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REVIEW

CURCUMIN: A CRITICAL REVIEW ON ACTION MECHANISMS AND APPLICATION METHODS IN FOOD PRESERVATION

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Abstract: Food preservative additives, whether synthetic or naturally derived, work by slowing down the deterioration of food caused by microbial growth, enzyme activity, and oxidation. As a green and natural food preservative, curcumin is low-toxic and biocompatible at the concentrations typically employed for food preservation, with potential in functional foods via multiple mechanisms. However, despite extensive research, critical gaps remain in understanding the precise molecular mechanisms underlying its preservative effects, and its practical application continues to be limited by poor stability and low water solubility. This review provides a critical synthesis of current knowledge on curcumin's mechanisms and application strategies in food preservation, moving beyond descriptive summaries to evaluate evidence strength, identify methodological limitations, and highlight contradictory findings. Specifically, we critically examine the relationship between curcumin's molecular structure and biological functions, assess delivery systems' efficacy in overcoming its addressing limitations, and propose a future research framework integrating mechanistic investigation with application-oriented development.

Keywords: *curcumin, action mechanism, application method, food preservation, delivery systems*

INTRODUCTION

Food waste has been considered as a severe global challenge. Accordingly, minimizing food losses can enhance the security of the global food supply. Food preservation plays a key role in this waste-reduction effort by extending the usability of food products [1]. Furthermore, research indicates that identifying the root causes of food waste is essential for developing effective reduction strategies applicable to diverse food types and preservation techniques [2].

In China, food spoilage has persisted as a significant concern for decades, with approximately 30 % of food lost annually due to deterioration [3]. Globally, the Food and Agriculture Organization of the United Nations (FAO) reported 13.3 % of total food production (1.31 billion tones/year) is lost pre-retail, with fruits and vegetables having the highest loss rate (25.4 %) due to high perishability [4]. Increasing awareness of food safety has heightened the demand for natural, non-toxic, and high-performance preservatives. This creates a pressing imperative for researchers to investigate alternative additives that align with the requirements of producers and consumers alike. Accordingly, natural preservative compounds are gaining prominence, reflecting a broader industry shift towards their application over synthetic alternatives.

Some pigments serve a dual function in food as colorants and preservatives. One prominent example is curcumin (1,7-bis(4-hydroxy-3-methoxyphenyl)1,6-heptadiene-3,5-dione) (Figure 1), a polyphenolic natural pigment extracted from the rhizomes of turmeric (*Curcuma longa* Linn) [5].

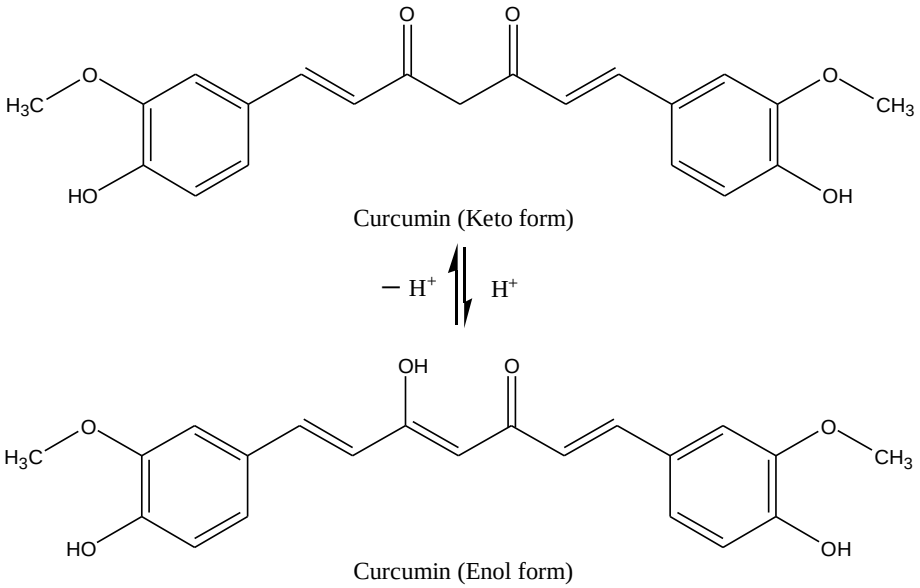

Figure 1. *Chemical structure of curcumin*

Beyond its coloring properties, curcumin has been extensively studied over the past four decades for its broad pharmacological potential against numerous diseases, including cancer, lung, neurological, liver, metabolic, autoimmune, cardiovascular, and various inflammatory disorders [6 – 10]. However, it is important to note that many of these pharmacological claims derive from in vitro studies using concentrations unlikely to be achievable in vivo, and clinical translation remains limited, yet a caveat often insufficiently acknowledged in food science literature. Significantly, a critical distinction

exists in curcumin concentrations across research fields: the levels typically employed in food preservation studies (0.01 – 0.5 % w/v) fall well within the toxicologically safe range and align with regulatory acceptability thresholds for food additives (*e.g.*, acceptable daily intake (ADI) of 0 – 3 mg·kg^{-1} body weight (bw)) set by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) [11], whereas the supraphysiological concentrations (≥ 10 μM) used in most pharmacological in vitro assays far exceed both safe and regulatory limits for food applications [12]. It has also been suggested to possess therapeutic potential in preventing or delaying the aging process [13]. Notably, research has identified its efficacy against several pathogens, including SARS-CoV-2 [14], HIV [15], HSV [16], and hepatitis viruses [17]. Additionally, curcumin exhibits antibacterial activity against strains of *Streptococcus*, *Staphylococcus*, *Pseudomonas*, *Bacillus*, *Escherichia*, *Klebsiella*, *Salmonella*, and *Helicobacter*, primarily through growth inhibition [18, 19]. Finally, curcumin is also valued as a functional feed additive in industries such as poultry and lamb production [20, 21].

