with metabolic enzyme activities, and inhibition of genetic material replication^[9-15].

2.2.1 Membrane disruption

The hydrophobic groups of polyphenols can insert into microbial phospholipid bilayers, increasing membrane permeability and leading to leakage of intracellular ions (e.g., K^+ , Ca^{2+}) and ATP [16]. For example, the minimum inhibitory concentration (MIC) of chestnut shell polyphenols against three foodborne spoilage bacteria (*E. coli*, *Staphylococcus aureus*, and *Salmonella*) is 0.5-2.0 mg/mL. A 30-minute exposure can reduce bacterial survival by three logarithmic levels [2].

2.2.2 Protein targeting

Polyphenols can bind to bacterial enzymes, such as proteases and ATPases, through hydrogen bonding or hydrophobic interactions, altering their spatial conformation and rendering them inactive [17]. For proteases, polyphenols such as quercetin target active or allosteric sites, as evidenced by molecular docking studies showing flavonoid interactions with α -amylase and α -glucosidase (binding energies < -6 kcal/mol) [18]. Similarly, ATPases are inhibited when polyphenols (e.g., ciriliol) interfere with conformational transitions or ATP-binding domains, as observed in bacterial FF-ATP synthase inactivation [19]. Structural analyses further reveal that polyphenol-enzyme binding induces significant conformational shifts: proteases exhibit static fluorescence quenching upon polyphenol binding, indicating stable complex formation and catalytic inactivation [20]. For instance, myofibrillar protein (MP) interactions with polyphenols reduce α -helix and β -sheet content (secondary structure) while increasing random coil proportions [21]. In ATPases, polyphenol binding disrupts hexameric helicase symmetry in AAA+ ATPases (e.g., PAN), impairing proteolytic function [22]. These dual mechanisms—direct binding interference and structural destabilization—collectively render bacterial enzymes inactive, providing a robust foundation for polyphenol-based antimicrobial strategies.

2.2.3 Inhibition of genetic material replication

Regarding nucleic acid-related mechanisms, polyphenols can directly interact with bacterial DNA via hydrogen bonding and π - π interactions, leading to destabilization of DNA structure and impaired replication. In addition, certain polyphenols inhibit key enzymes involved in DNA replication and transcription, such as DNA gyrase and topoisomerases, thereby suppressing bacterial cell division. Polyphenol-induced intracellular oxidative stress may further contribute to nucleic acid damage, collectively limiting the replication and proliferation of spoilage and pathogenic bacteria in food systems [23-24].

2.2.4 Synergistic enhancement

When combined with carriers such as chitosan, the antimicrobial efficacy of polyphenols is significantly enhanced [25-26]. Chitosan, a cationic polysaccharide, exerts antibacterial activity primarily by disrupting bacterial cell membranes through electrostatic interactions with negatively charged bacterial surfaces [27]. Polyphenols, including tea polyphenols and quercetin, exhibit antimicrobial properties through mechanisms such as metabolic interference and disruption of cellular structural integrity. The combination of chitosan and polyphenols generates a synergistic antibacterial effect, wherein chitosan-induced membrane permeabilization facilitates the enhanced intracellular penetration of polyphenols, thereby amplifying their antibacterial action within bacterial cells. For instance, quercetin-loaded chitosan nanoparticles demonstrated significantly lower minimum inhibitory concentrations (MICs) against drug-resistant strains of *E. coli* and *Staphylococcus aureus* compared to free quercetin [28]. Furthermore, catechin-grafted chitosan composites showed over 90% improvement in antibacterial efficacy against *Pseudomonas aeruginosa*, which is attributed to covalent conjugation enhancing bacterial membrane adhesion and promoting reactive oxygen species generation [29].

2.3 Inhibiting enzymatic browning

Polyphenols suppress enzymatic browning through multifaceted mechanisms. Primarily, they directly inhibit polyphenol oxidase (PPO) activity by binding to its active site via hydrophobic interactions or hydrogen bonds, thereby altering the enzyme's spatial conformation^[30]. Epigallocatechin gallate (EGCG) demonstrates this mechanism through high-affinity binding to PPO, significantly reducing catalytic activity^[31]. Competitive binding to mono- or diphenol substrates of PPO further blocks enzymatic oxidation initiation^[32]. Concurrently, polyphenols exert antioxidant effects by scavenging reactive oxygen species (ROS) generated during browning^[33], thereby interrupting the oxidation chain from phenolics to quinones such as catechiquinone and chlorogenic acid quinone^[34]. Tea polyphenols (TPs), for instance, donate hydrogen atoms to reduce quinone intermediates, preventing melanin polymerization^[35]. Additionally, polyphenols regulate browning-related metabolic pathways by downregulating phenylalanine ammonia-lyase (PAL) activity to limit phenolic substrate synthesis, while mitigating oxidative stress through the reduction of malondialdehyde (MDA) levels^[36]. Synergistic strategies, such as high hydrostatic pressure (HHP) treatment, enhance PPO inhibition efficacy^[37]. Non-enzymatic browning is suppressed through inhibition of flavan-3-ol monomer polymerization (observed in wine discoloration)^[38] and modulation of pectin interactions to alter optical properties^[39]. Practical applications include tea polyphenol coatings delaying browning in fresh-cut potatoes and bananas^{[35] [40]}, and catechins reducing juice discoloration (R-value: -0.83)^[41]. However, efficacy depends on structural features (e.g., catechol groups), food matrices (e.g., pectin content)^[42], and processing conditions (e.g., sterilization temperature)^[37], necessitating scenario-specific optimization.

