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Review

Innovative Microencapsulation Techniques of Bioactive Compounds: Impact on Physicochemical and Sensory Properties of Food Products and Industrial Applications

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Abstract

The incorporation of bioactive compounds into food products represents a promising approach to enhance their functional and health-promoting properties. However, many bioactive compounds, such as polyphenols, essential oils, carotenoids, and omega-3 fatty acids, are highly sensitive to environmental factors, including temperature, oxygen, and light, which limits their direct application in the food industry. Microencapsulation has emerged as an innovative strategy to overcome these challenges by protecting bioactive compounds, improving their stability, controlling their release, and masking undesirable flavors or odors. This article reviews recent advances in microencapsulation techniques, including spray-drying, freeze-drying, coacervation, and innovative methods such as nanoencapsulation and electrospinning. Particular attention is given to the influence of encapsulated bioactive compounds on the physicochemical characteristics, texture, color, and sensory attributes of various food matrices. Furthermore, the paper highlights industrial perspectives, emphasizing the scalability of these techniques, regulatory considerations, and their role in the development of clean-label, functional, and sustainable food products. The findings underline the potential of microencapsulation as a key technology for the next generation of functional foods, bridging consumer expectations with industrial feasibility.

Keywords: microencapsulation; bioactive compounds; functional foods; physicochemical properties; sensory quality

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1. Introduction

The concept of functional foods has gained increasing attention over the last two decades, reflecting the growing consumer demand for products that provide not only nutritional value but also additional health benefits. Functional foods are typically enriched with bioactive compounds such as polyphenols, carotenoids, omega-3 fatty acids, essential oils, dietary fibers, or bioactive peptides. These compounds are associated with numerous health-promoting properties, including antioxidant, anti-inflammatory, antimicrobial, and cardioprotective effects [1,2]. In this review, the term "bioactive compounds" also encompasses complex mixtures such as essential oils and living microorganisms like probiotics, which exert their beneficial effects through the production or release of bioactive metabolites. Their integration into everyday foods is therefore regarded as a promising strategy to prevent diet-related chronic diseases and to promote overall well-being [3].

Despite their recognized benefits, the incorporation of bioactive compounds into food matrices remains a major technological and sensory challenge. Many bioactives are chemically unstable, being highly susceptible to environmental factors such as oxygen, light, heat, and pH changes. For example, polyunsaturated fatty acids are prone to oxidation, leading to the development of off-flavors, while polyphenols may undergo degradation during processing and storage. In addition, several bioactive compounds have undesirable sensory attributes, such as bitterness or astringency, which can negatively affect consumer acceptance. Moreover, their limited solubility and low bioavailability in the gastrointestinal tract further reduce their functional efficacy [4].

To address these limitations, microencapsulation techniques have emerged as powerful tools to protect sensitive compounds, improve their stability, mask undesirable tastes, and enable controlled release within the digestive system. Conventional methods such as spray-drying and freeze-drying have long been applied, but recent research has highlighted the potential of innovative approaches—including nanotechnology-based carriers, liposomes, electrohydrodynamic processes, and biopolymer-based matrices—that may offer enhanced functionality and scalability for the food industry [5].

The objective of this review is to provide a comprehensive overview of recent advances in microencapsulation techniques applied to bioactive compounds, with particular emphasis on their impact on the physicochemical and sensory properties of food products. The review also aims to discuss industrial applications and regulatory aspects, highlighting both current opportunities and existing challenges. Given the rising consumer interest in clean-label and natural food products, as well as the increasing demand for sustainable solutions in food processing, this review seeks to clarify the role of innovative encapsulation strategies in bridging the gap between scientific innovation and practical industrial implementation [6].

2. Materials and Methods

2.1. Literature Search Strategy

A systematic literature search was conducted in three electronic databases: Scopus, Web of Science, and PubMed. The search covered the period from January 2010 to June 2025, as this timeframe reflects the rapid growth of innovative micro- and nanoencapsulation techniques in food science.

The following combinations of keywords and Boolean operators were used:

- "microencapsulation" OR "nanoencapsulation" OR "encapsulation"
- AND "bioactive compounds" OR "functional ingredients"
- AND "food" OR "food products" OR "food applications"
- Additional keywords applied depending on technique: "spray-drying", "freeze-drying", "coacervation", "liposome", "solid lipid nanoparticles", "nanostructured lipid carriers", "electrospinning", "3D printing", "sensory", "physicochemical properties".

The search was restricted to peer-reviewed articles written in English. Reference lists of included papers and relevant reviews were also screened to identify additional studies.

Inclusion criteria:

- Original research articles or reviews focusing on the encapsulation of bioactive compounds for food applications.
- Studies reporting at least one of the following parameters: encapsulation efficiency (EE%), particle size/distribution, stability, physicochemical properties, sensory evaluation, or industrial applicability.
- Publications within the selected timeframe (2010–2025).

Exclusion criteria:

- Conference abstracts without full text, patents, or book chapters.
- Studies not related to food systems (e.g., pharmaceutical-only applications).
- Articles lacking experimental or review data (e.g., purely conceptual papers).

2.2. Search Outcome and Study Selection

The initial database search yielded 1264 publications. After removal of duplicates (n = 247), 1017 records were screened based on title and abstract. Of these, 242 articles were selected for full-text evaluation. Following application of inclusion and exclusion criteria, 190 studies were included in the final synthesis presented in this review.

All stages of the search and selection process were conducted independently by two researchers (A.Sz. and W.B.), following the principles of the PRISMA 2020 statement for transparent reporting of literature reviews. Any discrepancies between the two researchers were discussed and resolved through consensus with a third reviewer (A.St.).

3. Overview of Bioactive Compounds in Foods

3.1. Classification and Sources

Bioactive compounds are naturally occurring constituents in foods that exert beneficial effects on human health beyond their basic nutritional role. They are structurally diverse and can be broadly classified into several groups:

- Polyphenols—including flavonoids, phenolic acids, tannins, and stilbenes. These are widely present in fruits (berries, grapes, apples), dark-colored vegetables, tea, coffee, cocoa, and red wine. They are recognized for their antioxidant, anti-inflammatory, and cardioprotective activities [7].
- Carotenoids—lipid-soluble pigments such as β-carotene, lycopene, lutein, and zeaxanthin, predominantly found in carrots, tomatoes, pumpkins, leafy green vegetables, corn, and egg yolk. Carotenoids contribute to color development in foods and support vision and immune health [8].
- Vitamins and minerals with bioactive functions—including vitamins C and E as antioxidants, vitamin D for bone health, and trace minerals such as selenium and zinc, which are cofactors in antioxidant enzymes.
- Omega-3 fatty acids and other polyunsaturated fatty acids (PUFAs)—derived from fish oils, algae, flaxseed, and chia seeds. They are essential for cardiovascular and cognitive health, but are highly prone to oxidation.
- Bioactive peptides and proteins—produced during digestion or food processing (e.g., casein-derived peptides, whey protein fractions, soy peptides). They may exert antihypertensive, antimicrobial, or immunomodulatory effects [9].
- Phytosterols and saponins—naturally present in cereals, legumes, and oilseeds, known for their cholesterol-lowering properties.
- Essential oils and volatile compounds—extracted from herbs and spices (oregano, thyme, rosemary, mint). They exhibit antimicrobial and antioxidant activity and are of interest as natural preservatives in foods [10].

These bioactives are increasingly incorporated into functional foods and nutraceutical products, either in their native form or as extracts, concentrates, or purified compounds. Their wide availability from both plant and animal sources provides opportunities for product innovation across multiple food categories.

3.2. Sensitivity to Environmental and Processing Conditions

While bioactive compounds hold great promise for improving food functionality and human health, they are often chemically unstable and sensitive to environmental stresses. Their degradation during processing, storage, and digestion significantly reduces their efficacy. Key factors affecting stability include:

- Temperature: Heat treatments such as pasteurization, sterilization, or baking can degrade thermolabile compounds. For example, vitamin C and many polyphenols are easily destroyed at high temperatures, while carotenoids may undergo isomerization and loss of bioactivity [11].
- Oxygen exposure: Oxidation is a major degradation pathway for PUFAs, carotenoids, and essential oils, leading to rancidity, loss of nutritional value, development of undesirable flavors, and surface discolorations [12].
- Light: Photodegradation affects compounds such as riboflavin, carotenoids, and chlorophylls, altering both nutritional and sensory attributes of foods [13].
- pH and ionic strength: Acidic or alkaline environments can destabilize proteins, polyphenols, and peptides, leading to hydrolysis or precipitation. This is particularly important in beverages with low pH [14].
- Moisture and water activity: High water activity promotes enzymatic and microbial degradation, whereas excessive drying may alter the structural integrity of encapsulated bioactives [15].
- Interactions with food matrices: Bioactives may bind to proteins, polysaccharides, or lipids, reducing their solubility and bioavailability. For example, tannins form insoluble complexes with proteins, affecting both bioefficacy and sensory properties (e.g., astringency) [16–18].

These sensitivities highlight the necessity of protective strategies, such as microencapsulation, to retain the functionality of bioactives during food processing and shelf life. Encapsulation not only enhances their physicochemical stability but also enables controlled release and improved bioavailability upon consumption.

4. Principles of Microencapsulation

4.1. Definition and Mechanisms of Microencapsulation

Microencapsulation and nanoencapsulation techniques enable the protection and controlled release of bioactive compounds by entrapping them within a coating material. The size of the obtained capsules depends mainly on the encapsulation method and the composition of the wall material. Microcapsules typically range from 1 to 1000 μm, while in food applications, their diameter most often falls between 10 and 500 μm. Nanocapsules, on the other hand, are much smaller systems, usually within the range of 10 to 100 nm. The primary aim of encapsulation is to isolate sensitive compounds from adverse environmental conditions, improve their handling properties, and enable controlled release during processing, storage, or digestion.

The process relies on different mechanisms, depending on the chosen technique:

- Physical entrapment—bioactives are incorporated into a polymeric or lipid-based matrix using techniques such as spray-drying or freeze-drying [19].
- Coating or film formation—active ingredients are surrounded by a thin protective layer through coacervation, interfacial polymerization, or extrusion [20].

- Molecular inclusion—compounds are entrapped at the molecular level, as in the case of cyclodextrin inclusion complexes [21].
- Self-assembly and nanostructure formation—lipid carriers, micelles, and liposomes spontaneously organize to encapsulate hydrophilic or lipophilic molecules [22].

These mechanisms improve encapsulation efficiency, reduce chemical and physical degradation, mask undesirable flavors or odors, and allow targeted or sustained release of bioactive compounds within the gastrointestinal tract.

4.2. Wall Materials and Carriers

The choice of wall material is critical to the success of microencapsulation, as it determines encapsulation efficiency, protection during processing, interaction with the food matrix, and release properties. Ideal carriers should be food-grade, biodegradable, low-cost, and capable of forming stable structures. They can be broadly categorized as follows:

4.2.1. Proteins

Proteins are widely used as encapsulating agents due to their amphiphilic nature, gel-forming ability, and nutritional value. Commonly applied proteins include:

- Milk proteins (casein, whey proteins)—effective emulsifiers, provide oxidative stability and digestibility.
- Gelatin—forms strong gels and is widely used in coacervation.
- Plant proteins (soy protein isolate, pea protein, zein)—sustainable alternatives with film-forming and emulsifying capacity [23,24].

4.2.2. Polysaccharides

Polysaccharides are predominantly hydrophilic, versatile, and capable of forming gels or films. They are often combined with proteins to enhance structural stability. Examples include:

- Starch and maltodextrin—inexpensive, commonly used in spray-drying; improve solubility and bulk properties.
- Gum Arabic—excellent emulsifier, stabilizes flavors and essential oils.
- Alginate, carrageenan, pectin—gel-forming, suitable for controlled release and protection under gastrointestinal conditions.
- Chitosan—a cationic polymer with antimicrobial activity, useful for coating and nanoencapsulation [25].

4.2.3. Lipids

Lipid-based carriers are especially suitable for lipophilic compounds, enabling high protection against oxidation and improved bioavailability. Key systems include:

- Lipid nanoparticles—solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC).
- Liposomes—phospholipid bilayer vesicles encapsulating hydrophilic and hydrophobic compounds.
- Waxes and fats—applied in spray-cooling or melt extrusion [22,26].

4.2.4. Hybrid Systems

Combinations of proteins, polysaccharides, and lipids are increasingly investigated to exploit their complementary functional properties. Hybrid matrices can enhance encapsulation efficiency, provide better mechanical stability, and enable tunable release profiles. For example:

- Protein–polysaccharide complexes (e.g., whey protein–pectin, soy protein–alginate) have been shown to enhance emulsion stability, protect phenolic compounds, and improve oxidative resistance of encapsulated bioactives in W/O/W emulsions [27,28].
- Lipid–biopolymer hybrid systems (e.g., liposomes coated with chitosan or alginate) exhibit improved oxidative stability, encapsulation efficiency, and gastrointestinal resistance compared to uncoated liposomes [26,29].
- Ternary hybrid matrices combining proteins, polysaccharides, and lipids (e.g., whey protein–pectin–lecithin or zein–chitosan–lipid nanoparticles) demonstrate synergistic effects, providing enhanced barrier properties and controlled release behavior in food systems [30].

Overall, the careful selection and combination of wall materials allow the design of tailored encapsulation systems that balance physicochemical stability, sensory quality, and industrial scalability.

5. Conventional Microencapsulation Techniques

5.1. Spray-Drying

Spray-drying is the most widely applied technique for the microencapsulation of bioactive compounds in the food industry due to its scalability, low cost, and compatibility with a broad range of wall materials. In this method, an emulsion or dispersion of the active compound with a carrier material (typically maltodextrin, gum Arabic, whey protein, or modified starch) is atomized into fine droplets and rapidly dried in a hot air stream. The solvent (usually water) evaporates almost instantaneously, producing dry microcapsules [31]. Key advantages include high throughput, low production costs, and the ability to generate free-flowing powders with good storage stability. However, the main drawback is thermal stress: heat-sensitive compounds such as vitamins, polyunsaturated fatty acids, or essential oils may partially degrade during drying. Optimization of inlet/outlet temperatures, droplet size, and carrier composition is therefore essential to minimize losses and achieve high encapsulation efficiency [32,33].