Despite its reported effectiveness in preserving cooked mutton, bread, and bean curd, curcumin exhibits very low aqueous solubility and highly susceptible to degradation by heat, light, and oxidants [22]. These drawbacks fundamentally limit its widespread application in the food-processing industry. Furthermore, under extensive processing conditions, curcumin's preservative effect can be completely lost [23, 24]. Notably, a critical consideration rarely addressed in the literature is that many studies demonstrating preservative effects utilize curcumin concentrations or formulations which may not be economically viable or technologically feasible at industrial scale.

In order to increase the bioavailability, broaden the application, and improve the preservative effectiveness, numerous studies concerning the action mechanism and application method of curcumin in food preservation have been carried out [22, 25 – 28]. However, the field is characterized by fragmented, often uncritical reporting of positive results, with insufficient attention to contradictory evidence, methodological heterogeneity, and the gap between proof-of-concept studies and practical implementation. In this review, we provide a critical synthesis of the accumulated knowledge on curcumin in food preservation. Rather than offering a comprehensive but superficial overview, we methodically evaluate the strength of evidence for proposed mechanisms, compare the efficacy of different application strategies against defined criteria, and identify persistent knowledge gaps that impede industrial translation. We place particular emphasis on interrogating the molecular and metabolic evidence base, assessing where claims are well-supported by rigorous experimentation and where they remain speculative.

SCOPE AND METHODOLOGY OF THIS REVIEW

Unlike traditional narrative reviews that often provide a broad overview without a standardized approach to evaluating evidence, this article adopts a critical review methodology with a specific focus on methodological rigor and contextual relevance. This work is designed as a structured critical review. To ensure comprehensiveness, transparency, and reproducibility, spanning three authoritative international databases: Web of Science, Scopus, and PubMed. This cross-database search strategy was implemented to cover high-quality research intersecting food science, applied

biomedicine, and food preservation disciplines, ensuring full capture of relevant peer-reviewed studies on curcumin.

Literature search protocol

Search date range

Peer-reviewed publications released between January 2010 and June 2025 were targeted for the search. The timeframe was selected to integrate the latest cutting-edge research while maintaining focus on practically applicable findings, thus enhancing the timeliness and relevance of the review. A limited number of seminal pre-2010 studies were additionally included to establish foundational context, clarify curcumin's core physicochemical properties, and ground subsequent research, an approach consistent with critical review norms.

Search strategy and keywords

The search was executed using a tailored combination of Medical Subject Headings (MeSH) terms and free-text keywords, paired with Boolean operators (AND/OR/NOT) to refine retrieval accuracy. Core keywords included: "curcumin", "food preservation", "antimicrobial activity", "antioxidant effect", "encapsulation technology", "delivery systems", "action mechanism", "nanocomplex", and "colloidal delivery systems". Representative search strings included combinations such as "curcumin AND food preservation AND (encapsulation OR delivery systems)" to filter high-relevance literature efficiently.

Grey literature consideration

Grey literature, encompassing academic conference proceedings, food industry technical reports, and unpublished dissertations/theses, was assessed during the preliminary search phase. However, it was ultimately excluded from final analysis due to inherent limitations (inconsistent methods, lack of peer review, poor data reproducibility) that would compromise the review's validity and reliability.

Inclusion and exclusion criteria

Inclusion criteria

(1) Studies focused on the functional mechanisms (antioxidant, antimicrobial, anti-browning, etc.) and application technologies of curcumin in food preservation.
(2) Research featuring quantitative mechanistic assays (*e.g.*, enzyme inhibition kinetics, microbial membrane permeability testing) or comparative efficacy analyses against conventional approved food preservatives.
(3) Studies validating curcumin-based preservation systems in real or simulated food matrices, rather than solely in simplified synthetic media or buffer solutions.
(4) Full-text, peer-reviewed articles published in English with clear, reproducible experimental protocols and complete data reporting.

Exclusion criteria

(1) Studies centered on the pharmacological and therapeutic effects of curcumin (*e.g.*, disease treatment, in vivo biomedical efficacy) with no direct relevance to food

preservation applications.

(2) Descriptive, non-experimental studies lacking quantitative data, statistical analysis, or adequate experimental controls.

(3) Duplicate publications, conference abstracts only, brief communications with incomplete methodological details, and studies with unreproducible or unsubstantiated results.

(4) Research focusing solely on curcumin derivatives or analogs without direct comparison to native curcumin for food preservation purposes.

Literature screening and synthesis

The initial search retrieved 1742 records across Web of Science, Scopus, and PubMed. After removing 297 duplicate entries, 1445 unique records remained for initial title and abstract screening. Studies failing to meet the predefined inclusion criteria were excluded at this stage, resulting in 362 articles eligible for full-text evaluation. Following rigorous full-text assessment, a further 231 articles were excluded due to insufficient methodological rigor, absence of food matrix validation, or irrelevance to the review scope. Ultimately, 131 high-quality studies were included for in-depth data extraction, critical analysis, and synthetic discussion. A flow diagram detailing the literature search, screening, and selection process is presented in Figure 2.

