

# Encapsulated Plant Extracts as Potential Clean-Label Alternatives to Synthetic Preservatives in Carbohydrate-Based Foods: Mechanisms, Efficacy, and Industrial Prospects

**Bima Putra Pratama<sup>1</sup>, Bovi Wira Harsanto<sup>2</sup>, Muhamad Alif Razi<sup>3</sup>,  
Bantari Wisynu Kusuma Wardhani<sup>4</sup>, Andi Thafida Khalisa<sup>5</sup>, Aswin Rafif Khairullah<sup>6</sup>,  
Sri Yuliani<sup>1</sup>, Bambang Triwiyono<sup>1</sup>, Lulum Leliana<sup>7,\*</sup>, Ulvi Fitri Handayani<sup>8</sup>,  
Yelsi Listiana Dewi<sup>8</sup>, Rizka Gitami Sativa<sup>1</sup>, Niken Harimurti<sup>1</sup> and Iceu Agustinisari<sup>1</sup>**

<sup>1</sup>Research Center for Process Technology, National Research and Innovation Agency (BRIN), Banten 15310, Indonesia

<sup>2</sup>Department of Agricultural Product Technology, Universitas Veteran Bangun Nusantara Sukoharjo, Central Java 57521, Indonesia

<sup>3</sup>Electrical Engineering Study Program, Faculty of Engineering, UPN Veteran Jakarta, West Java 16514, Indonesia

<sup>4</sup>Research Center for Pharmaceutical Ingredients and Traditional Medicine, National Research and Innovation Agency (BRIN), West Java 16911, Indonesia

<sup>5</sup>Faculty of Military Pharmacy, Indonesia Defense University, West Java 16810, Indonesia

<sup>6</sup>Research Center for Veterinary Science, National Research and Innovation Agency (BRIN), West Java 16911, Indonesia

<sup>7</sup>Department of Food and Agricultural Product Technology, Faculty of Agricultural Technology, Gadjah Mada University, Yogyakarta 55281, Indonesia

<sup>8</sup>Research Center for Animal Husbandry, National Research and Innovation Agency (BRIN), West Java 16911, Indonesia

(\*Corresponding author's e-mail: [lulum.leliana@ugm.ac.id](mailto:lulum.leliana@ugm.ac.id))

Received: 6 September 2025, Revised: 16 September 2025, Accepted: 23 September 2025, Published: 20 November 2025

## Abstract

Carbohydrate-based foods, including breads, noodles, cereals, and snacks, are highly susceptible to microbial spoilage and oxidative deterioration, leading to significant reliance on synthetic preservatives such as propionates, sorbates, and benzoates. Concerns about their potential health risks, environmental persistence, and negative consumer perception have intensified the search for natural, clean-label alternatives. This review aims to evaluate the potential of encapsulated plant extracts as replacements for synthetic preservatives, examining their antimicrobial mechanisms, encapsulation strategies, food applications, and industrial and regulatory considerations.

Evidence from studies published between 2000 and 2025 indicates that encapsulation substantially improves stability, bioactivity, and functionality of plant bioactives, with encapsulation efficiencies commonly reaching 70% to 95%, retention of 60% to 90% phenolics, and bioaccessibility increases of up to 4-fold compared with free compounds. Applications in breads, cookies, noodles, and cereals demonstrate extended mold-free shelf life by 2 to 3 days, lipid oxidation reductions of 20% to 40%, and in several cases performance equal to or superior to synthetic preservatives. Spray drying, freeze drying, coacervation, and electrohydrodynamic techniques each offer unique benefits, while carrier materials such as maltodextrin, gum arabic, and proteins are critical for optimizing outcomes.

These findings suggest that encapsulated plant extracts represent potentially credible clean-label preservation systems, as their demonstrated functional efficacy aligns with regulatory frameworks such as FDA GRAS provisions, EFSA additive lists, and Codex standards. Their dual grounding in scientific evidence and regulatory compatibility

highlights their promise for industrial adoption as safe, effective, and consumer-preferred alternatives in carbohydrate-based foods.

**Keywords:** Antimicrobial activity, Bioactive compounds, Carbohydrate-based foods, Encapsulation technology, Plant extracts

### Abbreviations

ABTS	2,2'-Azino-bis(3-Ethylbenzothiazoline-6-Sulfonic Acid) Assay
ANVISA	Agência Nacional de Vigilância Sanitária)
Aw	Water Activity
BHT	Butylated Hydroxytoluene
BPOM	Badan Pengawas Obat dan Makanan
CMC	Carboxymethyl Cellulose
CFR	Code of Federal Regulations
CFU	Colony Forming Unit
Codex	Codex Alimentarius
DE	Double Emulsion
DE*	Dextrose Equivalent
DPPH	2,2-Diphenyl-1-Picrylhydrazyl Assay
EE	Encapsulation Efficiency
EFSA	European Food Safety Authority
EGCG	Epigallocatechin Gallate
FAO	Food and Agriculture Organization
FCM	Food Contact Materials
FCS	Food Contact Substance
FDA	U.S. Food and Drug Administration
FD	Freeze Drying
FRAP	Ferric Reducing Antioxidant Power
FTIR	Fourier-Transform Infrared Spectroscopy
GA	Gum Arabic
GRAS	Generally Recognized as Safe
GSFA	General Standard for Food Additives
HCA	Hydroxycitric Acid
HPLC	High-Performance Liquid Chromatography
IC <sub>50</sub>	Half-Maximal Inhibitory Concentration
JECFA	Joint FAO/WHO Expert Committee on Food Additives
kV	kilovolt
MAP	Modified Atmosphere Packaging
MD	Maltodextrin
MHLW	Ministry of Health, Labour and Welfare, Japan
MIC	Minimum Inhibitory Concentration
NHC	National Health Commission of China
NP	Nanoparticle
OSA	Octenyl Succinic Anhydride
OTA	Ochratoxin A
PGPR	Polyglycerol Polyricinoleate
PLM	Polarized Light Microscopy

PPI	Pea Protein Isolate
RH	Relative Humidity
ROS	Reactive Oxygen Species
SD	Spray Drying
SEM	Scanning Electron Microscopy
SPI	Soy Protein Isolate
TBARS	Thiobarbituric Acid Reactive Substances
Tg	Glass Transition Temperature
TFC	Total Flavonoid Content
TPC	Total Phenolic Content
W1/O/W	Water-in-Oil-in-Water Double Emulsion
WPC	Whey Protein Concentrate
WPI	Whey Protein Isolate
$\beta$ -CD	Beta-Cyclodextrin
HP- $\beta$ -CD	Hydroxypropyl-Beta-Cyclodextrin

## Introduction

Carbohydrate-based foods represent a dominant portion of the global diet, supplying more than 50% - 70% of daily caloric intake in many regions of Asia and Africa and approximately 40% - 50% in Western countries. These foods, ranging from cereals and noodles to baked goods and snack products, are valued not only as sources of carbohydrates and proteins but also for their contribution of micronutrients and dietary fiber [1,2]. However, their high water activity and nutrient-rich composition make them highly prone to microbial spoilage. Mold spoilage in bread alone is estimated to account for nearly 5% - 10% of production losses in industrial bakeries [3]. Fungal genera such as *Aspergillus*, *Fusarium*, and *Penicillium* are frequently isolated from stored cereal-based foods, and their metabolites contribute to significant food safety risks. Heat-stable mycotoxins such as deoxynivalenol can persist even after baking, with degradation levels of only 20% - 30% during typical bread-making processes [4], while ochratoxin A has been reported to survive at concentrations above 70% of its original level after thermal processing [4,5].

To mitigate these risks, the food industry employs synthetic preservatives. Potassium sorbate, for example, is typically added to bread at levels of 0.1 - 0.3 % (w/w), effectively inhibiting mold growth for up to 14 days [6]. Similarly, sodium propionate at concentrations of 0.1% - 0.4% is widely used to suppress *Aspergillus* and *Penicillium* species. Although these additives are efficient, increasing evidence links them to adverse +

health effects. Studies have reported gastrointestinal disturbances in consumers exposed to sulfite levels above 50 ppm, while nitrites in processed foods are associated with increased risk of colorectal cancer, with hazard ratios ranging from 1.2 to 1.5 in large cohort analyses [7,8]. These concerns have contributed to a growing consumer preference for “clean-label” foods, with market surveys indicating that nearly 70% of European and North American consumers prefer products without artificial preservatives [9].

Plant-derived extracts have emerged as promising alternatives, supported by a growing body of empirical data. For example, pomegranate peel extract reduced *E.coli* (*E. coli*) and *Salmonella* counts in date fruits by more than 3 log CFU/g during 21 days of storage [10]. Similarly, basil leaf extract extended bread shelf life by approximately 4 days compared with untreated controls [11], while encapsulated garlic extract reduced fungal colony counts in wheat bread by up to 90% [12]. The bioactive compounds responsible for these effects - phenolics, terpenoids, flavonoids, aldehydes, and tannins - exhibit minimum inhibitory concentration (MIC) values as low as 100 - 200  $\mu$ g/mL against foodborne fungi [3,13].

Nevertheless, direct use of plant extracts is constrained by issues of solubility, volatility, and sensory impact. Encapsulation has proven effective in addressing these challenges. For instance, encapsulated carvacrol in starch nanofibers prolonged bread shelf life from 5 to 12 days under ambient storage [14].

Encapsulated  $\beta$ -carotene demonstrated a 2-fold increase in stability during 30 days of storage compared with its free form [14]. Furthermore, encapsulated curcumin exhibited bioaccessibility levels exceeding 40%, compared with less than 10% for the unencapsulated compound [16].

The objective of this manuscript is to provide a comprehensive review of the potential of encapsulated plant extracts as alternatives to synthetic preservatives in carbohydrate-based foods, highlighting their mechanisms of bioactivity, the effectiveness of different encapsulation techniques in enhancing the stability and bioavailability of active compounds, and their applications in extending shelf life and maintaining product quality. In addition, this review aims to address the technological, sensory, and regulatory challenges that currently limit large-scale implementation, while offering future perspectives on strategies that may accelerate industrial adoption toward safer, more sustainable, and consumer-preferred clean-label preservation solutions.

## Data collection methods

### Literature collection and search strategy

This review was developed from an extensive body of peer-reviewed literature on plant extracts, their antimicrobial and antioxidant properties, and their encapsulation for application in carbohydrate-based foods. Publications were identified through structured searches in Scopus, Web of Science, ScienceDirect, and PubMed between 2000 and 2025 using combinations of terms such as *plant extracts*, *essential oils*, *encapsulation*, *spray drying*, *freeze drying*, *double emulsion*, *complex coacervation*, *electrospraying*, and *carbohydrate-based foods*. Additional sources were included through citation screening of key reviews and primary studies, as well as regulatory databases and guidance documents from EFSA, FDA, Codex, and related authorities.

### Inclusion and exclusion criteria

Eligible studies reported empirical data or comprehensive reviews on: (i) antimicrobial or antioxidant activity of plant-derived compounds; (ii) encapsulation techniques such as spray/freeze drying, double emulsions (including Pickering and emulgels), complex coacervation, electrospraying, or hydrogel

microcapsules; and (iii) applications in carbohydrate-rich matrices (bread, noodles, pasta, cereals, biscuits) with outcomes on shelf life, quality, or bioaccessibility. Regulatory and safety papers relevant to food use were also considered. Exclusion criteria were studies focusing only on non-carbohydrate foods, purely synthetic preservatives, patents or editorials without experimental data, or articles not written in English.

### Categorization and data extraction

The final collection was organized into 4 themes: (1) Mechanisms and bioactivity of plant extracts against spoilage and oxidation; (2) encapsulation technologies and their impact on stability and release; (3) applications of encapsulated extracts in carbohydrate-based foods; and (4) regulatory, safety, and consumer acceptance. For comparative synthesis, we extracted wall material composition and concentrations, extract loads, process parameters (e.g., spray/freeze drying conditions, emulsion ratios, electrospraying voltage in kV), and encapsulation outcomes such as efficiency, stability, and bioactivity. Where exact values were not reported, approximations were noted based on comparable protocols from the same technique family.

## Synthetic preservatives in carbohydrate-based foods

### Common synthetic preservatives

Synthetic preservatives are widely employed in carbohydrate-based foods to prevent microbial spoilage and extend shelf life. Bakery items such as bread, cakes, and pastries are particularly prone to mold contamination, while pasta and cereals require preservation during storage and distribution. Among the most frequently used preservatives are sorbates, benzoates, propionates, and sulfites.

Potassium sorbate is commonly applied at concentrations of 0.1 - 0.3 % (w/w) in bread and snack products, effectively inhibiting the growth of molds such as *Penicillium* and *Aspergillus* for up to 10 - 14 days under ambient conditions [6]. Sodium benzoate is widely used in cereal-based beverages and sweet bakery products, where it suppresses yeasts and molds but is less effective at neutral pH levels. Propionates, particularly calcium and sodium propionate, are extensively incorporated into bread formulations at levels of 0.1% - 0.4% to inhibit *Bacillus subtilis* and other rope-forming bacteria. Sulfites, although more

common in dried fruit and beverages, are also used in certain starch-rich matrices to prevent browning and microbial activity. These preservatives offer proven efficacy; however, their continuous use has drawn scrutiny due to potential toxicological risks and consumer rejection.

Synthetic preservatives have long been utilized to safeguard carbohydrate-based foods against microbial spoilage. Their use spans a variety of formulations, from bakery and pasta products to cereals, due to their proven

ability to inhibit molds, yeasts, and rope-forming bacteria. However, each preservative has specific functional roles as well as associated limitations related to pH stability, sensory effects, or health concerns. To provide a concise overview, **Table 1** summarizes the most common synthetic preservatives employed in carbohydrate-based foods, including their typical applications, primary microbial targets, and key limitations.

**Table 1** Common synthetic preservatives in carbohydrate-based foods.

No.	Preservative agents	Typical Use (Bread, Pasta, Cereals) and Usage Level (% flour basis)	Target Microorganism	Limitation / Concern	Reference
1	Calcium propionate (E282)	Widely used in bread and tortillas; seldom in pasta/cereals; 0.1% - 0.4% (bread/tortillas); rarely in pasta/cereals	Molds; rope-forming <i>Bacillus spp.</i>	At higher levels can reduce baker's yeast activity; occasional off-notes; use levels governed by GMP/GRAS	[17]
2	Potassium sorbate/ Sorbic acid (E202/E200)	Common in bread, pastries/tortillas, some breakfast cereals; 0.05% - 0.2% (bread, pastries); up to 0.3% in cereals	Primarily molds & yeasts; some bacteria	pH-dependent (more active at lower pH); some strains can degrade sorbate; potential sensory effects at high doses	[18]
3	Sodium benzoate (E211)	Mainly acidic products & chemically-leavened baked goods (not typical for yeast breads/pasta; limited in cereals); 0.05% - 0.1% (acidic bakery fillings); rarely used in main dough	Yeasts, molds, some bacteria	Effective only at low pH ( $\leq \sim 4.5$ ); risk of benzene formation in beverages when benzoates + vitamin C + heat/light; flavor interactions in some foods	[19]
4	Sodium diacetate (E262(ii))	Used in bread/tortillas and dry mixes; also other foods; 0.1% - 0.3% (bread/tortillas)	Molds; helps suppress rope-forming bacteria	Can impart vinegar-like flavor at higher use levels; usage limited by GMP	[20]
5	Fumaric acid (acidulant)	Widely used in tortillas; also some refrigerated biscuits/chemically-leavened bakery to control pH; 0.2% - 0.5% (tortillas/biscuits); encapsulated forms slightly lower	Indirectly inhibits molds by lowering pH; boosts efficacy of propionates/sorbates	Can add sourness; if unencapsulated may interact with leavening; governed by 21 CFR 172.350	[21]
6	Parabens (methyl/ethyl/propyl p-hydroxybenzoates)	Historically in select bakery icings/fillings (regional); usage now limited in some jurisdictions; 0.05% - 0.1% (icings/fillings, historical use)	Molds & yeasts	Regulatory restrictions (e.g., EU withdrew propyl paraben as a food preservative; general category limits); consumer perception concerns	[22]

Notes: "GMP/GRAS" = "good manufacturing practice / generally recognized as safe" per U.S. FDA; actual maximum levels depend on product, pH, and local law. Benzoates are rarely used in yeast-leavened bread because typical crumb pH is too high for efficacy; sorbates and propionates are preferred there. In tortillas, acidification (often with fumaric acid) + propionate/sorbate is a common combined strategy to extend mold-free shelf life.

### Health and environmental concerns

Although synthetic preservatives are effective, their safety profiles raise increasing concerns. Sodium benzoate, for instance, can form benzene in the presence of ascorbic acid, a compound with carcinogenic potential. Sulfite levels exceeding 50 ppm have been linked to allergic reactions and asthma attacks in sensitive individuals [23]. Similarly, nitrites used in starch-based processed foods may form nitrosamines, compounds classified as probable human carcinogens, with risk ratios for colorectal cancer ranging from 1.2 to 1.5 in frequent consumers [8].

From an environmental perspective, residues of benzoates, sorbates, and propionates contribute to wastewater contamination during food production. Their persistence in effluents has raised concerns regarding aquatic toxicity and microbial resistance. The European Food Safety Authority (EFSA) has highlighted microbial adaptation as an emerging issue, with some molds developing tolerance to propionates at concentrations previously considered inhibitory. These findings reinforce the urgency to develop safer, biodegradable alternatives for use in carbohydrate-rich foods.

### Regulatory restrictions and consumer perception

The use of synthetic preservatives is tightly regulated, with maximum permissible limits varying across jurisdictions. The European Union allows sorbates at levels up to 2,000 mg/kg in bakery products, while benzoates are restricted to 150 mg/kg in cereal-based goods. In the United States, the Food and Drug Administration (FDA) sets maximum limits of 0.1 % (w/w) for sorbates and benzoates in most food applications. Sulfites above 10 ppm must be declared on product labels due to their allergenic potential. In contrast, some countries in Asia and Africa maintain less restrictive standards, which can result in higher exposure levels.

Consumer attitudes toward synthetic preservatives are increasingly negative. Surveys across Europe and North America indicate that nearly 70% of consumers actively avoid foods containing artificial additives, prioritizing “clean-label” products with natural preservation strategies [9]. This shift in perception has been a key driver in the development of plant-based

alternatives. Furthermore, the global market for natural food preservatives, valued at USD 796 million in 2022, is projected to grow at a compound annual growth rate of 67% through 2030, reflecting the strong demand for safer, sustainable preservation technologies.

### Plant extracts as natural preservatives

Plant extracts have emerged as promising alternatives to synthetic preservatives due to their wide array of bioactive compounds with antimicrobial and antioxidant properties. These extracts, derived from leaves, seeds, fruits, roots, and flowers, are particularly relevant in preserving carbohydrate-rich foods where spoilage by fungi and bacteria remains a serious challenge. Recent studies have reported that more than 70% of evaluated plant extracts exhibit measurable antimicrobial activity against foodborne pathogens or spoilage microorganisms [10,24]. Their natural origin, combined with growing consumer demand for safer food products, makes them highly attractive candidates for incorporation into sustainable food systems.

### Bioactive compounds in plant extracts

The preservative activity of plant extracts is largely attributed to their rich content of secondary metabolites, particularly phenolics, flavonoids, alkaloids, and terpenoids. These compounds exhibit a wide range of antimicrobial and antioxidant effects that are influenced by their polarity, chemical structure, and concentration. Recent studies have demonstrated that the antimicrobial efficacy of plant-derived compounds often compares favorably with synthetic preservatives, with minimum inhibitory concentration (MIC) values ranging from as low as 25  $\mu\text{g/mL}$  for phenolic acids against *Klebsiella pneumoniae* to 0.0625  $\mu\text{g/mL}$  for cinnamaldehyde against *Aspergillus* species [25,26]. The diversity of these bioactive compounds and their target specificity against bacteria and fungi highlights their potential role in extending the shelf life of carbohydrate-based foods.

