Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 15 March 2026
Revised 24 April 2026
Accepted 10 May 2026

Natural Resources for Human Health 2026, Vol. 6 (3): 665–677

KEYWORDS:
clean-label preservatives; nanoencapsulation; essential oils; polyphenols; controlled release; antimicrobial activity; food shelf life; spray drying

Encapsulation Technologies for Plant Extracts: Enhancing the Efficacy of Clean-Label Food Preservatives

Karpagavalli[1], Uma A[2], Sorabh Lakhanpal[3], Ibrokhim Sapaev[4], Girish Kalele[5], Sathish Kumar Venkatachalam[6], Jahnavi Pandya[7]

[1]Pharmaceutics, Meenakshi College of Pharmacy, Meenakshi Academy of Higher Education and Research. karpagavalli@maher.ac.in
[2]Meenakshi College of Physiotherapy, Meenakshi Academy of Higher Education and Research. umaa@maher.ac.in
[3]School of Pharmaceutical Sciences, Lovely Professional University, Phagwara, Punjab 144411, India. sorabh.lakhanpal@lpu.co.in
[4]Department of Physics and Chemistry, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers National Research University, Tashkent, Uzbekistan; University of Tashkent for Applied Science; School of Engineering, Central Asian University, Tashkent, Uzbekistan. sapaevibrokhim@gmail.com
[5]Centre for Research Impact & Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140401, Punjab, India. girish.kalele.orp@chitkara.edu.in
[6]Department of Microbiology, School of Allied Health Sciences, VIMS Hospital, Salem Campus, Vinayaka Mission's Research Foundation (DU), Tamil Nadu, India. vmkvmcsathish@gmail.com
[7]Department of Pharmaceutics, Parul Institute of Pharmacy, Parul University, Vadodara, Gujarat, India. jahnavi.pandya37595@paruluniversity.ac.in

ABSTRACT: The global reformulation of processed foods toward "clean-label" compositions has intensified the search for natural preservatives capable of replacing synthetic antioxidants and antimicrobials such as butylated hydroxytoluene, nitrites, benzoates and sorbates. Plant extracts and essential oils rich in polyphenols, terpenoids and flavonoids are attractive candidates because they combine antioxidant and antimicrobial functionality with a favourable consumer perception. Their direct incorporation into foods is nonetheless constrained by chemical instability, volatility, poor aqueous solubility, pronounced sensory impact and limited bioavailability, which together erode preservative performance during processing and storage. Encapsulation has emerged as the principal technological strategy to overcome these barriers by entrapping bioactive compounds within protective carrier matrices, thereby improving stability, masking off-notes, enabling controlled release and permitting efficacy at lower effective doses. This review critically synthesises the state of the art in micro- and nanoencapsulation of plant-derived preservatives, comparing spray drying, freeze drying, complex coacervation, emulsion-based systems, liposomes, ionic gelation, molecular inclusion and electrohydrodynamic processing with respect to encapsulation efficiency, particle characteristics, cost and scalability.

Clean-label constraints on wall materials are examined, and the mechanisms by which encapsulation enhances antioxidant and antimicrobial efficacy are analysed alongside

Natural Resources for Human Health
eISSN: 2583-1194

release kinetics and mathematical modelling. Representative food-application case studies demonstrate shelf-life extensions of up to two- to fourfold relative to controls. Reported encapsulation efficiencies span roughly 54–99%, with nano-scale carriers frequently yielding the strongest antimicrobial gains at reduced doses. The review closes by outlining regulatory, safety and scale-up challenges and identifying research priorities—standardised reporting, digestion-relevant release testing and techno-economic assessment—required to translate encapsulated plant preservatives into commercial clean-label products.

1. INTRODUCTION

Consumer scrutiny of ingredient lists has become one of the strongest forces shaping contemporary food product development. The "clean-label" movement—broadly understood as a preference for foods formulated with few, familiar and minimally processed ingredients and without additives perceived as artificial—has moved from a niche marketing claim to a mainstream reformulation imperative. [1,2] Within this movement, chemical preservatives occupy a position of particular sensitivity, because additives such as nitrites, sulphites, benzoates and synthetic phenolic antioxidants have been repeatedly associated in the public imagination, and in parts of the toxicological literature, with adverse health outcomes. [2,3] The resulting commercial pressure to remove or replace these compounds is substantial, yet preservation remains non-negotiable: without effective control of oxidation and microbial growth, food safety, quality and waste all deteriorate.

Plant extracts and essential oils (EOs) are the most widely investigated natural substitutes for synthetic preservatives. Their preservative action derives from secondary metabolites—phenolic acids, flavonoids, tannins, and terpenoid constituents of EOs such as carvacrol, thymol, eugenol and cinnamaldehyde—that exert antioxidant activity through radical scavenging and metal chelation, and antimicrobial activity through disruption of microbial membranes, inhibition of metabolic enzymes and interference with quorum sensing and biofilm formation. [3,4] Because they are derived from edible botanical sources, these compounds align with clean-label expectations and frequently carry additional health-positive connotations. [2,5]

Despite this promise, the direct addition of plant extracts to real food matrices is beset by well-documented limitations. Many bioactives are chemically labile and degrade under the heat, light, oxygen and pH extremes encountered during processing and storage; EOs are volatile and sparingly water-soluble; and both classes can impart intense, sometimes objectionable, aromas and flavours at the concentrations required for efficacy. [4,6] Polyphenols additionally suffer from low bioaccessibility and can interact with proteins and other matrix components, further reducing the fraction that remains active. [7] Consequently, effective doses are often high enough to compromise sensory acceptability or cost-competitiveness, and the measured performance of a free extract in a food is typically far below its intrinsic potential.