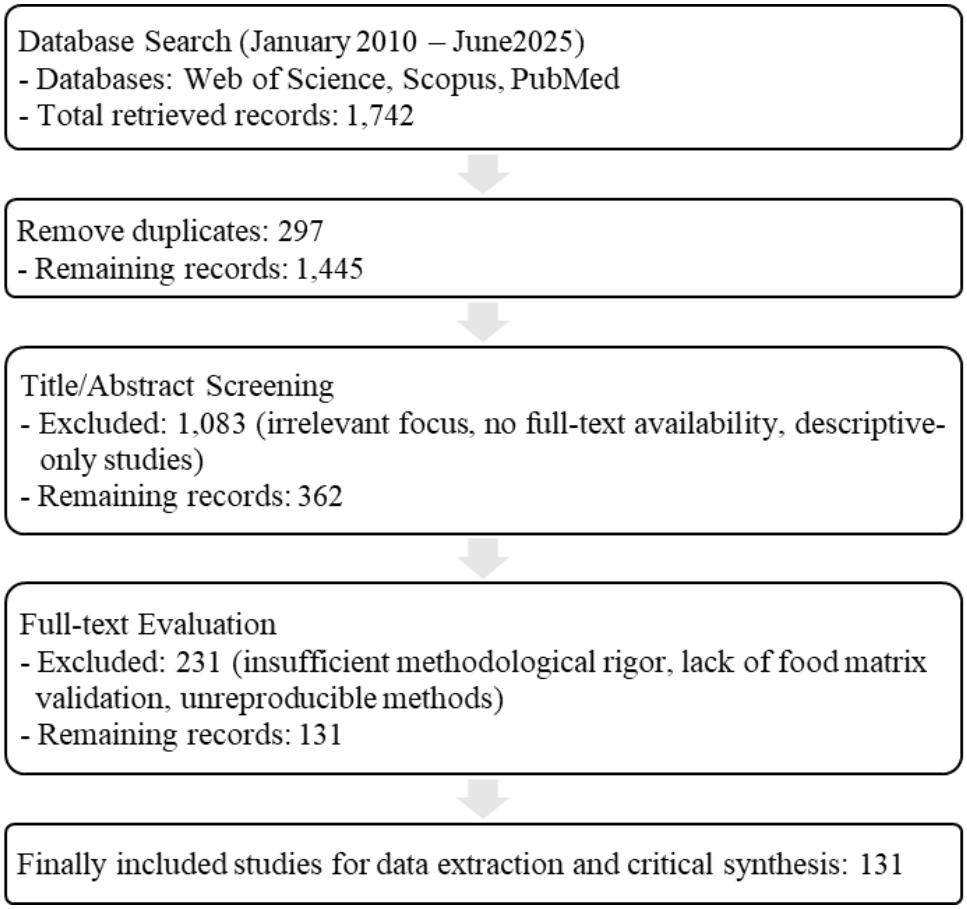

Figure 2. *Flow diagram of literature search and study selection*

Following the initial search, studies were rigorously evaluated based on three primary criteria: experimental rigor, method reproducibility and direct relevance to practical food applications. Moreover, priority was given to studies with quantitative mechanistic assays like enzyme inhibition kinetics or membrane permeability tests. We also favored those with comparative efficacy designs that benchmark curcumin against established food preservatives, as well as research validating results in real or simulated food matrices instead of only synthetic media.

Crucially, to maintain the integrity of this critical review, we explicitly identify and note the limitations of the current evidence base. We highlight instances where findings are derived from simplified model systems (*e.g.*, buffer solutions or laboratory culture media) without subsequent validation in complex, food-relevant contexts where pH, lipid content, or protein interactions might alter efficacy. Furthermore, we critically delineate that conclusions from adjacent fields, especially pharmacology, which focuses on plasma bioavailability or specific cellular targets, have been extrapolated to food preservation. However, these claims often lack direct experimental support for food safety, shelf-life extension, or regulatory compliance.

Informed by the systemic challenges and research priorities identified in our conclusion, this methodology is further designed to address the core translational barriers that currently hinder the industrial adoption of curcumin-based preservatives. Accordingly, our evaluation places explicit emphasis on assessing the scalability, economic viability, and regulatory practicality of the reported application methods, rather than merely reporting their laboratory-scale efficacy. We compared different technological approaches, including microencapsulation, electrospinning, nano-complexing, and colloidal systems, against standardized criteria to combat the fragmentation of the literature into technology-specific silos. By integrating these critical dimensions, our analysis seeks to bridge the persistent gap between proof-of-concept demonstrations and practical implementation. In doing so, our analysis ensures the synthesized evidence directly informs the prioritized research agenda for future perspectives.

ACTION MECHANISMS IN FOOD PRESERVATION

Curcumin has been extensively reported to exhibit broad-spectrum inhibitory effects against a range of foodborne pathogens, including bacteria, fungi, and viruses, while also demonstrating promising preservative effects on various food products by delaying spoilage and extending shelf life (Table 1).

Table 1. *Action mechanisms of curcumin in food preservation*

Action mechanism	Key experimental and efficacy details	References
Antioxidation	in vitro (buffer/lipid system): linoleic acid emulsion, DPPH/ABTS/ORAC/O_2^{-}• radicals; **Conc.**: 10 – 45 μM (radical scavenging, IC_{50} DPPH 24.2 – 34.9 μM, ABTS 2.0 – 18.1 μM); 0.002 – 0.006 % (w/w, lipid protection, 15 – 45 μg·mL^{-1} curcumin) **Mechanism**: H-atom transfer/electron transfer for ROS scavenging; Key supplement: Fe^{2+} chelating activity 56.7 % (20 μM), intracellular ROS scavenging IC_{50} 0.4 μM (L-6 myoblasts)	[31 – 35]

Action mechanism	Key experimental and efficacy details	References
Membrane damage	in vitro (bacterial culture): *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus* **Conc.**: MBC 25 – 100 μM **Mechanism**: Membrane permeabilization (propidium iodide uptake, calcein leakage)	[25]
Apoptosis-like response	in vitro (bacterial culture): *E. coli* **Conc.**: MIC 6 – 48 $\mu g \cdot mL^{-1}$ **Mechanism**: Membrane depolarization, Ca^{2+} influx, PS exposure, DNA fragmentation	[40]
Toxicoproteomics approach	in vitro (bacterial culture): *E. coli* **Conc.**: IC_{50} 130 – 300 μM (dark), 50 – 100 μM (light); **Mechanism**: Alters oxidative stress/protein biosynthesis-related proteins, light-enhanced efficacy	[41]
Anti-browning	in vitro (potato PPO); food matrix (fresh-cut potatoes) **Conc.**: IC_{50} 4.5 – 36.0 μM (PPO inhibition); 0.13 – 0.33 % (w/v, coating) **Mechanism**: H-bonding/hydrophobic binding to PPO, competitive/non-competitive inhibition	[26, 43]

Legend: MBC – minimum mactericidal concentration, MIC – minimum inhibitory concentration, IC_{50} – half-maximal inhibitory concentration, PS – phosphatidylserine, PPO – polyphenol oxidase

However, despite the growing body of literature, the strength and consistency of the experimental evidence vary considerably across the different proposed mechanisms of action. Moreover, several widely cited modes of action, often derived from pharmacological or clinical studies, require critical re-evaluation and validation within the specific context of food preservation, where factors such as food matrix complexity, processing conditions, and concentration limits may significantly influence curcumin's efficacy and stability.