To provide a structured overview, **Table 2** compiles representative bioactive compounds identified from various plant extracts, their polarity, observed antimicrobial or antifungal activity, microbial targets, and associated references. This compilation underscores the broad chemical spectrum of plant-derived molecules and illustrates their capacity to act against a wide range

of spoilage microorganisms relevant to carbohydrate-based food systems.

**Table 2** Representative bioactive compounds in plant extracts with documented antimicrobial and antifungal activity.

No	Compound name	Plant source	Polarity	Antimicrobial activity	Target microbes	Reference
1	Syringic acid, caffeic acid, gentisic acid, quercetin	<i>Seriphidium kurramense</i>	Polar	MIC: $25 \pm 0.37$ $\mu\text{g/mL}$ ( <i>K. pneumoniae</i> ), $50 \pm 0.19$ $\mu\text{g/mL}$ ( <i>C. albicans</i> )	<i>Klebsiella pneumoniae</i> , <i>Candida albicans</i>	[25]
2	Eugenol	Clove oil	Non-polar	MIC 125 $\mu\text{g/mL}$	<i>Salmonella typhi</i>	[27]
3	$\beta$ -sitosterol, taraxerol, friedelin, methyl linoleate, 7-oxositosterol	<i>Opuntia dillenii</i> (stem)	Semi-polar to Non-polar	Stronger than polar extract	<i>E.coli</i>	[28]
4	Coumaric acid, farnesene, gingidiol, shikimic acid, shogaol	<i>Zingiber officinale</i> (rhizome)	Polar	Antibacterial activity	<i>E.coli</i>	[28]
5	Phenolic compounds and esters	Clove flower + thyme leaf	Polar	Inhibition zone 15.8 - 25.2 mm	<i>Bacillus cereus</i> , <i>Staphylococcus aureus</i> , <i>E. coli</i> , <i>Candida albicans</i>	[29]
6	Phenolic compounds, flavonoids	<i>Syzygium aromaticum</i> (bud)	Polar	84% inhibition	<i>Aspergillus niger</i>	[30]
7	Phenolics, flavonoids, saponins	<i>Trigonella foenum-graecum</i> (leaf)	Polar	30% gel more effective	<i>Malassezia spp.</i>	[31]
8	Phenolic compounds	<i>Piper betle</i> (betel leaf)	Polar	ZOI 24.6% (bacteria), 20.3% (fungi)	<i>E. coli</i> , <i>S. aureus</i> , <i>Candida albicans</i>	[32]
9	Phenolics, ferulic acid, flavonoids	Citrus peel	Polar	100% inhibition (1.5 g/L)	<i>Monilinia fructicola</i> , <i>Botrytis cinerea</i>	[33]
10	Phenolics, flavonoids	Pomegranate peel	Polar	Increases tomato resistance	<i>Fusarium oxysporum</i>	[34]
11	Cinnamaldehyde, eugenol	Cinnamon	Polar to Non-polar	Inhibition zone $13.0 \pm 1.73$ mm	<i>Penicillium spp.</i>	[35]
12	Alkaloids, flavonoids, terpenes	<i>Carica papaya</i> leaf	Polar	MIC50 0.625 mg/mL	<i>Fusarium spp.</i>	[36]
13	Thymol, p-cymene	Thyme leaf	Polar to Non-polar	MIC 128 - 512 $\mu\text{g/mL}$	<i>Rhizopus oryzae</i>	[37]
14	Eugenol, cinnamaldehyde	Clove, cinnamon	Polar	MIC 0.0625 - 0.125 mg/mL	<i>Aspergillus spp.</i>	[26]
15	Phenolic compounds, flavonoids	Chamomilla (flower)	Polar	Strong inhibition effect	<i>Keratinophilic fungi</i>	[38]
16	Polyphenols, flavonoids	<i>Agave spp.</i>	Polar	20% - 75% disease reduction	<i>Penicillium expansum</i>	[39]
17	Flavonoids, phenolics	Citrus peel, cistus	Polar	Inhibition 17.7% - 82.3% OTA	<i>Aspergillus carbonarius</i>	[40]
18	Phenolics, flavonoids	<i>Achillea millefolium</i>	Polar	Inhibition 20% concentration	<i>Fusarium spp.</i>	[41]
19	Catechins	Green tea leaf	Polar	Inhibition zone > 17 mm	<i>Candida spp.</i>	[42]
20	Carvacrol, carvone	Oregano leaf	Polar to Non-polar	Inhibition 45.6% - 95.6%	<i>Aspergillus spp.</i>	[43]

No	Compound name	Plant source	Polarity	Antimicrobial activity	Target microbes	Reference
21	Flavonoids, tannins, alkaloids	Turmeric, wheat bran	Polar	90.78% aflatoxin inhibition	<i>Aspergillus flavus</i>	[44]
22	Phenolics, flavonoids	Olive leaf	Polar	Inhibition 58.13% - 87.96%	<i>Fusarium proliferatum</i>	[45]
23	Curcumin	Turmeric (rhizome)	Polar	Inhibition 26.6% - 94.9%	<i>Aspergillus parasiticus</i>	[46]
24	Phenolics, flavonoids	Guava leaf	Polar	IC <sub>50</sub> 69.29 - 3,444.62 µg/mL	<i>Candida spp.</i>	[47]
25	Curdione, curcumin, etc.	Turmeric (rhizome)	Polar to Non-polar	Inhibition of ergosterol	<i>Fusarium graminearum</i>	[48]

Notes: MIC = Minimum Inhibitory Concentration, IC<sub>50</sub> = Half-maximal Inhibitory Concentration, ZOI = Zone of Inhibition, OTA = Ochratoxin A.

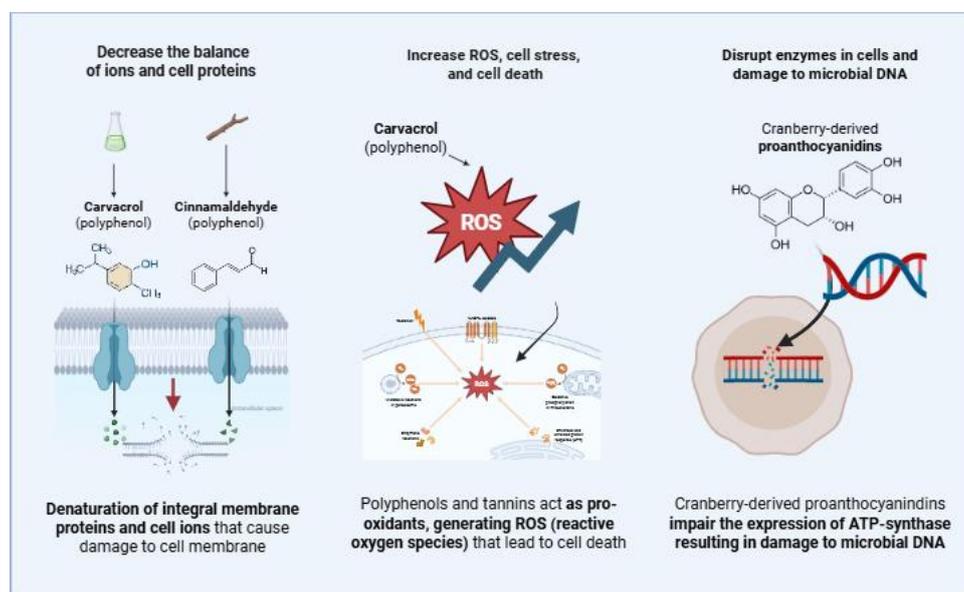
### Preservative mechanism of plant extracts

The preservative efficacy of plant extracts is linked to multiple mechanisms that act synergistically. A primary mechanism is microbial membrane disruption, where compounds such as carvacrol and thymol integrate into the microbial lipid bilayer, causing leakage of ions and proteins. For instance, cinnamaldehyde and carvacrol induced observable structural collapse in *E. coli* and *Staphylococcus aureus* (*S. aureus*) membranes [49].

Another important mechanism is the production of reactive oxygen species (ROS). In the presence of transition metals, polyphenols and tannins can act as pro-oxidants, stimulating ROS formation. These highly reactive molecules then attack microbial DNA, proteins, and lipids, ultimately causing cell damage and death [50]. Plant bioactives also inhibit microbial enzymes

and metabolic pathways. Cranberry-derived proanthocyanidins decreased ATP synthase expression in *Pseudomonas aeruginosa*, impairing energy metabolism [51]. Furthermore, hydroxyanthraquinones were found to bind strongly to DNA gyrase-topoisomerase IV complexes, limiting bacterial DNA replication [52].

To provide a clearer conceptual understanding of these pathways, **Figure 1** schematically illustrates the main mechanisms of antimicrobial and antioxidant action of plant extracts, including ROS generation and membrane disruption. This mechanistic framework demonstrates why plant extracts are capable of broad-spectrum antimicrobial activity while also protecting foods from oxidative deterioration. The figure was designed by the authors, based on the references cited in the preceding paragraph.



**Figure 1** Preservative mechanisms of plant extracts through antimicrobial actions.

### Challenges of direct use in carbohydrate foods

Despite their potential, direct application of plant extracts faces technological and sensory challenges. Many compounds are volatile and degrade during processing; for example, polyphenols lose up to 40% of activity when exposed to baking temperatures above 150 °C [53]. Plant extracts also interact with proteins and starches, forming complexes that reduce their bioavailability [53]. Sensory drawbacks, including bitterness, astringency, or undesirable coloration, limit consumer acceptance; more than 30% of panelists in bakery trials reported bitterness when extracts exceeded 0.6% [54]. Additionally, low solubility of lipophilic compounds such as curcumin restricts their functionality in hydrophilic matrices like dough [55]. These constraints highlight the importance of encapsulation as a strategy to stabilize, mask, and optimize the delivery of plant bioactives in carbohydrate-based foods.

### Encapsulation strategies for plant extracts

The integration of plant extracts into carbohydrate-based foods is hindered by their sensitivity to environmental stressors, low solubility, and potential adverse sensory effects. Encapsulation has therefore become an essential strategy to stabilize bioactive compounds, regulate their release, and enhance bioavailability. By entrapping phenolics, flavonoids, alkaloids, or terpenoids within protective matrices, encapsulation improves stability, masks strong flavors or odors, and enables incorporation into hydrophilic carbohydrate-rich food systems [56,57].

### Encapsulation materials

Biopolymer-based carriers such as chitosan, maltodextrin, starch derivatives, proteins, and gums are most frequently applied. Chitosan is valued for its antimicrobial activity and mucoadhesive nature. For example, Raharjo *et al.* [58] reported quercetin retention of 71.6% and encapsulation efficiency (EE) above 85 % when using chitosan-gum arabic blends for stem bark extract. Maltodextrin is widely employed due to its solubility, low viscosity, and high glass transition temperature, allowing spray-dried powders with 70% - 90% EE [59]. Modified starches such as OSA-starch improve emulsification of hydrophobic phenolics, while proteins (e.g., whey protein isolate, pea protein) form

strong intermolecular networks enhancing encapsulation stability [60]. Natural gums, such as gum arabic and carrageenan, are used for their emulsifying capacity and ability to produce stable microcapsules. In practice, combinations of 2 or more carriers often provide synergistic benefits, improving retention and controlled release.

### Encapsulation techniques

#### *Spray drying*

Spray drying is the most widely adopted technique for encapsulating plant extracts because it is scalable, economical, and capable of producing free-flowing powders. In this process, a liquid feed is atomized into a drying chamber at 150 - 180 °C inlet air temperature, producing microcapsules. Cheng *et al.* (2025) encapsulated Sesbania flower extract using gum arabic, achieving retention of 16.86 mg GAE/g dry basis of total phenolics and antioxidant activity of 24.63 μM Trolox/g (DPPH) [61]. Encapsulation efficiencies of 80-95% are commonly reported for phenolic-rich extracts [62]. Spray drying also improves storage stability; curcumin encapsulated in skim milk powder maintained 80% antioxidant capacity for 90 days at 25 °C, compared to 40% in free form [63].

#### *Freeze drying*

Freeze drying preserves thermo-labile compounds by sublimating water under vacuum at -40 to -80 °C. Although energy-intensive, this method maintains volatile and heat-sensitive phenolics. Ganje *et al.* [60] encapsulated rosemary extract in maltodextrin-whey protein matrices and achieved EE of 84% - 89 % with spherical morphology confirmed by SEM [60]. The powders retained phenolic content for 60 days, demonstrating superior stability compared to spray-dried samples. Alam *et al.* [64] encapsulated kinnow peel extract via freeze drying, reporting retention of 92.8% phenolics and 92.2% flavonoids, confirming freeze drying as an effective but costly method for functional plant extracts.

#### *Coacervation*

Coacervation works through electrostatic attraction between oppositely charged polymers, forming a dense coacervate phase. Phenolic-rich

extracts become trapped inside these droplets, which are then solidified into microcapsules that protect the compounds and enable controlled release. Akram *et al.* [65] encapsulated date seed extract using pea protein-starch coacervation, achieving EE values of 79% - 83% and controlled release between 69% - 97% in simulated gastrointestinal digestion [65]. The coacervates also enhanced phenolic bioaccessibility up to 62.7%. Rajabi and Razavi [66] demonstrated coacervation combined with spray drying for saffron petal and *Stachys* extracts, producing nanocapsules with diameters 385 - 579 nm and intestinal release up to 88%. Coacervation therefore provides efficient encapsulation and controlled delivery, although sensitivity to pH and ionic strength requires precise formulation.

#### Emulsification and nanoemulsion

Emulsion-based systems enable simultaneous encapsulation of hydrophilic and lipophilic components. Nanoemulsions, with droplet sizes < 200 nm, enhance solubility and bioavailability of poorly soluble compounds. Bayomy *et al.* [67] developed an alginate-based nanoemulsion containing *Chlorella vulgaris* extract, yielding particle sizes of 17 - 23.6 nm and enhanced antimicrobial activity against *E. coli* and *S. aureus*. For carbohydrate foods, emulsified polyphenols have been incorporated into cereal coatings, showing microbial inhibition and stability for 30 - 40 days [68]. Controlled release over 7 - 14 days is a typical feature of nanoemulsions, providing extended shelf life benefits.

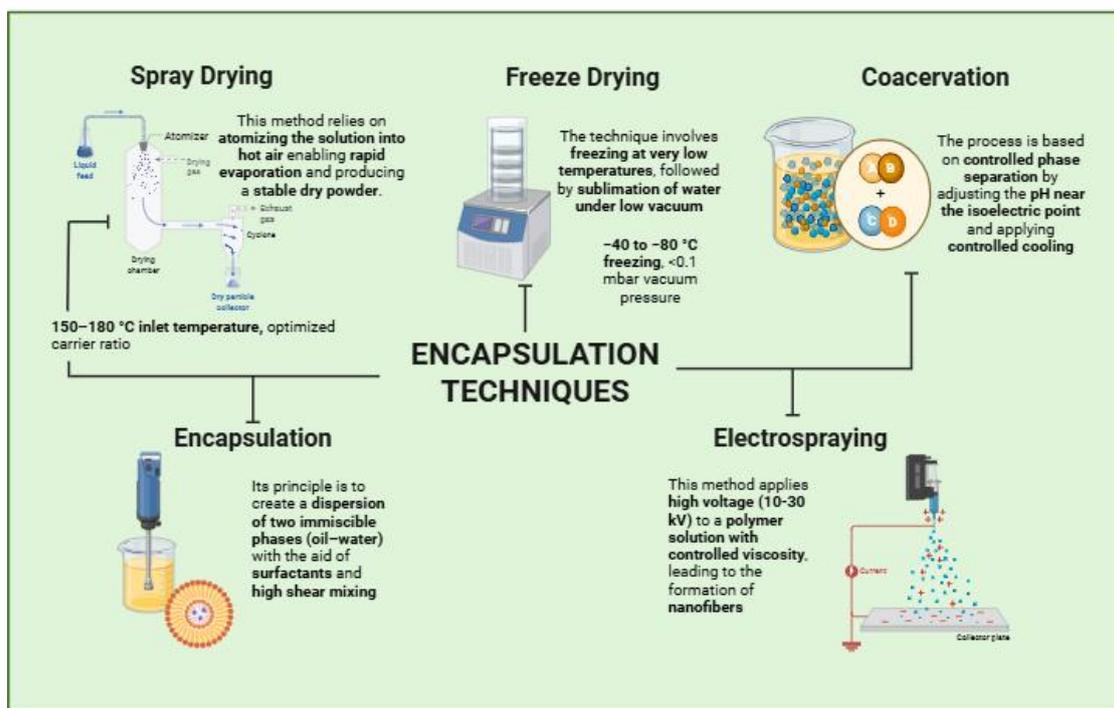
Coacervation is based on phase separation of polymers (e.g., gelatin, gum arabic), where changes in pH, ionic strength, or interaction with oppositely

charged polyelectrolytes cause the polymer to separate from solution and form a coating around the core material. Emulsification, in contrast, involves creating oil-water emulsions stabilized by surfactants or biopolymers, where bioactive compounds are entrapped within dispersed droplets that can later be solidified or dried.

#### Electrospinning and electrospraying

Electrohydrodynamic methods such as electrospinning and electrospraying operate by applying a high-voltage electric field (typically 10 - 30 kV) to a polymer solution or emulsion, which overcomes surface tension and stretches the liquid into ultrafine jets that solidify into nanofibers or nanoparticles. Aliabbasi *et al.* [69] encapsulated curcumin in chickpea protein-Balangu seed gum complexes, reporting EE of 93.7% and complete intestinal release within 480 min [69]. Similarly, electrosprayed turmeric polyphenols produced nanofibers with > 90% EE and improved water solubility [70]. These approaches are particularly attractive for active edible films or packaging in carbohydrate-based foods, combining preservative and barrier functions.

**Figure 2** provides a schematic overview of major encapsulation techniques used to stabilize plant-derived bioactive compounds in carbohydrate-based food systems, illustrating 5 approaches: Spray drying, freeze drying, coacervation, emulsification, and electrospinning/electrospraying. The figure was designed by the authors, based on the relevant references regarding methods and processing conditions cited in the preceding paragraph.



**Figure 2** Schematic illustration of major encapsulation techniques.

### Encapsulation efficiency, release kinetics, and stability

Encapsulation efficiency (EE) is a primary parameter for evaluating encapsulation success, generally ranging between 70% and 95% depending on wall material and technique [71]. Spray drying achieves high EE (80% - 95%) as rapid solvent evaporation traps compounds effectively, whereas freeze drying is slower, where ice crystal formation can expel some molecules, lowering EE but preserving thermo-labile stability.

Release kinetics determine the delivery profile of plant extracts during food processing and digestion. Weibull and Peppas-Sahlin models are often applied to describe release behavior [65]. For example, coacervated phenolics showed intestinal release of 60% - 80% over 4 - 6 h, aligning with targeted preservation in carbohydrate-rich matrices. Nanoemulsions provided more gradual release profiles, with bioactive retention up to 14 days in food simulants.

Stability is critical for practical applications. Encapsulation reduces degradation from oxygen, light, and moisture, thereby extending shelf life.

Anthocyanins encapsulated in maltodextrin retained 80% antioxidant activity after 30 days compared to 35% - 40% in free form [72]. Carotenoids encapsulated in biopolymer matrices remained stable for 40 days in dark storage, confirming encapsulation as a powerful strategy for extending bioactivity [73]. Furthermore, encapsulated  $\beta$ -carotene in pea protein isolate improved bioaccessibility by 30% compared to non-encapsulated forms [74].

To provide a consolidated overview of the wide range of encapsulation approaches explored for plant extracts, Table 3 summarizes representative studies employing spray drying, freeze drying, coacervation, emulsification, and electrospaying techniques. The table highlights wall materials, processing conditions, encapsulated compounds, encapsulation efficiency, and key findings, thereby offering a comparative perspective on how different strategies influence the retention of bioactive compounds, antioxidant activity, antimicrobial performance, and product stability in carbohydrate-based food systems.

