Lipid-Based Delivery Systems and Encapsulation Techniques in Food Applications: A Survey

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Abstract

This survey provides a comprehensive analysis of lipid-based delivery systems and encapsulation techniques in food applications, focusing on their role in enhancing the stability, bioavailability, and efficacy of bioactive compounds. The paper is structured to explore the historical development and emerging advancements in these technologies, emphasizing their significance in the controlled release of functional ingredients. Key sections examine the mechanisms, advantages, and limitations of lipid-based systems, such as nanoemulsions and liposomes, and their applications in functional foods, packaging, and preservation. Encapsulation techniques, including microencapsulation and nanoencapsulation, are detailed, highlighting their effectiveness in stabilizing sensitive compounds. The survey also addresses the challenges and regulatory considerations associated with nanoencapsulation, underscoring the need for continued research to optimize these technologies. Future research directions are suggested, focusing on improving flavor release profiles, exploring new materials, and ensuring safety and regulatory compliance. The implications for the food industry and consumer health are significant, offering innovative solutions for enhancing the nutritional profile and therapeutic efficacy of food products, while emphasizing the importance of addressing safety and regulatory challenges to ensure consumer trust and acceptance.

1 Introduction

1.1 Structure of the Survey

This survey provides a thorough examination of lipid-based delivery systems and encapsulation techniques in food applications. The **Introduction** establishes the importance of these technologies in enhancing the stability, bioavailability, and efficacy of bioactive compounds. The survey is organized into several key sections.

The **Background and Definitions** section elucidates core concepts, defining essential terms such as nanoencapsulation and controlled release, and discussing their significance in the food industry. This is followed by a review of the **Historical Development and Emerging Techniques**, which traces the evolution and recent advancements in encapsulation and lipid-based systems.

The section on **Lipid-Based Delivery Systems** categorizes various types utilized in food applications, detailing their mechanisms, advantages, and limitations, including systems like liposomes and nanostructured lipid carriers.

Next, **Encapsulation Techniques** are analyzed, focusing on methods such as microencapsulation and nanoencapsulation, alongside physical-mechanical and chemical approaches, as well as the application of polymer and lipid-based nanocarriers.

In the **Food Applications** section, the survey discusses the implementation of these technologies in functional foods, diverse food products, and their roles in packaging and preservation. The subsequent

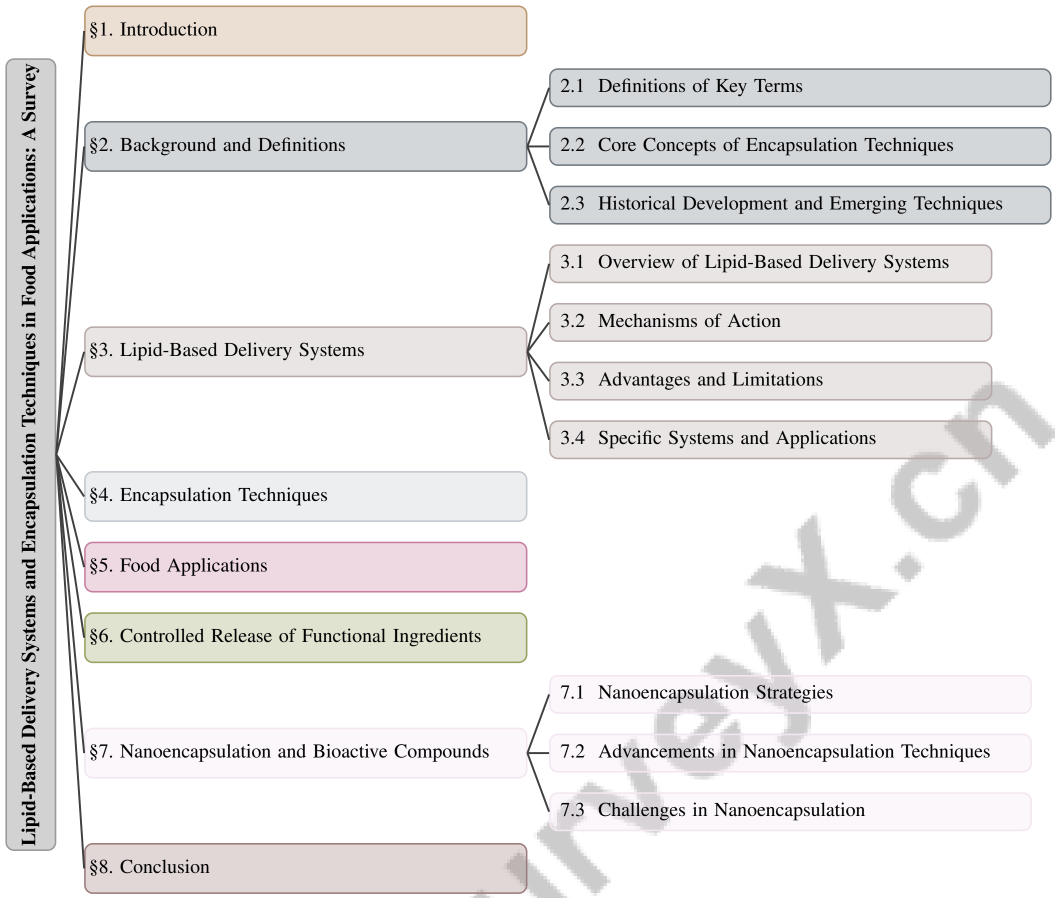

Figure 1: chapter structure

section on **Controlled Release of Functional Ingredients** explores how lipid-based systems facilitate controlled release, examining frameworks, mechanisms, and enhancement techniques.