Encapsulation—the entrapment of an active "core" within a protective "wall" or carrier matrix—offers a unifying solution to these problems. By physically isolating the bioactive from the surrounding environment, encapsulation improves oxidative and thermal stability, masks unwanted sensory notes, converts lipophilic actives into dispersible powders or aqueous colloids, and—crucially—enables the controlled or triggered release of the active where and when it is needed. [6,8,9] These functions translate directly into enhanced preservative efficacy, frequently allowing the same or greater effect to be achieved at a lower dose. [9,10] The purpose of this review is to provide a critical, technique-oriented account of how encapsulation enhances the performance of plant-derived clean-label preservatives. Figure 1 summarises the conceptual pipeline connecting botanical sources, extraction, encapsulation and food application, together with the barriers that encapsulation is designed to overcome.

Natural Resources for Human Health
eISSN: 2583-1194

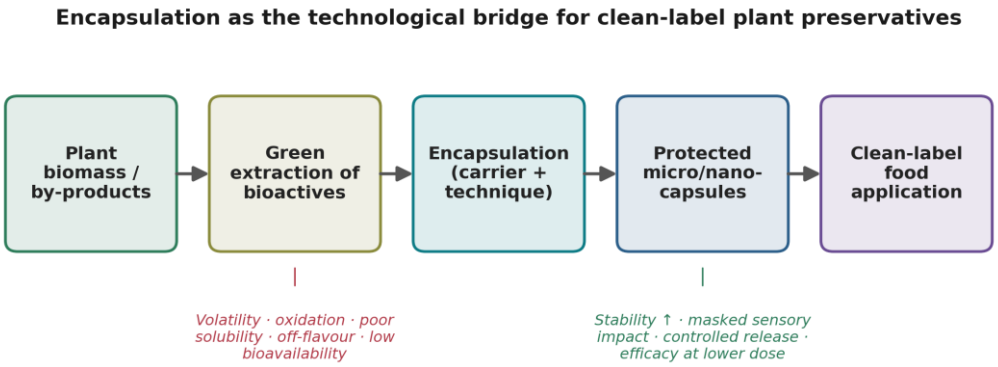

Figure 1. Conceptual pipeline for the deployment of encapsulated plant extracts as clean-label preservatives. Encapsulation functions as a technological bridge that converts intrinsically potent but unstable and sensorially difficult bioactives into stable, controlled-release ingredients suitable for real food systems.

2. CLEAN-LABEL PRESERVATION: DRIVERS AND REGULATORY CONTEXT

The clean-label concept lacks a single statutory definition, which complicates both formulation and communication. In practice it is operationalised through three overlapping consumer expectations: short ingredient lists, ingredients recognisable as "kitchen-cupboard" substances, and the absence of E-number-coded or synthetic additives. [1,2] For preservation specifically, this creates a demanding brief—the replacement ingredient must not only deliver antimicrobial or antioxidant function but must itself be label-friendly, which excludes many otherwise effective encapsulation aids.

Regulatory frameworks intersect with, but are distinct from, the clean-label market signal. The Codex General Standard for Food Additives and regional regulations (for example EU Regulation 1333/2008 and the corresponding US FDA GRAS system) determine what may lawfully be added and at what levels, whereas clean-label status is a market-perception construct layered on top of legality. [2] A recurring practical difficulty is that few natural or "clean" preservatives can replace a synthetic counterpart on a one-for-one basis; multiple hurdles usually must be combined, and encapsulation is one of the most powerful tools for closing the residual efficacy gap. [2,3] This context frames the remainder of the review: the objective is not merely to encapsulate a bioactive, but to do so with carriers and processes that are themselves compatible with a clean label.

3. PLANT EXTRACTS AS NATURAL PRESERVATIVES

3.1 Bioactive classes and mechanisms of action

The preservative capacity of plant extracts is a function of their phytochemical profile. Phenolic acids (for example gallic, ferulic and rosmarinic acids) and flavonoids act predominantly as antioxidants by donating hydrogen atoms to lipid-derived radicals and by chelating pro-oxidant transition metals, thereby retarding lipid oxidation and the associated development of rancidity. [3,5] Terpenoid and phenylpropanoid constituents of EOs—notably carvacrol and thymol from oregano and thyme, eugenol from clove, and cinnamaldehyde from cinnamon—are strongly antimicrobial: their lipophilicity allows them to partition into and destabilise microbial membranes, dissipating ion gradients, causing leakage of intracellular contents and, at higher concentrations, cell death. [4,11] Additional mechanisms include inhibition of ATPases and other metabolic enzymes, interference with nucleic-acid synthesis, generation of intracellular oxidative stress, and suppression of quorum sensing and biofilm formation. [4]

Table 1 collates the most extensively studied botanical sources, their characteristic bioactive constituents and their principal microbial or oxidative targets. In general, Gram-positive bacteria are more susceptible than Gram-negative bacteria, whose outer membrane restricts the ingress of hydrophobic terpenoids—one of several reasons why nano-scale delivery, which improves interaction with cell envelopes, is especially valuable. [11]