**Table 3** Comparative studies on encapsulation of plant extracts using different techniques, wall materials, and performance outcomes (Spray drying method).

No	Wall Material & Extract Concentration	Inlet Temp (°C)	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
1	Gum Arabic (GA, 20 %w/v)/ Sesbania flower extract (10 %w/v)	150 - 160	Sesbania flower extract (SFE)	TPC 70.5%; TFC 51.4%	GA preserved phenolics, flavonoids, and antioxidants; extended shelf life.	[61]
2	Chitosan (10%) + GA (10%)/ Hopea bark extract (10 %w/v)	175	<i>Hopea beccariana</i> bark extract	Quercetin retention 71.6%	Optimized blend gave antimicrobial activity & high solubility.	[58]
3	Maltodextrin (20%) + GA (10%) + $\beta$ -CD (5%) + Tween 20 (0.5%) / Oregano extract (5 %w/v)	170 - 180	Oregano extract (rosmarinic acid, carvacrol)	Up to 99.8 %(carvacrol)	Maltodextrin + GA + $\beta$ - CD improved EE and yield significantly.	[59]
4	Soy lecithin (5%) / PPI (5%)/ trans-Cinnamaldehyde (5 %w/v)	180	trans- Cinnamaldehyde	Spray drying (SD): 95.7%; Freeze drying (FD): 83.9%	SD produced smaller spherical particles (~8 $\mu$ m) vs FD crystalline (~144 $\mu$ m).	[75]
5	Skim milk (20%) / Curcumin (5 %w/v)	160	Curcumin	60% - 80%	Milk proteins improved curcumin stability and rehydration capacity.	[63]
6	Maltodextrin (MD, 10% - 30% more) / Pomegranate peel extract (2 %w/v)	120	Pomegranate peel phenolics	88.6%	Moderate inlet temp + MD preserved polyphenols best.	[76]
7	MD (15%) + GA (10%)/ Ciriguela peel extract (5 %w/v)	150	Ciriguela peel phenolics	Up to 99.8%	MD + GA mixture maximized EE and antioxidant retention.	[77]
8	MD (10%) + GA (10%) $\pm$ Chitosan (0.5% - 1%)/ Green tea extract (5 %w/v)	150	Green tea catechins	71.4% - 88.0%	150 °C optimal: < 150 gave poor powders, > 150 degraded catechins.	[78]
9	Alginate (1% - 2%) + Carrageenan (1% - 2%) + Starch (5%) / Green tea extract (5 %w/v)	100 - 180	Green tea polyphenols	MT-Car: 92.7%	Carrageenan gave highest EE; mid-range temps best for phenolics & powder quality.	[79]
10	GA (10%) + MD (10%)/ Lemongrass leaf extract (5 %w/v)	130	Lemongrass leaf extract	71% - 88%	GA:MD improved antioxidant activity; higher temps reduced TPC/TFC.	[80]
11	GA (10%) + MD (10%) + $\beta$ -CD (5%) / Pistacia leaf extract (4 %w/v)	120, 150 and 180	<i>Pistacia lentiscus</i> leaf extract	68% - 88%	$\beta$ -CD/GA enhanced phenolic stability & antioxidant activity; spherical particles.	[81]
12	MD (10%) + Inulin (5%) + GA (10%) / Pineapple peel extract (2 %w/v)	170	Pineapple peel extract	76.8% - 99.8%	MD/Inulin/GA affected yield and phenolic retention; MD + GA highest EE.	[77]
13	GA (10%) + Polydextrose (5%) + PHGG (5%) / Grape skin extract (5 %w/v)	140	Grape skin phenolics	81.4% - 99.6%	Carbohydrate walls strongly influenced EE, powder properties, and phenolic protection.	[82]
14	MD (10% - 20%, SD vs FD)/ Acerola pulp extract (2 %w/v)	170	Acerola pulp/residue extracts	96% - 97%	SD gave higher practicality and different morphology than FD.	[83]

No	Wall Material & Extract Concentration	Inlet Temp (°C)	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
15	GA (10%)/Cagaita fruit extract (1 %w/v)	175	<i>Eugenia dysenterica</i> (cagaita) fruit extracts	91% - 96%	Inlet temp impacted physical properties; GA effective encapsulant.	[84]

Notes: TPC = total phenolic content; TFC = total flavonoid content.

**Table 4** Comparative studies on encapsulation of plant extracts using different techniques, wall materials, and performance outcomes (Freeze drying method).

No	Wall Material & Extract Concentration	Freeze-drying condition	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
1	Maltodextrin 30 %w/w) + Soy lecithin 1% atau PPI 1% / trans-cinnamaldehyde 5 %w/w)	-45 °C, vacuum	trans-cinnamaldehyde	83.93%	FD yielded crystalline, large particles (~144 µm); lower EE vs spray drying.	[75]
2	Maltodextrin 10% - 20% + GA 10% / Grape skin anthocyanins 1% - 2%	-40 °C, 48 h	Anthocyanins (grape skin)	74% - 82%	FD preserved anthocyanin color better than SD but had lower yield.	[85]
3	Maltodextrin 20 %w/v) / Elderberry extract 5 %w/v)	-50 °C, 72 h	Elderberry extract	81.5%	High polyphenol retention; FD improved antioxidant activity.	[86]
4	GA 10% + Whey protein isolate 10% / Saffron aqueous extract 2%	-55 °C, 48 h	Saffron aqueous extract	70%	FD protected crocin stability; microstructure more porous vs SD.	[87]
5	Maltodextrin DE20, 20 %w/v) / Açai pulp 5%	-40 °C, 48 h	Açai pulp	66%	FD powders more hygroscopic, lower solubility vs SD.	[88]
6	MD 20% + Inulin 10% + GA 10% / Blueberry juice 5%	-50 °C, 0.05 mbar	Blueberry polyphenols	77%	FD gave higher retention of anthocyanins vs hot-air and SD.	[89]
7	GA 15% + MD 15% + Starch 10% / Rosemary extract 2%	-45 °C	Rosemary extract	80%	FD improved antioxidant activity, particle structure more irregular.	[90]
8	MD 20% + Alginate 1% + Chitosan 1% / β-Carotene 0.1%	-40 °C	β-Carotene	69%	FD preserved ascorbic acid better but produced fragile powders.	[91]
9	Maltodextrin 20 %w/v) / Mango pulp 5%	-40 °C, 48 h	Mango pulp	70%	FD powders had better flavor retention, but sticky/low yield.	[92]
10	Whey protein isolate 15% / Coffee oil 2%	-50 °C, 72 h	Coffee oil	76%	FD capsules protected aroma better than SD.	[93]
11	Gelatin 10% + MD 10% / Jussara fruit juice 5%	-55 °C	Jussara fruit extract	75%	FD maintained antioxidant properties, morphology highly porous.	[94]
12	GA 10% + MD 15% / Curcumin 0.1% - 0.2%	-40 °C	Curcumin extract	68% - 72%	FD increased stability but low flowability.	[95]
13	Maltodextrin 20% / Black carrot anthocyanins 2%	-50 °C	Black carrot anthocyanins	73%	FD maintained color intensity well;	[96]

No	Wall Material & Extract Concentration	Freeze-drying condition	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
					hygroscopic nature increased.	
14	Whey protein hydrolysate 10–15% / Olive leaf extract 2%	−40 °C, 48 h	Olive leaf phenolics	80%	FD showed higher antioxidant retention but costly/low scalability.	[97]
15	MD 20% + GA 10% / Pomegranate extract 2%	−50 °C	Pomegranate extract	78%	FD maintained ellagitannin activity; powders sensitive to humidity.	[98]

**Table 5** Comparative studies on encapsulation of plant extracts using different techniques, wall materials, and performance outcomes (Coacervation method).

No	Wall Material & Extract Concentration	Drying / Process	Encapsulated Compound	Encapsulation Efficiency (%)	Key Findings	Reference
1	WPI + GA (coacervates; pH ~4; oil payload > 80%) / Sunflower, lemon & orange oils (5%)	Spray drying after coacervation	Sunflower, lemon & orange oils	80%	WPI–GA formed smooth shells at pH ~4; suitable for oil microencapsulation.	[99]
2	Gelatin + GA (ratio ≈ 1:1; total solids 10 %w/w) / Flaxseed oil (core load 20% - 30%)	Wet microcapsules (cross-linked)	Flaxseed oil	84%	Optimized coacervation and crosslinking improved oil entrapment and stability.	[100]
3	Gelatin + polysaccharide (GA system; total solids 10% - 15%) / Lutein (0.2% - 0.5 %w/w)	Spray drying	Lutein	85%	Process optimization improved physicochemical stability of lutein microcapsules.	[101]
4	Gelatin + GA (1:1, 10 %w/w) / Camphor oil (core load 20%)	Vacuum oven drying	Camphor oil	99%	Demonstrated controllable release from gelatin–GA microcapsules.	[102]
5	Gelatin + GA (1:1, 10 %w/w) / Turmeric oleoresin (core 10% - 20%)	Freeze drying	Turmeric oleoresin	49 to 73%	Optimized GA–gelatin coacervation successfully encapsulated turmeric oleoresin.	[103]
6	Flaxseed protein + flaxseed gum (coacervates, ~10 %w/w) / Flaxseed oil (20% load)	Cross-linked; Freeze drying	Flaxseed oil	87%	Plant-protein/gum pair formed coacervates; crosslinking strengthened shells.	[104]
7	Soy protein + GA (ratio 1:1; solids 10 %w/w) / Flaxseed oil (20% - 25%)	Oven drying	Flaxseed oil	70-86%	Explored soy/GA coacervation for oil; reported controlled release behavior.	[105]
8	Gelatin + GA (1:1, 10 %w/w) / Fish oil (ω-3; 20 %w/w)	Freeze-drying; beverage fortification	Fish oil (ω-3)	76%	Produced stable fish-oil microcapsules used to fortify pomegranate juice.	[106]
9	Gelatin + GA (1:1, 10 %w/w) + TG cross-linking / Microalgal oil (ω-3; 20%)	Oven drying	Microalgal oil (rich in ω-3)	80%	Transglutaminase cross-linking enhanced capsule stability and controlled release.	[107]
10	Gelatin + Almond gum (1:1, ~10 %w/w) / Rosemary essential oil (5% - 10%)	Oven drying	Rosemary essential oil (REO)	43.6%	Almond-gum/gelatin coacervates effectively encapsulated and protected REO.	[108]
11	Pea protein (soluble) + GA (1:1; 10 %w/w) / Flaxseed oil (15% - 20%)	Spray drying	Flaxseed oil	44.6%	Demonstrated pea-protein/GA coacervation as	[109]

No	Wall Material & Extract Concentration	Drying / Process	Encapsulated Compound	Encapsulation Efficiency (%)	Key Findings	Reference
					an alternative to gelatin systems.	
12	Gelatin + SHMP (coacervates) + starch sodium octenyl succinate / Fish oil ( $\omega$ -3, 20%)	Freeze-drying (with starch sodium octenyl succinate aid)	Fish oil	98%	Hybrid coacervation system improved encapsulation and oxidative stability.	[110]
13	Gelatin + GA (1:1, 10 %w/w) / Zataria multiflora essential oil (core 10%)	Freeze drying	Zataria multiflora essential oil	47%	Prepared antimicrobial EO microcapsules via classical gelatin-GA coacervation.	[111]
14	Gelatin + GA (1:1, 10 %w/w) / Carvacrol (core 10%)	Freeze drying	Carvacrol	89%	Showed typical GA-gelatin coacervation route and characterization for carvacrol.	[112]
15	Gelatin + GA + CMC (10 - 15 %w/w) / Orange oil (flavor, 10% - 20%)	Oven drying	Orange oil (flavor)	69%	Reported process parameters (pH, ratios, agitation) affecting capsule yield/size.	[113]

**Table 6** Comparative studies on encapsulation of plant extracts using different techniques, wall materials, and performance outcomes (Emulsification method).

No	Emulsion Type / Wall Material & Extract Concentration	Drying	Encapsulated Compound	Encapsulation Efficiency (EE)	Key findings	Reference
1	W1/O/W; WPI 2 - 4 % (w/v) + maltodextrin 15 % (w/v); DE10/21) + PGPR 4 % (b/b); core: Rosemary extract (5 - 10 %w/v)	Spray drying	Rosemary leaf polyphenol extract	TPC 39.6 - 42.8; rosmarinic acid 62.2% - 67.4%	Double emulsions survived spray-drying and rehydration; higher protein (4 %wPI) improved EE; MD type had minor effect.	[114]
2	W1/O/W; WPI 2 % (w/v) $\pm$ polysaccharide (GA 1% - 2%, CMC 1% - 2%, chitosan 0.5% - 1%); PGPR 4% (b/b minyak); core: Grape seed extract (5.3 g/kg procyanidins)	Spray drying	Grape seed procyanidin-rich extract	79%	Premix membrane emulsification + spray drying produced microcapsules; interfacial composition strongly affected microcapsule properties and procyanidin retention.	[115]
3	W1/O/W; W1: Pectin 3 % (w/v) + berry extract (5 - 10 %v/v); oil: PGPR 2 - 3 % (b/b); W2: CMC 1% - 2% + lecithin 1% - 2%	None (liquid double emulsion/ DE)	Bilberry & blackcurrant extracts (anthocyanins)	95.0 $\pm$ 0.8% to 97.0 $\pm$ 0.6% (at t0)	Amidated pectin slightly increased initial EE and reduced leakage versus unmodified pectin over 20 days.	[116]
4	Double Pickering; W1: pectin 3 - 5 % (w/v) + butterfly pea extract (5 - 8 %v/v); oil: PGPR 3% - 5%; W2: NCC 1 - 3 % (w/v)	None (liquid DE)	Butterfly pea (Clitoria ternatea) petal extract (anthocyanins)	$\sim$ 86.6 - 89.8 at day 0 ( $\downarrow$ to $\sim$ 71% - 79% by day 7)	Cellulose-stabilized DEs protected anthocyanins and slowed pH-/light-driven loss; initial TAC $\sim$ 90 % with gradual decline during storage.	[117]
5	W1/O/W emulgel; alginate 1.5% - 2% + $\kappa$ -carrageenan 0.5 - 1 % (w/v); beads with Ca <sup>2+</sup> /K <sup>+</sup> ; core: purple basil extract (5 - 10 %v/v)	Ionotropic gelation (Ca <sup>2+</sup> /K <sup>+</sup> ) + electrospraying	Purple basil leaf extract (anthocyanins)	70.7 - 87.9	Emulsion-filled hydrogel beads greatly improved anthocyanin retention and bioaccessibility versus non-emulsion beads.	[118]
6	W1/O/W2; oil: PGPR 3% - 4% + Tween 80 1% - 2%;	None (liquid DE)	Elderberry extract (anthocyanins)	55% - 70%	Double emulsions mitigated pH-induced	[119]

No	Emulsion Type / Wall Material & Extract Concentration	Drying	Encapsulated Compound	Encapsulation Efficiency (EE)	Key findings	Reference
	W2: Gum arabic 10 - 15 % (w/v); core: Elderberry extract (5 - 10 %v/v)				color changes, improving coloring stability for hydrophilic extract.	
7	W1/O/W; oil: PGPR 3% - 4%; W2: hydrophilic emulsifier (Tween 80 1% - 2%); core: Black carrot extract (5 %v/v)	None (liquid DE)	Black carrot anthocyanin-rich extract	NR	W/O/W emulsions protected extract against pH-triggered color change by retaining anthocyanins in inner water droplets.	[120]
8	W/O/W; protein (WPI/soy 2 - 4 %w/v) + low-HLB emulsifier 3% - 5% + carbs (maltodextrin/GA 10% - 15%); core: Berry anthocyanins (5 - 10 %v/v)	None (liquid DE)	Berry anthocyanin extracts	NR	Demonstrated formulation-stability relationships for anthocyanin-loaded double emulsions over storage.	[121]
9	W1/O/W; oil: PGPR 5% + corn oil; W2: Gum arabic 15% + Tween 80 1% - 2%; core: Black carrot extract (36 mg anthocyanin/g powder; 5 - 10 %v/v)	None (liquid DE)	Black carrot extract (anthocyanins)	NR	Optimized extract loading and phase ratio to boost coloring power while maintaining DE stability across pH/temperature.	[122]
10	Emulsion-templated hydrogel; alginate 2% + pectin 2 % (w/v); grape peel extract (5 - 10 %v/v)	Ultrasonic/ionotropic gelation (hydrogel microcapsules) and vacuum oven drying	Grape peel anthocyanin-rich extract	70% - 89%	Combining emulsification with ultrasonic gelation improved incorporation and protection versus single-technique beads.	[123]
11	W1/O/W; W1: cactus pear extract 85% + glycerol 15%; oil: corn oil 87% + PGPR 13 % (b/b); W2: WPI 10 % (w/v) + MD/GA (15% - 20%)	Spray drying	Cactus pear (Opuntia) peel/pulp extract (betalains & phenolics)	70% - 97%	W/O/W + spray drying yielded powders with improved color and bioactive retention vs. conventional spray drying.	[124]
12	W1/O/W; outer: GA + MD blends 40:60, 50:50, 60:40 (10 - 15 %w/v total); core: cactus pear extract (5 - 10 %v/v)	None (liquid DE; then added to yogurt)	Cactus pear extract (betalains & polyphenols)	NR	Fortifying yogurt with extract-loaded DE improved pigment/phenolic stability and acceptable sensory traits during storage.	[125]
13	W1/O/W; carriers: Maltodextrin 10% - 15% + GA 5% - 10%; core: acerola extract (vit C 5 %w/v equiv.)	Spray drying	Acerola fruit extract (vitamin C & phenolics)	77% - 91%	Response-surface optimization of inlet/outlet temps produced free-flowing powders while preserving bioactives.	[126]
14	Double emulsion + coacervation; wall: Gelatin 1% - 2% + GA 1 - 2 % (w/v); core: anthocyanin-rich extract (5 - 8 %v/v)	Spray & freeze drying (comparison)	Anthocyanin-rich plant extract	84% - 94%	Double-emulsion/complex-coacervate route enabled controlled release; drying method affected retention kinetics.	[127]
15	W1/O/W2; W1: Blueberry pomace extract 20 % (w/w); oil: corn oil 76% + PGPR 4 % (b/b); W2: WPI 2.5 % (w/v)	None (liquid DE)	Blueberry pomace extract (TPC & TA)	74% - 85%	Processing conditions (homogenization pressure, shear) tuned droplet size/ $\zeta$ -potential and affected phenolics/anthocyanin entrapment.	[128]

**Table 7** Comparative studies on encapsulation of plant extracts using different techniques, wall materials, and performance outcomes (Electrospraying method).