The focus then shifts to **Nanoencapsulation and Bioactive Compounds**, addressing strategies, advancements, and challenges, including safety and regulatory considerations. Finally, the **Conclusion** encapsulates key findings and outlines potential future directions, with subsections identifying research areas and implications for the food industry and consumer health.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Definitions of Key Terms

Understanding lipid-based delivery systems and encapsulation techniques in food science necessitates clear definitions. Nanoencapsulation involves enclosing bioactive compounds within nanoscale carriers, enhancing their stability, solubility, and bioavailability, crucial for preserving sensitive natural compounds during processing and digestion [1]. Bioactive compounds, such as phytochemicals, bioactive peptides, vitamins, and minerals, naturally occur in foods and can modulate metabolic processes, improving health outcomes. Their role in chronic disease prevention by reducing inflammation and oxidative damage has spurred the development of functional foods enriched with these components [2, 3].

Controlled release mechanisms strategically release bioactive compounds over time, optimizing therapeutic effects while minimizing side effects [4, 5]. Lipid-based nanoparticles enhance the delivery and stability of photosensitive materials and drugs [5]. Essential oils (EOs), natural extracts with therapeutic properties, benefit from encapsulation techniques like microemulsions, nanoemulsions, liposomes, solid lipid nanoparticles, and nanostructured lipid carriers, improving their stability and efficacy [6].

These definitions underscore the significance of lipid-based delivery systems and encapsulation techniques in food science and technology. Techniques such as micro- and nanoencapsulation are vital for enhancing the stability, bioavailability, and controlled release of sensitive nutrients and flavors, addressing challenges like nutrient degradation and undesirable interactions in food products. These methodologies enable food scientists to enhance sensory attributes, nutritional value, and safety, driving innovations in the food industry [7, 8, 9, 10, 6].

2.2 Core Concepts of Encapsulation Techniques

Encapsulation techniques are pivotal in the food industry for enhancing the stability, bioavailability, and efficacy of bioactive compounds, often limited by low bioavailability and stability. Techniques such as microencapsulation and nanoencapsulation stabilize sensitive compounds like antioxidants and vitamins, protecting them from degradation during processing and storage [2]. Microencapsulation forms a protective barrier around small particles or droplets, preserving the integrity of core materials in diverse food matrices [11], while nanoencapsulation offers superior protection and controlled release capabilities, enhancing bioavailability and targeted delivery [12].

Nanostructured lipid-based delivery systems, including liposomes and solid lipid nanoparticles, are key nanocarriers that enhance the functionality of bioactive compounds through improved stability and bioavailability [12]. Nanocellulose's role in stabilizing Pickering emulsions is crucial for providing stability and enhancing the delivery of bioactive compounds [13]. Nanoemulsions, produced via low-energy and high-energy techniques, encapsulate and deliver bioactive compounds, significantly improving food safety, quality, and bioavailability [7]. The interaction of spherical nanoparticles with lipid-bilayer membranes is critical for controlling membrane morphology in synthetic systems, essential for developing effective encapsulation strategies [14].

Encapsulation techniques extend to natural biopolymers, facilitating the incorporation of hydrophobic and hydrophilic compounds into various food products, enhancing their functional properties [15]. The classification of nanoencapsulation techniques into chemical, physicochemical, and physicomechanical methods underscores the importance of eco-friendly approaches in advancing food technology [1]. These techniques address critical challenges related to food wastage and spoilage, highlighting their significance in developing functional foods.

2.3 Historical Development and Emerging Techniques

The historical development of encapsulation techniques in the food industry reflects a shift from traditional methods to advanced technologies, addressing the instability and low bioavailability of bioactive compounds. Early methods like extrusion and spray drying laid the groundwork for modern encapsulation strategies [12], significantly influencing current approaches that enhance the stability and efficacy of encapsulated ingredients.

The evolution of nanoencapsulation methods has been particularly notable for carotenoids, with advancements in polymeric nanocapsules improving their protection and delivery [12]. Innovations in nanocellulose-stabilized Pickering emulsions have emerged as promising approaches for enhancing the stability and bioavailability of bioactive compounds in food applications [13]. Recent advancements in oil nanoencapsulation technologies are critical for producing stable oil nanocapsules with enhanced functional properties [7], emphasizing formulation and stability considerations in effective encapsulation strategies.

Since 2015, rapid advancements in nanoencapsulation strategies for natural compounds have employed diverse techniques to enhance the delivery and efficacy of bioactive ingredients in food products [1]. Coaxial electrospraying has gained attention for producing multilayer encapsulation structures, offering novel solutions for stabilizing and controlling the release of bioactive compounds [15]. The historical development of encapsulation techniques is also exemplified by advancements in lycopene encapsulation methods, which have significantly improved the stability and bioavailability of this important antioxidant [16].

Ongoing advancements in encapsulation and lipid-based systems are driven by the need to enhance the stability, bioavailability, and efficacy of bioactive compounds. This evolution is particularly significant in food science and technology, meeting consumer demands for natural and health-promoting products. Techniques like nanoencapsulation improve the delivery and functionality of bioactive compounds, while nanostructured lipid-based delivery systems, including nanoemulsions and liposomes, are vital for overcoming challenges related to the low solubility and instability of bioactive compounds during food processing and digestion. This dynamic field holds considerable promise for revolutionizing food manufacturing by facilitating the creation of high-quality, nutrient-rich products that meet contemporary health standards [1, 10, 17, 18].

3 Lipid-Based Delivery Systems

Lipid-based delivery systems have become increasingly prominent for enhancing the stability and bioavailability of bioactive compounds in food applications. These systems utilize unique structural properties to encapsulate, protect, and deliver sensitive ingredients, thus overcoming challenges associated with traditional methods. The following subsection categorizes these systems based on structural and functional characteristics, highlighting their significance in food technology.