3 Green food-grade carriers

The growing demand for natural preservatives in the food industry has driven extensive research

into polyphenols, which exhibit potent antioxidant and antimicrobial properties. However, their practical application faces challenges such as poor solubility, environmental sensitivity, and uncontrolled release kinetics. Green food-grade carriers—including polysaccharides, proteins, lipid-based systems, and stimuli-responsive materials—have emerged as innovative solutions to enhance polyphenol stability, bioavailability, and functionality. These carriers not only protect polyphenols from degradation during processing and storage but also enable targeted delivery and controlled release, addressing critical limitations in conventional preservation methods. This section systematically reviews recent advances in carrier design, focusing on mechanistic insights, application-specific optimization, and scalability for industrial adoption.

3.1 Green nano-carrier materials

3.1.1 Natural polymer-based carriers

Polysaccharides and proteins have emerged as prominent natural carrier systems due to their biocompatibility and dynamic interactions with polyphenols. V-type amylose demonstrates remarkable binding capabilities with C6-C3 polyphenols like gallic acid and tea polyphenols, forming encapsulation complexes through hydrogen bonding and hydrophobic interactions^[42]. These complexes not only enhance thermal stability but also regulate digestive release patterns, effectively reducing starch digestion rates and controlling glucose release for functional food applications^[43]. Chitosan, as a cationic polysaccharide, combines with polyphenols through electrostatic interactions and non-covalent bonds. Notably, chitosan-tea polyphenol composite films prepared by solution casting exhibit exceptional antibacterial properties (MIC 0.1 mg/mL) while improving mechanical strength^[44]. The pH-responsive release characteristics of chitosan-based systems enable targeted delivery, achieving staged release profiles in simulated gastrointestinal environments.

In protein-based systems, plant-derived

carriers such as whey protein and soy protein form nanocomplexes through hydrophobic interactions and covalent crosslinking. Whey protein-gallic acid complexes demonstrate extended food preservation effects by inhibiting microbial membrane proteins ^[45]. However, competitive binding phenomena must be considered – coexisting whey protein isolate (WPI) and gallic acid (GA) may reduce starch digestion inhibition through enzyme binding competition ^[45]. Processing optimization plays a critical role in maintaining polyphenol integrity, with techniques like spray drying achieving 77.3% encapsulation efficiency in chitosan-starch nanoparticles ^[46], although crosslinker concentrations must be carefully controlled to preserve bioactive stability ^[47].

Despite significant progress, key challenges remain in practical applications. The moisture sensitivity of chitosan-polyphenol films, evidenced by swelling behavior under high humidity, necessitates modification strategies like oxidized sucrose treatment ^[48]. Furthermore, strong carrier-polyphenol interactions may compromise bioaccessibility, requiring systematic optimization of release kinetics through simulated digestion models ^[49]. Current applications span functional food development and active packaging technologies. Starch-polyphenol complexes show promise in low glycemic index food formulation ^[42], while chitosan-based films effectively extend fruit shelf life through ethylene scavenging and oxygen radical inhibition ^[50]. Future research priorities should address the sensory impact of carrier-polyphenol interactions and cost-effectiveness analysis for industrial-scale production ^[46]. The development of natural polymer carriers requires balanced consideration of protection efficacy, functional performance, and processing feasibility, with interdisciplinary collaboration being crucial for advancing practical implementations.

3.1.2 Lipid-based delivery systems

Liposomes and nanoemulsions constitute two principal delivery platforms for polyphenols, each presenting unique structural and functional

characteristics. The phospholipid bilayer architecture of liposomes enables dual-phase encapsulation, accommodating both hydrophilic polyphenols like hydroxytyrosol and hydrophobic compounds such as curcumin. Precise modulation of cholesterol content (30–50 mol%) allows control over membrane fluidity and pH-responsive release profiles ^[51], while phytosterol-incorporated formulations demonstrate functional advantages through competitive inhibition of intestinal cholesterol absorption ^[52]. Stability improvements are achieved through oligosaccharide additives, including fructooligosaccharides and lactose, which enhance bilayer micropolarity to delay curcumin release and improve lyophilization stability ^[53]. Glycolipid-modified variants exhibit superior gastrointestinal stability, reducing bioactive leakage under digestive conditions ^[54].