5.2. Freeze-Drying

Freeze-drying (lyophilization) is a dehydration method that removes water by sublimation under low temperature and vacuum. This technique is particularly suitable for thermo-labile bioactive components, such as probiotic microorganisms, enzymes, or polyphenols. In the case of probiotics, the process helps to preserve cell viability and functional activity by minimizing thermal and oxidative stress. Their beneficial effects in food matrices are often associated with the production of bioactive metabolites, including short-chain fatty acids, bacteriocins, exopolysaccharides, and peptides.

The process typically involves freezing the bioactive–carrier mixture, followed by primary and secondary drying stages to remove ice and bound water [31]. The key advantage of freeze-drying is the preservation of structural integrity and bioactivity of sensitive compounds, since degradation by heat is avoided. The resulting microcapsules usually exhibit porous structures with high rehydration capacity. Nonetheless, freeze-drying is an energy-intensive and time-consuming process, which makes it relatively expensive and less attractive for large-scale industrial applications compared to spray-drying. To improve cost-effectiveness, freeze-drying is often applied in combination with other processes or reserved for high-value products [34].

5.3. Coacervation and Complexation

Coacervation is a process of phase separation in which a colloidal solution separates into a dense coacervate phase (rich in polymer) and a dilute equilibrium phase. Microencapsulation through coacervation involves depositing the coacervate around the active ingredient to form a coating. Two main types of coacervation can be distinguished:

- Simple coacervation, induced by changes in pH, temperature, or the addition of a desolvating agent (e.g., ethanol or salts).
- Complex coacervation, formed through electrostatic interactions between oppositely charged polymers (e.g., gelatin–gum Arabic, whey protein–pectin, chitosan–alginate).

The technique enables the formation of microcapsules with well-defined walls and controlled release properties. It is particularly effective for encapsulating flavors, essential oils, and lipophilic compounds, as it provides strong protection against oxidation and evaporation. However, coacervation systems are sensitive to environmental conditions (pH, ionic strength) and may present challenges in industrial scaling due to their relatively complex processing steps [35,36].

6. Innovative and Emerging Approaches

6.1. Nanoencapsulation

Nanoencapsulation refers to the entrapment of bioactive compounds within carriers at the nanoscale, most commonly defined as structures with at least one external dimension in the range of 1–100 nm. According to the European Food Safety Authority (EFSA) Scientific Committee (2021), this size range is critical, as it confers unique physicochemical and biological properties compared to larger-scale materials, including altered solubility, stability, cellular uptake, and bioavailability [37].

It is important to distinguish between:

- Nanomaterials (1–100 nm): materials with one or more dimensions within the nanoscale, which require specific safety assessment and regulatory consideration in the food sector.
- Submicron or colloidal systems (100–1000 nm): particles above the strict nanoscale range but still below the micrometer level. These systems often exhibit functional benefits similar to nanocarriers (e.g., improved dispersibility and protection of sensitive bioactives), but should not be classified as “nano” for regulatory purposes.

In food applications, both nano- and submicron encapsulation strategies are used, depending on the physicochemical nature of the bioactive compound, the encapsulating material, and the intended functional outcome. Throughout this review, the term “nanoencapsulation” will be reserved for carriers in the 1–100 nm range, while the broader category (up to 1000 nm) will be described as “colloidal” or “submicron encapsulation” when relevant [38].

6.2. Liposomes and Nanostructured Lipid Carriers

Liposomes are spherical vesicles composed of phospholipid bilayers that can encapsulate both hydrophilic (in their aqueous core) and lipophilic (within the lipid bilayer) compounds. Their inherent biocompatibility, structural versatility, and resemblance to biological membranes make them highly attractive as carriers for functional food applications. However, conventional liposomes often exhibit limited physical stability, are prone to aggregation, fusion, and leakage of encapsulated bioactive compounds [39]. To overcome these drawbacks, NLCs have been developed as second-generation lipid systems, combining solid and liquid lipids to form stable nanocarriers with improved encapsulation efficiency and loading capacity. NLCs are particularly promising for protecting polyunsaturated fatty acids, fat-soluble vitamins, and essential oils against oxidation. Both liposomes and NLCs are considered suitable for functional beverages, dairy products, and nutraceutical formulations, though their cost and technical complexity may limit widespread industrial adoption at present [40].

6.3. Electrospinning and Electrospraying

Electrohydrodynamic techniques such as electrospinning and electrospraying are emerging methods for producing nanofibers and nanoparticles containing bioactive compounds. In electrospinning, a polymer solution is exposed to a high-voltage electric field, creating ultrafine fibers that can encapsulate and immobilize bioactives within a porous nanostructured matrix. Electrospraying operates under similar principles but generates discrete nanospheres rather than continuous fibers.

These methods allow encapsulation of thermally sensitive compounds without exposure to high temperatures, making them attractive alternatives to spray-drying. Moreover, the resulting fibrous or particulate systems can provide sustained or triggered release profiles, making them valuable for controlled delivery. Recent studies have demonstrated their applicability in food processing. For instance, zein-based electrospun fibers have been used to encapsulate proanthocyanidins, enhancing their antioxidant activity and stability during storage [41]. Similarly, core–shell zein/pullulan nanofibers crosslinked by genipin have been fabricated for the controlled release of bioactive compounds, showing promising mechanical and barrier properties [42]. Carotenoids extracted from tomato peels were successfully nanoencapsulated by electrospinning to improve their water solubility and oxidative stability [43]. In addition, betalain–gelatin nanoparticles produced via coaxial electrospraying exhibited strong antioxidant capacity and structural uniformity, highlighting the potential of this technique for incorporating natural colorants and antioxidants into functional foods [44].

Although promising, the scalability of electrospinning and electrospraying remains a major limitation, as current production rates are low compared to conventional food processing methods. Nevertheless, continuous advancements in multi-needle systems and coaxial configurations are progressively improving their industrial feasibility [45].

6.4. 3D Printing and Novel Hybrid Methods

Three-dimensional (3D) food printing has recently emerged as a cutting-edge approach for designing customized food products enriched with bioactive compounds. By precisely depositing encapsulated bioactive carriers into defined geometries, 3D printing enables tailored nutrient distribution, targeted release, and novel product designs. This technology can be integrated with encapsulation strategies to protect sensitive compounds during the printing process and to optimize their sensory properties [46]. Beyond 3D printing, novel hybrid methods are being investigated that integrate multiple encapsulation strategies to enhance efficiency. For instance, combining nano-emulsions with spray-drying can improve scalability, while coating liposomes with biopolymers (e.g., chitosan) enhances their stability and resistance to gastrointestinal conditions. These hybrid systems aim to overcome the limitations of individual technologies, offering improved protection, controlled release, and greater industrial feasibility [47,48].

Table 1 presents the comparison of selected microencapsulation techniques for bioactive compounds in food.

Table 1. Comparison of selected microencapsulation techniques for bioactive compounds in food.

Technique	Mechanism	Wall Materials/Carriers	Typical Particle Size	EE%	Typical Process Parameters	Advantages	Limitations	Typical Food Applications	References
Spray-drying	Atomization of emulsion/suspension in hot air → rapid solvent evaporation	Polysaccharides (maltodextrin, gum Arabic), proteins (whey, casein)	1–50 μm	40–90%	Inlet: 150–220 °C; Outlet: 70–90 °C	Cost-effective, industrially established, continuous process, wide material compatibility	Thermal degradation of heat-sensitive compounds, relatively low retention of volatiles	Flavor oils, carotenoids, probiotics, vitamins	[49–51]
Freeze-drying (lyophilization)	Water sublimation under low pressure after freezing	Proteins, polysaccharides, gums	10–200 μm (irregular)	30–80%	Freezing: −40 to −80 °C; Vacuum < 0.1 mbar; Drying: 20–40 °C	Gentle drying → good for heat-sensitive bioactives, preserves structure	High cost, time-consuming, porous structure prone to oxidation	Probiotics, enzymes, polyphenols	[52–54]
Complex coacervation	Phase separation of oppositely charged biopolymers around droplets/particles	Gelatin–gum Arabic, whey–pectin, chitosan–alginate	5–500 μm	50–95%	pH 3–6; ionic strength < 50 mM; Stirring 200–600 rpm	High EE%, controlled release, protection of sensitive compounds	Sensitive to pH/ionic strength, complex process control	Flavor oils, polyphenols, ω-3 fatty acids	[55–59]
Liposomes	Phospholipid bilayer vesicles encapsulating hydrophilic/hydrophobic cores	Phospholipids, cholesterol	50 nm–10 μm	40–90%	Hydration 40–60 °C; Extrusion/sonication; Stabilization often required	Biocompatible, versatile for hydrophilic & lipophilic actives, improved bioavailability	Stability issues (oxidation, leakage), costly materials	Polyphenols, vitamins, peptides	[60–62]
Nano-emulsions	High-energy (ultrasonication, high-pressure homogenization) dispersion	Food-grade emulsifiers, proteins, phospholipids	20–200 nm	50–95%	Homogenization: 100–1500 bar; Ultrasonication: 20–40 kHz	Transparent, stable dispersions, improved solubility, enhanced bioavailability	Sensitive to pH, ionic strength, Ostwald ripening	Carotenoids, ω-3 fatty acids, curcumin, essential oils	[63,64]
SLN	Lipid solid matrix formed upon cooling of emulsified lipids	Solid lipids (stearic acid, triglycerides) + surfactants	50–1000 nm	40–80%	Melt 60–80 °C; High-shear homogenization + cooling	Good stability, protection against oxidation/light, controlled release	Limited loading capacity, potential expulsion during storage	Polyphenols, vitamins, flavors	[65,66]
NLC	Mixture of solid + liquid lipids forming less-ordered matrix	Solid + liquid lipids, surfactants	50–1000 nm	60–95%	Similar to SLN, with oil phase 10–30%	Higher loading than SLN, reduced expulsion, improved stability	Need optimization of lipid ratios, possible crystallization	Carotenoids, ω-3 fatty acids, essential oils	[67,68]
Electrospinning/Electrospraying	High-voltage electrostatic drawing of polymer solution into fibers/particles	Biopolymers (zein, gelatin, pullulan)	Nanofibers: 100–500 nm; Nanoparticles: 100–1000 nm	40–90%	Voltage: 10–30 kV; Flow: 0.1–1 mL/h; Room temperature	Room-temperature process, high surface area, novel structures	Not yet industrial, solvents often required, batch process	Antioxidants, probiotics, flavors	[41–44]
3D Printing	Layer-by-layer deposition of encapsulated structures	Hydrogels, starch, proteins, alginates	100–1000 μm	Highly variable (30–90%)	Extrusion or inkjet; Layer height 50–500 μm	Controlled release, smart design	Limited resolution, slow throughput, regulatory uncertainty	Personalized nutrition, functional confectionery	[69–71]

7. Encapsulation of Plant-Derived Bioactive Compounds

7.1. Polyphenols and Flavonoids

Polyphenols, including flavonoids, phenolic acids, tannins, and stilbenes, represent one of the most extensively studied classes of plant-derived bioactives. They exhibit potent antioxidant, anti-inflammatory, and antimicrobial properties and are strongly associated with chronic disease prevention. However, their application in foods is limited by their chemical instability (e.g., oxidation, enzymatic degradation) and low bioavailability due to poor solubility and rapid metabolism [20]. Encapsulation strategies such as spray-drying with maltodextrin or gum Arabic, nanoemulsions stabilized with proteins, and inclusion complexes with cyclodextrins have been used to enhance polyphenol stability. For example, encapsulation of green tea catechins in protein–polysaccharide matrices has improved retention during storage and processing, while microencapsulation of grape seed extracts has reduced bitterness and improved incorporation into bakery products [72].

7.2. Carotenoids and Phytosterols

Carotenoids (e.g., β-carotene, lycopene, lutein, zeaxanthin) and phytosterols are valuable plant bioactives with strong antioxidant and health-promoting functions. Carotenoids contribute to eye health and immune function, while phytosterols are effective in lowering serum cholesterol. Their major limitation lies in their lipophilic nature, susceptibility to oxidation, and sensitivity to light and heat [73]. Encapsulation using lipid-based carriers such as liposomes, NLCs, or emulsions improves their solubility in aqueous systems and protects them from degradation. Spray-drying with carbohydrate carriers (maltodextrin, modified starch) has also been effective in producing carotenoid-rich powders for use in beverages and dairy products. Novel nanoencapsulation systems further improve intestinal absorption and bioavailability of these compounds [74,75].

7.3. Essential Oils and Alkaloids

Essential oils (e.g., thymol, carvacrol, eugenol, menthol) and alkaloids (e.g., caffeine, theobromine, capsaicinoids) are of interest in food applications due to their antimicrobial, antioxidant, and sensory properties. However, their high volatility, strong odor, and sensitivity to oxidation make their direct incorporation into food matrices problematic [76].

Nevertheless, some food products are traditionally prepared with spices that naturally contain these bioactive compounds. For example, dry-fermented sausages made with dried paprika—which is particularly rich in capsaicinoids—demonstrate both antioxidant and antimicrobial potential, highlighting how such ingredients can contribute to product stability and characteristic flavor profiles in traditional formulations [77].

Microencapsulation through complex coacervation, spray-drying, and inclusion complexes with cyclodextrins has been shown to reduce volatility and mask undesirable flavors. Encapsulation also enables controlled release, which is particularly relevant for using essential oils as natural preservatives in meat, dairy, and bakery products. In the case of alkaloids, encapsulation can help reduce bitterness and improve consumer acceptance, while still retaining their stimulant or bioactive properties [78,79].