3.1 Overview of Lipid-Based Delivery Systems

Lipid-based delivery systems play a critical role in improving the stability, bioavailability, and efficacy of bioactive compounds in food applications. They are categorized by structural and functional properties, including nanoemulsions, liposomes, and polymeric nanoparticles. Nanoemulsions effectively encapsulate hydrophobic compounds, enhancing their solubility and stability in aqueous environments, crucial for integration into food matrices [7, 1]. Liposomes, with their bilayered vesicular structures, encapsulate both hydrophilic and hydrophobic compounds, offering protection and controlled release [19, 20]. Polymeric nanoparticles, often made from biodegradable polymers like PLA and PLGA, preserve probiotics' viability during gastrointestinal transit, enhancing functional efficacy [11, 16].

Emerging technologies like nanocellulose-stabilized Pickering emulsions provide innovative approaches within lipid-based systems, offering enhanced stability and bioavailability [13]. Modulating binding energies between nanoparticles and lipid membranes is a novel concept for tuning membrane morphology, enriching lipid-based systems [14]. Categorizing these systems by encapsulation methodologies, including physical, physicochemical, and chemical processes, provides a structured framework for understanding their diverse applications and potential in food technology [7].

3.2 Mechanisms of Action

Lipid-based delivery systems utilize intricate mechanisms to enhance the delivery and bioavailability of bioactive compounds in food applications. These systems protect sensitive compounds from degradation, preserving functional efficacy. For example, incorporating bioactive compounds into lipid matrices shields them from oxidation and high temperatures during processing [16]. Advanced techniques like 3D food printing control baking conditions to preserve polyphenols' antioxidant properties, optimizing processing parameters [20].

Computational models like Hopfield-enhanced Particle Swarm Optimization (HoPSO) provide insights into optimizing lipid-based systems, enhancing encapsulation and release processes [21]. These systems, including nanostructured lipid carriers like nanoemulsions and liposomes, protect sensitive ingredients during processing and enable targeted delivery, preserving bioactive compounds' functional properties and potentially reducing chronic disease risks [8, 22, 18].

3.3 Advantages and Limitations

Lipid-based delivery systems enhance bioactive compounds' stability and bioavailability, making them suitable for functional food applications [16]. They provide a protective matrix that shields sensitive compounds from environmental degradation, preserving functional properties and extending shelf life. Polymeric nanoparticles offer controlled release and stability advantages over traditional methods [16, 17].

Challenges include nanoemulsions' thermodynamic instability, leading to degradation through processes like gravitational separation and Ostwald ripening [23]. Economic feasibility, potential

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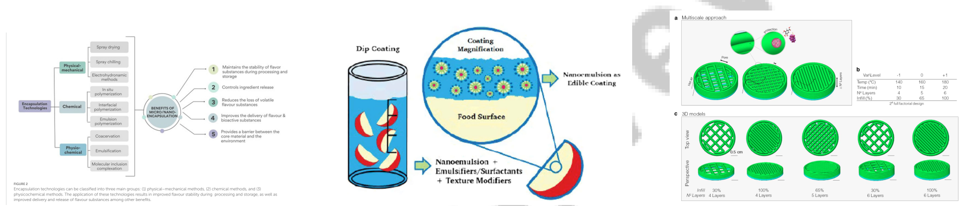
toxicological effects, and biological barriers to absorption present further obstacles [24, 19]. The need for formulations delivering bioactive compounds over extended periods remains critical, with traditional optimization techniques highlighting the need for innovative approaches [21]. Despite these challenges, controlled morphological changes in synthetic membranes offer promising avenues for tailoring lipid-based systems for specific applications [14].

3.4 Specific Systems and Applications

Lipid-based delivery systems include various specific systems enhancing bioactive compounds' stability, bioavailability, and controlled release. Liposomes, known for biocompatibility, encapsulate hydrophilic and hydrophobic substances, enhancing functional efficacy [25]. Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) encapsulate essential oils and bioactive compounds, offering improved stability and controlled release [6]. Polymeric nanoparticles, especially those using biodegradable polymers like PCL and PLGA, effectively carry carotenoids like lycopene, enhancing stability and bioavailability [4].

Innovative techniques like coaxial electrospraying create multilayer microcapsules, enabling simultaneous encapsulation of hydrophilic and hydrophobic compounds, offering enhanced protection and controlled release [15]. Lipid-based systems, such as nanoemulsions and multi-layer emulsions, address challenges like low solubility and instability during processing, facilitating effective incorporation into food products. Advancements in nanostructured lipid-based systems improve functionality and absorption, enabling targeted release, contributing to novel food products with enhanced nutritional quality and health benefits [26, 8, 22, 18].



(a) Encapsulation Technologies: Classification and Benefits[10]

(b) Dip Coating Process for Food Surface Coating[26]

(c) Multiscale Approach in 3D Printing: A Study on the Influence of Variables on the Structure and Properties of 3D Models[20]

Figure 2: Examples of Specific Systems and Applications

As illustrated in Figure 2, lipid-based delivery systems are pivotal in food science and pharmaceuticals, offering innovative solutions for encapsulating and delivering bioactive compounds. The examples highlight their versatility and benefits. The first image classifies encapsulation technologies into physical-mechanical, chemical, and physicochemical groups, emphasizing benefits like enhanced stability and controlled release of flavors. The second image depicts the dip coating process for food surface coating, showcasing practical applications in creating edible coatings that enhance food quality and shelf life. The third image presents a multiscale approach in 3D printing, underscoring variable influences on structural and property outcomes, pivotal for tailoring lipid-based systems for specific applications. These examples underscore lipid-based delivery systems' diverse applications and significant advantages in modern science and industry [10, 26, 20].

4 Encapsulation Techniques

4.1 Microencapsulation and Nanoencapsulation

Microencapsulation and nanoencapsulation are vital techniques in the food industry, enhancing the stability, bioavailability, and controlled release of bioactive compounds. Microencapsulation involves enclosing active ingredients within protective coatings, significantly improving the stability and viability of sensitive compounds like probiotics during processing and storage [11]. Techniques such as Emulsion Evaporation Technique (EET) are employed for microencapsulation, notably in the encapsulation of lycopene within PLGA nanoparticles, which boosts its stability and bio-accessibility.