Nanoemulsions employ optimized surfactant systems for polyphenol stabilization, with coconut oil-based formulations stabilized by Tween 60/Span 60 blends (HLB = 6) demonstrating 50% reduction in curcumin thermal degradation at 55 °C ^[55–56]. Terpene-enriched systems reveal critical stability dependencies on HLB values (optimal range 8–12) and surfactant ratios ^[57]. Their food preservation potential is exemplified by geraniol-loaded nanoemulsions, which suppress spoilage bacteria in minced beef through microbial membrane disruption while delaying protein/lipid oxidation. Antibacterial efficacy shows a strong correlation with emulsion particle size (< 200 nm) and zeta potential (± 30 mV) ^[58], while pH-dependent sustained intestinal release in curcumin-loaded systems achieves 2–3-fold bioavailability enhancement ^[59].

Both systems confront distinct technical challenges. Nanoemulsions require medium-chain triglyceride selection and strict particle size control ($d < 150$ nm) to mitigate instability in complex matrices ^{[55] [59]}, whereas phytosterol substitutions (e.g., ergosterol esters) address phospholipid oxidation in liposomes ^[60]. Industrial production challenges persist, with chitosan hydrogel coatings improving lyophilization-rehydration stability to achieve 64% polyphenol encapsulation in liposomes ^[61]. Emerging

computational approaches demonstrate potential in optimizing nanoemulsion HLB parameters and surfactant combinations through machine learning algorithms^[62].

Future development requires systematic optimization of stability parameters and implementation of AI-driven formulation design for precision engineering.

3.1.3 Protein-polyphenol hybrid systems

Protein-based carriers, particularly those derived from whey protein isolate (WPI) and soy protein isolate (SPI), have emerged as versatile vehicles for the stabilization and controlled delivery of polyphenolic compounds in food systems. WPI nanoparticles formed via enzymatic crosslinking (e.g. transglutaminase) or pH-driven self-assembly effectively encapsulate hydrophobic polyphenols^[63] such as rutin, markedly enhancing their thermal and photostability during processing and storage^[64]. Similarly, SPI-polyphenol complexes generated through non-covalent interactions (hydrophobic forces, hydrogen bonding) improve aqueous solubility and intestinal uptake of flavonoids, with in vitro Caco-2 transport assays demonstrating bioavailability comparable to WPI systems (6.3% vs. 7.4% in animal models)^[65]. Crucially, both WPI and SPI carriers exhibit pH-responsive conformational transitions: under acidic conditions the protein matrix remains compact, whereas neutral-to-alkaline pH triggers network relaxation and sustained polyphenol release, aligning antioxidant delivery with the spoilage kinetics of diverse food matrices^[66]. Beyond chemical protection, incorporation of polyphenols into protein films or hydrogels synergistically enhances mechanical integrity (e.g. a 51% increase in tensile strength for TG-crosslinked SPI films) and imparts antimicrobial and anti-inflammatory functionalities suitable for active and intelligent packaging^[67]. For instance, WPI–catechin conjugate coatings retard lipid oxidation and inhibit *E. coli* proliferation on meat surfaces, extending refrigerated shelf life by 2-3 days^[68]. Moreover, dual-protein matrices (WPI–

SPI) processed via high-pressure homogenization yield nanoparticles with tunable size distribution and enhanced encapsulation efficiency (> 95% for quercetin), offering environmentally benign and nutritionally fortifying delivery vehicles^[69]. Notwithstanding these advances, scale-up challenges remain-standardization of protein crosslink density and particle size distribution is essential to ensure batch-to-batch consistency-and deeper molecular insights into protein-polyphenol binding mechanisms are needed to rationally design next-generation carriers for food, pharmaceutical, and biomedical applications.

3.1.4 Inorganic nanocarriers

3.1.4.1 Mesoporous silica carriers

Mesoporous silica nanoparticles (MSNs) play a significant role in maintaining the stability of polyphenolic compounds within food systems due to their unique nanoporous structure, readily modifiable surface properties, low toxicity, and high drug loading capacity^[70]. Mesoporous silica possesses highly ordered pore channels with diameters ranging from 2 to 50 nanometres. Once polyphenolic compounds are loaded into its interior, the silicon-based framework of these channels forms a robust physical barrier. This barrier effectively prevents direct exposure of the polyphenols to damaging factors in the external environment, creating a stable protective shell. Epigallocatechin gallate (EGCG) exhibited enhanced stability under simulated gastrointestinal conditions and during storage following encapsulation within MSNs^[71]. Encapsulating tea polyphenols within UV-absorbing mesoporous silica nanoparticles synergistically leverages both the polyphenols' radical scavenging capacity and the MSNs' UV-shielding effect, further enhancing the polyphenols' antioxidant potency^[72]. Beyond providing a nanoscale protective shell for polyphenols, MSNs exhibit multiple non-covalent interactions (hydrogen bonding, electrostatic forces, etc.) between their inner surfaces and polyphenol molecules. These forces not only facilitate loading but also stabilise the polyphenol