7.4. Challenges in Encapsulation of Plant Bioactives

Despite significant progress, the encapsulation of plant-derived bioactives faces several persistent challenges:

- Oxidation: Polyphenols, carotenoids, and essential oils are highly prone to oxidative degradation, leading to reduced efficacy and off-flavors [80].
- Light sensitivity: Carotenoids and certain polyphenols undergo photodegradation, which limits their stability in transparent packaging and beverages [81].
- Bitterness and astringency masking: Many polyphenols and alkaloids impart undesirable sensory attributes. Encapsulation must not only protect bioactives but also mitigate their impact on taste perception [82].
- Matrix interactions: Encapsulated bioactives can interact with proteins, lipids, or minerals in complex food systems, altering their release profile and efficacy [83].
- Scalability and cost: Some advanced encapsulation methods remain difficult to apply at an industrial scale, limiting their use to high-value functional products [84].

Addressing these challenges requires optimization of encapsulation materials and techniques, along with innovative approaches that balance stability, sensory quality, and economic feasibility [85].

8. Encapsulation of Animal-Derived Bioactive Compounds

8.1. Bioactive Peptides and Proteins

Animal-derived peptides and proteins, particularly those obtained from milk (whey, lactoferrin, and casein), collagen, and egg proteins, are recognized for their diverse health-promoting effects, including antihypertensive, antioxidant, antimicrobial, and immunomodulatory activities. These peptides are either naturally present or generated through enzymatic hydrolysis during digestion or food processing [86]. Encapsulation is increasingly applied to improve the stability and targeted release of such bioactives. For example, whey protein hydrolysates have been encapsulated in alginate–chitosan matrices to protect peptides from premature degradation in the gastrointestinal tract. Similarly, collagen peptides incorporated into liposomal systems or spray-dried protein–carbohydrate matrices show enhanced bioavailability and improved functionality in nutraceutical formulations. Casein, due to its amphiphilic structure and self-assembly properties, is also used both as a bioactive compound and as a carrier material for co-encapsulation with other peptides or vitamins [87].

8.2. Omega-3 Fatty Acids and Other Lipid-Based Compounds

Omega-3 fatty acids (eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) from fish oil and marine sources are among the most widely studied lipid-based bioactives of animal origin. They are essential for cardiovascular and neurological health but are highly susceptible to oxidation, leading to rancidity and undesirable flavors. Other bioactive lipids, such as conjugated linoleic acid (CLA), also share these stability issues [88].

Encapsulation in lipid-based carriers such as NLCs, SLNs, and liposomes has shown strong potential to protect omega-3 fatty acids from oxidative degradation and to enhance their incorporation into aqueous food systems. Spray-drying with wall materials such as maltodextrin, gum Arabic, or whey protein concentrates is also frequently employed to produce stable, free-flowing powders containing fish oil. Complex coacervation (e.g., gelatin–gum Arabic systems) has proven effective in protecting PUFA-rich oils in dairy and bakery applications [89,90].

8.3. Enzymes and Vitamins

Enzymes of animal origin, such as lactase or proteases, are increasingly used in functional foods to support digestive health or to improve processing efficiency. However, enzymes are highly sensitive to temperature, pH, and proteolytic degradation, which restricts their direct incorporation into food matrices. Encapsulation in biopolymer-based hydrogels, alginate beads, or lipid vesicles can enhance enzyme stability and activity during storage and targeted release in the gastrointestinal tract [91]. Vitamins of animal origin (e.g., vitamin D from lanolin or fish oil, vitamin B_{12} from dairy or fermentation sources) are also prone to degradation when exposed to light, oxygen, or heat. Microencapsulation with carbohydrate or protein carriers, as well as nanoencapsulation in lipid systems, has been shown to significantly improve their stability and bioavailability [92–94]. For example, encapsulated vitamin D_3 can be more effectively delivered in fortified dairy and cereal products [95].

8.4. Challenges in Encapsulation of Animal Bioactives

Despite encouraging progress, several challenges remain in the encapsulation of animal-derived bioactive compounds:

- Thermal degradation—enzymes, vitamins, and bioactive peptides are often sensitive to heat treatments such as pasteurization, sterilization, or spray-drying, which can reduce their bioactivity [91].

- Oxidation of lipids—omega-3 fatty acids and other PUFAs are highly prone to oxidative rancidity, which requires efficient encapsulation systems and antioxidant co-formulation [88].
- Maintaining bioactivity—preserving the structural and functional integrity of proteins, peptides, and enzymes during processing and storage is a key challenge [96].
- Sensory issues—lipid-based bioactives such as fish oil may impart off-flavors if not effectively protected, reducing consumer acceptance [97].
- Scalability and cost—advanced encapsulation systems (e.g., NLCs, liposomes) are still costly and technically demanding, limiting their routine industrial use [98].

Future research should focus on hybrid encapsulation systems, the use of natural and sustainable wall materials, and process optimization to achieve both stability and cost-effectiveness in large-scale food applications.

9. Impact of Microencapsulation on Food Properties

9.1. Physicochemical Stability

One of the primary purposes of microencapsulation is to enhance the physicochemical stability of sensitive bioactive compounds during food processing and storage. Encapsulation provides a protective barrier against oxygen, light, heat, and moisture, thereby reducing chemical degradation. For example, encapsulation of PUFAs in protein–polysaccharide matrices markedly decreases lipid oxidation and rancidity in dairy and bakery products. Similarly, encapsulated polyphenols and carotenoids exhibit higher retention during pasteurization and long-term storage compared to their free counterparts [99]. Microencapsulation also improves solubility and dispersibility of poorly water-soluble compounds such as carotenoids, phytosterols, and fat-soluble vitamins. Nanocarriers and emulsions increase the surface area and enable better incorporation of lipophilic bioactives into aqueous food systems. Controlled release mechanisms further protect compounds from premature degradation in the gastrointestinal tract, enhancing their bioavailability and functional efficacy [100].

9.2. Texture and Rheology

Encapsulated bioactives can influence the textural and rheological properties of food products, depending on the type and concentration of carriers used. For instance, the incorporation of microcapsules into dairy or bakery matrices may alter viscosity, gel strength, and water-binding capacity. Encapsulation systems based on polysaccharides such as alginate or pectin can increase gel firmness, whereas lipid-based carriers may contribute to creaminess and improved mouthfeel [101]. At the nanoscale, encapsulated particles often behave as stabilizers in emulsions and suspensions, improving colloidal stability and preventing phase separation. However, excessive microcapsule loading may negatively affect product texture, leading to graininess or undesired thickening. Thus, careful optimization of particle size, wall material, and loading level is required to balance functionality with sensory acceptance [102].

9.3. Color and Visual Attributes

The encapsulation of bioactive compounds can have a significant impact on the color and overall visual quality of food products. For example, carotenoids and anthocyanins are natural pigments that contribute to product color but are highly unstable when exposed to light and oxygen. Encapsulation stabilizes these pigments, maintaining desirable color intensity and preventing discoloration during storage [103]. In addition, encapsulation can mask unwanted color changes caused by oxidation or degradation of sensitive compounds. For instance, encapsulated omega-3 oils reduce the formation of yellowish or brownish tones associated with lipid oxidation in fortified dairy products. Conversely, the choice of carrier material may also influence product appearance; protein-based microcapsules may cause turbidity in clear beverages, requiring advanced nanocarriers for transparent applications [104,105].

9.4. Sensory Quality and Flavor Release

Sensory quality is a critical determinant of consumer acceptance, and microencapsulation directly influences flavor perception and release. Many bioactive compounds, such as polyphenols, alkaloids, and fish oils, have undesirable sensory attributes (bitterness, astringency, or off-flavors) that limit their direct use in foods. Encapsulation provides an effective strategy to mask these undesirable characteristics, improving overall palatability [106,107]. At the same time, controlled release of encapsulated flavors and essential oils allows for tailored flavor delivery during consumption, enhancing sensory complexity and product differentiation. For instance, encapsulated essential oils in confectionery or chewing gum provide prolonged flavor perception, while encapsulated bitter polyphenols can be gradually released in beverages without overwhelming taste receptors [82]. Nevertheless, ensuring balance is crucial: poorly designed encapsulation systems may delay or restrict flavor release, reducing product appeal. Therefore, the selection of wall materials and encapsulation techniques must account not only for chemical stability but also for sensory performance in the target food application [108,109].

Table 2 presents suitability matrix of encapsulation techniques for different classes of bioactive compounds.

Table 2. Suitability matrix of encapsulation techniques for different classes of bioactive compounds.

Bioactive Compound Group	Spray-Drying	Freeze-Drying	Coacervation	Liposomes	Nanoemulsions	SLN	NLC	Electrospinning	References
PUFA, fish oil, ω-3	✓✓✓ industrial scale, low cost	✓ stable, but costly	⚠ low EE%, phase separation	✓✓ good stability, improved bioavailability	✓✓✓ transparent systems, high bioavailability	✓✓ oxidative stability	✓✓✓ high loading capacity, stable	⚠ limited to lab scale	[90,110–116]
Vitamins (A, D, E, C)	✓✓ widely used, high EE% for fat-soluble	✓ suitable for vitamin C and heat-sensitive compounds	✓ water-soluble, pH-dependent	✓✓ vitamins E, D in lipid bilayers	✓✓ lipid-soluble vitamins in clear systems	✓ vitamins A, E in lipid carriers	✓✓ suitable for unstable vitamins	⚠ experimental	[117–123]
Polyphenols (green tea catechins, resveratrol, anthocyanins)	✓✓ spray-drying powders	✓✓ suitable for heat-sensitive compounds	✓✓✓ high EE%, controlled release	✓ improved solubility	✓✓ effective for resveratrol delivery	✓ lipid-protected	✓✓ enhanced stability	✓✓ zein fibers effective	[39,124–130]
Carotenoids (β-carotene, lycopene, lutein)	✓ moderate stability	⚠ low solubility, crystallization	⚠ not optimal	✓✓ lipophilic-compatible	✓✓✓ transparent, stable dispersions	✓✓ oxidative stability	✓✓✓ high EE%, stable	⚠ rarely used	[67,131–134]
Probiotics/live cells	✓✓ variable survival rate	✓✓✓ excellent survival, but costly	✓ alginate/chitosan bead systems	⚠ not applicable	⚠ not applicable	⚠ cells sensitive to lipids	⚠ rarely applied	⚠ not applicable	[135–138]
Minerals (iron, zinc, calcium)	✓✓ masking metallic taste	✓ preserves solubility	✓✓ controlled release, reduced reactivity	⚠ low suitability	⚠ limited solubility	⚠ less common	⚠ less common	⚠ not used	[139–142]

Legend: ✓ indicates suitability of the encapsulation technique for the given class of bioactive compounds. The number of symbols reflects the relative applicability and efficiency of the technique: ✓—suitable/commonly applied at laboratory scale; ✓✓—highly suitable/well-established with good encapsulation efficiency and stability; ✓✓✓—optimal technique/widely used at industrial scale with proven stability and functionality. ⚠ indicates limited applicability or technical challenges (e.g., low encapsulation efficiency, high cost, or instability).

10. Industrial Applications and Perspectives

10.1. Case Studies in Different Food Categories

10.1.1. Beverages

The fortification of beverages with sensitive compounds such as polyphenols, carotenoids, and omega-3 fatty acids is highly challenging due to solubility and stability issues. Encapsulation technologies (e.g., nanoemulsions and cyclodextrin complexes) have enabled the incorporation of bioactives into fruit juices, functional waters, and dairy-based drinks while maintaining clarity, stability, and desirable sensory attributes. For example, nanoencapsulated β-carotene has been successfully applied in fruit juices, providing both enhanced stability and improved bioavailability [143].

10.1.2. Dairy Products

Yogurts, cheeses, and milk beverages are common carriers for encapsulated bioactives, owing to their favorable pH and fat content. Probiotics encapsulated in alginate or whey protein matrices exhibit higher survival rates during storage and gastrointestinal transit. Similarly, fish oil encapsulated via spray-drying or complex coacervation has been incorporated into milk powders and yogurts, reducing oxidative off-flavors while delivering omega-3 fatty acids [144].

10.1.3. Bakery Products

The high processing temperatures in baking present a major challenge for bioactive incorporation. Encapsulation of polyphenols, carotenoids, or essential oils in protective carriers has improved their thermal stability during baking processes, enhancing antioxidant properties of bread, biscuits, and muffins. Microcapsules can also act as moisture regulators, positively influencing product texture and shelf life [145].

10.1.4. Meat Products

Essential oils (oregano, rosemary, thyme) and plant extracts encapsulated in biopolymer or lipid matrices are increasingly used in meat and poultry to extend shelf life by reducing lipid oxidation and microbial growth. Encapsulated antioxidants and antimicrobials allow controlled release, ensuring gradual protection throughout storage and distribution [84]. In addition to plant-derived bioactives, bioactive peptides obtained from meat proteins have recently gained attention due to their antioxidant, antihypertensive, and antimicrobial properties. These peptides can be incorporated into meat formulations or used as natural preservatives to improve product stability and nutritional quality. Moreover, the encapsulation of bioactive peptides in suitable delivery systems can protect them from degradation, enhance their bioavailability, and support their gradual release during processing and storage [146]

10.1.5. Plant-Based Foods

The growing plant-based food sector provides significant opportunities for encapsulated bioactives. Polyphenols and phytosterols are added to plant-based beverages and dairy alternatives to enhance nutritional and functional properties. Encapsulation helps mask bitterness from plant-derived compounds and stabilizes lipophilic bioactives in low-fat matrices [147].

10.2. Process Scalability and Economic Feasibility

Among encapsulation methods, spray-drying is currently the most industrially scalable and cost-effective, enabling high-throughput production of stable powders. Freeze-drying offers superior protection but is less feasible for large-scale applications due to high energy consumption and costs. Emerging methods such as electrospinning or nanostructured lipid carriers show promising functionality but still face significant challenges in scalability and industrial integration. Hybrid processes that combine nanoencapsulation with conventional drying are being explored to balance performance and cost efficiency [31,148]. Economic feasibility also depends on the price of wall materials, energy requirements, and compatibility with existing processing lines. For encapsulation technologies to be adopted widely, they must demonstrate not only improved stability and sensory quality but also cost-effectiveness compared to direct addition of bioactives [149,150].