Method Name	Encapsulation Scale	Encapsulation Techniques	Application in Food Industry
CE[15]	Multilayer Microcapsules	Coaxial Electrospraying	Bioactive Food Ingredients
LNP[16]	Nanoencapsulation	Emulsion Evaporation	Functional Food Development
NMIM[14]	-	-	-

Table 1: Summary of encapsulation methods, scales, techniques, and their applications in the food industry. The table compares various methods such as coaxial electrospraying and emulsion evaporation, highlighting their specific uses in enhancing the stability and delivery of bioactive food ingredients.

The selection of coating materials and methods is crucial for maximizing encapsulation efficiency, with biopolymer matrices frequently used to achieve optimal results [15].

Nanoencapsulation operates at the nanoscale, offering superior protection and controlled release capabilities. Nanoliposomes and nanoemulsions exemplify this technology, enhancing encapsulation and stability for delivering sensitive bioactive compounds [1]. This approach is promising for improving the application of oils in food products, significantly enhancing food safety, quality, and shelf life [7]. Techniques including emulsification, solvent evaporation, and high-pressure homogenization are utilized to fabricate nanoparticles, each providing distinct advantages in encapsulation efficiency and stability [16].

Innovative strategies, such as modulating binding energy between nanoparticles and lipid bilayer membranes, further refine encapsulation techniques by optimizing membrane morphology to enhance bioactive compound delivery [14]. These advancements highlight the crucial role of microencapsulation and nanoencapsulation in food technology, offering effective solutions for stabilizing and delivering bioactive ingredients. Table 1 provides a comprehensive overview of different encapsulation methods, their scales, techniques, and specific applications within the food industry, emphasizing their role in improving the stability and delivery of bioactive compounds.

4.2 Physical-Mechanical and Chemical Methods

Physical-mechanical and chemical methods are pivotal in encapsulating bioactive compounds, providing diverse strategies to enhance their stability, bioavailability, and controlled release in food applications. Notable physical-mechanical methods include spray drying and extrusion, which are effective for encapsulating flavor substances and preserving their sensory qualities during processing and storage [10]. Spray drying rapidly removes solvent through atomization, forming a protective matrix around core materials to maintain volatile compound stability. Conversely, extrusion uses mechanical force to encapsulate active ingredients within a solid matrix, offering a robust barrier against environmental degradation.

Emerging technologies like ultrasound-assisted extraction and supercritical fluid extraction are gaining traction for their efficiency in enhancing encapsulation processes [27]. These methods reduce processing times and improve extraction yields, facilitating the integration of bioactive compounds into food matrices with minimal functionality loss. Ultrasound-assisted extraction employs acoustic cavitation to disrupt cellular structures, while supercritical fluid extraction uses supercritical CO_2 as a solvent, providing a green and efficient alternative for extracting and encapsulating sensitive compounds.

Chemical methods, including emulsion and solvent evaporation, are crucial for nanoparticle fabrication. Emulsion techniques disperse one liquid phase into another immiscible phase, forming stable droplets that encapsulate bioactive compounds. Solvent evaporation is prevalent in nanoparticle synthesis, removing an organic solvent from an emulsion to yield solid particles that encapsulate active ingredients, enhancing their stability and bioavailability. This method protects sensitive bioactive compounds from adverse environmental conditions and allows controlled release, improving functionality in food applications, particularly for nutrient retention and delivery of flavors, colors, and preservatives [7, 9, 24, 1, 23].

Advanced techniques like electrospinning and electrospraying have emerged as innovative methods for creating fibrous and particulate structures for encapsulation. Electrospinning draws polymer solutions into fine fibers using an electric field, providing a high surface area for encapsulation and controlled release of bioactive compounds. Electrospraying similarly uses an electric field to produce fine droplets, forming microcapsules that offer enhanced protection and release profiles for sensitive ingredients. The utilization of physical-mechanical and chemical methods, including micro- and nanoencapsulation techniques, demonstrates significant potential in enhancing the stability, bioavailability, and targeted delivery of bioactive compounds in food technology, addressing challenges related to volatility and reactivity during processing and storage [9, 17, 1, 10, 28].

4.3 Polymer and Lipid-Based Nanocarriers

Polymer and lipid-based nanocarriers play a crucial role in encapsulating bioactive compounds, offering enhanced stability, bioavailability, and controlled release essential for effective applications in food technology. These nanocarriers are particularly effective at encapsulating volatile flavor compounds, thereby preserving their sensory qualities during processing and storage [10]. Research on liposomal technologies has shown significant advancements in protecting sensitive ingredients, improving nutrient absorption, and enhancing food sensory qualities [8]. Liposomes, with their bilayered structure, can encapsulate both hydrophilic and hydrophobic compounds, making them versatile carriers for various bioactive ingredients.

Polymeric nanocarriers, made from polylactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA), are widely used for encapsulating compounds like lycopene, a potent antioxidant with low bioavailability [16]. These biodegradable polymers provide a protective matrix that enhances lycopene's stability and bioavailability, facilitating its incorporation into functional food products. The use of PLA and PLGA in encapsulating lycopene exemplifies the potential of polymer-based nanocarriers to improve the delivery and efficacy of bioactive compounds.

A survey of various nanocarriers highlights their applications in both pharmaceuticals and food, addressing critical safety considerations associated with their use [22]. The integration of polymer and lipid-based nanocarriers in food technology underscores their importance in advancing the encapsulation and delivery of bioactive compounds, providing a robust framework for enhancing the functionality and stability of food products.

5 Food Applications

Recent advancements in food science and technology have significantly improved the functionality and nutritional value of food products. This section explores lipid-based delivery systems and encapsulation techniques as essential tools in developing innovative food solutions, focusing on their roles in functional foods, food products, and packaging to enhance food quality and safety. The following subsection delves into their applications in functional foods, emphasizing mechanisms that enhance the stability and bioavailability of bioactive compounds.