Botanical source	Major bioactive constituents	Principal activity	Representative target organisms / substrates
Oregano / thyme (Origanum, Thymus)	Carvacrol, thymol, p-cymene	Antimicrobial, antioxidant	E. coli, S. aureus, L. monocytogenes; lipid oxidation
Rosemary (Rosmarinus officinalis)	Carnosic acid, carnosol, rosmarinic acid	Antioxidant, antimicrobial	Lipid/protein oxidation in meat; spoilage flora
Clove / cinnamon	Eugenol, cinnamaldehyde	Antimicrobial	Moulds, yeasts, Gram-positive bacteria
Grape / pomace, elderberry	Anthocyanins, flavonols, phenolic acids	Antioxidant	Lipid oxidation; oxidative browning
Green tea	Catechins (EGCG), gallic acid	Antioxidant, antimicrobial	Rancidity; Gram-positive bacteria
Pomegranate / onion peel	Ellagitannins, quercetin, anthocyanins	Antioxidant, antimicrobial	Spoilage bacteria; oxidation
Garlic (Allium sativum)	Allicin, diallyl sulphides	Antifungal, antibacterial	Bread spoilage fungi; foodborne pathogens

Table 1. Representative plant sources used as clean-label preservatives, their principal bioactive constituents and typical targets. Susceptibility is generally higher for Gram-positive than Gram-negative bacteria, motivating nano-scale delivery for the latter.

3.2 Limitations of free plant extracts

Five recurring limitations undermine the use of free extracts. First, chemical instability: polyphenols oxidise and EO terpenoids isomerise or evaporate under heat, light and oxygen. Second, volatility, which causes progressive loss of the very compounds responsible for antimicrobial action. Third, poor aqueous solubility of lipophilic actives, which limits their dispersion and contact with microorganisms in high-moisture foods. Fourth, sensory impact—the strong odour and taste of EOs restrict usable concentrations. Fifth, matrix interactions and low bioaccessibility, whereby binding to proteins, lipids and fibre sequesters the active in an inert form. [4,6,7] Encapsulation is designed to attenuate all five simultaneously, which is why it has become the dominant enabling technology in this field.

4. ENCAPSULATION TECHNOLOGIES

Encapsulation approaches for food bioactives can be organised by their governing physical principle: dehydration of an emulsion or solution (spray and freeze drying); phase separation of biopolymers (coacervation); dispersion of an oil phase to colloidal dimensions (emulsion and nanoemulsion systems); self-assembly of amphiphiles into vesicles (liposomes); cross-linking of hydrocolloids (ionic gelation); host–guest molecular complexation (cyclodextrin inclusion); and electrohydrodynamic atomisation (electrospraying and electrospinning). [8,9,12] Table 2 compares these platforms across the parameters that matter most for clean-label preservation, and Figure 2 summarises the encapsulation-efficiency ranges reported across the literature.

Technique	Governing principle	Typical particle size	EE range (%)	Key advantages	Main limitations
Spray drying	Atomisation + rapid solvent evaporation	10–100 µm	54–98	Low cost, continuous, highly scalable	Thermal loss of volatiles; larger particles

Natural Resources for Human Health
eISSN: 2583-1194

Technique	Governing principle	Typical particle size	EE range (%)	Key advantages	Main limitations
Freeze drying	Sublimation of frozen emulsion/solution	Porous flakes / µm	60–95	Gentle, good for heat-labile actives	Slow, energy-intensive, batch
Complex coacervation	Electrostatic biopolymer phase separation	1–500 µm	70–96	High payload, excellent barrier	Sensitive to pH/ionic strength; cross-linker needs
Nanoemulsion	High-energy or spontaneous emulsification	20–200 nm	60–92	Transparent, high bioavailability, low dose	Ostwald ripening; surfactant load
Nanoliposome	Self-assembly of phospholipid bilayers	50–300 nm	55–90	Amphiphilic co-encapsulation; biocompatible	Physical/oxidative instability; cost
Ionic gelation	Cross-linking of polysaccharides (e.g. chitosan)	100–800 nm	65–93	Mild, aqueous, no heat	Modest payload; polydispersity
Molecular inclusion	Host–guest complexation (cyclodextrins)	nm (molecular)	62–90	Strong volatile retention; defined stoichiometry	Limited capacity; guest-size selectivity
Electrospraying	Electrohydrodynamic atomisation	0.1–10 µm	70–99	Ambient, high EE, tunable morphology	Low throughput; solvent/conductivity limits

Table 2. Comparison of principal encapsulation technologies for plant-derived preservatives. Efficiency ranges are indicative values compiled from the reviewed literature and vary with core–wall ratio, carrier chemistry and process parameters.

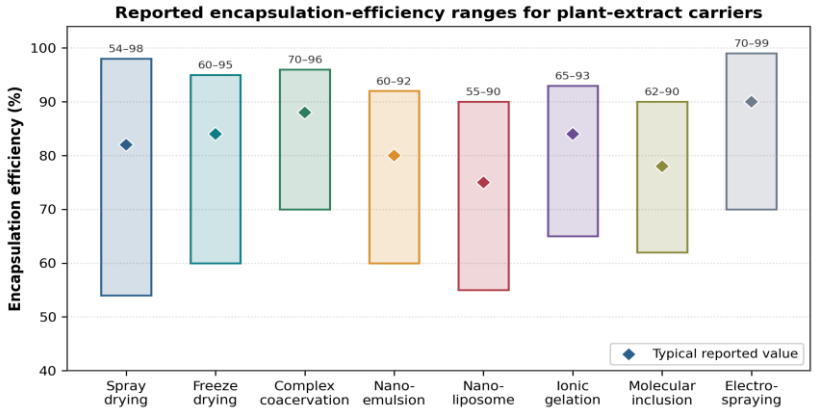

Figure 2. Reported encapsulation-efficiency ranges for the major carrier technologies. Bars span the low–high range synthesised from the literature; diamonds denote a representative typical value. Electrospraying and optimised nano spray drying can exceed 98%, whereas efficiency is most sensitive to process temperature in spray drying and to core–wall ratio across all methods.