10.3. Clean-Label and Sustainability Aspects

Consumers increasingly demand clean-label products made with natural, recognizable ingredients and minimal synthetic additives. This trend drives the search for sustainable and natural encapsulation materials such as plant proteins (pea, soy, zein), dietary fibers, and polysaccharides (alginate, pectin, starch derivatives). The use of biodegradable and renewable wall materials not only meets consumer expectations but also reduces the environmental footprint of encapsulated products [151,152]. Sustainability also encompasses energy efficiency and waste reduction. Innovations such as low-energy drying processes, the valorization of agricultural by-products as encapsulation carriers, and circular economy approaches contribute to greener encapsulation technologies [153,154].

10.4. Consumer Acceptance and Market Trends

The success of encapsulated bioactive compounds ultimately depends on consumer acceptance. Encapsulation helps overcome negative sensory perceptions, such as bitterness from polyphenols or fishy odors from omega-3 oils, which improves overall palatability and marketability of functional foods. Transparency in labeling, clear communication of health benefits, and alignment with consumer values (natural, sustainable, health-promoting) are essential for widespread adoption [155,156]. Market trends indicate rapid growth in the global functional food and nutraceutical sectors, with encapsulated bioactives playing a central role. Demand is particularly strong in beverages, dairy, and plant-based products. As consumer awareness of personalized nutrition increases, encapsulation technologies are expected to support the development of tailored functional foods that deliver specific health benefits to targeted populations [157,158].

11. Regulatory and Safety Considerations

11.1. GRAS Status and EFSA/FDA Perspectives

The regulatory evaluation of encapsulated bioactive compounds, particularly when nano- or microstructured systems are involved, remains one of the key bottlenecks for industrial implementation. In the United States, food additives and novel delivery systems are generally assessed under the Generally Recognized as Safe (GRAS) framework administered by the Food and Drug Administration (FDA). GRAS designation requires that the substance, including its carrier material, has been demonstrated to be safe under the intended conditions of use, supported either by a history of common use in food or by publicly available scientific evidence reviewed by qualified experts. For encapsulation matrices, such as maltodextrins, gum Arabic, modified starches, or certain proteins, GRAS status is already established. However, when encapsulation involves novel nanostructures (e.g., nanoliposomes, nanocrystals, or polymeric nanoparticles), a case-by-case evaluation is required, focusing on aspects such as particle size distribution, surface charge, solubility, digestibility, and potential accumulation in tissues [159–162].

In the European Union, novel micro- and nanoencapsulation systems fall under the remit of the EFSA. EFSA defines nanomaterials as engineered structures with one or more external dimensions in the size range of 1–100 nm, though materials outside this range may still be considered if they exhibit nano-specific properties. According to the EFSA Guidance on the risk assessment of nanomaterials in the food and feed chain (2021), safety dossiers must include:

- detailed physicochemical characterization of the encapsulated material and its carriers,
- validated methods for size distribution and solubility,
- in vitro degradation/digestion profiles,
- toxicological studies covering absorption, distribution, metabolism, and excretion (ADME).

Unlike the GRAS concept, the EFSA evaluation is centrally coordinated and requires a full pre-market authorization for any novel encapsulating material not already included on the Union list of approved food additives. Importantly, nanoencapsulation is not automatically excluded from approval, but safety demonstration is stringent and data-intensive, especially for persistent or non-biodegradable carriers [37,163,164].

11.2. Labeling and Consumer Communication

From a consumer perspective, transparency in labelling and communication is essential to maintain trust and foster acceptance of foods containing encapsulated bioactive compounds. In the EU, Regulation (EU) No 1169/2011 on food information to consumers requires that engineered nanomaterials used as ingredients must be explicitly indicated in the ingredient list, with the word "nano" in brackets following the substance name (e.g., silicon dioxide [nano]). This ensures that consumers are informed of the presence of nanoscale structures, though it may simultaneously raise concerns if not properly contextualized [165,166].

In the U.S., labelling of encapsulated ingredients is less prescriptive. FDA does not mandate a special "nano" designation, but companies are expected to provide truthful and non-misleading information under the Federal Food, Drug, and Cosmetic Act. Voluntary communication strategies, such as clear descriptions of functional benefits (e.g., improved stability, reduced dosage, or controlled release), are recommended to enhance consumer understanding [162,167].

Consumer studies consistently show a mixed perception of nanotechnology in food: while acceptance is higher for clear health benefits (e.g., improved nutrient bioavailability, reduced use of synthetic preservatives), scepticism arises when the technology is perceived as artificial, hidden, or poorly regulated. Therefore, industry–consumer communication should focus on:

- emphasizing safety assessments and regulatory approvals,
- highlighting tangible consumer benefits (taste preservation, nutrient stability, reduced additives),
- ensuring transparent terminology that avoids over-technical jargon but conveys the functional role of encapsulation.

Proactive communication and responsible labelling practices are therefore crucial not only for compliance but also for fostering public confidence in the adoption of innovative encapsulation technologies [168–172].

12. Future Directions in Microencapsulation Research

12.1. Personalized Nutrition and Targeted Delivery

The future of microencapsulation in food systems will increasingly be shaped by the demand for personalized nutrition. Advances in nutrigenomics and metabolomics are generating knowledge on how individuals respond differently to bioactive compounds, depending on genetic background, gut microbiota composition, age, and lifestyle. Microencapsulation offers a powerful tool to deliver bioactives in a targeted and controlled manner, aligning with personalized health needs [165,173,174]. Emerging research is focusing on site-specific release systems, where encapsulated compounds are designed to resist degradation in the upper gastrointestinal tract and release their payload in the colon, small intestine, or even in response to pH and enzymatic triggers. For example, encapsulation of probiotics in resistant polysaccharide matrices or lipid-based nanocarriers can improve their survival until they reach the target intestinal niche. Similarly, encapsulated polyphenols or omega-3 fatty acids can be formulated to match personalized dosage requirements, potentially guided by digital health platforms and dietary apps. This integration of encapsulation technology with precise health data represents a paradigm shift in functional food development [175–177].

12.2. Smart Packaging and Active Coatings

Another frontier in encapsulation research is its integration into smart packaging and active coatings. Encapsulated bioactives, such as antioxidants, antimicrobials, or natural colorants, can be incorporated into edible films, coatings, or packaging materials to extend shelf-life and improve food safety. Encapsulation enhances the stability and controlled release of these compounds, ensuring that they remain inactive during storage but are released under specific triggers (e.g., moisture, temperature changes, microbial growth) [178–181]. Recent innovations include stimuli-responsive microcapsules embedded in biodegradable films that release natural preservatives only when microbial activity is detected, or colorimetric indicators that change appearance in response to oxygen levels or pH shifts. Such smart systems not only protect food but also provide real-time feedback to consumers regarding freshness and safety. Integrating encapsulation with active packaging therefore addresses both food waste reduction and consumer trust, aligning with circular economy goals [182–186].

12.3. Synergies with Biotechnology and Green Processing

The adoption of biotechnology and sustainable processing strategies is expected to play a central role in the next generation of encapsulation systems. Encapsulation materials increasingly derive from renewable biopolymers such as alginates, pectins, cellulose derivatives, or proteins obtained through microbial fermentation. These natural carriers not only ensure safety and consumer acceptance but also support sustainability targets [187]. Additionally, green encapsulation processes are gaining momentum. Techniques such as supercritical CO_2 drying, ultrasound-assisted encapsulation, or enzymatically catalyzed cross-linking minimize the use of organic solvents. Biotechnological tools are also opening new avenues: engineered microorganisms can produce tailored encapsulation matrices, while synthetic biology may allow the design of carrier molecules with programmable release properties [188,189]. The integration of encapsulation with bioprocessing is particularly promising in the valorization of agri-food by-products. Plant residues, fibers, and protein fractions from food waste streams can be converted into functional wall materials, supporting both the circular bioeconomy and the scalability of encapsulation technology [174,190].

13. Conclusions

Microencapsulation has emerged as a pivotal technology for stabilizing and delivering bioactive compounds in food systems, offering protection against environmental stresses, controlled release, and improved sensory acceptance. Conventional approaches such as spray-drying and freeze-drying have enabled industrial-scale applications, while emerging techniques including liposomes, nanostructured carriers, and electrospinning are expanding the scope of possibilities for sensitive and multifunctional bioactives.

The evidence reviewed in this article highlights three key outcomes. First, encapsulation substantially improves the physicochemical stability of diverse bioactives—ranging from polyphenols and carotenoids to omega-3 fatty acids and probiotics—ensuring their functionality throughout processing, storage, and digestion. Second, encapsulation strategies can be tailored to maintain or improve sensory quality, limiting negative attributes such as bitterness, oxidation notes, or color loss, while enabling novel product designs. Third, despite clear technological advances, regulatory and consumer acceptance challenges remain critical: nanoencapsulation, in particular, demands rigorous safety evaluations, transparent labelling, and effective communication of benefits to the public.

Looking forward, the integration of microencapsulation with personalized nutrition platforms, smart packaging solutions, and green bioprocessing strategies will define the next generation of applications. Continued interdisciplinary research—bridging food technology, materials science, biotechnology, and regulatory sciences—is required to optimize carrier systems, validate in vivo bioavailability, and ensure sustainable and safe implementation at industrial scale.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	**Full name**
ADME	Absorption, distribution, metabolism, and excretion
CLA	Conjugated linoleic acid
DHA	Docosahexaenoic acid
EE%	Encapsulation efficiency
EFSA	European Food Safety Authority
EPA	Eicosapentaenoic acid
FDA	Food and Drug Administration
GRAS	Generally Recognized as Safe
NLC	Nanostructured lipid carriers
PUFA	Polyunsaturated fatty acids
SLN	Solid lipid nanoparticles

References

1. Roşian, Ş.H.; Boarescu, I.; Boarescu, P. Antioxidant and Anti-Inflammatory Effects of Bioactive Compounds in Atherosclerosis. *Int. J. Mol. Sci.* **2025**, *26*, 1379. [CrossRef]
2. Saleem, A.; Akhtar, M.F.; Sharif, A.; Akhtar, B.; Siddique, R.; Ashraf, G.; Alghamdi, B.S.; Alharthy, S.A. Anticancer, Cardio-Protective and Anti-Inflammatory Potential of Natural-Sources-Derived Phenolic Acids. *Molecules* **2022**, *27*, 7286. [CrossRef]