5.1 Applications in Functional Foods

Lipid-based delivery systems and encapsulation techniques are crucial in functional foods, enhancing the stability, bioavailability, and efficacy of bioactive compounds. Nanoencapsulation improves the delivery and effectiveness of lipophilic bioactive compounds, such as lycopene, across various food matrices, thereby augmenting their nutritional and functional properties [16]. Encapsulating lycopene within nanocarriers not only boosts its bioavailability but also facilitates its application in functional foods, providing enhanced health benefits.

Nanocellulose-stabilized Pickering emulsions present an innovative encapsulation approach, enhancing the stability and functionality of bioactive compounds in food products [13]. These emulsions provide a robust framework for incorporating bioactive ingredients, improving the sensory and nutritional qualities of functional foods. Additionally, coaxial electrospraying has emerged as a promising technique for enhancing the encapsulation efficiency and protection of bioactive food ingredients, ensuring their stability during processing and storage [15].

Advanced encapsulation technologies, including nanoencapsulation and nanoemulsions, significantly enhance the delivery efficiency and bioavailability of bioactive compounds such as antioxidants, vitamins, and probiotics. These methods improve the stability and controlled release of these compounds, addressing nutritional deficiencies and augmenting the health benefits of food products. Utilizing carrier materials like carbohydrates, proteins, and lipids protects sensitive nutrients from degradation, leading to improved food quality, safety, and consumer acceptance [9, 17, 26, 10, 29].

These advancements underscore the transformative potential of lipid-based delivery systems and encapsulation techniques in the functional food sector.

5.2 Applications in Food Products

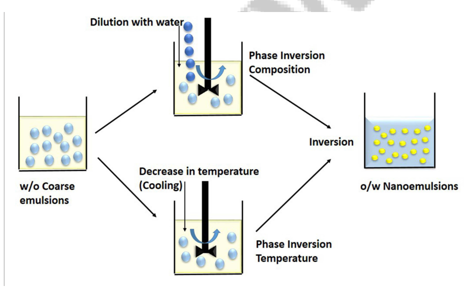
Lipid-based delivery systems and encapsulation techniques significantly enhance the quality, stability, and nutritional value of various food products. These systems are effective in incorporating bioactive compounds into complex food matrices, improving their functional properties and consumer appeal. For instance, nanoemulsions enhance the solubility and stability of lipophilic bioactive compounds like carotenoids, facilitating their incorporation into beverages and dairy products [7]. This enhancement improves nutritional profiles and extends shelf life by protecting sensitive ingredients from degradation.

Liposomal delivery systems provide a versatile approach for encapsulating both hydrophilic and hydrophobic compounds, enabling controlled release and targeted delivery [8]. This capability is particularly advantageous for formulating nutraceuticals and functional foods, where preserving bioactive compound efficacy is critical. Furthermore, encapsulating essential oils in solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) has been explored for their antimicrobial and antioxidant properties, enhancing food safety and preservation [6].

Polymeric nanoparticles, such as those made from PLA and PLGA, are utilized to encapsulate sensitive bioactive compounds like lycopene, improving their stability and bioavailability in food products [4]. This application is crucial in developing fortified foods, where the bioavailability of antioxidants and other health-promoting compounds is essential for delivering intended benefits.

Innovative encapsulation techniques, including coaxial electrospraying, allow for the simultaneous encapsulation of multiple bioactive compounds, offering synergistic effects in food products [15]. This approach enhances the functional properties of food products by ensuring the stability and efficacy of encapsulated ingredients during processing and storage.

The integration of lipid-based delivery systems and advanced encapsulation techniques in food products marks a pivotal evolution in food technology, significantly enhancing nutritional profiles, stability, and shelf life. These innovations protect sensitive nutrients and flavors from environmental factors while improving bioavailability and targeted release during consumption. Techniques such as micro- and nano-encapsulation facilitate the controlled release of bioactive compounds, ensuring essential nutrients remain effective and available for absorption, thus contributing to the development of functional foods with improved health benefits [7, 8, 9, 26, 10]. These technologies provide a robust framework for developing innovative food products that meet consumer demands for health, safety, and quality.



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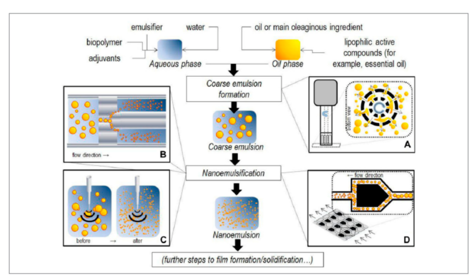

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Figure 3: Examples of Applications in Food Products

As illustrated in Figure 3, the section titled "Food Applications; Applications in Food Products" delves into the diverse and innovative uses of certain technologies within food products. This exploration is visually supported by a figure comprising two subfigures, each exemplifying distinct applications in this field. Although the current placeholders indicate errors in citation or image retrieval, the figure is designed to represent how these applications manifest in food products, potentially covering aspects such as enhancing nutritional value, improving preservation, or altering sensory attributes. By examining these examples, the discussion seeks to illuminate the practical implications and benefits of these applications in the food industry [24, 23].

5.3 Packaging and Preservation

Lipid-based delivery systems and encapsulation techniques play a crucial role in food packaging and preservation by enhancing the stability and efficacy of bioactive compounds. These technologies offer innovative solutions for extending food product shelf life while maintaining nutritional and sensory qualities. For instance, nanoencapsulation has been employed to encapsulate essential oils, providing antimicrobial and antioxidant properties essential for food preservation [6]. Encapsulating essential oils in nanostructured lipid carriers (NLCs) and solid lipid nanoparticles (SLNs) offers improved protection against environmental factors, thereby enhancing food product preservation.