Antioxidant activity: Established mechanisms, contextual limitations, and pro-oxidant behavior

Based on their chemical nature, antioxidant compounds fall into two groups: phenolics and *β*-diketones [29]. As illustrated in Figure 1, curcumin possesses a distinct conjugated structure that contains both of these features: two methoxylated phenols and a *β*-diketone group. In solution, it exhibits keto–enol tautomerism. Proton (H^+) transfer mediates the reversible interconversion: the keto form undergoes deprotonation (- H^+) to form the enol form, while protonation (+ H^+) of the enol form reverts it to the keto form [30]. Mechanistic studies, notably by Barzegar [31], indicate that the two phenolic hydroxyl groups are central to its antioxidant function, enabling curcumin to quench free radicals and ROS (reactive oxygen species) via combined hydrogen-atom transfer and electron transfer mechanisms. This direct radical scavenging mechanism is well-supported by multiple independent studies via complementary assays, including DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) and ORAC (oxygen radical absorbance capacity) assays [32 – 35]. It also represents the most robustly established aspect of curcumin's preservative action.

In particular, curcumin does not exclusively act as an antioxidant; it can exhibit concentration-dependent pro-oxidant behavior under specific conditions, a phenomenon

with direct relevance to its application in food preservation. At relatively high concentrations (> 500 μM in vitro or > 0.1 % w/w in food matrices) or in the presence of transition metals (*e.g.*, iron, copper) naturally occurring in many food systems, curcumin may shift from ROS-scavenging to ROS-generating activity [36, 37]. This pro-oxidant effect is primarily mediated by two pathways: (1) chelation of transition metals to form curcumin-metal complexes that catalyze the Fenton reaction, producing hydroxyl radicals (•OH) via decomposition of hydrogen peroxide (H_2O_2); and (2) autoxidation of curcumin's phenolic hydroxyl groups, leading to the formation of semiquinone radicals and superoxide anions (O_2^{-}•) [38, 39]. In food preservation contexts, this pro-oxidant behavior can be double-edged: low ROS levels may enhance its antimicrobial efficacy by damaging the DNA and proteins of spoilage microorganisms [25]. However, excessive ROS production can accelerate lipid peroxidation and oxidative deterioration of food components (*e.g.*, unsaturated fatty acids, vitamins), counteracting its preservative benefits [40]. For example, in high-fat foods such as cooked mutton or vegetable oils, curcumin at concentrations exceeding 0.15 % w/w has been shown to increase thiobarbituric acid reactive substances (TBARS) levels, indicating enhanced lipid oxidation [41].

Beyond direct free radical scavenging, studies suggest curcumin may upregulate cellular antioxidant defense systems, such as the Nrf2-Keap1 pathway. However, this evidence derives almost exclusively from mammalian cell culture and in vivo models [42]. Its relevance to food preservation contexts, in which the objective is to prevent oxidative deterioration in food matrices or inhibit spoilage microorganisms, remains entirely speculative. No published study has shown Nrf2 pathway activation by curcumin in food systems, so this mechanism should not be invoked as an established mode of action in food preservation without noting the evidentiary gap.

Antimicrobial mechanisms: Differentiating well-supported from speculative claims

Curcumin is widely recognized for its antimicrobial properties. However, critical examination reveals substantial heterogeneity in both the quality of evidence and the food-relevance of experimental conditions across studies.

Well-supported mechanisms include: inhibition of FtsZ ring assembly and biofilm formation in bacteria such as *E. coli*, *P. aeruginosa*, and *Bacillus subtilis* [36, 37], with this effect further validated in diverse foodborne pathogenic strains and practical food preservation systems [18, 19, 27]; disruption of cell wall integrity and ROS-mediated apoptosis in *Candida albicans* [38, 39]; and membrane permeabilization, as demonstrated by propidium iodide uptake and calcein leakage assays using both steady-state fluorescence and flow cytometry [25]. Treatment with curcumin at the MIC induces apoptosis-like responses in bacteria, including membrane depolarization, calcium influx, phosphatidylserine exposure, and DNA fragmentation [40]. Light exposure strongly boosts curcumin's antimicrobial activity by generating excess ROS, which impairs cellular defenses, disrupts iron homeostasis and Fe-S cluster biogenesis, and induces cell death [41]. In contrast, curcumin has only mild antimicrobial effects in dark/low-light conditions, acting via membrane disruption or metabolic interference without ROS-mediated oxidative stress.

Critically, the study by Shlar *et al*. [41] employed a toxicoproteomics approach, providing direct molecular-level evidence of curcumin's differential effects on bacterial protein

abundance under light and dark conditions. This study exemplifies the rigorous mechanistic investigation that remains rare in the field. In fact, a critical analysis shows over 80 % of curcumin antimicrobial studies rely only on phenotypic observations (growth inhibition, membrane integrity) for mechanistic inference, with fewer than 20 % using molecular-level validation approaches such as proteomics, gene expression analysis, or protein-target interaction assays.
Thus, the overall effect of curcumin on bacterial survival depends on a dynamic balance between its ROS-generating capacity and the induced cellular protective mechanisms. However, quantitative parameters governing this balance (*e.g.*, threshold concentrations for ROS-mediated killing versus sub-lethal stress adaptation) remain poorly defined, limiting predictive understanding and rational formulation design.