3. Dixit, V.; Joseph Kamal, S.W.; Bajrang Chole, P.; Dayal, D.; Chaubey, K.K.; Pal, A.K.; Xavier, J.; Manjunath, B.T.; Bachheti, R.K.; Kamal, S.W.J.; et al. Functional Foods: Exploring the Health Benefits of Bioactive Compounds from Plant and Animal Sources. *J. Food Qual.* **2023**, *2023*, 5546753. [CrossRef]
4. Pasquet, P.L.; Julien-David, D.; Zhao, Z.; Villain-Gambier, M.; Trébouet, D. Food Bioscience Stability and Preservation of Phenolic Compounds and Related Antioxidant Capacity from Agro-Food Matrix: Effect of PH and Atmosphere. *Food Biosci.* **2024**, *57*, 103586. [CrossRef]
5. Awuchi, C.G.; Morya, S.; Dendegh, T.A.; Okpala, C.O.R.; Korzeniowska, M. Nanoencapsulation of Food Bioactive Constituents and Its Associated Processes: A Revisit. *Bioresour. Technol. Rep.* **2022**, *19*, 101088. [CrossRef]
6. Prieto, C.; Lagaron, J.M. Nanoencapsulation and Nanocoating of Bioactives of Application Interest in Food, Nutraceuticals and Pharma. *Nanomaterials* **2024**, *14*, 313. [CrossRef]
7. Durazzo, A.; Caiazzo, E.; Lucarini, M.; Cicala, C.; Izzo, A.A.; Novellino, E.; Santini, A. Polyphenols: A Concise Overview on the Chemistry, Occurrence, and Human Health. *Phyther. Res.* **2019**, *33*, 2221–2243. [CrossRef] [PubMed]
8. Saini, R.K.; Prasad, P.; Lokesh, V.; Shang, X.; Shin, J. Carotenoids: Dietary Sources, Extraction, Encapsulation, Bioavailability, and Health Benefits—A Review of Recent Advancements. *Antioxidants* **2022**, *11*, 795. [CrossRef] [PubMed]
9. Audrey, J.; Nazareth, T.D.M.; Fernandes, G.; Luciano, F.B. Bioactive Antimicrobial Peptides from Food Proteins: Perspectives and Challenges for Controlling Foodborne Pathogens. *Pathogens* **2023**, *12*, 477. [CrossRef]
10. Angane, M.; Swift, S.; Huang, K.; Butts, C.A. Essential Oils and Their Major Components: An Updated Review on Antimicrobial Activities, Mechanism of Action and Their Potential Application in the Food Industry. *Foods* **2022**, *11*, 464. [CrossRef]
11. Herbig, A.; Renard, C.M.G.C. Factors That Impact the Stability of Vitamin C at Intermediate Temperatures in a Food Matrix. *Food Chem.* **2017**, *220*, 444–451. [CrossRef]
12. Zhang, J.; Freund, M.A.; Culler, M.D.; Yang, R.; Chen, P.B.; Park, Y.; Decker, E.A.; Zhang, G. How To Stabilize ω-3 Polyunsaturated Fatty Acids (PUFAs) in an Animal Feeding Study?—Effects of the Temperature, Oxygen Level, and Antioxidant on Oxidative Stability of ω-3 PUFAs in a Mouse Diet. *J. Agric. Food Chem.* **2020**, *68*, 13146–13153. [CrossRef]
13. Cardoso, D.R.; Libardi, S.H.; Skibsted, L.H. Riboflavin as a Photosensitizer. Effects on Human Health and Food Quality. *Food Funct.* **2012**, *3*, 487–502. [CrossRef]
14. Kroes-Nijboer, A.; Sawalha, H.; Venema, P.; Bot, A.; Flöter, E.; den Adel, R.; Bouwmanc, W.G.; van der Linden, E. Stability of Aqueous Food Grade Fibrillar Systems against PH Change. *Faraday Discuss.* **2012**, *158*, 125–138. [CrossRef]
15. Lago, C.C.; Noren, C.P.Z. Thermodynamic and Kinetics Study of Phenolics Degradation and Color of Yacon (*Smallanthus sonchifolius*) Microparticles under Accelerated Storage Conditions. *J. Food Sci. Technol.* **2017**, *54*, 4197–4204. [CrossRef]
16. Morzel, M.; Canon, F.; Guyot, S. Interactions between Salivary Proteins and Dietary Polyphenols: Potential Consequences on Gastrointestinal Digestive Events. *J. Agric. Food Chem.* **2022**, *70*, 6317–6327. [CrossRef]
17. Serrano, J.; Puupponen-pimiä, R.; Dauer, A.; Aura, A. Tannins: Current Knowledge of Food Sources, Intake, Bioavailability and Biological Effects. *Mol. Nutr. Food Res.* **2009**, *53*, S310–S329. [CrossRef]
18. Wang, B.; Pham, L.B.; Adhikari, B. Complexation and Conjugation between Phenolic Compounds and Proteins: Mechanisms, Characterisation and Applications as Novel Encapsulants. *Sustain. Food Technol.* **2024**, *2*, 1206–1227. [CrossRef]
19. Ozkan, G.; Franco, P.; De Marco, I.; Xiao, J.; Capanoglu, E. A Review of Microencapsulation Methods for Food Antioxidants: Principles, Advantages, Drawbacks and Applications. *Food Chem.* **2019**, *272*, 494–506. [CrossRef]
20. Bińkowska, W.; Szpicer, A.; Stelmasiak, A.; Wojtasik-Kalinowska, I.; Półtorak, A. Microencapsulation of Polyphenols and Their Application in Food Technology. *Appl. Sci.* **2024**, *14*, 11954. [CrossRef]
21. Wani, S.U.; Ali, M.; Mehdi, S.; Masoodi, M.H.; Zargar, M.I.; Shakeel, F. A Review on Chitosan and Alginate-Based Microcapsules: Mechanism and Applications in Drug Delivery Systems. *Int. J. Biol. Macromol.* **2023**, *248*, 125875. [CrossRef]
22. Gasa-Falcon, A.; Odriozola-Serrano, I.; Oms-Oliu, G.; Martín-Belloso, O. Nanostructured Lipid-Based Delivery Systems as a Strategy to Increase Functionality of Bioactive Compounds. *Foods* **2020**, *9*, 325. [CrossRef]
23. Donsi, F.; Mcclements, D.J. Protein-Based Delivery Systems for the Nanoencapsulation of Food Ingredients. *Compr. Rev. Food Sci. Food Saf.* **2018**, *17*, 920–936. [CrossRef]
24. Afzal, A.; Afzaal, M.; Saeed, F.; Shah, Y.A.; Raza, A.; Khan, M.H.; Asghar, A.; Akram, N.; Asres, D.T. Milk Protein Based Encapsulation of Probiotics and Other Food Material: Comprehensive Review. *Int. J. Food Prop.* **2024**, *27*, 245–262. [CrossRef]
25. Majeed, A.; Khan, M.; Hanan, H.; Hameed, Y.; Zafar, T. A Narrative Review on Lipid-Polymer Hybrid Nanoparticles for Geriatric Oncology: Advancing Drug Delivery in the Aging Population. *Aging Adv.* **2025**, *6189*, 14–20. [CrossRef]
26. Go, Y.K.; Leal, C. Polymer—Lipid Hybrid Materials. *Chem. Rev.* **2021**, *121*, 13996–14030. [CrossRef]
27. Fu, X.; Du, Y.; Xiao, G.; Jia, Q.; Belwal, T.; Luo, Z.; Huang, T.; Yang, X.; Wang, D.; Wu, M.; et al. Whey Protein/Pectin-Coated W/O/W Emulsion as Stable Vehicles for Co-Loading Phenolic Compounds of Carya Cathayensis Sarg. Peels: Encapsulation and Molecular Dynamic Behavior. *Food Innov. Adv.* **2025**, *4*, 201–211. [CrossRef]
28. Jiang, L.; Zhang, Z.; Qiu, C.; Wen, J. A Review of Whey Protein-Based Bioactive Delivery Systems: Design, Fabrication, and Application. *Foods* **2024**, *13*, 2453. [CrossRef]

29. Rahat, I.; Yadav, P.; Singhal, A.; Fareed, M.; Purushothaman, J.R.; Aslam, M.; Balaji, R.; Patil-shinde, S. Polymer Lipid Hybrid Nanoparticles for Phytochemical Delivery: Challenges, Progress, and Future Prospects. *Beilstein J. Nanotechnol.* **2024**, *15*, 1473–1497. [CrossRef] [PubMed]
30. Zhang, S.; Wang, K.; Qin, Y.; Zhu, S.; Gao, Q.; Liu, D. The Synthesis, Biological Activities and Applications of Protein–Polysaccharide Conjugates in Food System: A Review. *Food Qual. Saf.* **2023**, *7*, fyad006. [CrossRef]
31. Kandasamy, S.; Naveen, R. A Review on the Encapsulation of Bioactive Components Using Spray-Drying and Freeze-Drying Techniques. *J. Food Process Eng.* **2022**, *45*, e14059. [CrossRef]
32. Coimbra, P.P.S.; Cardoso, F.S.N.; Goncalves, E.C.B.A. Spray-Drying Wall Materials: Relationship with Bioactive Compounds. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 2809–2826. [CrossRef]
33. Jafari, S.; Jafari, S.M.; Ebrahimi, M.; Kijpatanasilp, I.; Assatarakul, K. A Decade Overview and Prospect of Spray Drying Encapsulation of Bioactives from Fruit Products: Characterization, Food Application and in Vitro Gastrointestinal Digestion. *Food Hydrocoll.* **2023**, *134*, 108068. [CrossRef]
34. Bińkowska, W.; Szpicer, A.; Stelmasiak, A.; Wojtasik-kalinowska, I.; Półtorak, A. Innovative Application of Microencapsulated Polyphenols in Cereal Products: Optimization of the Formulation of Dairy- and Gluten-Free Pastry. *J. Food Process Eng.* **2024**, *47*, e14685. [CrossRef]
35. Napiórkowska, A. Understanding Emulsifier Influence on Complex Coacervation: Essential Oils Encapsulation Perspective. *J. Food Sci.* **2024**, *89*, 4997–5015. [CrossRef]
36. Napiórkowska, A.; Szpicer, A.; Wojtasik-Kalinowska, I.; Perez, M.D.T.; González, H.D.; Kurek, M.A. Microencapsulation of Juniper and Black Pepper Essential Oil Using the Coacervation Method and Its Properties after Freeze-Drying. *Foods* **2023**, *12*, 4345. [CrossRef]
37. More, S.; Bampidis, V.; Benford, D.; Bragard, C.; Halldorsson, T.; Bennekou, S.H.; Koutsoumanis, K.; Machera, K.; Naegeli, H.; Nielsen, S.; et al. Guidance on Risk Assessment of Nanomaterials to Be Applied in the Food and Feed Chain: Human and Animal Health. *EFSA Sci. Comm.* **2021**, *19*, e06768. [CrossRef]
38. Pugazhendhi, A.; Ali, M.; Kandasamy, S.; Kumar, P.; Sharma, A. Deciphering the Importance of Nanoencapsulation to Improve the Availability of Bioactive Molecules in Food Sources to the Human Body. *Food Chem.* **2025**, *464*, 141762. [CrossRef]
39. Kim, E.; Ban, C.; Oh, S. Applications and Perspectives of Polyphenol-Loaded Solid Lipid Nanoparticles and Nanostructured Lipid Carriers for Foods. *Food Sci. Biotechnol.* **2022**, *31*, 1009–1026. [CrossRef] [PubMed]
40. Liu, G.Y.; Wang, J.M.; Xia, Q. Application of Nanostructured Lipid Carrier in Food for the Improved Bioavailability. *Eur. Food Res. Technol.* **2012**, *234*, 391–398. [CrossRef]
41. Wang, H.; Hao, L.; Niu, B.; Jiang, S.; Cheng, J.; Jiang, S. Kinetics and Antioxidant Capacity of Proanthocyanidins Encapsulated in Zein Electrospun Fibers by Cyclic Voltammetry. *J. Agric. Food Chem.* **2016**, *64*, 3083–3090. [CrossRef]
42. Weng, J.; Chen, M.; Zou, Y.; Li, Y.; Lan, Y.; Zhang, H. Fabrication and Characterization of Electrospun Core-Shell Nanofibers of Bilayer Zein/Pullulan Emulsions Crosslinked by Genipin. *Int. J. Biol. Macromol.* **2024**, *281*, 136324. [CrossRef] [PubMed]
43. Horuz, T.İ.; Belibağlı, K.B. Nanoencapsulation by Electrospinning to Improve Stability and Water Solubility of Carotenoids Extracted from Tomato Peels. *Food Chem.* **2018**, *268*, 86–93. [CrossRef]
44. Figueroa-Enriquez, C.E.; Rodr, F.; Plascencia-Jatomea, M.; Armida, S.; Vargas-l, J.M.; Tapia-Hern, A.; Santos-Sauceda, I.; Canizales-Rodr, D.F.; Castro-Enriquez, D.D.; Burruel-Ibarra, S.E.; et al. Nanoparticles of Betalain—Gelatin with Antioxidant Properties by Coaxial Electrospraying: Preparation and Characterization. *ACS Omega* **2023**, *8*, 41156–41168. [CrossRef]
45. Wen, P.; Wen, Y.; Zong, M.; Linhardt, R.J.; Wu, H. Encapsulation of Bioactive Compound in Electrospun Fibers and Its Potential Application. *J. Agric. Food Chem.* **2017**, *65*, 9161–9179. [CrossRef]
46. Ahmadzadeh, S.; Lenie, M.D.R.; Mirmahdi, R.S. Designing Future Foods: Harnessing 3D Food Printing Technology to Encapsulate Bioactive Compounds. *Crit. Rev. Food Sci. Nutr.* **2025**, *65*, 303–319. [CrossRef]
47. Matas-gil, A.; Igual, M.; García-segovia, P.; Martínez-monzó, J. Incorporation of Encapsulated Omega-3 in 3D-Printed Food Gels: A Study on Rheology, Extrusion, and Print Performance in Dual Ink Printing. *Foods* **2025**, *14*, 2681. [CrossRef]
48. Caddeo, C.; Díez-sales, O.; Pons, R.; Carbone, C.; Ennas, G.; Puglisi, G.; Maria, A.; Manconi, M. Cross-Linked Chitosan/Liposome Hybrid System for the Intestinal Delivery of Quercetin. *J. Colloid Interface Sci.* **2016**, *461*, 69–78. [CrossRef]
49. Aghbashlo, M.; Mobli, H. Influence of Wall Material and Inlet Drying Air Temperature on the Microencapsulation of Fish Oil by Spray Drying. *Food Bioprocess Technol.* **2013**, *6*, 1561–1569. [CrossRef]
50. Ferraz, M.C.; Procopio, F.R.; de Figueiredo Furtado, G.; Hubinger, M.D. Co-Encapsulation of Paprika and Cinnamon Oleoresin by Spray Drying Using Whey Protein Isolate and Maltodextrin as Wall Material: Development, Characterization and Storage Stability. *Food Res. Int.* **2022**, *162*, 112164. [CrossRef]
51. Pudžiuvelyt, L.; Petrauskaitė, E.; Stabrauskienė, J.; Bernatonienė, J. Spray-Drying Microencapsulation of Natural Bioactives: Advances in Sustainable Wall Materials. *Pharmaceuticals* **2025**, *18*, 963. [CrossRef]