Incorporating lipid-based delivery systems in food packaging materials significantly reduces the oxidation of sensitive compounds, such as polyunsaturated fatty acids and vitamins, which are prone to degradation during storage [2]. This reduction in oxidation extends the shelf life of food products while preserving their nutritional value and sensory attributes. Additionally, using polymeric nanoparticles to encapsulate volatile compounds in packaging materials provides a controlled release mechanism, ensuring the functional properties of these compounds are maintained throughout the storage period [16].

Moreover, lipid-based systems can enhance the barrier properties of packaging materials, preventing the permeation of oxygen and moisture, which are critical factors in food spoilage [1]. Developing bioactive packaging films that incorporate encapsulated bioactive compounds serves a dual function of protection and preservation, contributing to improved food safety and quality.

The integration of advanced technologies, particularly nanotechnology, in food packaging and preservation is pivotal for the evolution of food technology. These innovations enhance the shelf life and safety of food products by preventing contamination and degradation while improving nutritional value and sensory properties. By utilizing nanoparticles, the food industry can develop effective strategies for maintaining food integrity, ensuring consumer acceptability, and delivering functional benefits such as enhanced flavor stability and bioavailability, ultimately contributing to healthier and higher-quality food options [10, 30, 31, 29]. Leveraging the protective and stabilizing capabilities of lipid-based delivery systems enables the food industry to develop packaging solutions that meet consumer demands for quality, safety, and sustainability.

6 Controlled Release of Functional Ingredients

6.1 Framework and Mechanisms of Controlled Release

Controlled release systems are pivotal in maintaining the stability and bioavailability of bioactive compounds in food. These systems are designed to modulate the release of bioactive ingredients, ensuring their targeted delivery and enhanced therapeutic efficacy [16]. Lipid-based carriers, such as nanoemulsions and liposomes, offer a protective matrix that mitigates environmental degradation, thereby optimizing the encapsulated compounds' stability and bioavailability [7].

The release kinetics can be precisely controlled by adjusting particle size, surface charge, and encapsulating material composition, which is crucial for achieving desired therapeutic outcomes [16]. The interaction between nanoparticles and lipid membranes significantly influences morphological outcomes and release profiles, crucial for overcoming biological barriers and enhancing bioactive ingredient delivery [7].

Polymeric carriers offer an alternative approach, responding to environmental triggers like pH or temperature, facilitating targeted release under specific physiological conditions. This adaptability is vital for effectively delivering probiotics and other sensitive ingredients, which need protection from the harsh gastrointestinal tract environment to maintain health benefits [16].

Advancements in controlled release frameworks are integral to developing sophisticated delivery systems that enhance bioactive compounds' stability, bioavailability, and efficacy, addressing the challenges of incorporating these ingredients into food products. Innovations in oil preservation, including enhanced stability and controlled release, further underscore these systems' potential to improve food products' nutritional profiles [7].

6.2 Lipid-Based Systems in Controlled Release

Lipid-based systems are crucial for achieving the controlled release of bioactive compounds, significantly enhancing their stability, bioavailability, and efficacy in food applications. Systems like nanoemulsions, liposomes, and polymeric nanoparticles utilize their structural properties to modulate encapsulated compounds' release profiles, ensuring their availability at desired action sites. This is particularly beneficial for protecting sensitive ingredients, such as probiotics, from the gastric environment's harsh conditions, which can lead to significant viability loss [32].

For example, polycaprolactone (PCL) nanoparticles encapsulating lycopene demonstrate lipid-based systems' role in facilitating controlled release, improving therapeutic efficacy [33]. Similarly, lycopene-loaded PLGA nanoparticles show lipid-based systems' potential to achieve controlled release through optimized physicochemical properties, enhancing bioavailability [4].

Selecting appropriate stabilizers and preparation techniques is crucial for improving nanoemulsions' stability and functionality, key to enhancing bioactive compound delivery and effectiveness in food products [23]. Nanocellulose-stabilized Pickering emulsions further highlight lipid-based systems' potential in achieving controlled release, providing a stable matrix for encapsulating and delivering bioactive ingredients [13].

Moreover, developing multilayer structures through coaxial electrospraying enhances protection against degradation during processing and storage, facilitating controlled release of bioactive compounds [15]. This technique, along with optimizing nanocarrier formulations and exploring novel materials, represents a promising avenue for future research in lipid-based delivery systems [22].

Lipid-based delivery systems, particularly nanostructured forms like nanoemulsions and liposomes, are essential for achieving controlled release of bioactive compounds in food applications. These systems effectively address challenges related to low solubility, instability during food processing, and poor bioavailability of bioactive ingredients, thereby enhancing their functionality. Recent advancements in encapsulation techniques have led to innovative solutions that improve stability and absorption while facilitating targeted release, ultimately contributing to developing novel food products with enhanced nutritional quality and health benefits [22, 3, 26, 6, 18].

6.3 Techniques Enhancing Controlled Release

Techniques that enhance the controlled release of bioactive compounds are crucial for optimizing their stability, bioavailability, and efficacy in food applications. Nanoencapsulation significantly improves the controlled release profiles of bioactive ingredients by providing a protective barrier against environmental degradation, enhancing sensitive ingredients' stability and bioavailability [1].

Electrospinning is another innovative technique promising considerable enhancement in the stability and controlled release of bioactive compounds. This method fabricates fibrous structures offering a high surface area for encapsulation, facilitating the sustained release of active ingredients over extended periods. The versatility of electrospinning in food applications underscores its potential to tailor release profiles to meet specific functional requirements [28].

Integrating these advanced techniques into food technology not only improves delivery efficiency and bioavailability of bioactive compounds but also addresses challenges related to their incorporation into complex food matrices. By employing methods such as nanoencapsulation and electrospinning, the food industry can develop innovative delivery systems that enhance stability and bioavailability while facilitating targeted release during digestion. This significantly improves compounds' functional efficacy, like antioxidants and probiotics, catering to consumer preferences for high-quality, nutritious food products. Consequently, these methods possess the potential to transform functional food development, ensuring maximized health benefits effectively communicated to consumers [28, 9, 17, 26].