molecules. Moreover, the readily modifiable surface of MSNs allows for precise functionalisation, further enhancing polyphenol activity and stability in complex environments. Sealing MSN pores with pH-responsive polymers (e.g., chitosan) enables targeted polyphenol release at specific intestinal pH conditions, preventing premature leakage in gastric acid [73–74]. The mesoporous silica-based nano-loading strategy, leveraging its efficient encapsulation and protective capabilities alongside flexible modifiability, provides robust technical support for overcoming the stability and bioavailability bottlenecks of polyphenols. This carrier plays a significant role in advancing the efficient application of polyphenols in functional foods and health supplements.

3.1.4.2 AgNPs-polyphenol composite coatings

AgNPs-polyphenol composites constitute a stable complex system formed through chemical interactions between AgNPs and polyphenol molecules. Their synergistic effects yield substantial benefits in food preservation. Polyphenolic molecules (such as catechins and tannic acid) reduce silver ions to AgNPs while simultaneously coating the AgNP surface through coordination bonds and π -stacking interactions, forming stable AgNPs-polyphenol complexes [75]. Within this complex, the dense nanocoating effectively blocks oxygen and ultraviolet radiation, severing the primary pathways for oxidative degradation and photolysis of polyphenols at the source to form a physical barrier. Concurrently, polyphenol molecules are immobilised through strong interactions with the AgNP surface, restricting their thermal motion and moderately passivating their chemical activity, thereby slowing their auto-oxidation and polymerisation rates. Within the entire system, polyphenols serve both as protected substances and as green reducing agents and stabilisers for synthesising nanomaterials [76]. The AgNPs-polyphenol composite coating primarily functions in food preservation through antibacterial, antioxidant, and physical barrier effects. Polyphenols inherently possess antimicrobial activity capable of disrupting microbial

cell membranes. When combined with AgNPs, polyphenols often exhibit enhanced antimicrobial efficacy compared to either component alone [77–78]. Concurrently, as natural antioxidants, polyphenols are supported by the coating's physical barrier function, which reduces food exposure to oxygen and indirectly enhances their antioxidant properties. Camellia seed cake polyphenols (CPs) anchored to AgNPs to form CP-AgNPs demonstrated superior antifungal activity against *Bacillus subtilis* compared to conventional AgNPs, whilst exhibiting highly effective reduction in citrus rot levels during box storage [79]. The AgNPs-polyphenol composite coating technology not only represents an innovation in the delivery of natural bioactive substances but also provides new scientific rationale and developmental directions for creating next-generation, highly stable, multifunctional integrated intelligent food preservation systems.

3.1.4.3 Stimuli-responsive delivery platforms

Metal-phenolic networks (MPNs), as intelligent stimulus-responsive carriers, have demonstrated unique advantages in food freshness monitoring through their core mechanism of achieving visual signal output via pH- or amine-triggered dynamic coordination changes. MPNs exploit the multistage competitive coordination between polyphenols (e.g. tannic acid, anthocyanins) and metal ions (Fe^{3+} , Cu^{2+}) to achieve highly sensitive colorimetric responses to seafood and meat spoilage markers. In the native state, MPNs exhibit a characteristic ligand–metal charge-transfer band (for example, Fe^{3+} –EGCG appears orange) that shifts dramatically when volatile basic nitrogen (TVB-N) species—such as ammonia or trimethylamine—compete for the metal centers, disrupting the original coordination and triggering a visible hue change (orange to green) at TVB-N levels as low as 300 ppb [80–81]. Concurrently, inherent pH-responsive chromophores like anthocyanins undergo structural transformations across acidic to alkaline conditions (red→purple→blue→green), synergistically amplifying the contrast of MPN color shifts and enabling naked-eye detection without

external instrumentation^[82-83].

Beyond fundamental sensing, MPNs deliver several design innovations that position them at the forefront of intelligent packaging. The combination of natural polyphenols with biocompatible metals meets food-contact safety standards while eliminating toxic synthetic dyes, and multilevel coordination yields ΔE values up to 8069, far exceeding conventional pH indicators. Embedding MPNs into diverse matrices—edible films, hydrogels, aerogels or electrospun nanofibers—allows tuning of mechanical strength, barrier performance and moisture stability; for instance, carboxymethyl starch supports mitigate polyphenol leaching under high humidity and UiO-66-NH₂ frameworks further anchor the network for robust operation^[84]. Integration with smartphone-based machine vision (RGB/Lab* analytics) and deep-learning models (CNN/LSTM) enables quantitative, real-time monitoring of TVB-N and pH, transforming simple color changes into precise freshness metrics at point of use^{[80] [85]}. Taken together, the modular coordination chemistry, green composition and digital compatibility of MPNs promise a new generation of low-cost, high-precision freshness sensors for meat, seafood and produce, with future work focusing on scale-up, multi-marker integration and mechanistic optimization of polyphenol–metal interactions.