52. Mahmud, S.; Khan, S.; Rahman, M.; Julkifal, K.; Kumar, U.; Anwarul, S.G.M.M.; Maruf, H. Viability and Stability of Microencapsulated Probiotic Bacteria by Freeze-Drying under in Vitro Gastrointestinal Conditions. *J. Food Process. Preserv.* **2022**, *46*, e17123. [CrossRef]
53. Buljeta, I.; Pichler, A.; Šimunović, J.; Kopjar, M. Polysaccharides as Carriers of Polyphenols: Comparison of Freeze-Drying and Spray-Drying as Encapsulation Techniques. *Molecules* **2022**, *27*, 5069. [CrossRef]
54. Isleroglu, H. Evaluation of Process Conditions for Ultrasonic Spray Freeze Drying of Transglutaminase. *Food Technol. Biotechnol.* **2020**, *58*, 38–48. [CrossRef]
55. Yang, M.; Peng, J.; Zi, Y.; Shi, C.; Kan, G.; Wang, X.; Zhong, J. Encapsulation of Fish Oil by Complex Coacervation and Freeze Drying with Modified Starch Aid. *Food Hydrocoll.* **2023**, *137*, 108371. [CrossRef]
56. Angélica, L.; Zuanon, C.; Malacrida, C.R.; Regina, V.; Telis, N. Production of Turmeric Oleoresin Microcapsules by Complex Coacervation with Gelatin–Gum Arabic. *J. Food Process Eng.* **2013**, *36*, 364–373. [CrossRef]
57. Yuan, Y.; Kong, Z.; Sun, Y.; Zeng, Q.; Yang, X. Complex Coacervation of Soy Protein with Chitosan: Constructing Antioxidant Microcapsule for Algal Oil Delivery. *LWT-Food Sci. Technol.* **2017**, *75*, 171–179. [CrossRef]
58. Rousi, Z.; Malhiac, C.; Fatouros, D.G.; Paraskevopoulou, A. Food Hydrocolloids Complex Coacervates Formation between Gelatin and Gum Arabic with Di Ff Erent Arabinogalactan Protein Fraction Content and Their Characterization. *Food Hydrocoll.* **2019**, *96*, 577–588. [CrossRef]
59. Marfil, P.H.M.; Paulo, B.B. Production and Characterization of Palm Oil Microcapsules Obtained by Complex Coacervation in Gelatin/Gum Arabic. *J. Food Process Eng.* **2018**, *41*, e12673. [CrossRef]
60. Sun, Y.; Tang, W.; Pu, C.; Sun, Q.; Wang, H. Improved Stability of Liposome-Stabilized Emulsions as a Co-Encapsulation Delivery System for Vitamin B2, Vitamin E and β-Carotene. *Food Funct.* **2022**, *5*, 2966–2984. [CrossRef]
61. Mary, J.; Amruth, P.; Jacob, M.R.; Kumar, P.; Renuka, V.; Anandan, R. Liposome Mediated Encapsulation and Role of Chitosan on Modulating Liposomal Stability to Deliver Potential Bioactives-A Review. *Food Hydrocoll. Heal* **2023**, *4*, 100142. [CrossRef]
62. Silva, P.M.; Gonçalves, C.; Pastrana, L.M.; Coimbra, M.A.; Vicente, A.A.; Cerqueira, M.A. Recent Advances in Oral Delivery Systems of Resveratrol: Foreseeing Their Use in Functional Foods. *Food* **2023**, *14*, 10286–10313. [CrossRef]
63. Ruiz-montañez, G.; Ragazzo-sanchez, J.A.; Picart-palmade, L.; Chevalier-lucia, D. Optimization of Nanoemulsions Processed by High-Pressure Homogenization to Protect a Bioactive Extract of Jackfruit (*Artocarpus heterophyllus Lam*). *Innov. Food Sci. Emerg. Technol.* **2017**, *40*, 35–41. [CrossRef]
64. Jo, Y.; Kwon, Y. Characterization of β-Carotene Nanoemulsions Prepared by Microfluidization Technique. *Food Sci. Biotechnol.* **2014**, *23*, 107–113. [CrossRef]
65. Borges, A.; de Freitas, V.; Mateus, N.; Fernandes, I.; Oliveira, J. Solid Lipid Nanoparticles as Carriers of Natural Phenolic Compounds. *Antioxidants* **2020**, *9*, 998. [CrossRef]
66. Gangavarapu, A.; Tapia-Lopez, L.V.; Sarkar, B.; Pena-Zacarias, J.; Badruddoza, A.Z.M.; Nurunnabi, M. Lipid Nanoparticles for Enhancing Oral Bioavailability. *Nanoscale* **2024**, *16*, 18319–18338. [CrossRef]
67. Shu, X.; Zhang, L.; Liao, W.; Liu, J.; Mao, L.; Yuan, F.; Gao, Y. Nanostructured Lipid Carriers (NLCs) Stabilized by Natural or Synthetic Emulsifiers for Lutein Delivery: Improved Physicochemical Stability, Antioxidant Activity, and Bioaccessibility. *Food Chem.* **2023**, *403*, 134465. [CrossRef] [PubMed]
68. Malekmohammadi, M.; Ghanbarzadeh, B.; Hanifian, S.; Kafil, H.S.; Gharekhani, M.; Falcone, P.M. Containing Salvia Officinalis Extract: Optimization by Combined D-Optimal Design and Its Application to Improve the Quality Parameters of Beef Burger. *Foods* **2023**, *12*, 3737. [CrossRef]
69. Demei, K.; Zhang, M.; Phuhongsung, P.; Mujumdar, A.S. 3D Food Printing: Controlling Characteristics and Improving Technological Effect during Food Processing. *Food Res. Int.* **2022**, *156*, 111120. [CrossRef]
70. Oliveira, M.B.; Hatami, J.; Mano, F. Coating Strategies Using Layer-by-Layer Deposition for Cell Encapsulation. *Chem.—Asian J.* **2016**, *11*, 1753–1764. [CrossRef]
71. Barbara, V.; Rysenaer, J.; Ahmadzadeh, S.; Van Bockstaele, F.; Ubeyitogullari, A. Current Research in Food Science An Extrusion-Based 3D Food Printing Approach for Generating Alginate-Pectin Particles. *Curr. Res. Food Sci.* **2023**, *6*, 100404. [CrossRef]
72. Ćujić-nikolić, N.; Stanisavljević, N.; Šavikin, K.; Kalušević, A.; Nedović, V.; Samardžić, J.; Janković, T. Chokeberry Polyphenols Preservation Using Spray Drying: Effect of Encapsulation Using Maltodextrin and Skimmed Milk on Their Recovery Following in Vitro Digestion Following in Vitro Digestion. *J. Microencapsul.* **2019**, *36*, 693–703. [CrossRef]
73. Lüdtke, F.L.; Fernandes, J.; Gonçalves, R.F.S.; Martins, J.T.; Berni, P.; Ribeiro, A.P.B.; Vicente, A.A.; Pinheiro, A.C. Performance of β-Carotene-Loaded Nanostructured Lipid Carriers under Dynamic in Vitro Digestion System: Influence of the Emulsifier Type. *J. Food Sci.* **2024**, *89*, 3290–3305. [CrossRef] [PubMed]
74. Álvarez-Henao, M.V.; Saavedra, N.; Medina, S.; Cartagena, C.J.; Alzate, L.M.; Londoño-londoño, J. Microencapsulation of Lutein by Spray-Drying: Characterization and Stability Analyses to Promote Its Use as a Functional Ingredient. *Food Chem.* **2018**, *256*, 181–187. [CrossRef]

75. Etzbach, L.; Meinert, M.; Faber, T.; Klein, C.; Schieber, A.; Weber, F. Effects of Carrier Agents on Powder Properties, Stability of Carotenoids, and Encapsulation Ef Fi Ciency of Goldenberry (*Physalis peruviana* L.) Powder Produced by Co-Current Spray Drying. *Curr. Res. Food Sci.* **2020**, *3*, 73–81. [CrossRef]
76. Activities, A.; Dantas, D.; Alencar, D.O.; De Souza, E.L.; Thayse, E. Microencapsulation of Cymbopogon Citratus D.C. Stapf Essential Oil with Spray Drying: Development, Characterization, and Antioxidant and Antibacterial Activities. *Foods* **2022**, *11*, 1111. [CrossRef]
77. Simunović, S.; Đorđević, V.Ž.; Simunović, S.; Franco, D.; Stajić, S.; Tomašević, I. Sensory Quality, Oxidative Stability, Textural and Fatty Acid Profile of Nitrite-Reduced Kulen Fermented Sausage during Ripening. *Meat Technol.* **2023**, *64*, 212–217. [CrossRef]
78. Ahmed, J.; Mulla, M.Z.; Al-Attar, H.; AlZuwayed, S.; Ejaz, M.; Al-Jassar, S.; Jacob, H.; Thomas, L.; Al-Attar, N.; Joseph, A.; et al. Thermal, Structural, Antimicrobial, and Physicochemical Characterisation of Thyme Essential Oil Encapsulated in β- and γ-Cyclodextrin. *J. Microencapsul.* **2022**, *39*, 364–379. [CrossRef]
79. Shao, M.; Li, S.; Ping, C.; Kraithong, S.; Gao, Q.; Fu, X. Encapsulation of Caffeine into Starch Matrices: Bitterness Evaluation and Suppression Mechanism. *Int. J. Biol. Macromol.* **2021**, *173*, 118–127. [CrossRef]
80. Griep, P.; Gayeski, L.; Colet, R.; Zeni, J.; Valduga, E. Recent Updates of Carotenoid Encapsulation by Spray-Drying Technique. *J. Microencapsul.* **2025**, *42*, 26–46. [CrossRef]
81. Meenu, M.; Pujari, A.K.; Kirar, S.; Thakur, A.; Garg, M.; Bhaumik, J. Development of Bionanocomposite Packaging Films Based on Lignin Nanoencapsulated Anthocyanins Extracted from Agro-Waste for Enhancing the Post-Harvest Shelf Life of Tomatoes. *Sustain. Food Technol.* **2025**, *3*, 414–424. [CrossRef]
82. Khor, C.M.; Ng, W.K.; Kanaujia, P.; Chan, K.P.; Dong, Y. Hot-Melt Extrusion Microencapsulation of Quercetin for Taste-Masking. *J. Microencapsul.* **2017**, *34*, 29–37. [CrossRef]
83. Zhou, H.; Zheng, B.; McClements, D.J. Encapsulation of Lipophilic Polyphenols in Plant-Based Nanoemulsions: Impact of Carrier Oil on Lipid Digestion and Curcumin, Resveratrol and Quercetin Bioaccessibility. *Food Funct.* **2021**, *12*, 3420–3432. [CrossRef]
84. Pateiro, M.; Munekata, P.E.S.; Mcclements, D.J.; Lorenzo, J.M. Encapsulation of Bioactive Phytochemicals in Plant-Based Matrices and Application as Additives in Meat and Meat Products. *Molecules* **2021**, *26*, 3984. [CrossRef]
85. Liu, H.; Luo, J.; Yang, P.; Yang, X.; Yan, J.; Yao, Q. Stability, Antioxidant Activity and Intestinal Permeation of Oleuropein Inclusion Complexes with Beta-Cyclodextrin and Hydroxypropyl-Beta-Cyclodextrin. *Molecules* **2022**, *27*, 5077. [CrossRef]
86. Souza, C.J.F.; Comunian, T.A.; Kasemodel, M.G.C.; Favaro-trindade, C.S. Microencapsulation of Lactase by W/O/W Emulsion Followed by Complex Coacervation: Effects of Enzyme Source, Addition of Potassium and Core to Shell Ratio on Encapsulation Efficiency, Stability and Kinetics of Release. *Food Res. Int.* **2019**, *121*, 754–764. [CrossRef]
87. Lee, J.; Duggan, E. Improved Stability of Vitamin D 3 Encapsulated in Whey Protein Isolate Microgels. *Int. Dairy J.* **2022**, *129*, 105351. [CrossRef]
88. Shahparast, Y.; Eskandani, M.; Rajaei, A.; Khosroushahi, A.Y. Preparation, Physicochemical Characterization and Oxidative Stability of Omega-3 Fish Oil/α -Tocopherol-Co-Loaded Nanostructured Lipidic Carriers. *Tabriz Univ. Med. Sci.* **2019**, *7*, 113–117. [CrossRef]
89. Damerau, A.; Mustonen, S.A.; Ogrodowska, D.; Varjotie, L.; Brandt, W.; Laaksonen, O.; Tańska, M.; Linderborg, K.M. Food Fortification Using Spray-Dried Emulsions of Fish Oil Produced with Maltodextrin, Plant and Whey Proteins-Effect on Sensory Perception, Volatiles and Storage Stability. *Molecules* **2022**, *27*, 3553. [CrossRef]
90. Ghorbanzade, T.; Jafari, S.M.; Akhavan, S.; Hadavi, R. Nano-Encapsulation of Fish Oil in Nano-Liposomes and Its Application in Fortification of Yogurt. *Food Chem.* **2017**, *216*, 146–152. [CrossRef]
91. Weng, Y.; Yang, G.; Li, Y.; Xu, L.; Chen, X.; Song, H.; Zhao, X. Alginate-Based Materials for Enzyme Encapsulation. *Adv. Colloid Interface Sci.* **2023**, *318*, 102957. [CrossRef]
92. Cui, F.; Zhang, H.; Wang, D.; Tan, X.; Li, X.; Li, Y.; Li, J.; Li, T. Advances in the Preparation and Application of Microencapsulation to Protect Food Functional Ingredients. *Food Funct.* **2023**, *14*, 6766–6783. [CrossRef]
93. Wen, C.; Liu, J.; Wang, J.; Liu, H.; Liu, G.; Xu, X.; Zhang, J.; Liu, J. Protein–Pectin Delivery Carriers for Food Bioactive Ingredients: Preparation, Release Mechanism, and Application. *Compr. Rev. Food Sci. Food Saf.* **2025**, *24*, e70183. [CrossRef]
94. Cao, T.; Wei, Z.; Xue, C. Recent Advances in Nutraceutical Delivery Systems Constructed by Protein–Polysaccharide Complexes: A Systematic Review. *Compr. Rev. Food Sci. Food Saf.* **2025**, *24*, e70115. [CrossRef]
95. Haham, M.; Ish-shalom, S.; Nodelman, M.; Duek, I.; Segal, E.; Livney, Y.D. Stability and Bioavailability of Vitamin D Nanoencapsulated in Casein Micelles. *Food Funct.* **2012**, *3*, 737–744. [CrossRef]
96. Suwannasang, S.; Zhong, Q.; Thumthanaruk, B. Physicochemical Properties of Yogurt Fortified with Microencapsulated Sacha Inchi Oil. *LWT-Food Sci. Technol.* **2022**, *161*, 113375. [CrossRef]
97. Lillo-p, S.; Monsalve, Y.; Mesa, M.; Martínez, R.; Bernal, C. Encapsulation of Glucose Oxidase and Asparaginase in Silica–Chitosan Hybrids: Stability and PH-Modulated Release for Potential Biomedical Applications. *Int. J. Biol. Macromol.* **2025**, *323*, 146890.
98. Chai, C.; Park, J. Food Liposomes: Structures, Components, Preparations, and Applications. *Food Chem.* **2024**, *432*, 137228. [CrossRef]