No	Wall Material & Extract Concentration	Drying / Solidification (kV)	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
1	WPC (20 %w/v) + guar gum (0.5 %w/w of polymer) + resistant starch; folic acid 1.5 %w/w of polymer	Electrospraying 20 kV vs nanospray drying	Folic Acid	55% - 83%	Electrospraying produced spherical nano-, submicro-, and microcapsules with enhanced control over size distribution, leading to improved stability of folic acid during storage and thermal exposure.	[129]
2	Gelatin (5 %w/v), WPC (5 %w/v), SPI (5 %w/v); $\alpha$ -linolenic acid ~5 %w/w of wall	Emulsion electrospaying 15 kV	$\alpha$ -Linolenic Acid	70%	Emulsion electrospaying enabled the formation of protein micro/nanoparticles that enhanced the protection of thermosensitive lipophilic bioactives like $\alpha$ -linolenic acid.	[130]
3	Alginate 2 %w/v, alginate + RS (2% + 2%), chitosan 2% coating; probiotic suspension ~10 <sup>7</sup> CFU/mL	Wet electrospaying 12 kV	Lactobacillus plantarum (Probiotics)	Encapsulation yield 10%	Mucoadhesive alginate-chitosan electrospayed microcapsules improved gastrointestinal retention and acid protection for probiotics.	[131]
4	WPC nanocarriers 3 %w/v; olive leaf phenolics 2 %w/w	Electrospraying 18 kV	Olive Leaf Phenolics	40% - 70%	One-step electrospaying entrapped phenolics, demonstrating antioxidant/thermal stability and controlled release behavior.	[132]
5	Zein 5 %w/v in 80% ethanol; gallic acid 5 %w/w of zein	Electrospraying 15 kV	Gallic Acid	NR	Demonstrated food-grade zein electrospayed nanoparticles as protective carriers for gallic acid.	[133]
6	Zein 5 %w/v in 80% ethanol; quercetin 5 %w/w of zein	Electrospraying 15 kV	Quercetin	87.9% - 93.0%	High encapsulation efficiency and improved in vitro bioavailability of quercetin using	[134]

No	Wall Material & Extract Concentration	Drying / Solidification (kV)	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
					electrosprayed zein nanocarriers.	
7	Dextran 5 %w/v + WPI 5 %w/v; Se-enriched peptide 1 %w/w	Electrospraying 15 kV	Selenium-Enriched Peptide	37% - 46%	Mild electrospinning yielded food-grade microcapsules with good thermal stability and pH-tunable release.	[135]
8	Milk protein isolate 3 %w/v; curcumin 2 %w/w	Electrospraying 20 kV	Curcumin	80%	Electrosprayed curcumin particles showed enhanced stability and functionality in foods.	[136]
9	Glucose syrup 10 %w/v + maltodextrin 10 %w/v; fish oil 15 %w/w	Electrospraying 18 kV vs spray-drying	Fish Oil	84%	Side-by-side comparison: Oxidative stability and EE differed by method; electrospinning produced finer capsules; spray-drying had higher EE.	[137]
10	WPI 5 %w/v + bacterial cellulose 0.5 %w/v; EGCG 2 %w/w	Electrospraying 15 kV	Epigallocatechin gallate (EGCG)	Up to 98 % (HPLC)	EGCG exhibited enhanced stability against heat, humidity, and storage; WPI-BC proved to be an efficient food-grade carrier.	[138]
11	Zein 5 %w/v in 80% ethanol; resveratrol:zein ratio 1:50 (w/w)	Electrospraying 15 kV	Resveratrol	68.5% at 1:50 ratio (resveratrol:zein, w/w)	Nanoparticles sized improved resveratrol stability, provided controlled release, and increased <i>ex-vivo</i> permeability (~1.15×) compared with free resveratrol; process operated at room temperature.	[139]
12	κ-Carrageenan 3 %w/v; D-limonene 2 %w/w	Electrospraying 20 kV	D-limonene	78% - 97%	Spherical nanoparticles, pH-sensitive release; greatly improved photo/thermal stability of D-limonene	[140]
13	HPMC 2 %w/v; <i>Rhus microphylla</i> fruit extract 5 %w/w	Electrospraying 20 kV	<i>Rhus microphylla</i> fruit extracts	Not reported	Strong antioxidant/antifungal effect; extended strawberry shelf life	[141]

No	Wall Material & Extract Concentration	Drying / Solidification (kV)	Encapsulated Compound	Encapsulation Efficiency (EE)	Key Findings	Reference
					by reducing decay and weight loss	
14	Zein 5 %w/v; lipophilic model bioactives 5 %w/w	Electrospraying 18 kV	Various Lipophilic Bioactives (Model Systems)	79% - 84%	Systematically mapped processing variables to control zein electrosprayed nanoparticle formation.	[142]
15	Gelatin 2 %w/v shell; betalain extract 2 %w/w core	Coaxial electrospraying 15 kV	Betalains	NR	Coaxial electrosprayed gelatin-betalain nanoparticles maintained antioxidant properties; edible-grade carrier.	[143]

Notes: NR = not reported.

### Applications in carbohydrate-based foods

Carbohydrate-based foods - especially breads, cakes, cookies, pasta/noodles, breakfast cereals, and snacks - are prone to staling (amylopectin retrogradation), fungal spoilage, and oxidative rancidity. Encapsulated plant extracts (polyphenols, flavonols, tannins, and non-volatile phytochemicals) are increasingly used to mitigate these degradative pathways by enabling controlled release, flavor masking, and protection from thermal/oxidative stress during processing and storage [144]. Relative to free extracts, encapsulation typically improves retention of actives after baking/extrusion by 15% - 40% and delays on-set of mold by  $\geq 2$  - 3 days in bakery matrices, depending on dose and water activity (aw) [24,145].

#### Bakery products (bread, cakes and cookies)

In bread, encapsulated spice and herb extracts inhibit rope spoilage and common molds (*Aspergillus spp./Penicillium spp.*) without relying on propionates. A 3×3 Box-Behnken optimization showed that 1% clove oil + 1% orange oil maintained moisture and rheological integrity after 7 days at 20 °C; microscopy (SEM, PLM) and TG-DTA confirmed structural stability of the optimized formula ( $R^2 = 0.9854$ ) [146]. Fortification of wheat flour with curcumin and quercetin at 2.5% - 5% (flour basis) increased ABTS/DPPH radical scavenging but reduced Mixolab dough stability and accelerated starch retrogradation; gas production/retention remained unaffected, preserving loaf volume, whereas sensory

liking decreased due to yellow hue and quercetin-linked bitterness [147].

Using aqueous spice extracts, 4% cinnamon yielded the softest crumb and mold-free shelf life > 6 days versus 4 days in control; 2% cinnamon maximized loaf volume ( $\approx 340 \text{ cm}^3$ ), while 4% clove produced the heaviest loaf ( $\approx 333 \text{ g}$ ). Low-level ginger increased hardness and reduced volume [16]. Substitution with soy protein isolate (SPI) at 2% - 8% decreased specific volume; 4% SPI balanced nutrition and acceptance, with microbiological safety 4 - 5 days (2% - 4% SPI) but a *Staphylococcus aureus* growth concern under challenge conditions, indicating the need for hurdle design [148]. Stevia extract breads showed paler crusts (lower Maillard index) but retained elastic crumb, supporting diet-focused claims [149]. In cookies/cakes, microencapsulated rosemary/oregano reduced peroxide and TBARS formation by > 20% - 30% over 6 - 8 weeks at 25 °C, while masking bitterness and preserving vanilla/butter notes [145].

#### Pasta and noodles

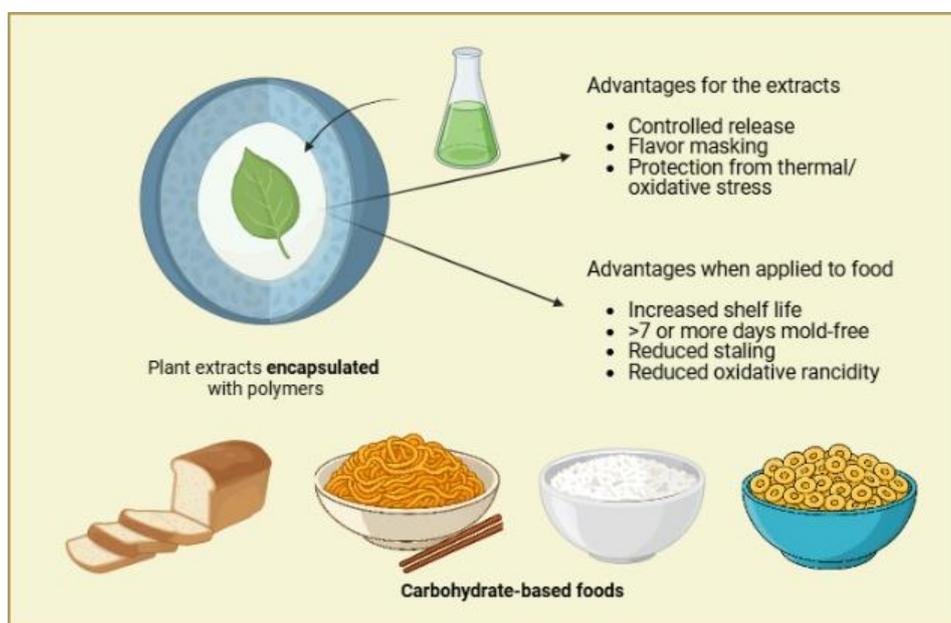
Extrusion, steaming, and drying can degrade polyphenols; encapsulation limits thermal loss and bitterness while maintaining cooking quality. Incorporation of encapsulated anthocyanins (purple sweet potato/black rice) improves color stability ( $\Delta E^*$  reduced by  $\approx 30\%$  - 50% after cooking) and increases antioxidant capacity (FRAP/DPPH) versus unencapsulated controls [144]. In instant noodles,

partial flour replacement with *Amaranthus* leaf powder (1% - 3%) increased fat from 1.55% → 4.57% (energy density rise) but preserved acceptance (60-panelist, 9-point hedonic), and delivered measurable DPPH activity [149]. A multi-component “emergency” noodle (semolina + SPI + green tea extract + CMC + spirulina + beef tallow) achieved a predicted shelf life of 1,197 days at 30 °C/75% RH; antioxidants (green tea extract) lowered lipid oxidation, while CMC increased water absorption and texture resilience during 120-day accelerated storage [150].

### Breakfast cereals and snack foods

Ready-to-eat cereals and extruded snacks exhibit high surface area and porosity, accelerating oxidation. Microencapsulated berry or pomegranate extracts in coatings decreased hexanal accumulation by 25% - 40% and stabilized  $a^*$  and  $b^*$  color coordinates during 12 - 16 weeks of ambient storage;  $a_w$  control (0.30 - 0.45) synergized with phenolics to delay rancidity [145]. For fried/roasted snacks, encapsulated curcumin/catechins

reduced pigment loss (retention ↑ ~20%) and off-flavor formation at 160 - 180 °C compared with free extracts, while maintaining crunch (instrumental hardness) and consumer liking ( $\Delta$ liking ≤ 0.3 on 9-point scale) [152]. **Figure 3** illustrates the integration of encapsulated plant extracts into carbohydrate-based foods, highlighting their role in enhancing product stability and functionality. The schematic shows how encapsulation enables controlled release, flavor masking, and protection of bioactive compounds against thermal and oxidative stress, which collectively contribute to increased shelf-life in breads, pasta, rice, cereals, and snack products. The figure was designed by the authors, based on the relevant references cited in the preceding paragraph.



**Figure 3** Functional benefits of encapsulated plant extracts in carbohydrate-based foods.

### Comparative Effectiveness Against Synthetic Preservatives (shelf life, microbial inhibition and sensory quality)

Across bakery and cereal matrices, encapsulated plant extracts frequently match - or in some formats exceed - the performance of calcium propionate (0.2% -

0.3%), BHT (50 - 200 ppm), or sodium benzoate (0.05% - 0.1%) for mold/yeast inhibition and lipid stabilization, with the advantages of clean-label positioning and reduced sensory penalties [145]. In pan breads, encapsulated cinnamon/clove systems achieved ≥ 2 extra mold-free days at 20 - 25 °C relative to untreated

controls and similar to propionates, while improving spice aroma retention through controlled release [24,146]. In cookies, encapsulated rosemary outperformed BHT in TBARS suppression after 6 - 8 weeks (effect size 5% - 10% absolute difference), with no significant change in overall liking ( $p > 0.05$ ) [145]. Variability arises from carrier type (maltodextrin, gum arabic, starch, proteins), encapsulation efficiency (typically 50% - 90%), and dose; thus, formulation-specific optimization is essential [153].

**Table 8** compiles studies on plant extract encapsulation across multiple techniques, reporting carriers, methods, and outcomes. Then, **Table 9** summarizes applied studies where encapsulated plant extracts were tested in carbohydrate-based foods, listing the encapsulation system, product, key results, and concise references.

**Table 8** Summary of recent studies on encapsulation of plant extracts using different carriers and techniques.

No	Plant Extract	Carrier Material	Encapsulation Technique	Encapsulation Result & Bioactivity	Reference
1	Green tea extract (catechins)	Maltodextrin (MD), gum arabic (GA), chitosan	Spray drying	Encapsulation efficiency (EE) 71.41% - 88.04%; improved powder stability.	[78]
2	Pomegranate peel extract	MD (100%) vs whey protein	Spray drying	EE 88.63% (with MD 100%); higher punicalagin/punicalin retention than WP; good solubility.	[76]
3	Ciriguela ( <i>Spondias purpurea</i> ) peel extract	MD + GA	Spray vs freeze drying (control)	Spray-dried EE 98.83%; TPC 476.82 mg GAE·g <sup>-1</sup> ; good 90-day stability (7 & 25 °C).	[154]
4	Pineapple peel extract	MD, GA, inulin	Spray drying	Antioxidant activity best retained at 150 °C with MD/GA; powders showed suitable flowability & stability.	[155]
5	Grape cane phenolic extract	HP-β-cyclodextrin + MD	Spray drying	Mean EE ≈ 80.5%; preserved antioxidant capacity; good powder properties.	[156]
6	Olive leaf extract	MD with pectin and/or GA	Spray drying	Hybrid MD-pectin/GA carriers improved EE and showed antimicrobial activity; stable during storage.	[157]
7	Cornsilk phenolic extract	MD	Freeze-drying vs spray/microwave	Freeze-drying delivered highest phenolic recovery and antioxidant activity vs other methods.	[158]
8	Blackberry ( <i>Rubus fruticosus</i> ) aqueous extract	GA or polydextrose	Spray drying	High powder solubility (~88% - 97%); retained phenolics; GA yielded brighter powders.	[159]
9	<i>Moringa oleifera</i> leaf polyphenols	Carboxymethyl-cellulose (CMC), tragacanth, locust bean gum	Spray drying	Wall material strongly influenced outcomes; CMC often gave higher EE for TPC/TFC and good stability.	[160]
10	Grape seed extract phenolics	Whey protein concentrate + MD + GA (blends)	Freeze drying	Blends achieved high EE and strong antioxidant retention; morphology and release characterized.	[161]

No	Plant Extract	Carrier Material	Encapsulation Technique	Encapsulation Result & Bioactivity	Reference
11	Nettle ( <i>Urtica dioica</i> ) leaf extract	MD, GA (varied ratios)	Spray drying	Process yield 64.6% - 87.2%, solubility 94.8% - 98.5%; carrier & temperature significantly affected encapsulation/loading capacity.	[162]
12	Tucumã ( <i>Astrocaryum vulgare</i> ) almond coproduct extract	MD	Spray drying	> 80% of TPC retained within microparticles; strong DPPH/ABTS activity; spherical microcapsules.	[163]
13	Yerba mate ( <i>Ilex paraguariensis</i> ) extract	$\beta$ -cyclodextrin	Spray drying	Encapsulation with $\beta$ -CD improved powder properties and stability; morphology optimized by carrier ratio.	[164]
14	Jaboticaba ( <i>Myrciaria jaboticaba</i> ) pomace extract	MD	Spray drying	MD protected anthocyanins; FTIR confirmed encapsulation; microcapsules suitable for functional foods.	[165]
15	Açaí ( <i>Euterpe oleracea</i> ) fruit antioxidants	Zein protein	Electrospraying	Electrosprayed zein capsules enhanced thermal stability and <i>in-vitro</i> bioaccessibility of antioxidants.	[166]

**Table 9** Applications of encapsulated plant extracts in carbohydrate-based foods.

No	Food Product	Encapsulated Extract	Encapsulation Method	Observed Effect	Reference
1	Wheat bread	Garcinia fruit (HCA) extract	Spray-dried microcapsules (MD, WPI, MD + WPI)	Higher HCA retention through baking; bread volume/texture acceptable; improved functional antioxidant content.	[167]
2	Bread	Green tea polyphenols	Spray-/freeze-dried microcapsules	Maintained bread quality; protected catechins vs free extract; improved antioxidant potential.	[168]
3	Wheat bread	Spray-dried hawthorn bark, soybean, onion husk extracts (inulin/MD carriers)	Spray-dried microcapsules	Increased polyphenols & antioxidant activity; good quality attributes during <i>in-vitro</i> digestion.	[169]
4	Wheat bread	Saskatoon berry extract	Microcapsules (MD or MD + inulin)	+ 93% antioxidative properties (microcaps > powder); good sensory, improved bioaccessibility.	[170]
5	Bread	Mixed plant polyphenols	Encapsulated (formulation optimized)	Higher antioxidant activity with good consumer acceptability; balanced texture/porosity.	[171]
6	Bread (formulation target)	Phenolic-rich powder (H-CPP)	Spray-dried with polysaccharide carriers	Stable encapsulates suitable for bread - supports antioxidant delivery with workable dough properties.	[172]

No	Food Product	Encapsulated Extract	Encapsulation Method	Observed Effect	Reference
7	Cookies	Grape seed extract	Microencapsulation (2 systems)	Higher antioxidant activity; bitterness/astringency partly masked; consumer liking at parity with control.	[173]
8	Biscuits	Olive leaf extract	Microencapsulation	Improved oxidative stability under accelerated storage; maintained physicochemical quality.	[174]
9	Biscuits	Olive leaf extract	Micro- & nanoencapsulation	Encapsulation modulated phenolic profile and bioaccessibility during gastrointestinal simulation.	[175]
10	Cookies	Cherry pomace phenolics	Spray-dried microcapsules	Enhanced antioxidant capacity; acceptable sensory reported.	[176]
11	Cookies	Grape seed extract	Microencapsulation	Summarizes significantly stronger antioxidant activity when microencapsulated GSE used in cookies.	[177]
12	Biscuits	Grape skin extract (in walnut paste)	Encapsulated paste (MD/gums)	Increased oxidative induction time; encapsulation helped stability; sensory workable.	[178]
13	Pasta (baked applications tested)	Grape skin extract (in walnut paste)	Encapsulated paste	Antioxidant preservation depending on matrix/thermal step; encapsulants aided shelf-life trends.	[179]
14	Crackers	Red onion skin anthocyanins	Microencapsulation	Value-added coloration + antioxidant boost; quality maintained.	[180]
15	Cake	Red onion peel extract	Microencapsulation	Improved antioxidant content; acceptable sponge cake quality.	[181]
16	Sponge cake	Green tea extract	Microencapsulation	Delayed quality decay; antioxidant protection during storage.	[182]
17	Instant fried noodles	Black hollyhock & borage extracts	Microencapsulated plant extracts	Improved oxidative stability of noodles; lower peroxide/anisidine under storage.	[183]
18	Fresh wheat noodles	Chlorophyll (plant pigment)	Microcapsules	Better dough handling & cooking quality; color stability; antioxidant effect.	[184]
19	Pasta	(Olive leaf flour; not encaps.)	Microencapsulation	Context on antioxidant retention in pasta; complements OLE encapsulation studies in baked goods.	[185]
20	Fresh pasta	Olive pomace extract	Microencapsulation	Microencapsulation increased total phenolics vs free extract; acceptable color/texture.	[186]
21	Macaroni	Fenugreek aerial parts extract	Encapsulation (details in paper)	Improved color/antioxidant; sensory acceptable; encapsulated > free for stability.	[187]
22	Rice cake (garaetteok)	$\beta$ -Carotene (plant carotenoid)	Freeze-dried emulsion powder (MD/GA walls)	High encapsulation efficiency; $\beta$ -carotene survived processing; functional coloration/antioxidant.	[188]
23	(Model bakery use reported)	Grape pomace phenolics	MD+GA microencapsulation	Strong antioxidant activity of microcaps; intended as bakery antioxidant ingredient.	[189]

No	Food Product	Encapsulated Extract	Encapsulation Method	Observed Effect	Reference
24	Cookies	Grape skin/seed polyphenols	Encapsulated & powder (comparison)	Antioxidant enrichment; acceptable up to certain levels; microcaps mitigated sensory impact.	[190]
25	Whole-wheat cocoa biscuits	Grape skin extract	MD microencapsulation	↑ Total phenolics & antioxidant capacity; acceptable sensory at 1.2–2.3% loading.	[178]
26	Cookies (printed)	Polyphenol-rich plant extract	Encapsulated + process design	Up to 115% higher bioactivity vs free extract; tunable moisture & phenolics by printing/baking profile.	[191]
27	Chocolate bar	Cocoa shell phenolics	Microencapsulation (protein/polysaccharide)	Increased phenolics; acceptable sensory/color; functional antioxidant claim support.	[192]
28	Bakery applications	Olive leaf bioactives	Encapsulation strategies	Practical requirements to maintain sensory while extending oxidative stability.	[193]
29	Bread	Green tea polyphenols	Spray-dried	Summarizes multiple bread trials: antioxidant retention with minimal texture penalties.	[194]
30	Bread	Green tea/rosemary extracts (polyphenols)	Microencapsulation	Demonstrated antioxidant-enriched bread concept with processing considerations for sensory quality.	[195]

### Processing constraints and industrial challenges

Despite clear functional gains, industrial deployment of encapsulated plant extracts faces constraints spanning processing stability, dough rheology, sensory trade-offs, and economics.