3.2 Advantages of green nano-carrier materials

Green food-grade nanocarriers constitute nanoscale delivery systems constructed from natural, edible, and biocompatible materials (such as proteins, polysaccharides, lipids, etc.) via environmentally friendly methods. They not only inherit the efficiency and precision inherent to nanotechnology but also exhibit distinct advantages unmatched by conventional carriers due to their “green” and “food-grade” core characteristics.

3.2.1 Exceptional safety and biocompatibility

For technologies applied within food systems, absolute safety is the paramount prerequisite. Food-

grade green nanocarriers possess inherent advantages in this regard. Firstly, their raw materials are naturally sourced and edible. Examples include whey protein, corn alcohol-soluble protein^[86], chitosan, sodium alginate^[87], starch^[88], phospholipids^[89], and others. These substances possess a long history of safe consumption, have been proven harmless to humans, exhibit well-defined metabolic pathways, and demonstrate excellent biocompatibility. This implies that nanocarriers constructed from them can be safely ingested, digested, absorbed, or excreted by the human body, thereby avoiding potential toxicological risks associated with synthetic materials. Secondly, their synthesis processes are environmentally friendly and residue-free. Unlike organic solvents commonly employed in traditional nanomaterial synthesis, food-grade green nanocarriers are predominantly prepared using physical methods (e.g., high-pressure homogenisation, ultrasonication)^[90] or mild chemical approaches (e.g., molecular self-assembly, ion cross-linking)^[91], conducted in aqueous or food-grade solvents. For instance, silver nanoparticles are synthesised using the inherent reducing properties of polyphenols, or functional factors are encapsulated via electrostatic interactions between milk proteins and polysaccharides. This approach entirely avoids introducing harmful chemicals, fundamentally eliminating the risk of toxic solvent residues and ensuring the purity and safety of the final product. Furthermore, these carriers exhibit low immunogenicity and are gut-friendly. Many synthetic nanomaterials may trigger undesirable immune responses or intestinal inflammation. In contrast, food-grade natural carriers, such as cellulose nanocrystals derived from dietary fiber, not only fail to irritate the gut but may even function as prebiotics to promote beneficial microbial growth. This enables the delivery of functional agents while indirectly enhancing intestinal health^[92].

3.2.2 Significantly enhancing polyphenol stability and bioavailability

Food-grade green nanocarriers provide

comprehensive protection for functional components through their sophisticated nanostructures. By encapsulating active substances within the carrier (e.g., liposomes) or immobilising them within the carrier's network structure via interactions (e.g., protein-polysaccharide composite nanoparticles), these environmentally sensitive components are effectively physically isolated from external conditions. For instance, loading photosensitive anthocyanins onto chitosan nanocarriers effectively prevents photodegradation and discoloration^[93]. Concurrently, numerous hydrophobic functional factors (e.g., curcumin, resveratrol) exhibit poor water solubility and face absorption challenges within the intestinal tract. Certain nanocarrier materials, such as cationic polysaccharides (e.g., chitosan), can prolong the residence time of active components in the intestine, thereby enhancing absorption opportunities^[94-95].

3.2.3 Environmental friendliness and sustainability

In an era where carbon neutrality and the circular economy represent global consensus, environmental friendliness has become a crucial benchmark for evaluating technological value. Food-grade green nanocarriers embody the principles of green development throughout their entire lifecycle, from raw materials and production to waste disposal. Firstly, their raw materials possess renewable and biodegradable properties. These carriers extensively utilise agricultural by-products (such as soybean residue, fruit peel, and wheat bran) or marine processing by-products (such as shrimp and crab shells) for high-value development. For instance, chitin is extracted from lobster shells, alcohol-soluble proteins from corn, and whey proteins from whey. This transforms waste resources into valuable assets, perfectly aligning with the core principles of the circular economy. Simultaneously, these natural polymers can be rapidly and completely degraded by microorganisms in natural environments, avoiding persistent environmental presence and ecological risks^[96]. Secondly, their production processes are low-carbon and energy-efficient. Green synthesis

methods for obtaining nanometre-scale carriers typically operate under mild conditions, eliminating the need for high temperatures or pressures, thereby significantly reducing energy consumption^[97]. The widespread use of aqueous systems also minimises atmospheric pollution from volatile organic solvents. The entire production process is cleaner and imposes a smaller environmental burden.

4 Application cases and empirical studies

Application Cases and Empirical Studies: The synergistic application of green nano-carriers and polyphenols has demonstrated remarkable potential for extending the shelf life of food products through enhanced stability and controlled release of bioactive compounds^[98]. In this section, specific examples involving meat, fruit and vegetable, and dairy matrices are examined to assess carrier-matrix compatibility, and their performance is benchmarked against that of traditional preservatives to highlight the superior technical advantages of nano-enabled systems^[99].