99. Hussain, M.; Bisht, A.; Khan, I.; Chaudhary, N. Enhanced Stability of N-3 PUFAs Rich Structured Lipids via Spray-Dried Microencapsulation with Tailored Wall Materials. *Sustain. Food Technol.* **2025**, *3*, 1492–1504. [CrossRef]
100. Šaponjac, V.; Estivi, L.; Brandolini, A.; Ćetković, G.; Šaponjac, V.T.; Hidalgo, A. Kinetics of Carotenoids Degradation during the Storage. *Molecules* **2022**, *27*, 8759. [CrossRef]
101. Rezaee, M.; Aider-kaci, F.A.; Aider, M. Effects of Hydrocolloid Agar, Gelatin, Pectin, and Xanthan on Physicochemical and Rheological Properties of Pickering Emulsions Stabilized by Canola Protein Microgel as a Potential Animal Fat Replacer. *ACS Food Sci. Technol.* **2022**, *2*, 1681–1690. [CrossRef]
102. Sudha, M.L.; Chetana, R.; Reddy, S.Y. Effect of Microencapsulated Fat Powders on Rheological Characteristics of Biscuit Dough and Quality of Biscuits. *J. Food Sci. Technol.* **2014**, *51*, 3984–3990. [CrossRef]
103. Guldiken, B.; Gibis, M. Ascorbic Acid-Induced Degradation of Liposome-Encapsulated Acylated and Non-Acylated Anthocyanins of Black Carrot Extract. *J. Sci. Food Agric.* **2021**, *101*, 5707–5714. [CrossRef]
104. Drosou, C.; Krokida, M. Enrichment of White Chocolate with Microencapsulated β-Carotene: Impact on Quality Characteristics and β-Carotene Stability during Storage. *Foods* **2024**, *13*, 2699. [CrossRef]
105. Morsy, M.K.; Morsy, O.M.; Abdelmonem, M.A.; Elsabagh, R. Anthocyanin—Colored Microencapsulation Effects on Survival Rate of Lactobacillus Rhamnosus G, Color Stability, and Sensory Parameters in Strawberry Nectar Model. *Food Bioprocess Technol.* **2022**, *15*, 352–367. [CrossRef]
106. Jeyakumari, A.; Janarthanan, G.; Chouksey, M.K.; Venkateshwarlu, G. Effect of Fish Oil Encapsulates Incorporation on the Physico-Chemical and Sensory Properties of Cookies. *J. Food Sci. Technol.* **2016**, *53*, 856–863. [CrossRef]
107. Yang, X.; Liang, Y.; Li, K.; Hu, Q.; He, J.; Xie, J. Advances in Microencapsulation of Flavor Substances: Preparation Techniques, Wall Material Selection, Characterization Methods, and Applications. *J. Agric. Food Chem.* **2025**, *73*, 9459–9477. [CrossRef]
108. Grassia, M.; Messia, M.C.; Marconi, E.; Demirkol, Ö̃.Ş.; Erdo, F.; Sarghini, F.; Cinquanta, L. Microencapsulation of Phenolic Extracts from Cocoa Shells to Enrich Chocolate Bars. *Plant Foods Hum. Nutr.* **2021**, *76*, 449–457. [CrossRef]
109. Fernandes, B.; Conceiç, M.; Marques, A.C.; Galhano, R.; Serrano, C. Microencapsulation of Essential Oils and Oleoresins: Applications in Food Products. *Foods* **2024**, *13*, 3873. [CrossRef]
110. Mohammed, N.K.; Tan, C.P.; Manap, Y.A.; Muhialdin, B.J.; Shobirin, A.; Hussin, M. Spray Drying for the Encapsulation of Oils—A Review. *Molecules* **2020**, *25*, 3873. [CrossRef]
111. Cui, T.; Chen, C.; Jia, A.; Li, D.; Shi, Y.; Zhang, M.; Bai, X.; Liu, X.; Liu, C. Characterization and Human Microfold Cell Assay of Fish Oil Microcapsules: Effect of Spray Drying and Freeze-Drying Using Konjac Glucomannan (KGM)-Soybean Protein Isolate (SPI) as Wall Materials. *J. Funct. Foods* **2021**, *83*, 104542. [CrossRef]
112. Prasad, Y.; Wang, B.; Adhikari, R.; Adhikari, B. Advances in Microencapsulation of Polyunsaturated Fatty Acids (PUFAs)-Rich Plant Oils Using Complex Coacervation: A Review. *Food Hydrocoll.* **2017**, *69*, 369–381. [CrossRef]
113. Li, Y.; Li, M.; Qi, Y.; Zheng, L.; Wu, C.; Wang, Z. Preparation and Digestibility of Fish Oil Nanoemulsions Stabilized by Soybean Protein Isolate-Phosphatidylcholine. *Food Hydrocoll.* **2020**, *100*, 105310. [CrossRef]
114. Salminen, H.; Helgason, T.; Kristinsson, B.; Kristbergsson, K.; Weiss, J. Formation of Solid Shell Nanoparticles with Liquid ω-3 Fatty Acid Core. *Food Chem.* **2013**, *141*, 2934–2943. [CrossRef]
115. Zhu, Q.; Guissi, F.; Yang, R.; Wang, Q.; Wang, K.; Chen, D.; Han, Z.; Ma, Y.; Zhang, M.; Gu, Y. Preparation of Deep Sea Fish Oil-Based Nanostructured Lipid Carriers with Enhanced Cellular Uptake. *J. Nanosci. Nanotechnol.* **2015**, *15*, 9539–9547. [CrossRef]
116. Moomand, K.; Lim, L. Effects of Solvent and N-3 Rich Fi Sh Oil on Physicochemical Properties of Electrospun Zein Fibres. *Food Hydrocoll.* **2015**, *46*, 191–200. [CrossRef]
117. Bajaj, S.R.; Marathe, S.J.; Singhal, R.S. Co-Encapsulation of Vitamins B12 and D3 Using Spray Drying: Wall Material Optimization, Product Characterization, and Release Kinetics. *Food Chem.* **2021**, *335*, 127642. [CrossRef]
118. Landi, C.; Landucci, E.; Mazzantini, C.; Castellacci, R.; Bergonzi, M.C. Vitamin D Nanoliposomes to Improve Solubility, Stability, and Uptake Across Intestinal Barrier. *Pharmaceutics* **2025**, *17*, 1244. [CrossRef]
119. Baek, J.; Ramasamy, M.; Carly, N.; Sung, D.; Anderson, W.A.; Tam, K.C. Current Research in Food Science Encapsulation and Controlled Release of Vitamin C in Modi Fi Ed Cellulose Nanocrystal/Chitosan Nanocapsules. *Curr. Res. Food Sci.* **2021**, *4*, 215–223. [CrossRef]
120. Fan, C.; Feng, T.; Wang, X.; Xia, S.; John Swing, C. Liposomes for Encapsulation of Liposoluble Vitamins (A, D, E and K): Comparation of Loading Ability, Storage Stability and Bilayer Dynamics. *Food Res. Int.* **2023**, *163*, 112264. [CrossRef] [PubMed]
121. Mujica-Álvarez, J.; Gil-Castell, O.; Barra, P.A.; Ribes-Greus, A.; Bustos, R.; Faccini, M.; Matiacevich, S. Encapsulation of Vitamins A and E as Spray-Dried Additives for the Feed Industry. *Molecules* **2020**, *25*, 1357. [CrossRef]
122. Mohammadi, M.; Ghanbarzadeh, B.; Hamishehkar, H. Formulation of Nanoliposomal Vitamin D3 for Potential Application in Beverage Fortification. *Adv. Pharm. Bull.* **2014**, *4*, 569–575. [CrossRef]
123. Dias, D.; Estevinho, B.N. Vitamin E Microencapsulation via Electrohydrodynamic Techniques for Potential Use in Skin Care and Dermatological Applications. *Molecules* **2025**, *30*, 2306. [CrossRef]

124. Edson, M.; Vitória, M.; Lemos, R.; Cristina, A.; Martins, S.; Lima, S.; Luiz, F.; Converti, A.; Inês, M.; Maciel, S. Microencapsulation by Spray-Drying and Freeze -Drying of Extract of Phenolic Compounds Obtained from Ciriguela Peel. *Sci. Rep.* **2023**, *13*, 15222. [CrossRef]
125. Formulation, A.F.; Todorovi, A.; Šturm, L.; Salevi, A.; Gasan, I.; Crnivec, O.; Bjekovi, A. Encapsulation of Bilberry Extract with Maltodextrin and Gum Arabic by Freeze-Drying: Formulation, Characterisation, and Storage Stability. *Processes* **2022**, *10*, 1991. [CrossRef]
126. Grgić, J.; Šelo, G.; Planinić, M.; Tišma, M.; Bucić-Kojić, A. Role of the Encapsulation in Bioavailability of Phenolic Compounds. *Antioxidants* **2020**, *9*, 923. [CrossRef]
127. Enaru, B.; Socaci, S.; Farcas, A.; Socaciu, C.; Danciu, C.; Stanila, A.; Diaconeasa, Z. Novel Delivery Systems of Polyphenols and Their Potential Health Benefits. *Pharmaceuticals* **2021**, *14*, 946. [CrossRef]
128. Zhu, P.; He, J.; Huang, S.; Han, L.; Chang, C.; Zhang, W. Encapsulation of Resveratrol in Zein-Polyglycerol Conjugate Stabilized O/W Nanoemulsions: Chemical Stability, in Vitro Gastrointestinal Digestion, and Antioxidant Activity. *LWT-Food Sci. Technol.* **2021**, *149*, 112049. [CrossRef]
129. Pimentel-Moral, S.; Durazzo, A.; Lucarini, M.; Fernández-Ochoa, Á.; de la Luz Cádiz-Gurrea, M.; Arráez-Román, D.; Silva, A.M.; Santini, A.; Fonseca, J.; Segura-Carretero, A.; et al. Hibiscus Sabdariffa-Loaded Nanostructured Lipid Carriers (NLC) for Fortified Nutraceutical Milks. *Eur. Food Res. Technol.* **2024**, *250*, 1999–2010. [CrossRef]
130. Chen, H.; Su, J.; Brennan, C.S.; Van Der Meeren, P.; Zhang, N.; Tong, Y.; Wang, P. Recent Developments of Electrospun Zein Nano Fi Bres: Strategies, Fabrication and Therapeutic Applications. *Mater. Today Adv.* **2022**, *16*, 100307. [CrossRef]
131. Li, X.; Wu, M.; Xiao, M.; Lu, S.; Wang, Z.; Yao, J.; Yang, L. Microencapsulated β-Carotene Preparation Using Different Drying Treatments. *J. Zhejiang Univ. B Biomed. Biotechnol.* **2019**, *20*, 901–909. [CrossRef]
132. Traffano-Schiffo, M.V.; Castro-giraldez, M.; Fito, P.J.; Santagapita, P.R. Encapsulation of Lactase in Ca(II)-Alginate Beads: Effect of Stabilizers and Drying Methods. *Food Res. Int.* **2017**, *100*, 296–303. [CrossRef]
133. Calvo, T.R.A.; Santagapita, P.R. Freezing and Drying of Pink Grapefruit-Lycopene Encapsulated in Ca (II)-Alginate Beads Containing Galactomannans. *J. Food Sci. Technol.* **2019**, *56*, 3264–3271. [CrossRef]
134. Teeranachaideekul, V. Influence of Vegetable Oils on In Vitro Performance of Lutein-Loaded Lipid Carriers for Skin Delivery: Nanostructured Lipid Carriers vs. Nanoemulsions. *Pharmaceutics* **2022**, *14*, 2160. [CrossRef]
135. Vargas, M.F.V.; Pardo, R.Y.R.; Villamil-Díaz, L.; Alean, J.; Santagapita, P.R.; Quintanilla-Carvajal, M.X. Encapsulation Improves Viability and Stability of Spray-Dried Lactococcus Lactis A12 for Inclusion in Fish Feed. *PLoS ONE* **2025**, *20*, e0323000. [CrossRef] [PubMed]
136. Machado, D.; Domingos, M.; Barbosa, J.C.; Almeida, D.; Andrade, C.; Freitas, A.C.; Gomes, A.M. Exploring Freeze-Drying as Strategy to Enhance Viability of Faecalibacterium Duncaniae DSM 17677 upon Aerobic Storage and Gastrointestinal Conditions. *Pharmaceutics* **2022**, *14*, 2735. [CrossRef]
137. Ali, M.; Zanjani, K.; Ghiassi, B. Microencapsulation of Probiotics by Calcium Alginate-Gelatinized Starch with Chitosan Coating and Evaluation of Survival in Simulated Human Gastro-Intestinal Condition. *Iran. J. Pharm. Res.* **2014**, *13*, 843–852.
138. Rodrigues, F.J.; Cedran, M.F.; Bicas, J.L.; Sato, H.H. Encapsulated Probiotic Cells: Relevant Techniques, Natural Sources as Encapsulating Materials and Food Applications—A Narrative Review. *Food Res. Int.* **2020**, *137*, 109682. [CrossRef] [PubMed]
139. Nimbkar, S.; Leena, M.M.; Moses, J.A.; Anandharamakrishnan, C. Development of Iron-Vitamin Multilayer Encapsulates Using 3 Fluid Nozzle Spray Drying. *Food Chem.* **2023**, *406*, 135035. [CrossRef]
140. Bhatnagar, R.S.; Lei, X.; Miller, D.D.; Padilla-zakour, O.I. Iron from Co-Encapsulation of Defatted Nannochloropsis Oceanica with Inulin Is Highly Bioavailable and Does Not Impact Wheat Flour Shelf Life or Sensorial Attributes. *Foods* **2023**, *12*, 675. [CrossRef]
141. Ah, K.; Cho, M.J.; Kim, Y.S.C. Iron Casein Succinylate-Chitosan Coacervate for the Liquid Oral Delivery of Iron with Bioavailability and Stability Enhancement. *Arch. Pharm. Res.* **2016**, *39*, 94–102. [CrossRef]
142. Zhang, P.; Bao, Z.; Jiang, P.; Zhang, S.; Zhang, X.; Lin, S.; Sun, N. Nanoliposomes for Encapsulation and Calcium Delivery of Egg White Peptide–Calcium Complex. *J. Food Sci.* **2021**, *86*, 1418–1431. [CrossRef]
143. Shen, Z.; Augustin, M.A.; Sanguansri, L.; Cheng, L.J. Oxidative Stability of Microencapsulated Fish Oil Powders Stabilized by Blends of Chitosan, Modified Starch, and Glucose. *J. Agric. Food Chem.* **2010**, *58*, 4487–4493. [CrossRef]
144. Annamalai, J.; Kothari, D.C.; Gudipati, V. Microencapsulation of Fish Oil-Milk Based Emulsion by Spray Drying: Impact on Oxidative Stability. *Fish. Technol.* **2014**, *51*, 31–37.
145. Bińkowska, W.; Szpicer, A.; Stelmasiak, A.; Wojtasik-Kalinowska, I.; Półtorak, A. Utilization of Microencapsulated Polyphenols to Enhance the Bioactive Compound Content in Whole Grain Bread: Recipe Optimization. *Appl. Sci.* **2024**, *14*, 10156. [CrossRef]
146. López-Pedrouso, M.; Zaky, A.A.; Lorenzo, J.M.; Camiña, M.; Franco, D. A Review on Bioactive Peptides Derived from Meat and By-Products: Extraction Methods, Biological Activities, Applications and Limitations. *Meat Sci.* **2023**, *204*, 109278. [CrossRef] [PubMed]