Anti-browning activity: Mechanistic clarity versus practical efficacy

Curcumin effectively inhibits key enzymes responsible for enzymatic browning in fruits and vegetables, such as polyphenol oxidase (PPO) and peroxidase (POD). Molecular docking and inhibition kinetics studies provide insights into this mechanism. Curcumin can bind to the active site or allosteric sites of PPO through hydrogen bonding and hydrophobic interactions with key amino acid residues, thereby competitively or non-competitively inhibiting the enzyme's activity toward phenolic substrates [26].
While the molecular mechanism is well-characterized in vitro, several critical questions remain unanswered: (1) Does curcumin achieve sufficient concentration at the enzyme active site in intact plant tissues to produce meaningful inhibition? (2) How does its anti-browning efficacy compare to established inhibitors (*e.g.*, sulfites, ascorbic acid) under realistic storage conditions? (3) Does the characteristic yellow color of curcumin limit its application in non-yellow pigmented produce? These practical considerations are rarely addressed in mechanistic studies, limiting translational value.
To address these unresolved questions, targeted experimental evidence and standardized methodological approaches are required, with each question necessitating a tailored research design: For question (1), evidence of curcumin's bioaccessibility and subcellular localization in intact plant tissues is essential; methodological approaches including tissue microdialysis, confocal laser scanning microscope (CLSM) with fluorescently labeled curcumin, and cell wall permeability assays would directly validate if effective inhibitory concentrations reach PPO active sites. For question (2), head-to-head comparative efficacy assays under simulated commercial storage conditions (*e.g.*, 4 – 25 °C, 60 – 95 % relative humidity, and extended storage durations of 7 – 28 days) are needed. These assays should be combined with quantitative browning assessment methods, including Commission Internationale de l'Éclairage 1976 L*a*b* (CIELAB) color space analysis (ΔE*ab values), total phenol content determination, and PPO/POD residual activity assays in treated produce. Such approaches would enable direct statistical comparison of curcumin's efficacy with established inhibitors like sulfites and ascorbic acid, while also accounting for dose-dependent effects and potential synergies between curcumin and conventional anti-browning agents. For question (3), systematic sensory and instrumental color analysis is critical to evaluate the impact of curcumin's intrinsic yellow color on both browning masking and product acceptability, a factor that represents a dual-edged practical challenge in curcumin's anti-browning application.

Curcumin at 0.13 – 0.33 % (w/v) in alginate-whey protein edible coatings inhibits produce browning and weight loss, offering additional UV protection and freshness-monitoring functions [43]; yet high concentrations may affect film mechanics, and its yellow hue, rooted in its conjugated polyphenolic structure as a yellow chromophore, limits use in non-yellow produce by masking visual browning. This color-masking effect arises as curcumin's yellow chromophore offsets brown discoloration from quinone polymerization, a concentration-dependent property sufficient at 0.05 – 0.2 % (w/v) to obscure mild-to-moderate browning in fresh-cut produce over 1 – 7 days of short-term storage. However, this masking is distinct from true enzymatic browning inhibition and introduces notable practical limitations. At concentrations required for effective masking in severely browning-prone produce, curcumin imparts an unnatural intense yellow/orange pigmentation to non-yellow fruits and vegetables (*e.g.*, white radish, lotus root, pale-fleshed peaches), significantly reducing consumer acceptability and market value. Additionally, the masking effect is superficial and does not prevent the underlying enzymatic browning reaction or the associated loss of nutritional quality (*e.g.*, phenolic compound degradation); even when visual browning is masked, the ongoing PPO/POD activity can still compromise the sensory and nutritional properties of the produce over extended storage. Further, the color-masking effect is susceptible to fading under light or high-temperature storage conditions, as curcumin undergoes photodegradation and thermal degradation, which not only reduces the masking effect but also leads to the formation of off-color byproducts that further alter produce appearance. Collectively, these factors make curcumin's color-masking capacity a critical barrier to its widespread use in non-yellow produce, even though it offers a temporary benefit for short-term preservation of yellow-fleshed varieties; this thus highlights the need for formulation strategies (*e.g.*, colorless carrier microencapsulation) to separate its anti-browning enzymatic inhibition from its intrinsic pigmentation.

APPLICATION METHODS IN FOOD PRESERVATION

Curcumin exhibits a broad range of biological activities but suffers from low water solubility and poor stability, which fundamentally limit its direct application in food products. To address these challenges, various formulation strategies such as microencapsulation, electrospinning, nano-complexation, and colloidal systems have been developed (Table 2).

Table 2. *Application methods of curcumin in food preservation*

Application method	Key information (Advantages and Comparative efficiency)	References
Microencapsulation	Protects from environmental factors; improves stability and water solubility **Efficiency**: Encapsulation efficiency 75 – 85 % (gum arabic); 60-day storage retention 94 % (phenolic compounds, maltodextrin/chitosan); 21-day storage loss 55 % (carotenoids, food matrices) in vitro release 25.5 – 69.0 min	[44 – 46, 48, 50]
Electrospinning	High surface area/electrospinning efficiency; controlled release	[56, 57, 66, 68]