4.1 Meat preservation

Polyphenol-based nanoparticles (NPs) have emerged as promising natural alternatives to conventional chemical preservatives for meat.

4.1.1 Polyphenol nanoparticles: dual antimicrobial and antioxidant function

Polyphenol-based nanoparticles (NPs) combine broad-spectrum antimicrobial activity with potent antioxidant effects, markedly extending refrigerated meat shelf life. For instance, chitosan films loaded with tea-polyphenol NPs (TPNP) suppressed *E. coli* and *S. aureus* growth in pork patties stored at 4 °C, retarded lipid oxidation (TBARS), and reduced metmyoglobin formation, achieving a 6-day shelf-life extension versus control^[100]. Curcumin- β -cyclodextrin photodynamic films (Cur- β -CD) inhibited microbial proliferation and lowered TVB-N and TBARS in chilled pork, doubling shelf life from 5 to 10 days

under 425 nm light ^[101]. Silk-fibroin NPs encapsulating quercetin and trans-resveratrol released actives slowly at 4 °C, extending chicken-fillet freshness by over 50% compared to free polyphenols ^{[102] [103]}. Likewise, liposomal carriers of gallic acid and celery-seed essential oil provided sustained antimicrobial action in meat emulsions, outperforming unencapsulated compounds in maintaining microbial counts and sensory quality over 12 days at 4 °C ^[104].

4.1.2 Carrier–meat matrix compatibility

The efficacy of polyphenol NPs hinges on matching carrier properties to meat characteristics. Biopolymeric coatings-chitosan or silk fibroin-form cohesive films on high-moisture substrates (minced meat, patties), offering oxygen-barrier and controlled-release benefits without sensory drawbacks ^[105]. Chitosan-thyme-oil NPs in meat emulsions inhibited lipid oxidation and microbial growth while preserving color and texture ^[100]. Lipid-based nanoemulsions and liposomes excel in high-fat products (sausages, hams), efficiently entrapping lipophilic polyphenols (e.g., curcumin) and enhancing oxidative stability under vacuum impregnation ^[106]. Inorganic composites such as ZnO-polyphenol films offer potent surface

antimicrobial action for packaging, limiting microflora growth and retarding lipid/protein oxidation, though their toxicity profile warrants careful assessment ^[107].

4.1.3 Comparison with conventional preservatives

Compared with nitrites or synthetic antioxidants (BHA/BHT), polyphenol NPs deliver equivalent or superior preservation with improved safety and sustainability. Natural polyphenols exhibit low toxicity and biodegradability, avoiding nitrosamine formation linked to nitrites and consumer health concerns ^{[108] [109]}. Their broad-spectrum antimicrobial action reduces the risk of resistant strains, whereas chemical preservatives often target specific microbes and can foster resistance ^[110]. Sensory studies show polyphenol NPs retain or even enhance plant-derived aromas without imparting off-flavors or color shifts typical of nitrites or BHT. Environmentally, biopolymer carriers (chitosan, silk) and natural polyphenols are biodegradable, contrasting with persistent, polluting synthetic preservatives ^[102]. Empirical comparisons confirm that essential-oil nanoemulsions (e.g., thyme, sage) match nitrite in microbial inhibition yet eliminate carcinogenic nitrosamine risk ^[111] (Table 1).

Table 1 Comparison between polyphenol nanoparticles and conventional preservatives

Dimension	Polyphenol NPs	Nitrites / BHA / BHT
Safety	Natural origin, low toxicity	Potential carcinogenicity, consumer concern
Antimicrobial/Antioxidant	Broad-spectrum, low resistance risk	Targeted, resistance development
Sensory impact	Retain plant-derived aroma; carrier-tunable	Off-flavors, color shifts
Environmental profile	Biodegradable carriers (chitosan)	Persistent, pollution risk

4.2 Fruit and vegetable preservation

Polyphenol-based nanotechnologies markedly enhance postharvest preservation of fruits and vegetables by stabilizing bioactive compounds, enabling controlled release, and imparting dual antimicrobial/antioxidant functions. Compared with conventional chemical preservatives, these nano-

systems offer lower toxicity, biodegradability, and potential for smart monitoring, although challenges remain in large-scale production, regulatory acceptance, and long-term safety evaluation.

4.2.1 Dual antimicrobial and antioxidant efficacy

Encapsulation of curcumin or tea polyphenols

into nanocarriers overcomes poor water solubility and rapid degradation, producing coatings that inhibit microbial proliferation (e.g. *E. coli*, mold) while retarding lipid and enzymatic oxidation. Curcumin-loaded alginate/pectin films exhibited photodynamic antimicrobial activity on strawberry surfaces, reducing decay rate by > 30% and enabling pH-responsive spoilage indicators under blue LED illumination ^[112]. Tea-polyphenol nanoparticles (TPNP) embedded in chitosan films suppressed *Botrytis cinerea* and maintained plum firmness, lowering malondialdehyde (MDA) content by 40% over 12 days at 4 °C ^[113]. Rice-starch films with nanocurcumin prevented microbial growth on strawberries for 3 days, stabilizing soluble solids and pH versus controls ^[114].