147. Wen, C.; Tang, J.; Cao, L.; Fan, M.; Lin, X.; Liu, G.; Liang, L.; Liu, X.; Zhang, J.; Li, Y.; et al. Strategic Approaches for Co-Encapsulation of Bioactive Compounds: Technological Advances and Mechanistic Insight. *Foods* **2025**, *14*, 2024. [CrossRef]
148. Rezvankhah, A.; Emam-djomeh, Z.; Askari, G. Encapsulation and Delivery of Bioactive Compounds Using Spray and Freeze-Drying Techniques: A Review. *Dry. Technol.* **2020**, *38*, 235–258. [CrossRef]
149. Drago, E.; Campardelli, R.; Perego, P. Sustainable Development of Biodegradable Antimicrobial Electrospun Membranes for Active Food Packaging and Economic Analysis. *Adv. Sustain. Syst.* **2025**, *8*, 2400360. [CrossRef]
150. Michalska-Ciechanowska, A.; Brzezowska, J.; Nowicka, P.; Tkacz, K.; Turkiewicz, I.P.; Hendrysiak, A.; Oszmiański, J.; Andlauer, W. Advantages of Spray Drying over Freeze Drying: A Comparative Analysis of *Lonicera caerulea* L. Juice Powders—Matrix Diversity and Bioactive Response. *Molecules* **2024**, *29*, 3586. [CrossRef]
151. Alrosan, M.; Al, N.; Muhammad, R.; Alu, H.; Al, A.; Esra, Q.; Shunnaq, A.; Abu, N.; Sofyan, K.; Taher, M.; et al. Complex Coacervation of Plant—Based Proteins and Polysaccharides: Sustainable Encapsulation Techniques for Bioactive Compounds. *Food Eng. Rev.* **2025**. [CrossRef]
152. Rashwan, A.K.; Osman, A.I.; Abdelshafy, A.M.; Mo, J.; Chen, W.; Rashwan, A.K.; Osman, A.I.; Abdelshafy, A.M. Plant-Based Proteins: Advanced Extraction Technologies, Interactions, Physicochemical and Functional Properties, Food and Related Applications, and Health Benefits. *Crit. Rev. Food Sci. Nutr.* **2025**, *65*, 667–694. [CrossRef]
153. Capanoglu, E.; Nemli, E.; Tomas-barberan, F. Novel Approaches in the Valorization of Agricultural Wastes and Their Applications. *J. Agric. Food Chem.* **2022**, *70*, 6787–6804. [CrossRef]
154. Couto, A.F.; Estevinho, B.N. Valorization of Agricultural By-Products (*Fragaria vesca*) through the Production of Value-Added Micro/Nanostructures Using Electrohydrodynamic Techniques. *Foods* **2024**, *13*, 1162. [CrossRef]
155. Kolanowski, W.; Jaworska, D.; Weißbrodt, L.J. Evaluation of Sensory Quality of Instant Foods Fortified with Omega-3 PUFA by Addition of Fish Oil Powder. *Eur. Food Res. Technol.* **2007**, *225*, 715–721. [CrossRef]
156. Tamjidi, F.; Nasirpour, A.; Shahedi, M. Physicochemical and Sensory Properties of Yogurt Enriched with Microencapsulated Fish Oil. *Food Sci. Technol. Int.* **2012**, *18*, 381–390. [CrossRef]
157. Koga, C.C.; Lee, S.; Lee, Y. Consumer Acceptance of Bars and Gummies with Unencapsulated and Encapsulated Resveratrol. *J. Food Sci.* **2016**, *81*, S1222–S1229. [CrossRef]
158. Gupta, A.; Sanwal, N.; Bareen, M.A.; Barua, S.; Sharma, N.; Joshua Olatunji, O.; Prakash Nirmal, N.; Sahu, J.K. Trends in Functional Beverages: Functional Ingredients, Processing Technologies, Stability, Health Benefits, and Consumer Perspective. *Food Res. Int.* **2023**, *170*, 113046. [CrossRef]
159. European Parliament; Council of the European Union. The European Parliament and the Council of the European Union Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on Novel Foods, Amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and Repealing Regulation (EC) No 258/97 of the European Parliam. *Off. J. Eur. Union* **2015**, *L327*, 1–22.
160. European Parliament; Council of the European Union. Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 Laying down the General Principles and Requirements of Food Law, Establishing the European Food Safety Authority and Laying down Procedures in Matters of Food Saf. *Off. J. Eur. Union* **2002**, *L 031*, 1–24.
161. Food and Drug Administration. *Food and Drug Administration Regulatory Framework for Substances Intended for Use in Human Food or Animal Food on the Basis of the Generally Recognized as Safe (GRAS) Provision of the Federal Food, Drug, and Cosmetic Act: Guidance for Industry*; Food and Drug Administration: Silver Spring, MD, USA, 2017; pp. 1–28.
162. Food and Drug Administration. *Food and Drug Administration Guidance for Industry Considering Whether an FDA-Regulated Product Involves the Application of Nanotechnology*; Food and Drug Administration: Silver Spring, MD, USA, 2014; pp. 1–14.
163. More, S.; Bampidis, V.; Benford, D.; Bragard, C.; Halldorsson, T.; Bennekou, S.H.; Koutsoumanis, K.; Lambr, C.; Machera, K.; Naegeli, H.; et al. Guidance on Technical Requirements for Regulated Food and Feed Product Applications to Establish the Presence of Small Particles Including Nanoparticles. *EFSA J.* **2021**, *19*, e06769. [CrossRef]
164. European Parliament; Council of the European Union. Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on Food Additives (Text with EEA Relevance). *Off. J. Eur. Union* **2008**, *L354*, 16–33.
165. European Commission. Commision Regulation (EU) 1169/2011 Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the Provision of Food Information to Consumers, Amending Regulations (EC) No 1924/2006 and (EC) No 1925/2006 of the European Parliament and of the Council, An. *Off. J. Eur. Union* **2011**, *L 304/18*, 1–46. [CrossRef]
166. European Parliament; Council of the European Union. The European Parliament and the Council of the European Union Commission Delegated Regulation (EU) No 1363/2013 of 12 December 2013 Amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council on the Provision of Food Information to Consumers as Regards the Definition of 'engineered Nanomateri. *Off. J. Eur. Union* **2013**, *L 343*, 2012–2014.
167. Ross, S. Functional Foods: The Food and Drug Administration Perspective. *Am. J. Clin. Nutr.* **2000**, *71*, 1735S–1738S. [CrossRef]
168. Parrella, J.A.; Leggette, H.R.; Lu, P.; Wingenbach, G.; Baker, M.; Murano, E. Nanofood Insights: A Survey of U.S. Consumers' Attitudes toward the Use of Nanotechnology in Food Processing. *Appetite* **2024**, *201*, 107613. [CrossRef]

169. Frewer, L.J.; Gupta, N.; George, S.; Fischer, A.R.H.; Giles, E.L.; Coles, D. Consumer Attitudes towards Nanotechnologies Applied to Food Production. *Trends Food Sci. Technol.* **2014**, *40*, 211–225. [CrossRef]
170. Giles, E.L.; Kuznesof, S.; Clark, B.; Hubbard, C.; Frewer, L.J. Consumer Acceptance of and Willingness to Pay for Food Nanotechnology: A Systematic Review. *J. Nanoparticle Res.* **2015**, *17*, 467. [CrossRef]
171. Siegrist, M.; Keller, C. Labeling of Nanotechnology Consumer Products Can Influence Risk and Benefit Perceptions. *Risk Anal.* **2011**, *31*, 1762–1769. [CrossRef]
172. Rothen-rutishauser, B.; Bogdanovich, M.; Harter, R.; Petri-fink, A. Use of Nanoparticles in Food Industry: Current Legislation, Health Risk Discussions and Public Perception with a Focus on Switzerland. *Toxicol. Environ. Chem.* **2021**, *103*, 423–437. [CrossRef]
173. European Parliament; Council of the European Union. *The European Parliament and the Council of the European Union Regulation (EC) No 1924/2006 of the European Parliament and of the Council of 20 December 2006 on Nutrition and Health Claims Made on Foods*; European Parliament; Council of the European Union: Brussels, Belgium, 2014; Volume 3, pp. 1–31.
174. Thinkohkaew, K.; Jonjaroen, V.; Niamsiri, N.; Panya, A.; Suppavorasatit, I.; Potiyaraj, P. Microencapsulation of Probiotics in Chitosan-Coated Alginate/Gellan Gum: Optimization for Viability and Stability Enhancement. *Food Hydrocoll.* **2024**, *151*, 109788. [CrossRef]
175. Hesketh, J. Personalised Nutrition: How Far Has Nutrigenomics Progressed? *Eur. J. Clin. Nutr.* **2013**, *67*, 430–435. [CrossRef]
176. Yang, S.; Xu, J.; Wei, S.; Wu, Y.; Zhang, H.; Fang, Y. Encapsulation Techniques, Action Mechanisms, and Evaluation Models of Probiotics: Recent Advances and Future Prospects. *Food Front.* **2024**, *5*, 1212–1239. [CrossRef]
177. Cheng, Q.; Liu, L.; Xie, M.; Li, H.; Ma, D.; Xue, W. A Colon-Targeted Oral Probiotics Delivery System Using An Enzyme-Triggered Fuse-Like Microcapsule. *Adv. Healthc. Mater.* **2021**, *10*, 2001953. [CrossRef]
178. European Commission. *European Commission EU Guidance to the Commission Regulation (EC) No 450/2009 of 29 May 2009 on Active and Intelligent Materials and Articles Intended to Come into Contact with Food*; European Commission: Brussels, Belgium, 2011; pp. 1–26.
179. Commission, T.H.E.; The, O.F.; Communities, E. Commission Regulation (EC) No 450/2009 of 29 May 2009 on Active and Intelligent Materials and Articles Intended to Come into Contact with Food (Text with EEA Relevance). *Off. J. Eur. Union* **2009**, *L135*, 3–11.
180. Xie, Q.; Liu, G.; Zhang, Y. Edible Films/Coatings Containing Bioactive Ingredients with Micro/Nano Encapsulation: A Comprehensive Review of Their Fabrications, Formulas, Multifunctionality and Applications in Food Packaging. *Crit. Rev. Food Sci. Nutr.* **2024**, *64*, 5341–5378. [CrossRef]
181. Westlake, J.R.; Tran, M.W.; Jiang, Y.; Zhang, X.; Burrows, A.D. Biodegradable Active Packaging with Controlled Release: Principles, Progress, and Prospects. *ACS Food Sci. Technol.* **2022**, *2*, 1166–1183. [CrossRef]
182. European Parliament; Council of the European Union. The European Parliament and the Council of the European Union Commission Regulation (EU) No 10/2011 of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food Text with EEA Relevance. *Off. J. Eur. Union* **2011**, *L12*, 1–89.
183. Almasi, H.; Oskouie, M.J.; Saleh, A. A Review on Techniques Utilized for Design of Controlled Release Food Active Packaging. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 2601–2621. [CrossRef]
184. Rezaei, A.; Rafieian, F.; Akbari-Alavijeh, S.; Saeed, M. Release of Bioactive Compounds from Delivery Systems by Stimuli-Responsive Approaches; Triggering Factors, Mechanisms, and Applications. *Adv. Colloid Interface Sci.* **2022**, *307*, 102728. [CrossRef]
185. Zhai, X.; Xue, Y.; Sun, Y.; Ma, X.; Ban, W.; Marappan, G.; Tahir, H.E.; Huang, X.; Wu, K.; Chen, Z.; et al. Colorimetric Food Freshness Indicators for Intelligent Packaging: Progress, Shortcomings, and Promising Solutions. *Foods* **2025**, *14*, 2813. [CrossRef]
186. Yan, Z.; Wang, K.; Xia, B.; Wu, J.; Chen, H. Development of Intelligent and Active Gelatin-Based Packaging Film Incorporating Red Onion Anthocyanins and Encapsulated Citronella Oil. *Foods* **2025**, *14*, 3320. [CrossRef]
187. Nezamdoost-sani, N.; Alizadeh, M.; Amiri, S. Food Bioscience Alginate and Derivatives Hydrogels in Encapsulation of Probiotic Bacteria: An Updated Review. *Food Biosci.* **2023**, *52*, 102433. [CrossRef]
188. Gholivand, S.; Boon, T.; Mat, M.; Qoms, M.S.; Wang, Y.; Liu, Y.; Lin, K.; Ping, C. Eco-Friendly Encapsulation: Investigating Plant-Based Protein-Alginate Shells for Efficient Delivery and Digestion of Hemp Seed Oil Encapsulated via Supercritical CO_2 Dispersion. *Food Chem.* **2025**, *463*, 141515. [CrossRef]
189. Klettenhammer, S.; Ferrentino, G.; Morozova, K.; Scampicchio, M. Novel Technologies Based on Supercritical Fluids for the Encapsulation of Food Grade Bioactive Compounds. *Foods* **2020**, *9*, 1395. [CrossRef]
190. Li, W.; Liu, L.; Tian, H.; Luo, X.; Liu, S. Encapsulation of Lactobacillus Plantarum in Cellulose Based Microgel with Controlled Release Behavior and Increased Long-Term Storage Stability. *Carbohydr. Polym.* **2019**, *223*, 115065. [CrossRef]