Journal of Food and Agricultural Technology Research
https://globalpresspk.com/
ISSN: 3007-0953 (Online)
ISSN: 3007-0945 (Print)

Advances in the Encapsulation and Delivery of Food Functional Factors: Micro- and Nano-Delivery Carrier Platforms in Bio-Manufacturing

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Abstract: The encapsulation and delivery of food functional factors represent a transformative and groundbreaking innovation in food science, enabling the protection, stabilization, and controlled release of sensitive bioactive compounds. This review comprehensively explores advanced micro- and nano-delivery carrier platforms, including pickering emulsions, micro-emulsions, microcapsules, and nanoparticles, which offer enhanced stability, improve bioavailability, and highly targeted delivery of nutrients and other bioactive substances. By addressing significant challenges such as the instability, degradation and low bioavailability of bioactive compounds, as well as the need for efficient, scalable, and versatile carrier designs, these technologies integrate seamlessly with sustainable bio-manufacturing processes. Applications in functional foods dietary supplements and nutraceutical demonstrate their vast potential to enhance consumer health outcomes and streamline food production systems with greater efficiency. Future research efforts must prioritize scaling these innovative technologies, ensuring regulatory compliance, and developing highly adaptable, multifunctional delivery systems to meet the rapidly growing demand for functional food and wellness solutions.

Keywords: Encapsulation Technologies, Food Bio-Manufacturing, Nano-Delivery Systems, Functional Foods, Pickering Emulsions

Article History
Received: 31 December 2024; Revised: 16 January 2025; Accepted: 27 February 2025
Online: 7 March 2025; Published 30 May 2025
https://doi.org/10.69501/epgwv312

1. Introduction

The burgeoning field of food science and technology has witnessed a significant surge in interest in developing innovative strategies for enhancing the stability, bioavailability, and efficacy of food functional factors. Functional factors, including vitamins, minerals, probiotics, and polyphenols, are integral to enhancing human health and addressing nutritional deficiencies (Vlaicu et al., 2023). However, their inherent instability, susceptibility to environmental factors, and limited bioavailability present significant challenges in their effective incorporation into food systems (Zhang et al., 2024).

To address these challenges, the scientific community has increasingly embraced encapsulation technologies, leveraging their potential to enhance stability, precision, and efficacy in delivering functional compounds. The development of advanced delivery systems, such as micro- and nano-delivery platforms, has opened up new possibilities for targeted delivery of bioactive compounds to specific tissues or cells. These platforms, which include pickering emulsions, micro-emulsions, microcapsules, and nanoparticles, are engineered to overcome physical and chemical degradation, improve bioavailability, and enable targeted delivery (Li et al., 2024).

Pickering emulsions are a form of emulsion stabilized by solid particles rather than traditional surfactants. The solid particles adsorb to the oil-water interface, offering enhanced stability and controlled release properties, making them ideal for encapsulating hydrophobic bioactives. On the other hand, microemulsions are thermodynamically stable mixtures of oil, water, and surfactants, typically in the nanometer size range. These systems have the ability to encapsulate both hydrophobic and hydrophilic compounds, offering enhanced bioavailability and stability. Additionally, nanoparticles, including liposomes and solid lipid nanoparticles, are characterized by their small size and large surface area, making them highly efficient at encapsulating bioactive compounds and ensuring targeted delivery (da Silva Santos et al., 2019). The versatility of these systems makes them highly suitable for a wide range of food applications, from functional beverages to fortified foods and dietary supplements.

Their application extends beyond food systems, influencing areas such as nutraceuticals, pharmaceuticals, and cosmeceuticals, thereby bridging the gap between food science and advanced bio-manufacturing. A diverse range of encapsulation techniques, including emulsion-based methods, spray drying, and electrospinning, have been employed to encapsulate various food functional factors (Niu et al., 2020). In the context of advanced bio-manufacturing, these encapsulation systems align with sustainability goals by improving process efficiency and reducing waste. Moreover, they play a crucial role in meeting consumer demands for functional foods with enhanced health benefits (Aguilar-Pérez et al., 2023). With the growing emphasis on personalized nutrition and functional foods, encapsulation technologies have the potential to revolutionize the food industry by delivering bioactive compounds in a more effective and consumer-friendly manner.

Despite the numerous advantages, the implementation of micro- and nano-delivery systems in food biomanufacturing is not without challenges. One of the primary obstacles is scalability - transitioning from laboratory-scale systems to large-scale industrial production. Maintaining consistency in particle size, distribution, and overall performance across different batches is critical for the commercial viability of these technologies (Bauer et al., 2018). Additionally, there are concerns regarding the stability of encapsulated systems during storage and under varying environmental conditions, such as temperature fluctuations and changes in pH. The potential toxicity of certain nano-scale delivery systems also raises regulatory concerns, particularly regarding the safety of long-term consumption.