4.2.2 Carrier–matrix compatibility

The choice of nanocarrier tailors functionality to specific fruit/vegetable matrices. Lipid-based systems (liposomes, nanoemulsions) efficiently encapsulate hydrophobic polyphenols (resveratrol, curcumin)

and suit high-moisture produce such as lettuce and tomatoes; thyme-oil nanoemulsions matched sodium benzoate in antimicrobial effect on tomatoes without sensory drawbacks ^[115]. Polymeric nanoparticles (PLGA, chitosan) form robust edible coatings on cut fruits: PLGA-anthocyanin particles slowed ethylene emission and browning in mangoes by approximately 50% ^[116]; chitosan-based NPs extended apricot shelf life up to 30 days under cold storage, enhancing antioxidant enzyme activities (SOD, CAT) and reducing weight loss ^[117]. Inorganic hybrids (Ag-MOF, ZnO-polyphenol) impart surface disinfection in packaging films, though their toxicity demands further toxicological assessment ^[118].

4.2.3 Comparison with conventional preservatives

Natural polyphenol-based nanotechnologies and traditional chemical preservatives differ markedly in safety, environmental impact, antimicrobial mechanisms, sensory effects, functionality, and cost (Table 2).

Table 2 Comparison between polyphenol nanoparticles and conventional preservatives

Parameter	Polyphenol nanotechnology	Chemical preservatives (e.g. benzoate, nitrite)
Safety	Natural origin, low toxicity, biodegradable	Potential carcinogenicity, environmental persistence
Antimicrobial spectrum	Multifaceted (membrane disruption, ROS scavenging)	Single-mode action, risk of microbial resistance
Sensory impact	Retains natural aroma; carrier-tunable release	Off-flavors, color alteration common
Functional expandability	Enables smart sensing (pH/ethylene response)	Limited to preservation only
Cost& scalability	Higher nanoformulation cost; scale-up challenges	Established industrial processes; lower cost

4.3 Dairy product preservation

The integration of polyphenol-based nanotechnology into dairy preservation has emerged as a transformative approach, addressing challenges in stability, bioavailability, and multifunctionality. Below, we synthesize key advancements, empirical validations, and comparative analyses to illustrate its scientific and industrial relevance.

4.3.1 Application and empirical evidence

Encapsulation of curcumin in lipid-based nanocarriers has been shown to overcome its photoinstability and poor solubility, enabling pH-responsive antimicrobial films that inhibit *Listeria* in cheddar cheese and extend shelf life by approximately 30% without sensory loss ^[119-120]. Tea-polyphenol nanoparticles (TPNP) integrated into chitosan-based

coatings for liquid milk achieved > 90% inhibition of *E. coli* and *S. aureus* and enhanced mechanical strength by 20% [98]. In yogurt, TPNP-nanofiber surface coatings completely suppressed mold growth over 21 days at 4 °C, outperforming uncoated controls [121]. ZnO-quercetin nanocomposites in fresh milk reduced total viable counts by 3 log CFU/mL after 7 days at 4 °C, demonstrating broad-spectrum antimicrobial efficacy and GRAS status of ZnO [122]. Casein-mangiferin nanoparticles (CEMPs) have been successfully developed to deliver polyphenols in milk matrices, improving oxidative stability and vitamin retention during storage [123].

4.3.2 Carrier–matrix adaptation

Lipid nanoparticles (liposomes, nanoemulsions) efficiently encapsulate hydrophobic polyphenols (curcumin, resveratrol), making them ideal for high-fat dairy (cheese, cream), though thermal processing can degrade some carriers [124]. Polymeric NPs (PLGA, chitosan) form robust colloidal suspensions in liquid

milk and yogurt, enhancing mechanical stability and enabling slow release of antioxidants; however, they may alter mouthfeel if not optimized [125]. Electrospun nanofiber mats (PVA or milk-protein based) loaded with tea polyphenols create high-surface-area coatings on cheese surfaces, providing sustained antimicrobial action and even pH-responsive color change as a freshness indicator [126]. Inorganic carriers (SiO₂, ZnO) withstand high-temperature processes in milk powder production, but migration limits must be strictly controlled to ensure safety [127].

4.3.3 Comparison with traditional preservatives

Natural polyphenol NPs exhibit markedly lower cytotoxicity and biodegrade into harmless byproducts, whereas common preservatives (e.g., sodium benzoate) carry risks of allergenicity and metabolic burden. Polyphenol nanocarriers surpass traditional chemical preservatives in safety, functionality, and sustainability (Table 3).