In recent years, the field of food science has witnessed significant advancements in the development of nanoencapsulation strategies aimed at improving the delivery and efficacy of bioactive compounds. As illustrated in Figure 4, this figure delineates the hierarchical structure of these strategies, categorizing the main ideas into three primary sections: strategies for enhancing bioactive compound integration, recent advancements in nanoencapsulation techniques, and the challenges faced in safety and regulatory frameworks. Each section is meticulously divided into subcategories that detail specific innovations, applications, and the obstacles associated with nanoencapsulation in the food industry. This comprehensive framework not only highlights the progress made in the field but also underscores the complexities that researchers must navigate to ensure the successful application of these technologies in food products.

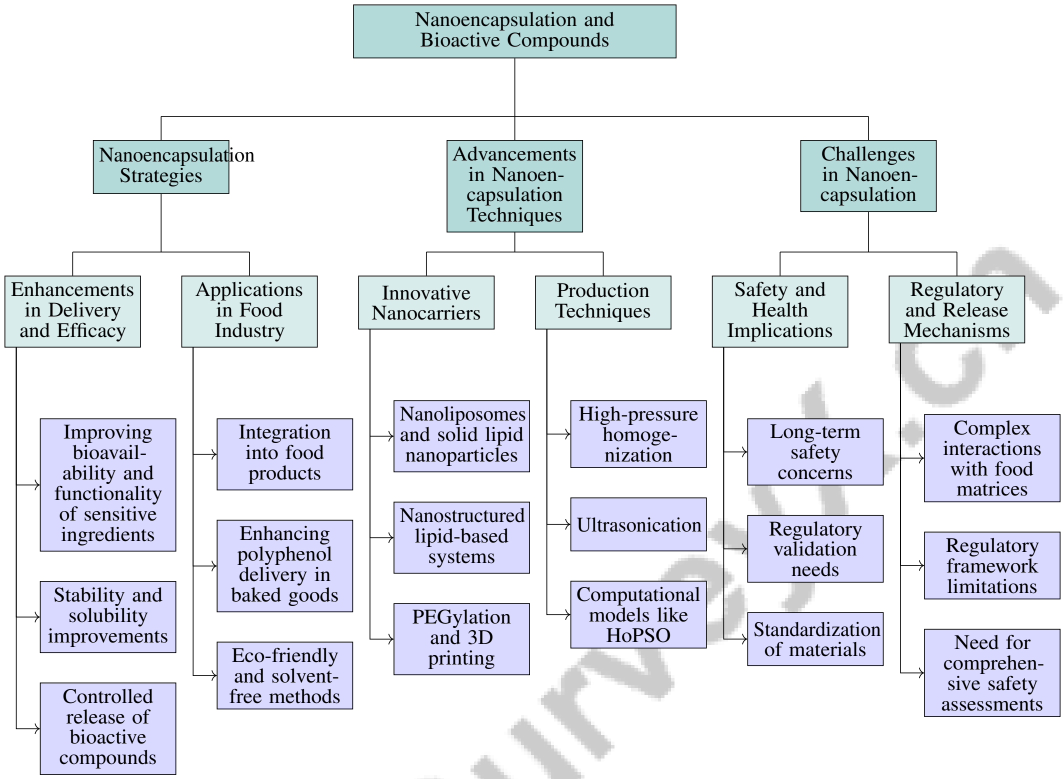

Figure 4: This figure illustrates the hierarchical structure of nanoencapsulation strategies, advancements in techniques, and challenges in the delivery and efficacy of bioactive compounds in food applications. It categorizes the main ideas into three primary sections: strategies for enhancing bioactive compound integration, recent advancements in nanoencapsulation techniques, and the challenges faced in safety and regulatory frameworks. Each section is further divided into subcategories, detailing specific innovations, applications, and obstacles associated with nanoencapsulation in the food industry.

7 Nanoencapsulation and Bioactive Compounds

7.1 Nanoencapsulation Strategies

Nanoencapsulation strategies significantly enhance the delivery and efficacy of bioactive compounds in food applications by addressing challenges related to stability, solubility, and controlled release. Various nanoparticles and techniques, such as lycopene nanoparticles, have been developed to improve the bioavailability and functionality of sensitive ingredients like volatile flavors and carotenoids, facilitating their integration into food products [16]. Nanocellulose-stabilized Pickering emulsions exemplify innovations that enhance the stability and functionality of bioactive compounds, contributing to improved sensory and nutritional qualities in food systems [13]. Eco-friendly methods highlight sustainable advances in nanoencapsulation [1].

These strategies extend to enhancing polyphenol delivery in baked goods, preserving antioxidant properties during processing [20]. Solvent-free methods and biocompatible nanoliposomes further underscore nanoencapsulation's potential in boosting food safety and quality [8]. Advances in nanoemulsion production and characterization are key to expanding their applications in the food industry, particularly regarding biological and toxicological considerations [26].

Future research should focus on optimizing nanoencapsulation techniques, conducting safety evaluations, and exploring innovative applications, especially in programmable foods [17]. Understanding the interactions between encapsulated ingredients and food components will provide insights into their functional efficacy and consumer health implications [9]. These advancements highlight the transformative potential of nanoencapsulation strategies in enhancing bioactive compound delivery and efficacy in food applications.

7.2 Advancements in Nanoencapsulation Techniques

Recent advancements in nanoencapsulation techniques have markedly improved the delivery and efficacy of bioactive compounds in food applications, addressing stability, solubility, and controlled release challenges. Novel nanocarriers, including nanoliposomes and solid lipid nanoparticles, have improved encapsulation efficiency and stability, enabling the incorporation of sensitive ingredients into diverse food matrices. Innovations in drug delivery technologies allow precise targeting of bioactive compounds, enhancing therapeutic efficacy while tackling bioavailability, stability, and solubility issues. Techniques such as nanostructured lipid-based systems, PEGylation, and 3D printing of soft materials are pivotal for optimizing release profiles and maximizing bioactive substance potential [34, 3, 6, 19, 18].