#### Stability during mixing and baking

Mechanical shear (mixing/kneading), fermentation/proofing, and baking ( $\geq 180 - 220$  °C surface; 95 - 100 °C crumb) can fracture particle shells or plasticize matrices, accelerating release and thermal degradation of sensitive phenolics. Spray-dried maltodextrin/gum arabic systems typically retain 60% - 80% polyphenols after a standard bake; poorly glassy carriers or high moisture can cut retention below 50% [153]. In noodles/pasta, extrusion at 80 - 110 °C and high specific mechanical energy reduces anthocyanin content unless protected; encapsulation can limit losses to  $\leq 25\% - 35\%$ , compared with  $> 50\%$  without encapsulation [144]. Process tuning - lower die temperature, higher feed moisture, and shorter residence time - helps preserve payloads, while post-process coatings provide the highest survivability [151].

### Interaction with dough rheology and texture

Encapsulation carriers act as hydrocolloids/solids that modulate gluten development and starch gelatinization. Polyphenol-rich systems may decrease gluten polymerization via thiol-quinone interactions, reducing specific volume and increasing crumb firmness; effects scale with dose and particle size. Curcumin/querceetin fortification at 2.5% - 5% shortened dough development time and stability on Mixolab while accelerating retrogradation, foreshadowing faster staling [147]. SPI substitution (2% - 8%) lowered loaf volume and consumer liking at 6% - 8%, indicating a narrow technological window [148]. Conversely, modest hydrocolloid carriers (e.g., CMC at 0.2% - 0.5%) improved water absorption and softened texture in noodles, offsetting oxidative and mechanical stress [151].

#### Sensory impact (flavor, aroma and color)

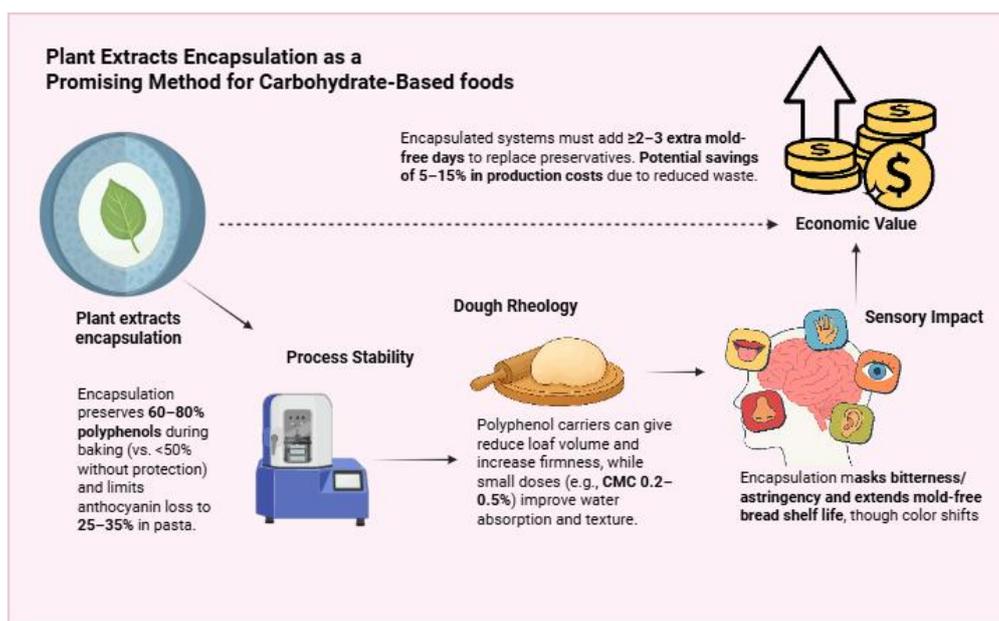
Bitterness/astringency of polyphenols and strong spice volatiles can limit acceptance. Encapsulation mitigates these effects by masking (matrix partitioning) and slowing release (Fickian diffusion through shells). In breads, cinnamon/clove encapsulates extended mold-free days without penalizing overall liking, while free

extracts more often produced off-notes [24]. Still, color shifts are common: curcumin induces yellow crumb ( $\Delta b^* > 5$ ), and anthocyanins shift  $L^*$  down and  $a^*$  up, requiring alignment with product identity or using target markets that accept color cues [144,147]. Aroma retention can be too low (loss during baking) or too high (over-spiced); shell composition and glass transition temperature ( $T_g$ ) should be tuned to release desired headspace concentrations across storage [153].

### Cost, scalability and shelf-life consistency

Economics favor spray drying (high throughput, low unit cost) and fluid-bed coating for snacks/cereals; nanoencapsulation/electrospinning offer superior protection but higher CAPEX/OPEX and tighter GMP constraints. Typical encapsulation yields are 50% - 90%, with unit costs sensitive to carrier price (maltodextrin vs.

proteins), energy, and cleaning time. To displace preservatives like calcium propionate, encapsulated systems must deliver  $\geq 2 - 3$  extra mold-free days at ambient  $a_w$ , maintain sensory quality, and fit existing lines [145]. Batch-to-batch variability - temperature/humidity excursions, packaging  $O_2$ , and  $a_w$  - drives inconsistent performance; adopting MAP with  $O_2 < 1\%$  and  $a_w$  control (0.92 - 0.94 in pan bread) improves reliability [153]. Regulatory alignment (GRAS status, natural/clean-label claims) and transparent sourcing further condition adoption. As shown in **Figure 4**, the schematic illustration highlights industrial implications of plant extract encapsulation in carbohydrate-based foods. The figure was created by the authors, drawing upon the literature cited in the prior paragraph.



**Figure 4** Industrial implications of plant extract encapsulation in carbohydrate-based foods.

Industrial success depends on matching encapsulation chemistry to process conditions and product identity: carriers with adequate  $T_g$  and moisture barrier for baking; particle sizes that minimize rheology penalties; and release kinetics that harmonize flavor while achieving microbial/oxidative targets. Cost-effective, scalable operations (spray drying/coating) coupled with package/ $a_w$  control and validated shelf-life models will enable encapsulated plant extracts to

function as credible, clean-label alternatives to synthetic preservatives in carbohydrate-rich foods [145].

### Regulatory landscape

#### Global regulatory framework

The regulation of encapsulated plant extracts sits at the intersection of food additive, flavoring, novel food, and packaging rules. In the United States, safety assessment follows either a food-additive petition or a Generally Recognized as Safe (GRAS) route under 21

CFR Part 170 by U.S. FDA 2024, with the key standard being “reasonable certainty of no harm” supported by publicly available data or expert consensus; encapsulating matrices (e.g., maltodextrin, gum arabic) must themselves be permitted food ingredients, while any nanostructured systems trigger careful scrutiny of identity, migration, and exposure [196].

In the European Union, encapsulated botanical substances may fall under the Food Additives Regulation, the Flavoring Regulation, or - when composition/structure or bioavailability is significantly altered - the Novel Foods Regulation (EU) 2015/2283, which requires pre-market authorization and EFSA risk assessment; use in food supplements invokes the Food Supplements Directive and applicable botanical lists [197].

Codex Alimentarius provides harmonized principles and specifications via the General Standard for Food Additives (GSFA) and the work of JECFA on ingredient specifications and exposure assessment, which many national authorities reference [198].

In Indonesia, the National Agency of Drug and Food Control (BPOM) regulates food additives, processing aids, and claims; encapsulation materials and botanical actives must align with the positive lists and labeling requirements, with additional oversight when nanotechnology is involved explained by Badan Pengawas Obat dan Makanan [199]. Across jurisdictions, active-packaging or controlled-release uses may be regulated as “food contact materials,” requiring migration testing and separate clearances [196,197].

### Approval pathways for encapsulated plant extracts

Approval pathways depend on (i) the regulatory status of the core (e.g., polyphenols, etc.), (ii) the wall material and processing aids, and (iii) whether encapsulation changes bioavailability or intended

technological function. If both core and wall are already permitted and the technological purpose (e.g., antioxidant, antimicrobial) fits within existing additive categories at established maximum use levels, manufacturers can proceed with compliance documentation and specifications (U.S. FDS, 2024; Codex Alimentarius Commission, 2023). Where encapsulation introduces nano-dimensions or novel carriers (e.g., hybrid biopolymers), authorities may require full dossiers covering identity/characterization, manufacturing, specifications, stability, exposure estimates, toxicology including genotoxicity, and where relevant, gastrointestinal fate and migration from matrices or packaging [197,200]. Health or function claims (e.g., “preserves freshness,” “supports immunity”) add a separate substantiation track under claims regulations [197,199].

### Labeling and consumer acceptance issues

Labeling must accurately declare ingredient classes and any allergens arising from wall materials (e.g., whey proteins), and comply with additive naming conventions; nano-specific disclosure may be mandatory where in force [197]. Clean-label expectations heighten sensitivity to carrier names (e.g., maltodextrin vs. “modified starch”) and to the perception that encapsulation is “processing,” underscoring the need for transparent communication of safety, purpose, and benefits [201]. For antimicrobial uses, positioning should emphasize food safety and shelf-life integrity while avoiding implied drug-like effects. Finally, traceable specifications (particle size distribution, loading, release profile) and adherence to positive lists support market acceptance and regulatory inspections [196,198]. **Table 10** provides an overview of regulatory frameworks for encapsulated plant extracts, highlighting authorities, status, approvals, and key challenges.

**Table 10** Overview of regulatory frameworks for encapsulated plant extracts.

Region	Authority	Current Status	Approval Examples	Gaps/Challenges
Global	Codex	GSFA establishes harmonized additive provisions and specifications that many countries reference; used to benchmark carriers (e.g., maltodextrin, gum arabic)	Use of plant-derived ingredients and carriers within GSFA food categories at set MLs (where listed).	Non-binding: Must be transposed nationally; limited granularity on encapsulation/nano-
	Alimentarius Commission [198]			

Region	Authority	Current Status	Approval Examples	Gaps/Challenges
		and functional classes (antioxidant, preservative).		specific release parameters.
United States	U.S. FDA [196]	Ingredients proceed via Food Additive Petition or GRAS (21 CFR Part 170); nano/encapsulation considered in identity, exposure, and safety narrative. Food-contact/active-packaging aspects handled via Food Contact Substance (FCS) notifications.	GRAS notices for botanical constituents and permitted carriers; FCS inventory for packaging systems enabling controlled release.	Public transparency varies for self-affirmed GRAS; migration/release and nanocharacterization data often scrutinized in dossiers.
European Union	European Commission/EFSA [197,201]	If encapsulation significantly alters composition/bioavailability or there's no EU history of safe use, authorization as Novel Food (Reg. (EU) 2015/2283) after EFSA risk assessment; additive uses fall under additives/flavourings legislation; active/intelligent food-contact materials require EFSA assessment.	Union tools include the Novel Food status catalogue; FCM/active packaging application routes published by EFSA.	Data needs: Nano-scale characterization, GI fate, migration, exposure; labeling for engineered nanomaterials where applicable.
Indonesia	Badan Pengawas Obat dan Makanan (BPOM) [199]	Encapsulated actives and wall materials must be permitted ingredients/additives and labeled per BPOM rules; nutrient/claim language and composition must follow national guidance.	Compliance with Pedoman Label Pangan Olahan and related additive/label provisions for formulated foods.	Evolving treatment of nano-enabled ingredients; clarity on disclosure and category-specific positive lists may be needed for novel encapsulates.
Australia & New Zealand	Food Standards Australia New Zealand (FSANZ) [202]	Non-traditional ingredients require pre-market assessment as Novel Food under Standards 1.1.1 & 1.5.1; additives follow separate schedules.	Approvals listed in the Code; encapsulated botanicals assessed when novelty or altered bioavailability is claimed.	Demonstrating history of use vs. novelty, and translating lab-scale encapsulation to exposure models for Code compliance.
Canada	Health Canada [203]	Use of additives via the Lists of Permitted Food Additives (incorporated by reference); Novel Foods guidance requires notification and safety assessment when composition/bioavailability is novel.	Posted summaries of completed novel-food safety assessments (Food Directorate).	Interface of encapsulation with "novelty" interpretation and exposure - case-by-case evidence often required.
China	National Health Commission (NHC) of the People's Republic of China [204]	"3 New Foods" regime: New food raw materials, new additives, and new food-related products (e.g., FCM) require NHC approval; official notices and catalogues published regularly.	Periodic announcements approving new raw materials/additives/FCMs (e.g., 2024 No. 2).	Navigating split frameworks (novel raw materials vs. health-food catalogues) and keeping pace with rolling approvals and GB standards.
Japan	Ministry of Health, Labour and Welfare (MHLW) of Japan [205]	Additives are limited to designated/existing lists; preparations/premixes governed by maximum use limits; encapsulated use must rely on permitted substances and functions.	Designated additives list and standards for use; existing natural flavourings out of scope.	Case-by-case confirmation for novel carriers or functions (e.g., antimicrobial release) beyond listed uses.

Region	Authority	Current Status	Approval Examples	Gaps/Challenges
Brazil	Agência Nacional de Vigilância Sanitária (ANVISA) of Brazil [206]	Updated framework: RDC 839/2023 for novel foods/ingredients (in force Mar 16, 2024) and consolidated additive lists via RDC 778/2023 + IN 211/2023; labeling and safety proof required.	Additive/processing-aid conditions of use consolidated; novel-food petitions per RDC 839/2023.	Transition to modernized procedures and public summaries; alignment of encapsulation/active-packaging claims with additive and FCM rules.

### Future perspectives

#### Advanced encapsulation approaches (nanocarriers, hybrid biopolymers and active-packaging integration)

Emerging systems aim to couple high payloads with programmed release, gastrointestinal targeting, and process robustness. Promising directions include zein-based nanocarriers for essential oils and phenolics, which enhance thermal stability and sustained activity in baked matrices; multilayered polyelectrolyte capsules (e.g., chitosan-alginate) that improve light/heat resilience of volatile antimicrobials; and hybrid polysaccharide-protein shells that balance barrier properties with clean-label appeal [207-209]. Active-packaging integrations - such as films embedding micro/nanoencapsulated botanicals or Pickering-emulsion reservoirs - enable controlled headspace release that suppresses mold while minimizing sensory impact [210]. At the nanoscale, responsive carriers tuned by pH, ionic strength, or enzymatic triggers can align release with food microenvironments or digestion phases [211].

#### Sustainability and circular bioeconomy considerations

Sustainable design prioritizes renewable wall materials (e.g., starches, pectins, chitosan from seafood by-streams), solvent-free or low-energy processes (e.g., spray-drying optimization, electro-hydrodynamic techniques), and end-of-life safety (biodegradability, minimal microplastic risk). Valorization of agricultural side streams to source both actives (polyphenols, terpenes) and carriers (hemicelluloses) aligns with circular-bioeconomy objectives and reduces scope-3 emissions. Life-cycle assessment should accompany technology selection to quantify trade-offs between shelf-life extension (reduced food waste) and processing footprints. Clean-label trajectories further motivate

carrier choices with simple names and low allergenicity while meeting functionality targets [212,213].

#### Research gaps and roadmap for industrial adoption

Despite encouraging results, reproducibility and scalability remain chokepoints. Priority research needs include: (i) Structure-function quantification linking carrier composition, interfacial architecture, and release kinetics to in-matrix efficacy and sensory outcomes; (ii) Process intensification to translate nanoemulsification, electrospraying, and layer-by-layer assembly into continuous, high-throughput lines with robust in-line quality controls for particle size distribution, loading, and residual solvents [213,214]; (iii) Stability models that couple moisture migration, temperature abuse, enzymatic activity, and matrix interactions to predict performance over distribution chains [215,209]; (iv) Human-relevant evidence - standardized digestion models and well-powered trials - to bridge *in vitro*/animal data with exposure-aligned endpoints, including bioavailability, microbiome interactions, and consumer acceptance; (v) Regulatory science for nano-enabled systems (tiered testing, migration/bioaccessibility methods, and harmonized labeling), developed with authorities to de-risk dossiers [200]. A practical roadmap for industry begins with design-to-spec: Define target microorganism/oxidation challenge, shelf-life goal, and sensory limits, then select carriers using decision matrices that include regulatory status, cost, viscosity/solids constraints, and allergen/ethical filters [216,217].

Next, deploy DoE-guided optimization (loading, wall ratios, process temperatures) and accelerated stress testing to map release and potency loss. Finally, integrate AI/ML models trained on formulation-process-performance datasets to recommend parameter windows

and flag failure modes, shortening development cycles [211]. Coupled with transparent safety dossiers and communication strategies, these steps can move encapsulated plant antimicrobials from promising prototypes to reliable, scalable, and consumer-trusted solutions.

## Conclusions

Encapsulated plant extracts represent credible and effective alternatives to synthetic preservatives in carbohydrate-based foods because they combine direct antimicrobial mechanisms, including microbial membrane disruption and reactive oxygen species generation, with the protective role of encapsulation that stabilizes labile phytochemicals during baking, extrusion, and storage. Unlike free extracts that often lose 30% - 50% of their activity under thermal or oxidative stress, encapsulated systems consistently preserve 60% - 90% of phenolics and maintain antioxidant capacity for extended periods. This distinction highlights their importance as clean-label solutions capable of maintaining microbial safety and oxidative stability without compromising consumer expectations.

Encapsulation technologies provide a viable strategy to replace conventional chemical preservatives by achieving high efficiencies between 70% and 95% and improving the stability, solubility, and bioavailability of plant-derived bioactives. Spray drying has been shown to offer scalability and cost-effectiveness, freeze drying ensures superior retention of thermo-sensitive compounds, and electrohydrodynamic methods deliver nano-scale carriers with controlled release. The unique contribution of this synthesis lies in demonstrating how wall materials such as maltodextrin, gum arabic, proteins, and chitosan interact with different techniques to optimize performance, thereby offering a framework for designing preservation systems tailored to carbohydrate-based foods.

Practical applications confirm that encapsulated extracts can match or even surpass the performance of synthetic preservatives such as calcium propionate or BHT by extending mold-free shelf life by 2 to 3 days, reducing lipid oxidation by 20% - 40%, and maintaining antioxidant capacity 15% - 40% better than free forms after processing. Although challenges remain with processing stability, sensory acceptance, and economic

feasibility, the integration of scalable encapsulation technologies with packaging innovations and compliance with regulatory frameworks demonstrates a clear pathway toward industrial adoption. Collectively, the evidence establishes encapsulated plant extracts as scientifically validated, sustainable, and consumer-preferred alternatives to synthetic preservatives in carbohydrate-rich foods.

## Acknowledgements

The authors would like to express their sincere gratitude to the National Research and Innovation Agency (BRIN) and the Indonesia Endowment Fund for Education (LPDP) of Indonesia for providing financial support and research facilities through the Decree of the Deputy for Research and Innovation Facilitation of the National Research and Innovation Agency Number 61/II.7/HK/2024 concerning Recipients of the Research and Innovation for Advanced Indonesia (RIIM) Program - Competitive Wave 7. This support has greatly contributed to the successful implementation of this research topic. The authors would also like to thank the Research Organization for Agriculture and Food (ORPP BRIN) for their material and immaterial support, as well as our partners from Institut Teknologi Sumatera (ITERA) and Universitas Gadjah Mada (UGM), Indonesia for their valuable collaboration.