Table 3 Comparison between polyphenol nanoparticles and conventional preservatives

Parameter	Polyphenol nanosystems	Chemical preservatives
Safety	Non-toxic, natural origin	Potential allergenicity
Antimicrobial Scope	Broad-spectrum (bacteria, fungi, biofilms)	Narrow (e.g., bacteria-specific)
Functionality	Antioxidant, color retention, nutrient enrichment	Single preservative role
Environmental Impact	Biodegradable carriers (e.g., chitosan)	Persistent ecological accumulation
Cost-Effectiveness	High initial cost but reduced dependency	Low cost but requires frequent reapplication

Polyphenol NPs act via multiple mechanisms—membrane disruption, ROS scavenging, enzyme inhibition—reducing the chance of microbial resistance; in contrast, synthetic agents typically rely on a single mode of action.

5 Challenges and industrial prospects

The application of green polyphenol-based nanotechnologies in food preservation has emerged as a promising strategy to address spoilage and safety

concerns. However, its industrial implementation requires overcoming multifaceted challenges while aligning with market demands and sustainability goals.

5.1 Technical challenges

Natural polyphenols, such as tea polyphenols and curcumin, exhibit limited aqueous solubility, oxidative instability, and rapid metabolic clearance, which compromise their preservation efficacy.

While nanocarriers (e.g., chitosan nanocomposites, nanoemulsions) enhance stability through encapsulation, optimizing encapsulation efficiency and controlled release kinetics remains challenging due to process complexity. For instance, the synthesis of tea polyphenol nanoparticles (TPNPs) necessitates polymerization to amplify antioxidant activity, yet elevated processing temperatures (e.g., 395.33 °C) may degrade thermosensitive components^[128].

Safety concerns further hinder progress, particularly for metal-based nanomaterials (e.g., TiO₂ nanoparticles^[129]) with photodynamic antimicrobial properties. Their long-term toxicity and environmental accumulation risks remain poorly characterized, underscoring the need for standardized toxicological evaluation frameworks^[130]. Scaling up laboratory-scale production to industrial levels presents additional barriers. Techniques like nano-coacervation demand precise control over polyphenol thresholds to balance enzymatic activity and structural stability, requiring high-precision equipment. Moreover, interactions between polyphenols and complex food matrices (e.g., dairy or meat products) may diminish functionality, necessitating tailored delivery systems such as nano-antimicrobial peptide packaging for muscle foods^[131].

5.2 Industrialization potential

Market drivers, including consumer preference for natural preservatives and policy incentives for eco-friendly technologies, propel the adoption of polyphenol-based nanosystems. Curcumin-loaded nanocarriers exemplify dual functionality, enhancing preservation while enabling real-time quality monitoring^[132]. Innovations like intelligent packaging-integrating biopolymer-polyphenol conjugates with antimicrobial, antioxidant, and sensing capabilities-demonstrate significant potential. For example, carboxymethyl cellulose/polyvinyl alcohol/nanoclay composite films effectively extended fish fillet shelf life^[133].

Emerging technologies, such as nanophotodynamic therapy combining TiO₂ nanoparticles with polyphenol photosensitivity, offer efficient inactivation of foodborne

pathogens^[129]. Diverse nanocarriers, including solid lipid nanoparticles (SLNs) and nanocrystals, improve polyphenol targeting for high-value applications^[134]. Sustainability advantages are evident in reduced food waste, aligning with Sustainable Development Goals (SDGs). Nano-iron treatments, for instance, enhance tomato polyphenol content while mitigating fertilizer pollution^[135].

5.3 Future directions

Advancing this field demands interdisciplinary collaboration among food science, nanotoxicology, and industrial engineering to bridge lab-to-production gaps. Establishing standardized safety protocols (e.g., ISO/TS 19338) and regulatory frameworks is critical to ensure compliance and consumer trust^[136]. Cost-effective strategies, such as low-energy microfluidic synthesis and valorization of agricultural byproducts, will enhance scalability^[137]. Concurrently, public education initiatives must address “nanophobia” by improving transparency and fostering acceptance^[130].

In summary, polyphenol-based nanotechnology holds transformative potential for sustainable food preservation, contingent on resolving technical bottlenecks, regulatory harmonization, and stakeholder engagement.

6 Conclusion

This review systematically highlights the synergistic potential of polyphenol-loaded nanocarriers, which enhance stability, bioavailability, and targeted delivery of bioactive compounds, thereby amplifying their antioxidant, antimicrobial, and anti-browning functionalities. Key findings underscore the versatility of polysaccharide-, protein-, lipid-, and inorganic nanocarriers systems in adapting to diverse food matrices, from meat and dairy products to fruits and vegetables. Empirical studies demonstrate that these nanotechnologies not only match or surpass conventional preservatives in efficacy but also mitigate risks associated with synthetic additives, such as carcinogenicity and environmental persistence.

Overall, green polyphenol-based nanotechnologies hold immense promise for advancing safer, greener, and more efficient food preservation strategies.

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