The integration of nanocellulose-stabilized Pickering emulsions enhances bioactive compound stability and functionality in food systems [13], while eco-friendly nanoencapsulation methods, including solvent-free preparations and biocompatible nanoliposomes, highlight potential advancements in food safety and quality [8]. Progress in nanoemulsion synthesis and characterization has expanded their food industry applications, addressing biological and toxicological impacts [26]. New production techniques, like high-pressure homogenization and ultrasonication, have improved the stability and bioavailability of encapsulated compounds, enhancing their functional properties and consumer appeal [1]. Computational models such as Hopfield-enhanced Particle Swarm Optimization (HoPSO) have refined encapsulation and release processes, optimizing nanoencapsulation strategies [21].

These advancements underscore the crucial role of nanoencapsulation techniques in improving the stability, solubility, and bioavailability of bioactive compounds in food applications, enhancing their delivery and efficacy while meeting consumer demands for natural and healthful products. This innovative approach not only protects sensitive compounds during processing and digestion but also facilitates the development of functional foods with desirable nutritional and sensory characteristics [1, 17]. By leveraging these innovations, the food industry can establish delivery systems that ensure the stability, bioavailability, and controlled release of bioactive ingredients, yielding substantial benefits for consumer health and product quality.

7.3 Challenges in Nanoencapsulation

Despite its potential, nanoencapsulation faces several challenges that must be addressed to fully exploit its capabilities in food applications. A primary concern is the long-term safety and health implications of consuming nanoencapsulated compounds, as significant gaps remain in understanding their effects on human health [25]. The absence of standardized materials for lipid-based systems complicates safety and efficacy assessments, necessitating extensive regulatory validation to ensure consumer protection [34].

Understanding release mechanisms within food systems also poses a significant challenge. The complex interactions between nanoencapsulated compounds and food matrices can influence the release and stability of bioactive ingredients, complicating predictions regarding their behavior and efficacy [12]. This limitation is particularly pronounced for carotenoids, where long-term stability and release profiles remain inadequately understood, hindering effective application in food products [12].

Regulatory considerations further complicate the adoption of nanoencapsulation technologies. Current regulatory frameworks may not adequately address the unique properties and potential risks associated with nanoscale materials, highlighting the need for comprehensive safety assessments and updated guidelines to facilitate their safe integration into the food industry [1]. These challenges underscore the importance of continued research and collaboration among scientists, industry stakeholders, and regulatory bodies to navigate the safety and regulatory hurdles associated with nanoencapsulation, ensuring its safe and effective use in enhancing food products.

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8 Conclusion

8.1 Future Research Directions

Research into lipid-based delivery systems and encapsulation techniques should focus on refining nanoencapsulation methods to improve flavor release and understand interactions between encapsulated substances and food matrices. Exploring advanced techniques like electrospinning could enhance throughput and integration with existing methods, leading to more efficient delivery systems. The development of innovative lipid materials for 3D printing also holds promise, particularly in optimizing processes for applications in personalized medicine. Investigating the encapsulation of specific bioactive compounds, such as lycopene, with an emphasis on formulation optimization and long-term stability, remains essential.

Safety evaluations of nanocarriers are crucial, necessitating the exploration of novel encapsulation techniques and comprehensive assessments of potential health impacts. Addressing research gaps, including the need for standardized evaluation methods and long-term safety data, is critical for regulatory compliance and consumer trust. Emphasizing eco-friendly extraction methods for nanocellulose and understanding its interactions within food matrices are vital areas of focus. Additionally, optimizing surfactant types and concentrations can significantly enhance the bioavailability of bioactive compounds.

Future studies should prioritize the exploration of biocompatible materials for encapsulation, optimization of coating processes, and the synergistic effects of probiotics and prebiotics in synbiotic formulations. Enhancing nanoencapsulation techniques, investigating new materials for wall structures, and overcoming regulatory challenges are essential for the commercialization of nanoencapsulated food products. Further research into optimizing nanoparticle shapes and sizes, along with integrating additional functionalities into vesicle systems, could improve responsiveness and efficacy. Developing safer nanoencapsulation methods, regulatory frameworks, and scalable industrial applications will be pivotal for advancing the field.

8.2 Implications for the Food Industry and Consumer Health

The adoption of lipid-based delivery systems and encapsulation techniques within the food industry offers substantial potential for enhancing the functionality and stability of bioactive compounds, addressing critical issues related to food safety and consumer health. These technologies provide innovative solutions for increasing the bioavailability and controlled release of sensitive ingredients, which is essential for maximizing their health benefits and therapeutic effectiveness. By incorporating bioactive compounds into lipid-based carriers, the food industry can protect these ingredients from environmental degradation, ensuring their stability during processing and storage.

Advanced encapsulation techniques enable the creation of functional foods with improved nutritional profiles, meeting consumer demand for health-promoting products. These technologies allow for the integration of a diverse range of bioactive compounds, such as antioxidants, vitamins, and essential oils, into food matrices, enhancing their sensory and nutritional attributes. This capability is crucial for addressing nutritional deficiencies and promoting consumer health by delivering bioactive compounds in a more bioavailable and effective form.

However, the widespread implementation of these technologies requires careful consideration of safety and regulatory aspects. Ensuring the long-term safety and efficacy of nanoencapsulated compounds is vital for building consumer confidence and securing regulatory approval. Comprehensive safety assessments and the establishment of standardized evaluation methods are necessary to mitigate potential health risks associated with consuming nanoencapsulated ingredients. By overcoming these challenges, the food industry can leverage lipid-based delivery systems and encapsulation techniques to improve product quality and consumer health, paving the way for innovative and sustainable food solutions.

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