4.1 Spray drying

Spray drying is the workhorse of food encapsulation: an emulsion or solution of the active in a carrier is atomised into a hot gas stream, producing a dry powder in a single continuous, inexpensive and highly scalable step. [8,12] For plant preservatives it converts lipophilic EOs and aqueous polyphenol extracts alike into free-flowing powders that are easy to handle and dose. The principal drawback is thermal: because inlet temperatures typically range from 120–200 °C, volatile terpenoids can be lost and surface oil can oxidise. Encapsulation efficiency is strongly temperature-dependent—one study of citrus oil reported a decline from roughly 76% to 45% as the inlet temperature rose from 110 to 190 °C—so process optimisation (moderate inlet temperature, appropriate core–wall ratio, low surface oil) is decisive. [13] Advances such as nano spray drying now achieve very fine particles and efficiencies exceeding 98% for oregano EO in whey-protein/maltodextrin carriers. [14]

4.2 Freeze drying

Freeze drying removes water by sublimation from a frozen state, avoiding the elevated temperatures of spray drying and thereby protecting heat-labile polyphenols and volatile aromatics. It typically yields porous, glassy matrices with good retention of bioactivity; for rosemary EO, maltodextrin–gum-arabic blends prepared by freeze drying gave high antioxidant retention, with carrier ratio governing particle size and efficiency. [15] Its limitations are economic rather than technical—it is slow, energy-intensive and inherently a batch operation—so it is favoured for high-value actives or where thermal damage must be minimised.

4.3 Complex coacervation

Complex coacervation exploits electrostatic association between oppositely charged biopolymers (classically gelatin and gum arabic) to form a dense coating around an emulsified core. It delivers high payloads and an excellent oxygen and moisture barrier, making it well suited to protecting easily oxidised EOs. [9,12] The method is sensitive to pH and ionic strength and often requires a cross-linking step to stabilise the wall; the traditional use of glutaraldehyde is incompatible with clean labels, prompting a shift toward enzymatic (transglutaminase) or plant-derived cross-linkers.

4.4 Emulsion and nanoemulsion systems

Emulsion-based delivery is especially natural for EOs, which are themselves oils. Reducing droplet size to the nanoscale (roughly 20–200 nm) dramatically increases interfacial area and improves solubility, physical stability and—most importantly for preservation—contact between the active and microbial cells, which frequently translates into stronger antimicrobial action at lower doses. [10,11] Optimised sonication of EO nanoemulsions has produced mean droplet sizes near 55 nm with low polydispersity, and such systems have improved the microbiological stability of dairy and other products. [11] Pickering emulsions stabilised by food-grade particles are an attractive surfactant-free, clean-label variant. The main technical concerns are Ostwald ripening and the surfactant load required for the smallest droplets.

4.5 Liposomes and nanoliposomes

Liposomes are vesicles formed by self-assembly of phospholipid bilayers around an aqueous core, allowing simultaneous encapsulation of hydrophilic and lipophilic actives within a biocompatible, food-grade carrier. [9] They have been used, for example, to deliver garlic-derived antifungals that suppressed spoilage moulds in bread. [16] Their weaknesses are physical and oxidative instability of the phospholipids and relatively high cost, both of which are active areas of formulation research (for instance the use of cholesterol or plant sterols to rigidify bilayers).

4.6 Ionic gelation and biopolymer nanoparticles

Mild, aqueous ionic gelation—typified by chitosan cross-linked with tripolyphosphate, or alginate with calcium—builds nanoparticles without heat or organic solvent, an obvious clean-label advantage. [9] Chitosan is itself antimicrobial, giving a useful synergy: cinnamon EO encapsulated in chitosan nanoparticles reached an encapsulation efficiency of about 93% at a particle size near 480 nm with strong, sustained antifungal activity. [17] Alginate matrices withstand acidic environments and provide controlled release, as demonstrated for rosemary and savory extracts in yogurt. [18]

4.7 Molecular inclusion with cyclodextrins

Cyclodextrins are cyclic oligosaccharides whose hydrophobic internal cavity can accommodate individual guest molecules, forming inclusion complexes at defined stoichiometry. This molecular-level entrapment is highly effective at retaining volatile terpenoids and at improving their aqueous handling, though capacity is limited by the one-guest-per-cavity geometry and by guest-size selectivity. [12] β-Cyclodextrin is widely used and generally regarded as label-friendly.

4.8 Electrohydrodynamic processing

Electrospraying and electrospinning apply a high voltage to a polymer solution to produce, respectively, fine particles or ultrathin fibres at ambient temperature—ideal for the most heat-sensitive actives. These techniques can achieve very high encapsulation efficiencies (up to ~99%) and precisely tunable morphologies, and electrospun fibre mats are attractive for active packaging. [12,19] Throughput remains the principal barrier to industrial adoption, although multi-needle and needleless configurations are narrowing this gap.