## Declaration of generative AI in scientific writing

This manuscript has not employed any generative AI tools in the preparation of its scientific content. The authors confirm that all analyses, interpretations, and conclusions were performed independently by the authors. Generative AI tools were not used beyond the scope permitted by the journal (i.e., limited to potential minor language or readability improvements under full human oversight). The authors remain fully responsible for the integrity, accuracy, and originality of the work.

## CRediT author statement

All authors contributed equally to this review article. **B.P.P.** conceptualized the review scope and structure, conducted literature screening, led the manuscript writing, and served as the principal investigator responsible for securing and managing the funding. **B.W.H.** contributed to refining the review methodology and selection criteria, while **M.A.R.**

supported in compiling and synthesizing literature sources. **S.Y.** provided critical input for thematic analysis and manuscript refinement, and **A.R.K.** contributed to literature mapping and database organization. **B.W.K.W.** and **A.T.K.** were responsible for editing the draft, creating illustrations, and formatting the visual design of the article. **B.T.** contributed to academic supervision and provided insights during manuscript preparation. **L.L.** contributed to funding management, and supervision of the manuscript writing. **U.F.H.** and **Y.L.D.** assisted in reviewing and organizing the extracted data, while **R.G.S.** contributed to compiling tables and cross-checking references. **N.H.** supported coordination and administrative tasks, and **I.A.** critically reviewed the final manuscript and provided substantial revisions. All authors reviewed and approved the final version of the manuscript.

## References

- [1] A Cappelli and E Cini. Challenges and opportunities in wheat flour, pasta, bread, and bakery product production chains: A systematic review of innovations and improvement strategies to increase sustainability, productivity, and product quality. *Sustainability* 2021; **13(5)**, 2608.
- [2] A Cappelli, N Oliva and E Cini. A systematic review of gluten-free dough and bread: Dough rheology, bread characteristics, and improvement strategies. *Applied Sciences* 2020; **10(18)**, 6559.
- [3] C Axel, E Zannini and EK Arendt. Mold spoilage of bread and its biopreservation: A review of current strategies for bread shelf life extension. *Critical Reviews in Food Science and Nutrition* 2017; **57(16)**, 3528-3542.
- [4] A Vidal, V Sanchis, AJ Ramos and S Marín. Thermal stability and kinetics of degradation of deoxynivalenol, deoxynivalenol conjugates and ochratoxin A during baking of wheat bakery products. *Food Chemistry* 2015; **178**, 276-286.
- [5] L Wu and B Wang. Evaluation on levels and conversion profiles of DON, 3-ADON, and 15-ADON during bread making process. *Food Chemistry* 2015; **185**, 509-516.
- [6] KK Kuorwel, MJ Cran, K Sonneveld, J Miltz and SW Bigger. Essential oils and their principal constituents as antimicrobial agents for synthetic packaging films. *Journal of Food Science* 2011; **76(9)**, R164-R177.
- [7] IE Ismail, MR Farag, M Alagawany, HK Mahmoud and FM Reda. Efficacy of some feed additives to attenuate the hepato-renal damage induced by aflatoxin B1 in rabbits. *Journal of Animal Physiology and Animal Nutrition* 2020; **104(4)**, 1103-1110.
- [8] I Gutiérrez-del-Río, J Fernández and F Lombó. Plant nutraceuticals as antimicrobial agents in food preservation: Terpenoids, polyphenols and thiols. *International Journal of Antimicrobial Agents* 2018; **52(3)**, 309-315.
- [9] D Bogueva. *Consumer perceptions and food*. Springer Nature, Singapore, 2024.
- [10] NK Alqahtani, TM Alnemr and SA Ali. Effects of pomegranate peel extract and/or lactic acid as natural preservatives on physicochemical, microbiological properties, antioxidant activity, and storage stability of Khalal Barhi date fruits. *Foods* 2023; **12(6)**, 1160.
- [11] S Takwa, C Caleja, JCM Barreira, M Soković, L Achour, L Barros and ICFR Ferreira. *Arbutus unedo* L. and *Ocimum basilicum* L. as sources of natural preservatives for food industry: A case study using loaf bread. *LWT* 2018; **88**, 47-55.
- [12] CMB Pinilla, RCS Thys and A Brandelli. Antifungal properties of phosphatidylcholine-oleic acid liposomes encapsulating garlic against environmental fungal in wheat bread. *International Journal of Food Microbiology* 2019; **293**, 72-78.
- [13] Y Sahan. Effect of *Prunus laurocerasus* L. (Cherry Laurel) leaf extracts on growth of bread spoilage fungi. *Bulgarian Journal of Agricultural Science* 2011; **17(1)**, 83-92.
- [14] LM Fonseca, EJD Souza, M Radünz, EA Gandra, E da R Zavareze and ARG Dias. Suitability of starch/carvacrol nanofibers as biopreservatives for minimizing the fungal spoilage of bread. *Carbohydrate Polymers* 2021; **252**, 117166.
- [15] J Yi, H Huang, Y Liu, Y Lu, Y Fan and Y Zhang. Fabrication of curcumin-loaded pea protein-pectin ternary complex for the stabilization and delivery of  $\beta$ -carotene emulsions. *Food Chemistry* 2020; **313**, 126118.

- [16] S Wang, Y Lu, X Ouyang and J Ling. Fabrication of soy protein isolate/cellulose nanocrystal composite nanoparticles for curcumin delivery. *International Journal of Biological Macromolecules* 2020; **165**, 1468-1474.
- [17] European Food Safety Authority. Re-evaluation of propionic acid - propionates (E 280 - 283) as food additives. *EFSA Journal* 2014; **12(7)**, 3779.
- [18] European Food Safety Authority. Re-evaluation of sorbic acid (E 200), potassium sorbate (E 202) and calcium sorbate (E 203) as food additives. *EFSA Journal* 2015; **13(6)**, 4144.
- [19] European Food Safety Authority. Re-evaluation of benzoic acid (E 210), sodium benzoate (E 211), potassium benzoate (E 212) and calcium benzoate (E 213) as food additives. *EFSA Journal* 2016; **14(3)**, 4433.
- [20] Electronic Code of Federal Regulations. 21 CFR §184.1754 - sodium diacetate, Available at: <https://www.ecfr.gov/current/title-21/chapter-I/subchapter-B/part-184/subpart-B/section-184.1754>, accessed May 2025.
- [21] Electronic Code of Federal Regulations. 21 CFR §172.350 - Fumaric acid and salts, Available at: <https://www.ecfr.gov/current/title-21/chapter-I/subchapter-B/part-172/subpart-D/section-172.350>, accessed May 2025.
- [22] Danish Environmental Protection Agency. *Survey of parabens (LOUS 2012 - Final report No. 136)*. Danish Environmental Protection Agency, Odense, Denmark, 2013.
- [23] H Vally and NLA Misso. Adverse reactions to the sulphite additives. *Gastroenterology and Hepatology from Bed to Bench* 2012; **5(1)**, 16-23.
- [24] RB Yadav, B Singh Yadav, R Yadav, RB Yadav, M Aggarwal and BS Yadav. Studies on the effects of spice extracts on the quality characteristics and storage life of bread. *Journal of Agricultural Engineering and Food Technology* 2016; **3(2)**, 128-134.
- [25] N Ali, I Naz, S Ahmed, SA Mohsin, N Kanwal, H Fatima and S Hussain. Polarity-guided phytochemical extraction, polyphenolic characterization, and multimode biological evaluation of *Seriphidium kurramense* (Qazilb.) Y. R. Ling. *Arabian Journal of Chemistry* 2022; **15(9)**, 104114.
- [26] F Hu, XF Tu, K Thakur, F Hu, XL Li, YS Zhang, JG Zhang and ZJ Wei. Comparison of antifungal activity of essential oils from different plants against 3 fungi. *Food and Chemical Toxicology* 2019; **134**, 110821.
- [27] KP Devi, SA Nisha, R Sakthivel and SK Pandian. Eugenol (an essential oil of clove) acts as an antibacterial agent against *Salmonella typhi* by disrupting the cellular membrane. *Journal of Ethnopharmacology* 2010; **130(1)**, 107-115.
- [28] MI Umar, A Javeed, M Ashraf, A Riaz, MM Mukhtar, S Afzal and R Altaf. Polarity-based solvents extraction of *Opuntia dillenii* and *Zingiber officinale* for *in vitro* antimicrobial activities. *International Journal of Food Properties* 2013; **16(4)**, 808-820.
- [29] FD Gonelimali, J Lin, W Miao, J Xuan, F Charles, M Chen and SR Hatab. Antimicrobial properties and mechanism of action of some plant extracts against food pathogens and spoilage microorganisms. *Frontiers in Microbiology* 2018; **9**, 1639.
- [30] SAF El-nagerabi, AHM Ahmed and AE Elshafie. *In vitro* evaluation of selected plant extracts as biocontrol agents against black mold *Aspergillus niger* Van Tieghem of onion bulbs (*Allium cepa* L.). *International Journal of Current Microbiology and Applied Sciences* 2016; **5(9)**, 149-160.
- [31] M Kulkarni, V Hastak, V Jadhav and AA Date. Fenugreek leaf extract and its gel formulation show activity against *Malassezia furfur*. *Assay and Drug Development Technologies* 2020; **18(3)**, 149-156.
- [32] A Ali, XY Lim and PF Wahida. The fundamental study of antimicrobial activity of *Piper betle* extract in commercial toothpastes. *Journal of Herbal Medicine* 2018; **12**, 47-52.
- [33] A Hernández, S Ruiz-Moyano, AI Galván, AV Merchán, F Pérez Nevado, E Aranda, MJ Serradilla, M de G Córdoba and A Martín. Anti-fungal activity of phenolic sweet orange peel extract for controlling fungi responsible for post-harvest fruit decay. *Fungal Biology* 2021; **125(3)**, 223-230.

- [34] M Saeed, M Azam, T Ahmad, S Akhtar, M Hussain, S Nasir and QU Ain. Utilization of pomegranate peel extract as antifungal coating agent against *Fusarium oxysporum* on tomatoes. *Journal of Food Processing and Preservation* 2022; **46(10)**, e17157.
- [35] V Valková, H Ďúranová, L Galovičová, NL Vukovic, M Vukic, PŁ Kowalczewski and M Kačániová. Application of 3 types of cinnamon essential oils as natural antifungal preservatives in wheat bread. *Applied Sciences* 2022; **12(21)**, 10888.
- [36] P Chávez-Quintal, T González-Flores, I Rodríguez-Buenfil and S Gallegos-Tintoré. Antifungal activity in ethanolic extracts of *Carica papaya* L. cv. Maradol leaves and seeds. *Indian Journal of Microbiology* 2011; **51(4)**, 452-456.
- [37] KS de Lira Mota, F de Oliveira Pereira, WA de Oliveira, IO Lima and E de Oliveira Lima. Antifungal activity of *Thymus vulgaris* L. essential oil and its constituent phytochemicals against *Rhizopus oryzae*: Interaction with ergosterol. *Molecules* 2012; **17(12)**, 14418-14433.
- [38] AT Abdullah and KF Kadhim. GC/MS analysis and antifungal activity of *Matricaria chamomilla* extracts against molecularly identified keratinophilic fungi. *Health Biotechnology and Biopharma* 2024; **7(2)**, 62-70.
- [39] M Khadiri, H Boubaker, L Askarne, A Farhaoui, M Taoussi, LA Haddou, M Cherrate, W Ouchari, MH Zerrouk and M Sobeh. Exploration of the antifungal potential of aqueous extracts from 2 agave species against major postharvest diseases in apples. *Postharvest Biology and Technology* 2024; **214**, 112992.
- [40] W Chtioui, S Heleno, Q Migheli and P Rodrigues. Plant extracts as biocontrol agents against *Aspergillus carbonarius* growth and ochratoxin A production in grapes. *International Journal of Food Microbiology* 2023; **390**, 110425.
- [41] W Kurska, A Jamiólkowska, J Wyrstek and R Kowalski. Antifungal effect of plant extracts on the growth of the cereal pathogen *Fusarium* spp. - An *in vitro* study. *Agronomy* 2022; **12(12)**, 3204.
- [42] Aladag. Antifungal activity of green tea leaves (*Camellia sinensis* L.) sampled in different harvest time. *Pharmacognosy Magazine* 2009; **5(20)**, 344-348.
- [43] S Kocić-Tanackov, G Dimić, I Tanackov, D Pejin, L Mojović and J Pejin. The inhibitory effect of oregano extract on the growth of *Aspergillus* spp. and on sterigmatocystin biosynthesis. *LWT* 2012; **49(1)**, 14-20.
- [44] SI Behiry, NA Hamad, FO Alotibi, AA Al-Askar, AA Arishi, AM Kenawy, IA Elsamra, NH Youssef, MM Elsharkawy and A Abdelkhalek. Antifungal and antiaflatoxic activities of different plant extracts against *Aspergillus flavus*. *Sustainability* 2022; **14(19)**, 12908.
- [45] I Muzzalupo, G Badolati, A Chiappetta, N Picci and R Muzzalupo. *In vitro* antifungal activity of olive (*Olea europaea*) leaf extracts loaded in chitosan nanoparticles. *Frontiers in Bioengineering and Biotechnology* 2020; **8**, 151.
- [46] Z Jahanshiri, M Shams-Ghahfarokhi, A Allameh and M Razzaghi-Abyaneh. Effect of curcumin on *Aspergillus parasiticus* growth and expression of major genes involved in the early and late stages of aflatoxin biosynthesis. *Iranian Journal of Public Health* 2012; **41(6)**, 72-79.
- [47] CF Bezerra, JE Rocha, MK do Nascimento Silva, TS de Freitas, AK de Sousa, ATL dos Santos, RP da Cruz, MH Ferreira, JCP da Silva and AJT Machado. Analysis by UPLC-MS-QTOF and antifungal activity of guava (*Psidium guajava* L.). *Food and Chemical Toxicology* 2018; **119**, 453-463.
- [48] C Chen, L Long, F Zhang, Q Chen, C Chen, X Yu, Q Liu, J Bao and Z Long. Antifungal activity, main active components and mechanism of *Curcuma longa* extract against *Fusarium graminearum*. *PLoS One* 2018; **13(3)**, e0194284.
- [49] R Di Pasqua, G Betts, N Hoskins, M Edwards, D Ercolini and G Mauriello. Membrane toxicity of antimicrobial compounds from essential oils. *Journal of Agricultural and Food Chemistry* 2007; **55(12)**, 4863-4870.
- [50] K Brudzynski, K Abubaker and D Miotto. Unraveling a mechanism of honey antibacterial action: Polyphenol/H<sub>2</sub>O<sub>2</sub>-induced oxidative effect on bacterial cell growth and on DNA degradation. *Food Chemistry* 2012; **133(3)**, 329-336.

- [51] RK Ulrey, SM Barksdale, W Zhou and ML Van Hoek. Cranberry proanthocyanidins have anti-biofilm properties against *Pseudomonas aeruginosa*. *BMC Complementary and Alternative Medicine* 2014; **14**, 499.
- [52] P Alov, M Al Sharif, H Najdenski, T Pencheva, I Tsakovska, MM Zaharieva and I Pajeva. New potential pharmacological targets of plant-derived hydroxyanthraquinones from *Rubia* spp. *Molecules* 2022; **27(10)**, 3274.
- [53] K Brudzynski and L Maldonado-Alvarez. Polyphenol-protein complexes and their consequences for the redox activity, structure and function of honey. A current view and new hypothesis - A review. *Polish Journal of Food and Nutrition Sciences* 2015; **65(1)**, 5-17.
- [54] S Davidova, AS Galabov and G Satchanska. Antibacterial, antifungal, antiviral activity, and mechanisms of action of plant polyphenols. *Microorganisms* 2024; **12(12)**, 2502.
- [55] A Gomes and PJDA Sobral. Plant protein-based delivery systems: An emerging approach for increasing the efficacy of lipophilic bioactive compounds. *Molecules* 2022; **27(1)**, 55.
- [56] Y Xu, X Yan, H Zheng, J Li, X Wu, J Xu, Z Zhen and C Du. The application of encapsulation technology in the food industry: Classifications, recent advances, and perspectives. *Food Chemistry: X* 2024; **21**, 101240.
- [57] M Calderón-Oliver and E Ponce-Alquicira. The role of microencapsulation in food application. *Molecules* 2022; **27(5)**, 1499.
- [58] D Raharjo, D Praseptiangga, MZ Zaman and A Yunus. Chitosan and gum arabic as wall materials to encapsulate *Hopea beccariana* Burck stem bark extract into powder form by spray drying. *Bioresource Technology Reports* 2025; **30**, 102131.
- [59] J Baranauskaite, L Ivanauskas, R Masteikova, D Kopustinskiene, A Baranauskas and J Bernatoniene. Formulation and characterization of Turkish oregano microcapsules prepared by spray-drying technology. *Pharmaceutical Development and Technology* 2017; **22(6)**, 792-803.
- [60] M Ganje, S Saeed and M Reza. Physicochemical properties, microstructure, and encapsulation efficiency of rosemary (*Rosmarinus officinalis* L.) extract microencapsulated by freeze-drying using whey protein isolate and maltodextrin. *Carbohydrate Polymer Technologies and Applications* 2025; **10**, 100861.
- [61] S Chheng, M Fikry, S Jafari, DK Mishra and K Assatarakul. Storage stability and packaging impact on spray-dried encapsulated *Sesbania* flower extract during long-term storage. *Journal of Stored Products Research* 2025; **112**, 102660.
- [62] CI Piñón-Balderrama, C Leyva-Porras, Y Terán-Figueroa, V Espinosa-Solís, C Álvarez-Salas and MZ Saavedra-Leos. Encapsulation of active ingredients in food industry by spray-drying and nano spray-drying technologies. *Processes* 2020; **8(8)**, 889.
- [63] MIL Neves, S Desobry-Banon, IT Perrone, S Desobry and J Petit. Encapsulation of curcumin in milk powders by spray-drying: Physicochemistry, rehydration properties, and stability during storage. *Powder Technology* 2019; **345**, 342-350.
- [64] M Alam, S Sid, S Giri, R Das, A Kishore and N Kumar. Encapsulated kinnow peel powder using freeze drying: Effect of maltodextrin and gum arabic concentrations on physiochemical, functional and thermal properties. *Food and Humanity* 2025; **4(2)**, 100546.
- [65] A Akram, JS Murugan, K Barathikannan, SK Tammina, K Sridhar, M Keewan and F Banat. Pea protein-potato peel starch complex coacervation for the encapsulation of bioactive date seed extract: Bio-functional characterization and *in vitro* release. *International Journal of Biological Macromolecules* 2025; **310(P4)**, 143484.
- [66] H Rajabi and SMA Razavi. Co-encapsulation of saffron petal and *Stachys schtschegleevii* extracts via complex coacervation and graphene oxide-assisted spray drying for co-delivery and stability enhancement. *LWT* 2025; **223**, 117705.
- [67] HM Bayomy, DPT Blackmore, ES Alamri, NA Ozaybi, SE Almasoudi, S Pearson, L Eyouni, NA AlFaris, GM Alshammari, M Muhammed and MAM Hussein. Developing sustainable approach for controlling foodborne pathogens, based on *Chlorella vulgaris* extract/alginate nanoemulsion, and enhanced via the dispersed zinc oxide nanoparticles. *International Journal of Biological Macromolecules* 2025; **305(P2)**, 141241.