By integrating encapsulation technologies, advanced biomanufacturing can optimize ingredient functionality, reduce waste, and improve the sustainability of food production. Additionally, the use of micro- and nano-delivery platforms allows for the development of novel food products with tailored nutritional benefits, addressing the growing consumer demand for functional foods and nutraceuticals. The ability to scale these technologies from laboratory research to industrial applications marks a significant advancement in food processing, contributing to more efficient, cost-effective, and sustainable biomanufacturing practices.

This review examines the principles and recent advancements in diverse micro- and nano-delivery systems, with a focus on their underlying mechanisms, broad-spectrum applications, and associated challenges. Additionally, it discusses their integration into bio-manufacturing processes and outlines future research directions aimed at fostering innovation and addressing existing limitations in this evolving field.

2. Need of study

The revolution in food science lies in harnessing cutting-edge micro- and nano-delivery carrier platforms to redefine how bioactive compounds are stabilized, protected, and delivered with precision (Otchere et al., 2023; Singh & Shagolsem, 2021). These advanced technologies, including pickering emulsions, micro-emulsions, microcapsules, and nanoparticles, offer unparalleled solutions to long-standing challenges such as instability, degradation, and low bioavailability of bioactive ingredients (Corona‐Hernandez et al., 2013). By enabling controlled and targeted release, these carriers enhance the functional efficacy of nutrients and bioactives, paving the way for innovative applications in functional foods, dietary supplements, and nutraceuticals. However, scaling these systems for industrial applications, ensuring regulatory compliance, and developing adaptable, multifunctional carriers remain critical hurdles. Addressing these challenges is essential for advancing sustainable bio-manufacturing and meeting the growing consumer demand for health-promoting food components such as bioactive peptides and probiotics.

3. Development of Delivery Carrier Platforms

The development of micro- and nano-delivery systems has revolutionized the food and pharmaceutical industries by addressing the challenges associated with the stability, bioavailability, and controlled release of bioactive compounds (Petrovic & Barbinta-Patrascu, 2023). These systems use various carrier platforms, which can encapsulate bioactive molecules, protecting them from degradation, ensuring their release in targeted regions, and enhancing their functionality. Over the years, the evolution of delivery platforms has resulted in highly sophisticated systems with diverse applications in functional foods, nutraceuticals, and beyond.

3.1. Pickering Emulsions

Pickering emulsions are a class of emulsions stabilized by solid particles that adsorb at the interface between the oil and water phases, rather than by conventional surfactants. These solid particles can be derived from various materials such as food-grade nanoparticles (Chen et al., 2023), plant proteins (Östbring et al., 2021), polysaccharides (Meng et al., 2024), or silica particles (Bruckmann et al., 2022). They are described as particle-stabilized systems primarily used for micro-scale delivery. Their potential in delivering bioactive compounds is highlighted due to their enhanced stability and environmental responsiveness (Berton-Carabin & Schroën, 2015). The particles are typically hydrophobic, allowing them to adsorb at the oil-water interface and reduce the interfacial tension Figure 1. Shows the O/W emulsion and W/O emulsions during pickering emulsions (Tian et al., 2024).

This results in enhanced emulsion stability, as the particles physically block the coalescence of oil droplets and prevent phase separation (Chang et al., 2023). In pickering emulsions, the structure and properties of the stabilizing particles play a crucial role in determining the stability and performance of the emulsion. The size, shape, and surface charge of the particles influences the emulsifying capacity and the final characteristics of the emulsion, such as viscosity and release profile.

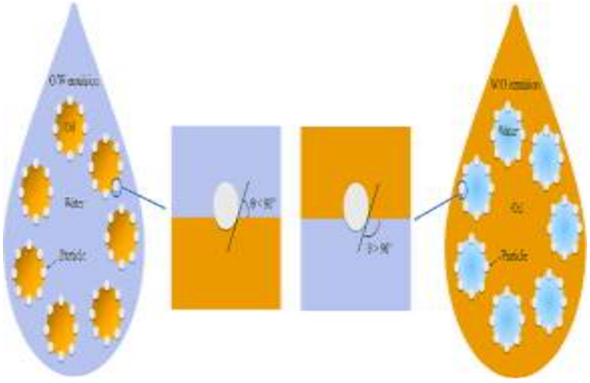

Figure 1. Schematic diagram of pickering emulsions (Tian et al., 2024).