5. CARRIER (WALL) MATERIALS AND CLEAN-LABEL CONSTRAINTS

The carrier is as important as the process. It governs encapsulation efficiency, payload, barrier properties, release behaviour and—uniquely in this field—label acceptability. Carriers fall into three broad classes: polysaccharides, proteins and lipids, frequently used in combination to exploit complementary properties (for example the emulsifying capacity of proteins with the film-forming, matrix-building capacity of maltodextrin). [8,9] Table 3 summarises the main options and their clean-label positioning. The overarching clean-label principle is to prefer carriers that are themselves recognisable food ingredients—starches, gums, milk and pea proteins, plant lipids—over chemically modified or synthetic polymers, and to avoid cross-linkers such as glutaraldehyde.

Class	Representative carriers	Functional role	Clean-label positioning
Polysaccharides	Maltodextrin, gum arabic, starches, chitosan, alginate, pectin, cyclodextrins	Matrix former, film former, emulsion stabiliser; chitosan adds antimicrobial synergy	Generally favourable; "native" starches and gums preferred over modified
Proteins	Whey, sodium caseinate, pea, soy, zein, gelatin	Emulsifier and coating; strong at oil–water interface	Favourable; plant proteins increasingly preferred; allergen labelling required
Lipids	Phospholipids (liposomes), waxes, solid lipids (SLN/NLC)	Carrier for lipophilic actives; bilayer/solid matrices	Favourable if food-grade; oxidation must be controlled
Cross-linkers	Transglutaminase, genipin (vs. glutaraldehyde)	Stabilise coacervate walls	Enzymatic / plant-derived options are clean-label compatible

Table 3. Carrier materials for encapsulating plant preservatives and their clean-label positioning. Combinations (e.g. whey protein isolate–maltodextrin) are common because they pair interfacial activity with matrix-forming capacity.

6. CHARACTERISATION OF ENCAPSULATED SYSTEMS

Rational design and fair comparison of encapsulated preservatives depend on a common set of physicochemical descriptors. Encapsulation efficiency (EE), the percentage of active successfully entrapped, is the headline metric but must be interpreted alongside loading capacity, which expresses payload relative to total mass. Particle size and polydispersity index, measured by dynamic light scattering, determine dispersibility, optical clarity and—in the nano range—interaction with microbial cells; sizes from tens of nanometres (nanoemulsions, liposomes) to tens of micrometres (spray-dried powders) are typical. [11,14] Zeta potential indicates colloidal stability and, for cationic chitosan systems, correlates with antimicrobial attachment; values around ±25–35 mV generally signify good stability, as reported for both chitosan (positive) and lipid nanoparticle (negative) systems.

[17,20] Morphology (SEM/TEM), thermal behaviour, FTIR confirmation of core–wall interaction, and in vitro release profiles complete the standard characterisation panel. [9,20] A persistent weakness in the literature is inconsistent reporting of these parameters, which hampers meta-analysis and rational benchmarking.

7. MECHANISMS OF EFFICACY ENHANCEMENT

7.1 Preservation of antioxidant capacity

The clearest benefit of encapsulation is protection of the active during processing and storage. By excluding oxygen and light and by buffering the active against heat and pH, the carrier slows the degradation that steadily depletes free extracts. Figure 3a illustrates the characteristic outcome: whereas a free extract loses a large fraction of its antioxidant capacity over several weeks of refrigerated storage, the encapsulated form retains most of its activity over the same period. This protection is why encapsulated antioxidants remain effective for longer and why lower initial loadings suffice. [6,9]

7.2 Enhancement and preservation of antimicrobial activity

For antimicrobial function, encapsulation contributes in two complementary ways. First, it preserves activity that would otherwise be lost to volatilisation, thermal degradation or matrix binding—Figure 3b shows the markedly higher fraction of antimicrobial activity retained after thermal processing, storage, simulated digestion and incorporation into a food matrix when the active is encapsulated rather than free. Second, nano-scale carriers can intrinsically potentiate activity by increasing the interfacial area and improving delivery of hydrophobic terpenoids to microbial membranes, so that minimum inhibitory concentrations fall and efficacy is achieved at lower doses. [10,11] This dose reduction is doubly valuable for clean labels because it simultaneously improves cost-effectiveness and reduces the sensory penalty of strongly flavoured EOs. An important caveat is that encapsulation is not universally activity-enhancing: if the carrier sequesters the active too tightly or dilutes it below its effective concentration, measured inhibition can decrease relative to the free oil, a result observed in some dairy applications. [9]

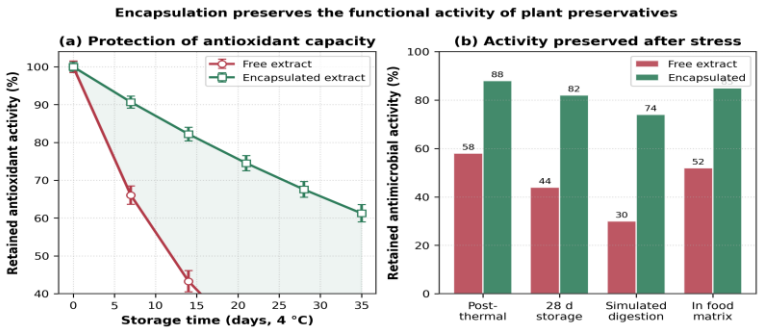

Figure 3. Functional protection conferred by encapsulation. (a) Retention of antioxidant capacity during refrigerated storage: the encapsulated extract decays far more slowly than the free extract. (b) Fraction of antimicrobial activity retained after four stress scenarios; encapsulated systems consistently preserve a larger share of the original activity. Values are representative trends compiled from the reviewed studies to illustrate the mechanism.