- [68] Y Ozogul, GT Karsli, M Durmuş, H Yazgan, HM Oztop, DJ McClements and F Ozogul. Recent developments in industrial applications of nanoemulsions. *Advances in Colloid and Interface Science* 2022; **304**, 102685.
- [69] N Aliabbasi, S Mehrabi, M Kheirandish, S Gashtasbi, M Mokhtarian, M Hosseini-Isfahani, A Vakilinezami, P Vakilinezami, T Mostaghim and H Rezaeinia. The novel nano-electrospray delivery of curcumin via ultrasound assisted *Balangu (Lallemantia royleana)* hydrocolloid-chickpea protein interaction. *Food Chemistry* 2025; **484**, 144388.
- [70] V Rivero-Buceta, L García-Fernández, C Campano, N Hernández-Herreros, MR Aguilar and MA Prieto. Design and synthesis of hollow particles based on bacterial cellulose and polyhydroxybutyrate for microbial entrapping using coaxial electrospray technology. *Carbohydrate Polymer Technologies and Applications* 2025; **10**, 100791.
- [71] F Sereti, M Alexandri, H Papapostolou, A Papadaki and N Kopsahelis. Recent progress in carotenoid encapsulation: Effects on storage stability, bioaccessibility and bioavailability for advanced innovative food applications. *Food Research International* 2025; **203**, 115861.
- [72] CAS Rabelo, N Taarji, N Khalid, I Kobayashi, M Nakajima and MA Neves. Formulation and characterization of water-in-oil nanoemulsions loaded with açai berry anthocyanins: Insights of degradation kinetics and stability evaluation of anthocyanins and nanoemulsions. *Food Research International* 2018; **107**, 418-426.
- [73] P Griep, LM da Silva, BP Tres, R Colet, A Junges, C Steffens, J Zeni and E Valduga. Effects of encapsulating agents and temperature in the microencapsulation of carotenogenic extracts from *Sporidiobolus salmonicolor* CBS 2636 and storage stability. *Biointerface Research in Applied Chemistry* 2023; **13(5)**, 449-462.
- [74] Q Guo, I Bayram, X Shu, J Su, W Liao, Y Wang and Y Gao. Improvement of stability and bioaccessibility of  $\beta$ -carotene by curcumin in pea protein isolate-based complexes-stabilized emulsions: Effect of protein complexation by pectin and small molecular surfactants. *Food Chemistry* 2022; **372**, 130726.
- [75] F Baghi, S Ghnimi, E Dumas and A Gharsallaoui. Microencapsulation of antimicrobial trans-cinnamaldehyde: Effect of emulsifier type, pH, and drying technique. *Applied Sciences* 2023; **13(10)**, 6184.
- [76] K Šavikin, N Nastić, T Janković, D Bigović, B Miličević, S Vidović, N Menković and J Vladić. Effect of type and concentration of carrier material on the encapsulation of pomegranate peel using spray drying method. *Foods* 2021; **10(9)**, 1876.
- [77] ME da Silva Júnior, MVRL Araújo, ACS Martins, M dos Santos Lima, FLH da Silva, A Converti and MIS Maciel. Microencapsulation by spray-drying and freeze-drying of extract of phenolic compounds obtained from ciriguela peel. *Scientific Reports* 2023; **13**, 40390.
- [78] JA Zokti, BS Baharin, AS Mohammed and F Abas. Green tea leaves extract: Microencapsulation, physicochemical and storage stability study. *Molecules* 2016; **21(8)**, 940.
- [79] KL Baltrusch, MD Torres and H Domínguez and N Flórez-Fernández. Spray-drying microencapsulation of tea extracts using green starch, alginate or carrageenan as carrier materials. *International Journal of Biological Macromolecules* 2022; **205**, 469-478.
- [80] TTA Tran and HVH Nguyen. Effects of spray-drying temperatures and carriers on physical and antioxidant properties of lemongrass leaf extract powder. *Beverages* 2018; **4(4)**, 80.
- [81] T Jović, I Elez Garofulić, P Čulina, S Pedisić, E Dobroslavić, E Cegledi, V Dragović-Uzelac and Z Zorić. The effect of spray-drying conditions on the characteristics of powdered *Pistacia lentiscus* leaf extract. *Processes* 2023; **11(4)**, 1229.
- [82] LS Kuck and CPZ Norena. Microencapsulation of grape (*Vitis labrusca* var. Bordo) skin phenolic extract using gum arabic, polydextrose, and partially hydrolyzed guar gum as encapsulating agents. *Food Chemistry* 2016; **194**, 569-576.
- [83] YRRS Rezende, JP Nogueira and N Narain. Microencapsulation of extracts of bioactive compounds obtained from acerola (*Malpighia emarginata* DC) pulp and residue by spray and freeze drying: Chemical, morphological and

- chemometric characterization. *Food Chemistry* 2018; **254**, 281-291.
- [84] MNG dos Santos, EP da Silva, HT Godoy, FA da Silva, SMC Celestino, L de O Pineli and C Damiani. Effect of freezing and atomization on bioactive compounds in cagait (*Eugenia dysenterica* DC) fruit. *Food Science and Technology* 2018; **38(3)**, 508-515.
- [85] Z Fang and B Bhandari. Encapsulation of polyphenols - A review. *Trends in Food Science and Technology* 2010; **21(10)**, 510-523.
- [86] DF Rocha-Parra, MC Lanari, MC Zamora and J Chirife. Influence of storage conditions on phenolic compounds stability, antioxidant capacity and colour of freeze-dried encapsulated red wine. *LWT* 2016; **70**, 162-170.
- [87] S Akhavan Mahdavi, SM Jafari, E Assadpoor and D Dehnad. Microencapsulation optimization of natural anthocyanins with maltodextrin, gum arabic and gelatin. *International Journal of Biological Macromolecules* 2016; **85**, 379-385.
- [88] RV Tonon, C Brabet and MD Hubinger. Anthocyanin stability and antioxidant activity of spray-dried açai (*Euterpe oleracea* Mart.) juice produced with different carrier agents. *Food Research International* 2010; **43(3)**, 907-914.
- [89] JM Mar, LS Silva, MS Rabelo, MP Muniz, SM Nunomura, RF Correa, VF Kinupp, PH Campelo, JA de Bezerra and EA Sanches. Encapsulation of Amazonian blueberry juices: Evaluation of bioactive compounds and stability. *LWT* 2020; **127**, 109152.
- [90] RVDB Fernandes, SV Borges and DA Botrel. Gum arabic/starch/maltodextrin/inulin as wall materials on the microencapsulation of rosemary essential oil. *Carbohydrate Polymers* 2014; **101**, 524-532.
- [91] EG Donhowe, FP Flores, WL Kerr, L Wicker and F Kong. Characterization and in vitro bioavailability of  $\beta$ -carotene: Effects of microencapsulation method and food matrix. *LWT* 2014; **57(1)**, 42-48.
- [92] M Cano-Chauca, PC Stringheta, AM Ramos and J Cal-Vidal. Effect of the carriers on the microstructure of mango powder obtained by spray drying and its functional characterization. *Innovative Food Science and Emerging Technologies* 2005; **6(4)**, 420-428.
- [93] M Ferrari, F Ravera, E De Angelis and L Navarini. Interfacial properties of coffee oils. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2010; **365(1-3)**, 79-85.
- [94] DRSF Paim, SDO Costa, EHM Walter and RV Tonon. Microencapsulation of probiotic jussara (*Euterpe edulis* M.) juice by spray drying. *LWT* 2016; **74**, 21-27.
- [95] J Guo, P Li, L Kong and B Xu. Microencapsulation of curcumin by spray drying and freeze drying. *LWT* 2020; **132**, 109892.
- [96] S Ersus and U Yurdagel. Microencapsulation of anthocyanin pigments of black carrot (*Daucus carota* L.) by spray drier. *Journal of Food Engineering* 2007; **80(3)**, 805-812.
- [97] E Zandona, M Vukelić, K Hanousek Čiča, A Zandona, J Mrvčić, M Katalinić, I Cindrić, A Abdurramani, IB Jurina and IB Zandona. Bioactive properties of the microwave-assisted olive leaf extract and its incorporation into a whey protein isolate coating of semi-hard cheese. *Foods* 2025; **14(9)**, 1496.
- [98] N Coşkun, S Sarıtaş, Y Jaouhari, M Bordiga and S Karav. The impact of freeze drying on bioactivity and physical properties of food products. *Applied Sciences* 2024; **14(20)**, 9317.
- [99] F Weinbreck, M Minor and CG De Kruif. Microencapsulation of oils using whey protein/gum arabic coacervates. *Journal of Microencapsulation* 2004; **21(6)**, 667-679.
- [100] S Liu, NH Low and MT Nickerson. Entrapment of flaxseed oil within gelatin-gum arabic capsules. *Journal of the American Oil Chemists' Society* 2010; **87(7)**, 809-815.
- [101] XY Qv, ZP Zeng and JG Jiang. Preparation of lutein microencapsulation by complex coacervation method and its physicochemical properties and stability. *Food Hydrocolloids* 2011; **25(1)**, 159-165.
- [102] CP Chang, TK Leung, SM Lin and CC Hsu. Release properties on gelatin-gum arabic microcapsules containing camphor oil with added polystyrene. *Colloids and Surfaces B: Biointerfaces* 2006; **50(2)**, 136-140.

- [103] LAC Zuanon, CR Malacrida and VRN Telis. Production of turmeric oleoresin microcapsules by complex coacervation with gelatin-gum arabic. *Journal of Food Process Engineering* 2013; **36(2)**, 154-161.
- [104] P Kaushik, K Dowling, S McKnight, CJ Barrow and B Adhikari. Microencapsulation of flaxseed oil in flaxseed protein and flaxseed gum complex coacervates. *Food Research International* 2016; **86**, 1-8.
- [105] D Dong, Z Qi, Y Hua, Y Chen, X Kong and C Zhang. Microencapsulation of flaxseed oil by soya proteins-gum arabic complex coacervation. *International Journal of Food Science and Technology* 2015; **50(7)**, 1635-1641.
- [106] A Habibi, J Keramat, M Hojjatoleslami and F Tamjidi. Preparation of fish oil microcapsules by complex coacervation of gelatin-gum arabic and their utilization for fortification of pomegranate juice. *Journal of Food Process Engineering* 2017; **40(2)**, e12385.
- [107] K Zhang, H Zhang, X Hu, S Bao and H Huang. Synthesis and release studies of microalgal oil-containing microcapsules prepared by complex coacervation. *Colloids and Surfaces B: Biointerfaces* 2012; **89**, 61-66.
- [108] F Amani, A Rezaei, MS Damavandi, AS Doost and SM Jafari. Colloidal carriers of almond gum/gelatin coacervates for rosemary essential oil: Characterization and *in-vitro* cytotoxicity. *Food Chemistry* 2022; **366**, 131998.
- [109] TA Comunian, D Freitas, G Drouin, A Maudhuit, G Roelens, D Poncelet, S Drusch and A Brodkorb. Microencapsulation of flaxseed oil in pea protein-gum arabic complex coacervates delays lipid digestion in liquid yoghurt. *Food Research International* 2024; **187**, 114307.
- [110] M Yang, J Peng, Y Zi, C Shi, G Kan, X Wang and J Zhong. Encapsulation of fish oil by complex coacervation and freeze drying with modified starch aid. *Food Hydrocolloids* 2023; **136**, 108371.
- [111] SA Khatibi, A Ehsani, M Nemati and A Javadi. Microencapsulation of *Zataria multiflora* Boiss. essential oil by complex coacervation using gelatin and gum arabic: Characterization, release profile, antimicrobial and antioxidant activities. *Journal of Food Processing and Preservation* 2021; **45(10)**, e15823.
- [112] J Sun, Y Cheng, T Zhang and J Zang. Microencapsulation of carvacrol by complex coacervation of walnut meal protein isolate and gum arabic: Preparation, characterization and bio-functional activity. *Foods* 2022; **11(21)**, 3382.
- [113] Z Dong, S Zhao, L Sun and J Li. Preparation of CMC/gum arabic/gelatin microcapsules encapsulating orange oil by complex coacervation. *Journal of Chinese Institute of Food Science and Technology* 2013; **13(1)**, 73-80.
- [114] A Bušić, D Komes, A Belščak-Cvitanovic, IV Cebin, I Špoljarić, G Mršić and S Miao. The potential of combined emulsification and spray drying techniques for encapsulation of polyphenols from rosemary (*Rosmarinus officinalis* L.) leaves. *Food Technology and Biotechnology* 2018; **56(4)**, 470-478.
- [115] R Berendsen, C Güell and M Ferrando. Spray dried double emulsions containing procyanidin-rich extracts produced by premix membrane emulsification: Effect of interfacial composition. *Food Chemistry* 2015; **175**, 471-478.
- [116] DA Sebben, SV Macwilliams, L Yu, PT Spicer, V Bulone, M Krasowska and DA Beattie. Influence of aqueous phase composition on double emulsion stability and colour retention of encapsulated anthocyanins. *Foods* 2022; **11(1)**, 36.
- [117] P Koirala, J Sriprabhom and T Winuprasith. Anthocyanin-rich butterfly pea petal extract loaded double Pickering emulsion containing nanocrystalline cellulose: Physicochemical properties, stability, and rheology. *Foods* 2023; **12(22)**, 4173.
- [118] BE Ozcan, O Saroglu, CY Karakas and A Karadag. Encapsulation of purple basil leaf extract by electrospraying in double emulsion (W/O/W) filled alginate-carrageenan beads to improve the bioaccessibility of anthocyanins. *International Journal of Biological Macromolecules* 2023; **244**, 126207.
- [119] LG Teixeira, S Rezende, A Fernandes, IP Fernandes, L Barros, JCM Barreira, FV Leimann, ICFR Ferreira and MF Barreiro. Water-in-oil-in-water double emulsions as protective carriers for

- Sambucus nigra* L. coloring systems. *Molecules* 2022; **27(2)**, 552.
- [120] J Liu, Y Tan, H Zhou, JL Muriel Mundo and DJ McClements. Protection of anthocyanin-rich extract from pH-induced color changes using water-in-oil-in-water emulsions. *Journal of Food Engineering* 2019; **263**, 1-9.
- [121] K Frank, E Walz, V Gräf, R Greiner, K Köhler and HP Schuchmann. Stability of anthocyanin-rich W/O/W emulsions designed for intestinal release in gastrointestinal environment. *Journal of Food Science* 2012; **77(1)**, N46-N53.
- [122] L Gracher-Teixeira, SCS Pituco, G Colucci, A Santamaria-Echart, AM Peres, MM Dias and MF Barreiro. Developing high-coloring natural systems using double emulsions with *Daucus carota* L. extract to meet high-performance requirements. *Foods* 2024; **13(24)**, 4177.
- [123] LB Norcino, JF Mendes, JA de Figueiredo, NL Oliveira, DA Botrel and LHC Mattoso. Development of alginate/pectin microcapsules by a dual process combining emulsification and ultrasonic gelation for encapsulation and controlled release of anthocyanins from grapes (*Vitis labrusca* L.). *Food Chemistry* 2022; **372**, 133256.
- [124] K Toledo-Madrid, T Gallardo-Velázquez and G Osorio-Revilla. Microencapsulation of purple cactus pear fruit (*Opuntia ficus indica*) extract by the combined method W/O/W double emulsion-spray drying and conventional spray drying: A comparative study. *Processes* 2018; **6(10)**, 182.
- [125] A de Jesús Cenobio-Galindo, G Díaz-Monroy, M Medina-Pérez, M Jesús Franco-Fernández, FE Ludeña-Urquizo, R Vieyra-Alberto and RG Campos-Montiel. Multiple emulsions with extracts of cactus pear added in a yogurt: Antioxidant activity, *in vitro* simulated digestion and shelf life. *Foods* 2019; **8(10)**, 429.
- [126] YT Dang, H Tran and TC Kha. Encapsulation of W/O/W acerola emulsion by spray drying: Optimization, release kinetics, and storage stability. *Foods* 2024; **13(10)**, 1483.
- [127] N Kanha, JM Regenstein, S Surawang, P Pitchakarn and T Laokuldilok. Properties and kinetics of the *in vitro* release of anthocyanin-rich microcapsules produced through spray and freeze-drying complex coacervated double emulsions. *Food Chemistry* 2021; **341**, 127950.
- [128] BSB Bamba, J Shi, CC Tranchant, SJ Xue, CF Forney, LT Lim, W Xu and G Xu. Coencapsulation of polyphenols and anthocyanins from blueberry pomace by double emulsion stabilized by whey proteins: Effect of homogenization parameters. *Molecules* 2018; **23(10)**, 2588.
- [129] R Pérez-Masiá, R López-Nicolás, MJ Periago, G Ros, JM Lagaron and A López-Rubio. Encapsulation of folic acid in food hydrocolloids through nanospray drying and electrospraying for nutraceutical applications. *Food Chemistry* 2015; **168**, 124-133.
- [130] LG Gómez-Mascaraque and A López-Rubio. Protein-based emulsion electrosprayed micro- and submicroparticles for the encapsulation and stabilization of thermosensitive hydrophobic bioactives. *Journal of Colloid and Interface Science* 2016; **465**, 259-270.
- [131] L Phuong Ta, E Bujna, S Kun, D Charalampopoulos and VV Khutoryanskiy. Electrosprayed mucoadhesive alginate-chitosan microcapsules for gastrointestinal delivery of probiotics. *International Journal of Pharmaceutics* 2021; **597**, 120342.
- [132] M Soleimanifar, SM Jafari, E Assadpour and A Mirarab. Electrosprayed whey protein nanocarriers containing natural phenolics: Thermal and antioxidant properties, release behavior and stability. *Journal of Food Engineering* 2021; **292**, 110644.
- [133] JA Tapia-Hernández, CL Del-Toro-Sánchez, FJ Cinco-Moroyoqui, S Ruiz-Cruz, J Juárez, DD Castro-Enríquez, CG Barreras-Urbina, GA López-Ahumada and F Rodríguez-Félix. Gallic acid-loaded zein nanoparticles by electrospraying process. *Journal of Food Science* 2019; **84(5)**, 818-829.
- [134] F Rodríguez-Félix, CL Del-Toro-Sánchez, FJ Cinco-Moroyoqui, J Juárez, GA López-Ahumada, E Carvajal-Millan, DD Castro-Enríquez, CG Barreras-Urbina and JA Tapia-Hernández. Preparation and characterization of quercetin-loaded zein nanoparticles by electrospraying and