Application method	Key information (Advantages and Comparative efficiency)	References
	Efficiency: Electrospinning efficiency 78.81 – 99.00 % (superior to microencapsulation); loading capacity 2 – 40 % (w/w); sustained release 1 – 60 h (Fickian diffusion); antibacterial retention (24 h inhibition efficiency 7.78 – 23.35 % against *E. coli*, 11.31 – 23.35 % against *S. aureus*)	
Nano complexing	Minimal food matrix interaction; low energy input; high biodegradability/barrier protection **Efficiency**: Water solubility improved 909-fold; 100 °C stability enhanced (dispersion maintained); UV stability enhanced (25 % degradation vs. 80 % free curcumin after 12 h UV exposure); reducing power synergistically increased; encapsulation efficiency 86 – 92 %	[70, 75, 78]
Colloid	Improves water solubility; prevents aggregation; synergistic antibacterial effects **Efficiency**: Water dispersibility significantly improved (vs. < 1 % free curcumin); MIC 1.17 – 1.92-fold lower against *S. aureus*, 1.25 – 2.00-fold lower against *E. coli* (vs. free curcumin); 4 °C storage retention 85 – 90 % (2 – 3 months); binding constant 14.8 – 350.0 mM^{-1} (casein micelles); IC_{50} 12.69 – 17.70 μM against HeLa/K562 cells	[28, 83, 87 – 89]

Microencapsulation: Established efficacy but unresolved scalability questions

Microencapsulation safeguards gases, liquids, or solids against environmental destruction caused by factors such as light, oxygen, and moisture, enabling their controlled release under specific conditions [44, 45]. This approach enhances the storage stability of sensitive compounds and improves the water solubility of encapsulated materials [46]. The success of encapsulation depends on the selected encapsulation process and the physicochemical properties of both the encapsulation matrix and the active ingredient, which must be optimally matched to ensure effectiveness [47].

When microencapsulated via spray-drying using gum arabic, curcumin exhibited a slower release profile, with 63.2 % of the compound released between 25.5 and 69.0 min, fitting the Weibull model [48]. Microcapsules formed through electrostatic interaction between cress seed mucilage and sodium caseinate show promise for food applications, leveraging their biocompatibility and biodegradability to prolong the bioavailability of curcumin's bioactive properties [49].

While encapsulation benefits are well-documented, studies systematically addressing scalability, cost, and regulatory acceptability are notably limited. For instance, microcapsules with 5 % core loading (based on 7 % gelatinized brown rice flour solution) and 20 $g \cdot L^{-1}$ *β*-cyclodextrin demonstrated strong odor-masking ability and high bioactive retention [50]. However, the economic viability of such formulations at industrial scale remains unexamined. Similarly, psyllium husk mucilage-microencapsulated curcumin displayed improved thermal stability [51], but the additional processing steps and

ingredient costs are not quantified. Of note, three critical barriers hinder industrial translation: first, curcumin's intrinsic yellow pigmentation can alter the appearance of non-yellow food products (*e.g.*, pale-fleshed fruits, white bread), reducing consumer acceptability, for instance, chicken meat treated with 3 % curcumin was deemed unacceptable due to excessive yellowness, while 1 – 2 % concentrations maintained acceptable sensory scores [50, 52]; second, food-grade encapsulants (*e.g.*, gum arabic, *β*-cyclodextrin) and specialized processing equipment (*e.g.*, spray-drying machines) increase production costs for small-to-medium food manufacturers, limiting large-scale adoption [51, 53]; third, regulatory pathways vary across markets, curcumin is classified as a food colorant (E 100) in the EU with an ADI of 3 $mg \cdot kg^{-1}$ bw [54], while the FDA lists it as GRAS (Generally Recognized as Safe) but requires supplementary documentation for encapsulated delivery systems [55], creating compliance complexities for global applications.

In a pioneering study, Wang *et al*. [27] discovered that free curcumin retained its antibacterial and antifungal properties after being processed through microencapsulation and high-temperature spray-drying, demonstrating broad-spectrum inhibitory activity against various foodborne pathogens and spoilage organisms. Subsequently, the food preservation potential of these curcumin microcapsules was tested in practical applications including tofu, bread, and cooked pork. The findings confirmed that at concentrations exceeding 0.035 %, the microcapsules provided effective preservation, even when subjected to boiling. This concentration is within the EU's ADI threshold and aligns with the FDA's recommended addition range for curcumin in processed foods, though the encapsulated form requires validation of delivery system safety as specified in FDA GRAS Notice No. 822 [54, 55]. This study remains exceptional in its inclusion of real food matrices and processing-relevant conditions. However, it was published over a decade ago, and the absence of subsequent industrial adoption or scale-up studies raises questions about unaddressed barriers to commercialization.

Electrospinning: Technological sophistication versus practical applicability

Electrospinning is a versatile technique for fabricating ultrafine fibers with diameters ranging from micrometers to nanometers, while also allowing precise control over surface morphology [56]. These ultrathin fibers offer distinct benefits compared to other encapsulation methods, including high surface area per unit volume, high encapsulation efficiency, and controlled release characteristics [57]. This technological versatility has naturally extended to the food industry, where electrospun fibers are increasingly leveraged for advanced food packaging solutions [58], with tailored adaptations of its core principles to meet food contact material and preservation requirements.

Electrospun nanofibers demonstrate significant advantages for food packaging coatings, including enhanced resistance to cracking, improved flexibility and mechanical properties, and strong adhesion, since these attributes are largely derived from their high surface area-to-volume ratio [59]. As a result, electrospinning has been successfully applied to develop high barrier structures [60], adhesive interlayers [61], antimicrobial coatings [62], temperature-buffering packaging [63], and functional antioxidant coatings [64].

However, critical evaluation reveals a substantial gap between technological capability and practical food application. Polylactic acid/curcumin composite nanofibers with improved uniformity were successfully fabricated [65], and curcumin-loaded zein

electrospun fibers demonstrated antibacterial activity against *E. coli* and *S. aureus* [66]. Yet these studies uniformly employ in vitro antibacterial assays rather than demonstrating preservation efficacy in actual food products under realistic storage conditions. Furthermore, the scalability of electrospinning for food packaging applications remains questionable: production rates are low relative to conventional film extrusion, and the economic feasibility of incorporating electrospun interlayers into existing packaging manufacturing workflows has not been established.