8. CONTROLLED RELEASE AND KINETIC MODELLING

Controlled release is arguably the most sophisticated advantage of encapsulation. Rather than exposing the food to a single, quickly dissipating pulse of active, an engineered carrier can deliver the preservative gradually, maintaining an effective concentration throughout the target shelf life, or can release it in response to a trigger such as moisture, pH, temperature or enzymatic action. [6,9] Figure 4 contrasts the immediate release of a non-encapsulated active with three encapsulated behaviours: a burst-dominated profile typical of nanoemulsions, a biphasic profile common to liposomes, and a sustained, diffusion-controlled profile characteristic of dense biopolymer matrices. Matching the release profile to the spoilage kinetics of the target food is a central design objective.

Natural Resources for Human Health
eISSN: 2583-1194

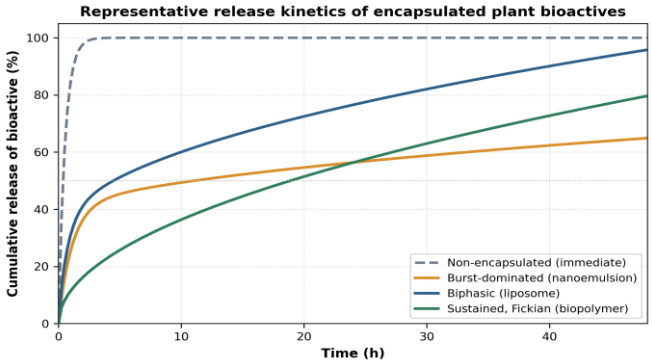

Figure 4. Representative in vitro release profiles. Non-encapsulated actives are released almost immediately, whereas carrier design tunes the rate from burst (nanoemulsion) through biphasic (liposome) to sustained, Fickian diffusion (biopolymer matrix). Curves are illustrative of the kinetic regimes discussed in the text.

Release data are conventionally interpreted through semi-empirical models (Table 4). Fitting the cumulative-release curve to these equations discriminates between diffusion-controlled and erosion/relaxation-controlled mechanisms and yields parameters useful for comparison and scale-up. The Korsmeyer–Peppas release exponent n is especially informative: for spherical particles, n ≈ 0.43 indicates Fickian diffusion, whereas higher values signal anomalous transport in which polymer relaxation or matrix erosion contributes to release. [21]

Model	Functional form	Physical interpretation	Typical applicability
Zero-order	$Q = k_0 t$	Constant release rate, independent of concentration	Ideal sustained-release matrices
First-order	$\ln(1-Q) = -k_1 t$	Rate proportional to remaining active	Water-soluble actives in porous carriers
Higuchi	$Q = k_H t^{1/2}$	Diffusion from a homogeneous matrix	Insoluble actives in polymer matrices
Korsmeyer–Peppas	$Q = k t^{n}$	n distinguishes Fickian vs. anomalous transport	General diagnostic for the first 60% of release
Weibull	$Q = 1 - \exp[-(t/\alpha)^{\beta}]$	Flexible empirical fit; β describes curve shape	Complex or multi-phasic profiles

Table 4. Common mathematical models used to characterise release of encapsulated bioactives. Q is the cumulative fraction released at time t; k terms are rate constants; n is the Korsmeyer–Peppas diffusional exponent.

9. APPLICATIONS IN FOOD SYSTEMS

The practical value of encapsulated plant preservatives is best demonstrated in real food matrices. Table 5 compiles representative studies spanning meat, poultry, fish, dairy and bakery products, together with the encapsulation approach and the principal preservation outcome; Figure 5 provides a multi-criteria comparison of the leading platforms, and Figure 6 summarises the shelf-life extensions achieved.

Extract / active	Technique & carrier	EE (%) / size	Principal outcome	Ref.
Cinnamon (C. verum) EO	Chitosan nanoparticles (ionic gelation)	~93% / ~480 nm	Strong sustained antifungal / anticandidal activity	17
Oregano EO	Nano spray drying (WPI–maltodextrin)	>98% / fine μm	High volatile retention; strong antibacterial activity	14

Extract / active	Technique & carrier	EE (%) / size	Principal outcome	Ref.
Rosemary extract	Nanoencapsulation, 1600 ppm	—	Beef shelf life extended to ~21 d vs. ~9 d control	20
Elderberry extract	Encapsulated meat extender	—	Reduced lipid & protein oxidation in beef burgers	22
Rosemary / savory	Alginate beads (ionic gelation)	—	Bioactivity retained; improved yogurt shelf life	18
Garlic actives	Phosphatidylcholine liposomes	—	Suppressed spoilage fungi in wheat bread	16
Beet-leaf phenolics	Chitosan film + mesoporous silica NPs	—	Controlled release; oxidative/microbial control in chicken	23
Thyme (T. capitatus) EO	Nanoemulsion	~55 nm	Enhanced antibacterial efficiency at low dose	11

Table 5. Representative applications of encapsulated plant preservatives in food systems. Where efficiency or size was not reported in a comparable form it is marked "—". Values should be verified against the primary sources before citation.