- study of *in vitro* bioavailability. *Journal of Food Science* 2019; **84(8)**, 2341-2351.
- [135] J He, Z Wang, L Wei, Y Ye, ZU Din, J Zhou, X Cong, S Cheng and J Cai. Electro-spray-assisted fabrication of dextran-whey protein isolation microcapsules for the encapsulation of selenium-enriched peptide. *Foods* 2023; **12(5)**, 1008.
- [136] S Rahbari, H Tavakolipour and A Kalbasi-Ashtari. Application of electro-spraying technique and mathematical modelling for nanoencapsulation of curcumin. *Heliyon* 2024; **10(1)**, e25680.
- [137] NE Rahmani-Manglano, EM Guadix, C Jacobsen and PJ García-Moreno. Comparative study on the oxidative stability of encapsulated fish oil by monoaxial or coaxial electro-spraying and spray-drying. *Antioxidants* 2023; **12(2)**, 266.
- [138] P Paximada, E Kanavou, E Apostolidis and IG Mandala. Encapsulation of catechin in electro-sprayed food-grade particles. *Food Hydrocolloids for Health* 2021; **1**, 100021.
- [139] H Jayan, MM Maria Leena, SK Sivakama Sundari, JA Moses and C Anandharamkrishnan. Improvement of bioavailability for resveratrol through encapsulation in zein using electro-spraying technique. *Journal of Functional Foods* 2019; **57**, 157-166.
- [140] N Fani, MH Enayati, H Rostamabadi and SR Falsafi. Encapsulation of bioactives within electro-sprayed  $\kappa$ -carrageenan nanoparticles. *Carbohydrate Polymers* 2022; **291**, 119761.
- [141] JL Guía-García, AV Charles-Rodríguez, P Silva, A Robledo-Olivo, MA Cerqueira and ML Flores-López. Electro-sprayed hydroxypropyl methylcellulose microcapsules containing *Rhus microphylla* fruit extracts and their application in strawberry (*Fragaria × ananassa*) preservation. *LWT* 2023; **186**, 115048.
- [142] M Panagiotopoulou, S Papadaki and M Krokida. Formation and characterization of zein electro-sprayed nanoparticles containing bioactive compounds. *South African Journal of Chemical Engineering* 2022; **39**, 117-124.
- [143] CE Figueroa-Enriquez, F Rodríguez-Félix, M Plascencia-Jatomea, A Sánchez-Escalante, JM Vargas-López, JA Tapia-Hernández, DF Canizales-Rodríguez, DD Castro-Enriquez, S Ruiz-Cruz and I Santos-Sauceda. Nanoparticles of betalain–gelatin with antioxidant properties by coaxial electro-spraying: Preparation and characterization. *ACS Omega* 2023; **8(41)**, 37924-37935.
- [144] L Feng Li, X Shi, SM Qi, XT Zhang, HY Fung, QR Li and QB Han. Strategies, techniques and applications for food authentication based on carbohydrates: A review. *Carbohydrate Polymers* 2024; **344**, 122533.
- [145] F Islam, F Saeed, A Imran, U Shehzadi, R Ali, F Nosheen, A Chauhan, A Asghar, M Ojukwu and A Asghar. Bio-preservatives and essential oils as an alternative to chemical preservatives in the baking industry: A concurrent review. *Journal of Food Science and Technology* 2024; **61(9)**, 4493-4506.
- [146] Fİ Şahin and N Acaralı. Extending shelf life and optimizing effective parameters by using clove oil (*Syzygium aromaticum* oleum)/orange oil (*Citrus aurantium* var. *dulcis* oleum) in bread: Thermal, morphological and sensory approach. *Journal of Food Science and Technology* 2023; **60(10)**, 3055-3067.
- [147] T Bojňanská, A Kolesárová, M Čech, D Tančinová and D Urminská. Extracts with nutritional potential and their influence on the rheological properties of dough and quality parameters of bread. *Foods* 2024; **13(3)**, 82.
- [148] YH Chang, CM Chang and PT Chuang. Shelf-life assessment of bread partially substituted with soy protein isolate. *Applied Sciences* 2023; **13(6)**, 3960.
- [149] NA Esaulko, ES Romanenko, MV Selivanova, EA Mironova, TS Aisanov, VE Miltusov and MS German. Quality improvement and shelf life extension of functional bakery products with the use of stevia. *IOP Conference Series: Earth and Environmental Science* 2019; **315(2)**, 022019.
- [150] ND Qumbisa, NZ Ngobese, U Kolanisi, M Siwela and GF Cynthia. Effect of *Amaranthus* leaf powder addition on the nutritional composition, physical quality and consumer acceptability of instant noodles. *South African Journal of Botany* 2022; **146**, 499-506.
- [151] F Shahabinejad, M Ghorbani, S Abbaszadeh, M Nejatian and M Taghdir. Functional instant noodle formulation for emergency conditions: Sensory

- and stability characteristics. *Food Science and Nutrition* 2024; **12(7)**, 4605-4614.
- [152] X Li, Z Xu, X Xu, K Zheng, S Pan, JM Regenstein, H Wang and L Wang. Carbohydrate-based fat mimetics: A focus on fat-mimicking mechanisms and a tribology perspective. *Trends in Food Science and Technology* 2025; **157**, 104885.
- [153] DJ McClements. *Food emulsions: Principles, practices, and techniques*. 3<sup>rd</sup> ed. CRC Press, Boca Raton, United States, 2015.
- [154] ME da Silva Júnior, MVRL Araújo, ACS Martins, M dos Santos Lima, FLH Da Silva, A Converti and MIS Maciel. Microencapsulation by spray-drying and freeze-drying of extract of ciriguela peel. *Food Chemistry Advances* 2023; **2**, 100151.
- [155] SC Lourenço, M Moldão-Martins and VD Alves. Microencapsulation of pineapple peel extract by spray drying using maltodextrin, inulin, and arabic gum as wall matrices. *Foods* 2020; **9(6)**, 718.
- [156] D Escobar-Avello, C Mardones, G Montenegro, D von Baer, J Luengo, RM Lamuela-Raventós, A Vallverdú-Queralt and C Gómez-Gaete. Encapsulation of phenolic compounds from a grape cane pilot-plant extract in hydroxypropyl beta-cyclodextrin and maltodextrin by spray drying. *Antioxidants* 2021; **10(11)**, 1823.
- [157] W Medfai, I Oueslati, E Dumas, Z Harzalli, C Viton, R Mhamdi and A Gharsallaoui. Physicochemical and biological characterization of encapsulated olive leaf extracts for food preservation. *Antibiotics* 2023; **12(6)**, 987.
- [158] H Pashazadeh, O Zannou, M Ghellam, I Koca, CM Galanakis and TMS Aldawoud. Optimization and encapsulation of phenolic compounds extracted from maize waste by freeze-drying, spray-drying, and microwave-drying using maltodextrin. *Foods* 2021; **10(6)**, 1396.
- [159] RT Rigon and CPZ Norena. Microencapsulation by spray-drying of bioactive compounds extracted from blackberry. *Journal of Food Science and Technology* 2016; **53(1)**, 151-160.
- [160] C Castro-López, C Espinoza-González, R Ramos-González, VD Boone-Villa, MA Aguilar-González, GCG Martínez-Ávila, CN Aguilar and JM Ventura-Sobrevilla. Spray-drying encapsulation of microwave-assisted extracted polyphenols from *Moringa oleifera*: Influence of tragacanth, locust bean, and carboxymethyl-cellulose formulations. *Food Research International* 2021; **144**, 110291.
- [161] K Yadav, RK Bajaj, S Mandal and B Mann. Encapsulation of grape seed extract phenolics using whey protein concentrate, maltodextrin and gum arabic blends. *Journal of Food Science and Technology* 2020; **57(2)**, 426-434.
- [162] E Cegledi, I Elez Garofulić, Z Zorić, M Roje and V Dragović-Uzelac. Effect of spray drying encapsulation on nettle leaf extract powder properties, polyphenols and their bioavailability. *Foods* 2022; **11(18)**, 2852.
- [163] LM de MC Ferreira, RR Pereira, FB Carvalho-Guimarães, MSN Remígio et al. Microencapsulation by spray drying and antioxidant activity of phenolic compounds from tucuma coproduct (*Astrocaryum vulgare* Mart.) almonds. *Polymers* 2022; **14(14)**, 2905.
- [164] M Galante, F Blando, M Guerra, L Milella, WLR Barbosa, RM Ribeiro-Costa and JOC Silva-Júnior. Microencapsulation by spray drying of yerba mate extract in  $\beta$ -cyclodextrin: Influence of particle morphology on microcapsules functional and physicochemical properties. *Food Research International* 2025; **174**, 117237.
- [165] SSDOS SANTOS, CM Paraíso, SCDA Costa, CYL Ogawa, F Sato and GS Madrona. Recovery of bioactive compounds from an agro-industrial waste: Extraction, microencapsulation, and characterization of jaboticaba (*Myrciaria cauliflora* Berg) pomace as a source of antioxidant. *Anais da Academia Brasileira de Ciências* 2022; **94(4)**, e20191372.
- [166] C López de Dicastillo, C Piña, L Garrido, C Arancibia and MJ Galotto. Enhancing thermal stability and bioaccessibility of açai fruit polyphenols through electrohydrodynamic encapsulation into zein electrosprayed particles. *Antioxidants* 2019; **8(10)**, 464.
- [167] PN Ezhilarasi, D Indrani, BS Jena and C Anandharamkrishnan. Microencapsulation of *Garcinia* fruit extract by spray drying using different wall materials: Physicochemical and release characteristics in staged simulated gastrointestinal conditions. *Journal of the Science of Food and Agriculture* 2014; **94(7)**, 1482-1490.

- [168] D Pasrija, PN Ezhilarasi, D Indrani and C Anandharamakrishnan. Microencapsulation of green tea polyphenols and its effect on incorporated bread quality. *LWT* 2015; **64(1)**, 289-296.
- [169] A Czubaszek, A Czaja, A Sokół-Lętkowska, J Kolniak-Ostek and AZ Kucharska. Changes in antioxidant properties and amounts of bioactive compounds from Saskatoon berry in wheat bread enriched with fruit microcapsules during *in vitro* digestion. *Molecules* 2021; **26(20)**, 6292.
- [170] S Lachowicz, M Świeca and E Pejcz. Biological activity, phytochemical parameters, and potential bioaccessibility of wheat bread enriched with powder and microcapsules made from Saskatoon berry. *Food Chemistry* 2021; **338**, 128026.
- [171] W Bińkowska, A Szpicer, A Stelmasiak, I Wojtasik-Kalinowska and A Półtorak. Utilization of microencapsulated polyphenols to enhance the bioactive compound content in whole grain bread: Recipe optimization. *Applied Sciences* 2024; **14(22)**, 10156.
- [172] SH Peighambardoust, A Akbarmehr and K Sarabandi. Exploring the physicochemical and functional properties of stabilized corn pollen protein hydrolysates via spray-drying for application in bread formulation. *Journal of Agriculture and Food Research* 2025; **21**, 101918.
- [173] G Davidov-Pardo, A Álvarez, E Saldanha, I Mignani, DJ McClements and O de Paredes López. Sensory and consumer perception of the addition of grape seed extracts in cookies. *Journal of Food Science* 2012; **77(12)**, S430-S438.
- [174] M Paciulli, M Grimaldi, M Rinaldi, A Cavazza, F Flammini, C Di Mattia, M Gennari and E Chiavaro. Microencapsulated olive leaf extract enhances physicochemical stability of biscuits. *Future Foods* 2023; **7**, 100209.
- [175] C Ciont, G Difonzo, A Pasqualone, MS Chis, F Ranga, K Szabo, E Simon, A Naghiu, L Barbu-Tudoran, F Caponio, OL Pop and DC Vodnar. Phenolic profile of micro- and nano-encapsulated olive leaf extract in biscuits during *in vitro* gastrointestinal digestion. *Food Chemistry* 2023; **428**, 136778.
- [176] V Tumbas Šaponjac, G Četković, J Čanadanović-Brunet, B Pajin, S Djilas, J Petrović, I Lončarević, S Stajčić and J Vulić. Sour cherry pomace extract encapsulated in whey and soy proteins: Incorporation in cookies. *Food Chemistry* 2016; **207**, 27-33.
- [177] D Pędziwiatr, MC Lamadrid and A Wojdyło. Cookies fortified with polyphenols extracts: Impact on phenolic content, antioxidant activity, inhibition of  $\alpha$ -amylase and  $\alpha$ -glucosidase enzyme, colour and sensory attractiveness. *Antioxidants* 2024; **13(9)**, 1108.
- [178] R Dordoni, G Duserm Garrido, L Marinoni, M Torri, M Di Mattia and G Spigno. Enrichment of whole wheat cocoa biscuits with encapsulated grape skin extract. *International Journal of Food Science* 2019; **2019**, 1269340.
- [179] R Dordoni, A Bassani, C Rossetti, GD Garrido, A Frustace and G Spigno. Encapsulated walnut paste with grape skin extract addition: Oxidative stability and use in biscuits. *Chemical Engineering Transactions* 2021; **87**, 73-78.
- [180] JM Lee, HK Kwak, SH Lee, EY Kim, HA Kim and JH Kim. Value-added crackers enriched with red onion skin (*Allium cepa* L.) anthocyanin microcapsules. *Processes* 2021; **9(7)**, 1122.
- [181] EM Elsebaie and RY Essa. Microencapsulation of red onion peel polyphenols fractions by freeze drying technicality and its application in cake. *Journal of Food Processing and Preservation* 2018; **42(1)**, e13654.
- [182] TTN Nhung, NTB Chau, LTM Hien, VTH Linh, NL Ha and DTA Dong. Characteristics of sponge cake preserved by green tea extract powder. *Journal of Food Processing and Preservation* 2022; **46(9)**, e16939.
- [183] M Zamankhani, S Mocini, PM Shotorbani, HM Ghazi and A Jafarpour. Improvement of the oxidative stability of instant fried noodles using free and microencapsulated borage (*Echium amoenum*) and black hollyhock (*Althaea rosea* var. *nigra*) extracts. *Food Science & Nutrition* 2024; **12(8)**, 508-525.
- [184] Y Xu, X Yan, H Zheng, J Li, X Wu, J Xu, Z Zhen and C Du. The application of encapsulation technology in the food industry: Classifications, recent advances, and perspectives. *Food Chemistry: X* 2024; **21**, 101240.

- [185] V Conti, C Piccini, M Romi, P Salusti, G Cai and C Cantini. Pasta enriched with carrot and olive leaf flour retains high levels of accessible bioactives after *in vitro* digestion. *Foods* 2023; **12**(19), 3540.
- [186] G Natrella, M Miccolis, GR Caponio, A Di Michele, L Zago, C Di Mattia and G Difonzo. Physicochemical and nutritional properties of functional fresh pasta with free and microencapsulated olive pomace extract. *Food Frontiers* 2025; **6**(4), 2035-2051.
- [187] EM Elsebaie, A Elkelawy, A Abdallah, R Ahmed, M Aboelnaga, S Hafez, MM El-Desoky, A Ali, MA El-Magd and S Abdel-Gawad. Technological and sensory aspects of macaroni with free and encapsulated fenugreek aerial parts extract. *Foods* 2022; **11**(3), 384.
- [188] HA No, MY Ryu, Y Choi, SM Yoon, SH Lee, HJ Park, JH Lee, JH Lee and JM Park. Preparation of functional rice cake by using  $\beta$ -carotene-encapsulated emulsion powder. *Journal of Food Science and Technology* 2020; **57**(10), 3449-3458.
- [189] M López-Astorga, M Leon-Bejarano, N Gámez-Meza, CL Del Toro-Sánchez, S Simsek and M Ovando-Martínez. Microencapsulated grape pomace extract as an antioxidant ingredient added to Greek-style yogurt: Storage stability and *in vitro* bioaccessibility. *Food Chemistry* 2025; **477**, 143550.
- [190] V Kuchtová, Z Kohajdová, J Karovičová and M Lauková. Physical, textural and sensory properties of cookies incorporated with grape skin and seed preparations. *Polish Journal of Food and Nutrition Sciences* 2018; **68**(4), 309-317.
- [191] MV Vieira, SM Oliveira, IR Amado, LH Fasolin, AA Vicente, LM Pastrana and P Fuciños. 3D printed functional cookies fortified with *Arthrospira platensis*: Evaluation of its antioxidant potential and physical-chemical characterization. *Food Hydrocolloids* 2020; **107**, 105893.
- [192] M Grassia, MC Messia, E Marconi, OS Demirkol, F Erdoğdu, F Sarghini, L Cinquanta and D Corona. Microencapsulation of phenolic extracts from cocoa shells to enrich chocolate bars. *Plant Foods for Human Nutrition* 2021; **76**(4), 449-457.
- [193] M Krzywonos, G Difonzo and A Pasqualone. Challenges and technological requirements in agri-food waste upcycling: The case study of olive leaf extract. *Future Foods* 2025; **11**, 100547.
- [194] B Samakar, AS Tajani, BS Fazly Bazzaz and V Soheili. Fortified bread with encapsulated ingredients: Impacts and potential applications. *Journal of the Science of Food and Agriculture* 2024; **104**(6), 2811-2823.
- [195] M Tayefe, LF Fadaye Eshkiki, Z Rahbar Dalir, AN Masoule and A Rahimi. Optimization of green tea extract, rosemary extract, and rice bran in multifunctional bread: A concept for reduction of acrylamide and phytic acid. *Heliyon* 2025; **11**(1), e41182.
- [196] US Food and Drug Administration. *Packaging & food contact substances (FCS)*. FDA, Maryland, United States, 2024.
- [197] European Food Safety Authority. *Novel food & traditional food applications*. European Food Safety Authority, Parma, Italy, 2023.
- [198] Codex Alimentarius Commission. *General Standard for Food Additives (GSFA) online database*. Codex Alimentarius, Rome, Italy 2023.
- [199] Badan Pengawas Obat dan Makanan (BPOM). *Pedoman label pangan olahan*. BPOM RI, Jakarta, Indonesia, 2020.
- [200] H Onyeaka, P Passaretti, T Miri and ZT Al-Sharify. The safety of nanomaterials in food production and packaging. *Current Research in Food Science* 2022; **5**, 763-774.
- [201] C Alae-Carew, R Green, C Stewart, B Cook, AD Dangour and PFD Scheelbeek. The role of plant-based alternative foods in sustainable and healthy food systems: Consumption trends in the UK. *Science of the Total Environment* 2022; **807**, 151041.
- [202] US Food Standards Australia New Zealand (FSANZ). *Novel foods*, Available at <https://www.foodstandards.gov.au/business/novel>, accessed May 2025.
- [203] Health Canada. *Lists of permitted food additives*. Health Canada, Ottawa, Canada, 2017.
- [204] National Health Commission of the People's Republic of China (NHC). *Laws & policies overview*. NHC, Beijing, China, 2024.
- [205] Ministry of Health, Labour and Welfare (Japan). *Food additives - Designated and existing*

- additives*. Ministry of Health, Labour and Welfare, Tokyo, Japan, 2024.
- [206] Agência Nacional de Vigilância Sanitária (ANVISA). *Resolução RDC no 778/2023 - Aditivos e coadjuvantes de tecnologia*. ANVISA, Brasília, Brazil, 2023.
- [207] AFR Silva, M Monteiro, R Nunes, A Baião, SS Braga, B Sarmiento, MA Coimbra, AMS Silva and SM Cardoso. Bread enriched with resveratrol: Influence of the delivery vehicles on its bioactivity. *Food Bioscience* 2022; **49**, 101887.
- [208] Y Zhang, H Ning, J Xu and L Lu. Layer-by-layer assembly of modified halloysite nanotube using chitosan and sodium alginate to control the release of carvacrol and improve its stability. *International Journal of Biological Macromolecules* 2024; **282**, 137091.
- [209] J He, G Goksen, X Cong, MR Khan, N Ahmad and W Zhang. Development and characterization of zein co-encapsulated wampee essential oil and propolis extract films for food preservation. *Food Control* 2025; **168**, 110855.
- [210] H Fasihi, N Noshirvani and M Hashemi. Novel bioactive films integrated with Pickering emulsion of ginger essential oil for food packaging application. *Food Bioscience* 2023; **51**, 102269.
- [211] F Khodadadi, M Nikzad and S Hamedi. Lignin nanoparticles as a promising nanomaterial for encapsulation of *Rosa damascena* essential oil: Physicochemical, structural, antimicrobial and *in vitro* release properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2024; **687**, 133580.
- [212] A Rehman Sheikh, RA Wu-Chen, A Matloob, MH Mahmood and M Javed. Nanoencapsulation of volatile plant essential oils: A paradigm shift in food industry practices. *Food Innovation and Advances* 2024; **3(3)**, 305-319.
- [213] M Yang, H Chao, Z Hou, L Wang, W Xu and X Zhao. Antimicrobial activity of octyl gallate nanoemulsion combined with photodynamic technology and its effect on food preservation. *International Journal of Food Microbiology* 2025; **429**, 111023.
- [214] Y Zhang, C Liu, Y Lin, H Wu, Y Lin, F Zhao and S Han. Development of food-grade xylanase encapsulation using electrospray dextran microparticles. *Food Hydrocolloids* 2024; **150**, 109716.
- [215] W Bińkowska, A Szpicier, I Wojtasik-Kalinowska and A Półtorak. Innovative methods of encapsulation and enrichment of cereal-based pasta products with biofunctional compounds. *Applied Sciences* 2024; **14(4)**, 1871.
- [216] SM Jafari, A Elham, H Yinghe and B Bhandari. Encapsulation efficiency of food flavours and oils during spray drying. *Drying Technology* 2008; **26(7)**, 816-835.
- [217] F Yu, Z Li, T Zhang, Y Wei, Y Xue and C Xue. Influence of encapsulation techniques on the structure, physical properties, and thermal stability of fish oil microcapsules by spray drying. *Journal of Food Process Engineering* 2017; **40(6)**, e12576.