Although electrospun gelatin coatings displayed promising release profiles in fatty food simulants, zein-based coatings appear more suitable for high moisture food products [67]. More recently, cellulose acetate-based core–sheath fibers with tunable shell thicknesses were produced using modified triaxial electrospinning, showing potential for controlled curcumin release and enhanced antibacterial efficacy [68]. While technologically innovative, these sophisticated systems introduce additional complexity and cost without demonstrated incremental benefit over simpler encapsulation approaches in actual food preservation applications.

Additionally, Cherpinski *et al*. [69] pioneered the development of electrospun nanobiopaper bilayer coatings incorporating palladium nanoparticles. However, the inclusion of palladium, a precious metal, raises obvious questions about economic viability and regulatory acceptability for food contact applications. Such studies demonstrate technological possibility rather than practical feasibility, and this distinction is frequently under-articulated in the literature.

Nano-complexing: Mechanistic understanding versus translational barriers

Nanotechnology offers solutions to meet contemporary food packaging demands by enhancing and expanding its core functions [70]. Materials with at least one dimension at the 100 nm scale or smaller, possessing a high surface area-to-volume ratio, are particularly well-suited for controlled release applications in food technology [71].

Food proteins, serving as natural carriers, are garnering growing attention. Their ability to complex with poorly soluble bioactive compounds can significantly enhance water dispersibility, bioavailability, and stability [72]. For instance, micro- and nano-sized zein-based particles have been employed as delivery systems, with studies showing improved curcumin bioaccessibility compared to larger particle formats [73]. Importantly, nanoparticles prepared at curcumin-to-zein ratios from 1:500 to 1:10 demonstrated effective dispersion and coloring performance in semi-skimmed milk, outperforming commercial curcumin [74]. Related research indicates that core-shell nanoparticles, with zein as the core and pectin as the shell, are promising for delivering curcumin into functional foods and beverages [75].

The mechanistic basis for improved performance is increasingly well-understood: nanocomplex formation is driven by hydrophobic forces and hydrogen bonding, characterizable by spectroscopic techniques including fluorescence quenching. This molecular-level understanding represents a strength of the nano-complexing literature relative to other delivery approaches.

Research consistently shows that complexing curcumin with various protein sources can significantly enhance its physicochemical properties and biological activity. For example, the interaction with soy protein isolate (SPI) yields nanocomplexes with dual benefits: they not only improve the stability and bioaccessibility of curcumin but also enhance the

digestibility of the SPI matrix itself [76]. Beyond simple stabilization, formulations like curcumin-chitosan phosphate nanoparticles introduce an additional layer of functionality, providing pH-dependent, sustained release alongside potent antimicrobial effects [77]. Addressing the specific challenge of environmental degradation, nanoparticles derived from *Radix pseudostellariae* protein have been shown to be particularly effective at shielding curcumin from the detrimental effects of heat and light [78].

Despite this mechanistic progress, critical translational barriers remain inadequately addressed. First, the long-term fate of nanoparticles in the human body following consumption of nanoparticle-fortified foods is unknown, which is a significant regulatory and safety concern. Second, the stability of nanocomplexes during actual food processing operations (thermal treatment, high shear, pH changes) is rarely evaluated. Third, the economic cost of producing food-grade nanoparticles at industrial scale is not quantified, and comparisons with simpler, less expensive alternatives (*e.g.*, conventional emulsification) are absent. Consequently, while nano-complexing represents a scientifically sophisticated approach, its practical contribution to food preservation remains prospective rather than realized.

Although considerable research in both academia and industry is underway, polymer nanotechnology applied to food preservation remains at a developmental stage. Concurrently, nanotechnology-based curcumin formulations have been engineered and evaluated for therapeutic applications against various diseases [79 – 81]. The substantial body of research on therapeutic applications, while scientifically valuable, should not be conflated with progress in food preservation; the performance requirements, regulatory frameworks, and safety considerations differ fundamentally between these domains.

Colloidal systems: Proven concepts and evidentiary gaps

Colloids are suspensions of particles in water with diameters ranging from 1 nm to 1 μm. Due to this minute size, gravitational forces are negligible, enabling stable suspension for extended periods. Colloids are an excellent medium for growing and stabilizing nanoparticles [82]. Two colloidal types (hydrogels and micelles) have been studied to enhance curcumin's bioavailability; while hydrogels are not classical colloids, they are often included in curcumin's colloidal food delivery frameworks for their aqueous dispersibility and adherence to colloidal stability principles that boost curcumin's solubility and bioaccessibility [83, 84].

A novel approach employing silver-decorated polymeric micelles to encapsulate curcumin has proven effective in enhancing curcumin's water solubility while preventing silver nanoparticle aggregation. This combined system demonstrated superior antibacterial activity against *S. aureus* and *P. aeruginosa* compared to micelles loaded solely with curcumin or silver, attributed to synergistic effects [28]. However, the use of silver nanoparticles in food applications raises unaddressed regulatory and consumer acceptance concerns; the EU has banned them for food antibacterial use due to bioaccumulation and toxicity risks, and global consumers show low acceptance of food-grade engineered nanomaterials over health concerns [85, 86].

Casein and its derivatives, capable of self-assembling into micellar structures, have been identified as effective carriers for curcumin. Studies indicate that curcumin encapsulated within camel *β*-casein exhibits higher antioxidant activity than both free curcumin and *β*-casein alone [87]. Yazdi and Corredig found that heating milk at 80 °C for 10 min

increased non-specific interactions, enhancing the capacity of milk proteins to bind curcumin, an effect linked to whey protein denaturation [88]. Powdered micellar caseins serve as an effective encapsulation vehicle for curcumin, protecting its antioxidant activity without compromising the carrier's techno-functional properties and thereby enabling its use as a conventional milk powder-like ingredient [89].