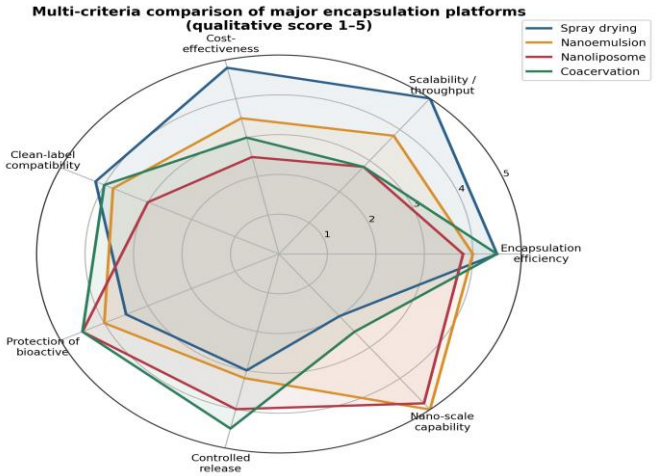

Figure 5. Qualitative multi-criteria comparison of four leading encapsulation platforms across seven design dimensions (1 = weak, 5 = strong). Spray drying leads on scalability and cost; nanoemulsions and nanoliposomes lead on nano-scale delivery and controlled release; coacervation excels at protection and payload. No single platform dominates, underscoring the need to match technique to product.

Across matrices, a consistent picture emerges: encapsulated plant preservatives extend the microbiologically and oxidatively acceptable shelf life by roughly two- to fourfold relative to untreated controls, and typically outperform the corresponding free extract at equal or lower dose. [16,18,20,22,23] For example, nanoencapsulated rosemary extract extended beef shelf life to about 21 days versus roughly 9 days for the control [20], and chitosan–laurel-EO coatings extended fish shelf life to about 14 days versus 5–6 days for untreated samples. [4] Figure 6 summarises these case studies.

Natural Resources for Human Health
eISSN: 2583-1194

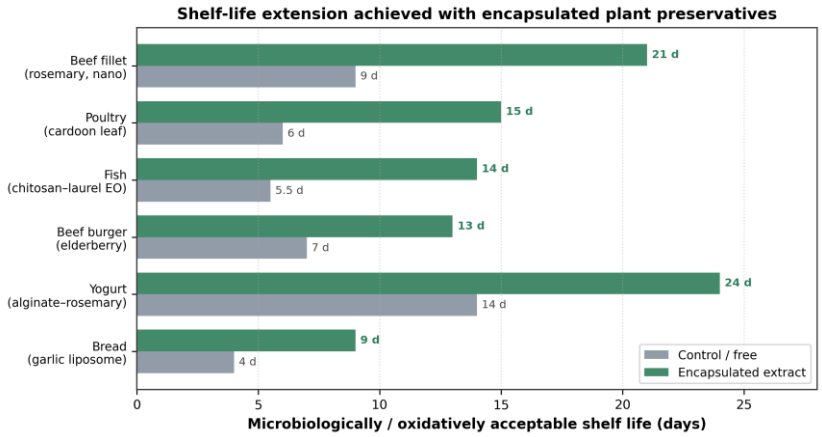

Figure 6. Shelf-life extension achieved with encapsulated plant preservatives across representative food case studies (green bars) relative to control or free treatments (grey bars). Extensions of roughly two- to fourfold are typical. Bars reflect values reported in, or synthesised from, the cited studies and are intended to illustrate the magnitude of benefit.

10. SAFETY, REGULATORY AND CLEAN-LABEL CONSIDERATIONS

Naturalness is not synonymous with safety, and encapsulated systems raise specific questions. Nanoscale carriers may alter the absorption and biodistribution of actives, so their toxicological profile cannot simply be inferred from that of the bulk material; regulators increasingly require nano-specific safety data. [9] Carrier and residual-solvent selection also matters—electrohydrodynamic and coacervation processes historically relied on organic solvents or synthetic cross-linkers that are incompatible with both safety expectations and clean labels, driving the field toward aqueous processing, food-grade solvents and enzymatic cross-linking. Finally, allergenicity of protein carriers (milk, soy) must be declared. The central clean-label tension is that the most effective encapsulation aids are not always the most label-friendly; resolving this trade-off—through the use of recognisable, minimally processed carriers—is a defining constraint of the field. [2,9]

11. CHALLENGES AND FUTURE PERSPECTIVES

Several obstacles stand between laboratory success and commercial deployment. Scale-up and cost remain decisive: spray drying scales readily but is thermally harsh, whereas the gentler nano-techniques that give the best efficacy gains often have limited throughput and higher cost. Standardisation is inadequate—encapsulation efficiency, particle size, loading and release are reported inconsistently, obstructing meta-analysis and benchmarking; the field would benefit from agreed minimum-reporting standards. Release testing is frequently performed in simple buffers that poorly represent real food matrices or gastrointestinal conditions, so digestion-relevant and matrix-relevant release protocols are needed. Regulatory pathways for nano-encapsulated additives are still maturing, and techno-economic and life-cycle assessments are scarce despite being essential for industrial decision-making. Promising directions include surfactant-free Pickering and Ostwald-stable nanoemulsions; valorisation of agri-food by-products as both bioactive and carrier sources, aligning the technology with circular-economy goals [5]; co-encapsulation of complementary antioxidants and antimicrobials for synergy; stimulus-responsive "smart" release triggered by spoilage-associated cues; and integration of encapsulated actives into active and intelligent packaging. [19]

12. CONCLUSION

Encapsulation has become the enabling technology that allows intrinsically potent but fragile plant extracts to function as practical clean-label preservatives. By protecting bioactives from degradation, masking their sensory impact, improving their dispersibility and controlling their release, encapsulation converts a promising but unreliable class of natural actives into stable, effective ingredients—frequently achieving equal or superior preservation at lower doses than the corresponding free extracts, with shelf-life extensions of two- to fourfold in real foods. No single platform is universally optimal: spray drying offers unmatched scalability and cost, nano-scale carriers offer the greatest efficacy gains, and coacervation offers the best barrier protection, so technique selection must be matched to the specific active, food matrix and label constraints. Realising the full commercial potential of encapsulated plant preservatives now depends less on discovering new bioactives than on engineering discipline—standardised characterisation, food- and digestion-relevant release testing, clean-label-compatible carriers and

processes, and rigorous techno-economic and safety assessment. Addressing these priorities would position encapsulated plant extracts as a cornerstone of the next generation of clean-label food preservation.

Declarations

Funding: The authors declare that no external funding was received for this work.

Conflicts of interest: The authors declare no conflict of interest.

Author contributions: Conceptualisation, A.O.; investigation and writing—original draft, A.O. and A.T.; visualisation, A.T.; writing—review and editing, A.T.; supervision, A.O. All authors read and approved the final manuscript.

Data availability: No new primary data were generated; all data discussed are available in the cited references.

REFERENCES

[1] Asioli D, Aschemann-Witzel J, Caputo V, et al. Making sense of the "clean label" trends: A review of consumer food choice behaviour and discussion of industry implications. Food Research International. 2017;99:58–71.

[2] Maruthai K, et al. Clean-label alternatives for food preservation: An emerging trend. Heliyon. 2024;10(6):e27957.

[3] Anwar F, et al. Incorporation of edible plant extracts as natural food preservatives: green extraction methods, antibacterial mechanisms and applications. (Review). 2024.

[4] Rathod NB, et al. Extraction of natural bioactive compounds using clean-label technologies and their application as muscle food preservatives. Frontiers in Sustainable Food Systems. 2023;7:1207704.

[5] Pérez-Pérez, et al. Advancing sustainable diets through encapsulation and co-encapsulation of bioactive compounds from agricultural by-products. Future Foods. 2026.

[6] Hosseini SF, Jafari SM. Introducing nano/microencapsulated bioactive ingredients for extending the shelf-life of food products. Advances in Colloid and Interface Science. 2020;282:102210.

[7] Munin A, Edwards-Lévy F. Encapsulation of natural polyphenolic compounds; a review. Pharmaceutics. 2011;3(4):793–829.

[8] Gharsallaoui A, Roudaut G, Chambin O, et al. Applications of spray-drying in microencapsulation of food ingredients: An overview. Food Research International. 2007;40(9):1107–1121.

[9] Ozkan G, Franco P, De Marco I, et al. A review of microencapsulation methods for food antioxidants: Principles, advantages, drawbacks and applications. Food Chemistry. 2019;272:494–506.

[10] Donsì F, Ferrari G. Essential oil nanoemulsions as antimicrobial agents in food. Journal of Biotechnology. 2016;233:106–120.

[11] Prakash B, et al. Nanoencapsulation: an efficient technology to boost the antimicrobial potential of plant essential oils in food system. Food Control. 2018;89:1–11.

[12] Fang Z, Bhandari B. Encapsulation of polyphenols – a review. Trends in Food Science & Technology. 2010;21(10):510–523.

[13] Jafari SM, et al. Encapsulation efficiency of food flavours and oils during spray drying. Drying Technology. 2008;26(7):816–835.

[14] Karim N, et al. Characterization of oregano essential oil particles produced by the novel nano spray drying technique. Molecules. 2021;26(24):7628.

[15] Ghorbanzade T, et al. Characteristics of lyophilized nanoencapsulated Rosmarinus officinalis essential oil with maltodextrin and gum arabic. Journal of Food Measurement and Characterization. 2025.

[16] Pinilla CMB, Thys RCS, Brandelli A. Antifungal properties of phosphatidylcholine–oleic acid liposomes encapsulating garlic against environmental fungal in wheat bread. International Journal of Food Microbiology. 2019;293:72–78.

[17] Matshetshe KI, et al. Anti-Candida and anti-leishmanial activities of encapsulated Cinnamomum verum essential oil in chitosan nanoparticles. Molecules. 2023;28(15):5749.

[18] Bara C, et al. The effect of aromatic plant extracts encapsulated in alginate on the bioactivity, textural characteristics and shelf life of yogurt. Antioxidants. 2023;12(4):893.

[19] Vilas-Boas AA, et al. Emerging trends in active packaging for food: a six-year review. Foods / Coatings. 2024.

[20] Ghaderi-Ghahfarokhi M, et al. Effects of encapsulated rosemary extract on oxidative and microbiological stability of beef meat during refrigerated storage. Food Science & Nutrition. 2019;7(12):3814–3822.

[21] Korsmeyer RW, Gurny R, Doelker E, et al. Mechanisms of solute release from porous hydrophilic polymers. International Journal of Pharmaceutics. 1983;15(1):25–35.

[22] Rocchetti G, Becchi PP, Lucini L, et al. Elderberry (Sambucus nigra L.) encapsulated extracts as meat extenders against lipid and protein oxidation during the shelf-life of beef burgers. Antioxidants. 2022;11(11):2130.

[23] El-Sayed HS, et al. Bioactive chitosan packaging films with encapsulated beet-leaf extract for preserving chicken fillets. Food Chemistry / Food Packaging and Shelf Life. 2025.

[24] Bouarab-Chibane L, et al. Antibacterial properties of polyphenols: characterization and QSAR study. Frontiers in Microbiology. 2019;10:829.

[25] Burt S. Essential oils: their antibacterial properties and potential applications in foods – a review. International Journal of Food Microbiology. 2004;94(3):223–253.