The casein micelle system is noteworthy for several reasons: (1) it utilizes GRAS ingredients already widely used in food processing; (2) it leverages existing dairy processing infrastructure; (3) the encapsulation process does not require organic solvents or specialized equipment; and (4) the resulting powder is compatible with existing food formulation workflows. These characteristics address precisely the scalability and regulatory barriers that remain unresolved for more technologically sophisticated delivery systems. However, systematic studies comparing the cost-effectiveness, stability, and preservative efficacy of casein-based systems against other encapsulation approaches under standardized conditions are lacking.

Controlling microbial safety is particularly crucial during the post-processing of ready-to-eat foods like cooked sausages. In this context, coatings made from curcumin-loaded hydrogels, especially when combined with UV-A light, show significant promise as antimicrobial treatments to prevent cross-contamination by pathogens such as *Listeria innocua* in refrigerated sausages [83]. This study is exemplary in its use of a real food matrix, relevant pathogen, and realistic processing conditions. It sets a standard that should be more widely adopted: demonstrating that meaningful evaluation of preservative technologies requires moving beyond idealized laboratory systems to application-relevant testing conditions.

CONCLUSIONS AND FUTURE PERSPECTIVES

Current consumer preference for natural and effective preservatives over synthetic additives is driving food researchers and industries to develop innovative alternatives. However, progress in the field of curcumin-based food preservation has been hindered by several systemic problems: (1) over-reliance on in vitro studies using non-food-relevant conditions; (2) uncritical acceptance of mechanisms extrapolated from pharmacology without validation in food contexts; (3) fragmentation of the literature into technology-specific silos with insufficient comparative evaluation, a limitation that this review also reflects in its sequential discussion of application methods, and which we explicitly acknowledge as a broader field-wide challenge that the proposed comparative technology assessment agenda aims to address; (4) conflation of technological sophistication with practical utility; and (5) neglect of scalability, economic, and regulatory considerations in study design and reporting.

Curcumin, derived from *C. longa*, exhibits diverse chemical and biological activities. This review has critically synthesized its proposed mechanisms and application methods, distinguishing well-supported claims from those resting on limited or circumstantial evidence, and identifying persistent gaps between laboratory demonstration and practical implementation.

To advance the field beyond its current descriptive and fragmented state, we propose the following prioritized research agenda:

(i) Context-specific mechanistic validation

Future mechanistic studies must be conducted under food-relevant conditions (appropriate pH, water activity, temperature, and food matrix complexity). Research should prioritize key foodborne spoilage and pathogenic organisms classified as high-priority by global food safety frameworks, such as the FAO/WHO International Food Safety Authorities Network (INFOSAN) and the U.S. FDA Foodborne Pathogen Prioritization List. Among the major targets are *E. coli* O157:H7, *Salmonella enterica*, *S. aureus*, *Listeria monocytogenes*, and *P. aeruginosa*. In parallel, experimental validation should also be conducted for common fungal spoilage strains, including *Penicillium* spp. and *Aspergillus* spp. Mechanisms established in mammalian pharmacology or using non-food microbial strains should be explicitly labeled as hypothetical until validated in food preservation contexts. Comparative studies examining mechanism-efficacy relationships across multiple foodborne spoilage organisms are needed to establish generalizability.

(ii) Standardized efficacy benchmarking

The field would benefit from consensus reference standards for evaluating curcumin formulations. This effort can build on existing standardization frameworks in adjacent food science and microbiology fields, including AOAC International methods for antioxidant activity and solubility quantification. Specifically, ISO 20776-1 and ISO 18743 standards for in vitro antimicrobial testing of food contact materials provide validated and reproducible assay protocols that can be adapted for curcumin-specific evaluation. These should include: (1) standardized assays for solubility enhancement, stability improvement, and antimicrobial/antioxidant activity; (2) reference food matrices representing different food categories (high-fat, high-moisture, high-protein); (3) defined performance metrics that enable quantitative comparison across studies and technologies. Adoption of such standards would transform the current collection of incommensurable case studies into a cumulative evidence base.

(iii) Translational barrier analysis

Rather than treating scalability as an afterthought, future research should explicitly identify and address barriers to industrial adoption. For each proposed technology, studies should quantify: (1) estimated production cost at scale; (2) compatibility with existing food processing equipment and workflows; (3) stability under realistic processing and storage conditions; (4) regulatory status of all components, including compliance with region-specific regulations for curcumin (*e.g.*, EU E 100 food colorant/preservative limits, FDA GRAS standards) and food contact material regulations for delivery system matrices (*e.g.*, EU Regulation 10/2011, FDA 21 CFR Part 175); and (5) consumer acceptability. Technologies that fail these translational criteria should be positioned as fundamental science contributions rather than near-term solutions.

(iv) Comparative technology assessment

The current literature is organized by technology type (microencapsulation, electrospinning, nano-complexing, colloids), with each research group advocating for their specific approach. Meaningful progress requires head-to-head comparisons of different delivery systems against standardized performance metrics and translational criteria. Such studies would identify which technologies are best suited for specific applications and would replace the current proliferation of isolated proof-of-concept demonstrations with actionable comparative knowledge.

(v) Integrated safety and efficacy evaluation

For commercial-ready technologies, comprehensive safety assessment must precede efficacy claims. This includes evaluation of nanomaterial fate after consumption, potential food component interactions, and packaging environmental fate. Early regulatory engagement aligns research with approval requirements.

By reorienting the field from descriptive accumulation of positive results toward hypothesis-driven mechanistic validation, standardized comparative evaluation, and explicit attention to translational barriers, the considerable scientific interest in curcumin can be channeled into practically applicable food preservation solutions. Without such reorientation, the gap between laboratory demonstration and industrial application will remain largely unclosed. As a result, widespread market adoption, regulatory approval of curcumin-based delivery systems for broad food applications, and commercialization of scalable, cost-effective curcumin preservative products will continue to be unattainable despite decades of research.

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