Pickering emulsions have garnered significant attention in the food industry for encapsulating lipophilic bioactive compounds, such as omega-3 fatty acids, essential oils, and antioxidants (Galani, 2024). These bioactive compounds are prone to oxidation, degradation, and low bioavailability, making them challenging to incorporate into food systems. By encapsulating them in Pickering emulsions, the stability of these compounds is greatly improved, and their bioavailability is enhanced. Furthermore, Pickering emulsions are free from synthetic surfactants, making them an eco-friendlier and consumer-friendly alternative for food applications.

Recent advancements in pickering emulsion technology have highlighted the utilization of plant-based materials as stabilizers. Plant-derived proteins, including those extracted from peas, soy, and rice, have demonstrated efficacy in stabilizing emulsions while addressing consumer preferences for sustainable and plant-based ingredients demonstrated in figure 2. (Gomes & Sobral, 2021). Furthermore, engineered nanoparticles, such as chitosan- or cellulose-based particles, have been developed to enhance the stability and functional performance of emulsions, show casing innovative approaches in material engineering to meet the demands of modern food systems.

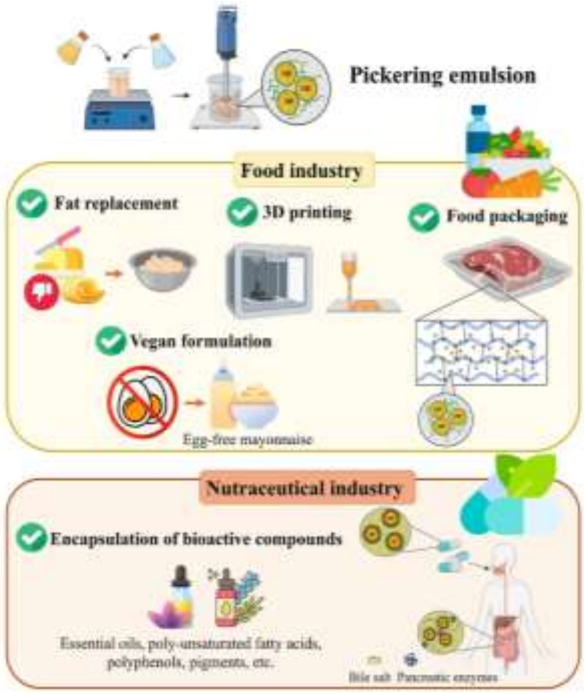

Figure 2. Applications of pickering emulsions in Food Science (Cassani & Gomez Zavaglia, 2024).

Despite their potential, pickering emulsions face several challenges. One major issue is the scalability of production (Chen et al., 2020). While laboratory-scale production methods have been established, there are still significant hurdles in scaling up the process for industrial applications. Additionally, Stability remains a critical challenge for encapsulated system, particularly under varying conditions, such as temperature fluctuations, pH changes, and storage conditions. A study by (Östbring et al., 2021) demonstrated that emulsions stabilized by rapeseed proteins exhibited significant destabilization at elevated storage temperatures and specific pH levels, underscoring the importance of optimizing storage conditions for such systems. Further research is needed to enhance their resilience and maintain functionality in diverse storage environments. Emerging trends in pickering emulsions focus on the development of multifunctional delivery systems designed to encapsulate both hydrophobic (e.g., essential oils, fat-soluble vitamins) and hydrophilic (e.g., peptides, water-soluble vitamins) bioactive compounds, particularly those derived from food and natural sources. These systems aim to enhance the stability, controlled release, and bioavailability of such compounds in food and pharmaceutical applications.

Additionally, there is a growing emphasis on employing biodegradable and sustainable materials as stabilizing particles, reflecting increasing consumer and industrial demand for eco-friendly approaches in food production. Advancements in particle architecture and emulsion formulation further aim to enhance efficiency and enable more precise, targeted delivery, paving the way for innovative applications in functional food systems.

3.2. Micro-emulsions

Micro-emulsions are thermodynamically stable, nano-sized systems with isotropic mixtures of oil, water, and surfactants, which form spontaneously under certain conditions (Jacob et al., 2024). These emulsions typically have particle sizes in the range of 10 to 200 nm and are stabilized by surfactants or co-surfactants that reduce the interfacial tension between the oil and water phases (Suhail et al., 2021). The composition of a micro-emulsion typically includes an oil phase (such as triglycerides or essential oils), a water phase, a surfactant (such as lecithin or Tween), and a co-surfactant (such as ethanol) (Bamanna et al.).

The stability of micro-emulsions is governed by the surfactant molecules' ability to reduce interfacial tension and form a stable film around the oil droplets. This film prevents coalescence and maintains the stability of the droplets over time. The unique ability of micro-emulsions to self-assemble and remain stable without additional energy input makes them an ideal choice for encapsulating bioactive compounds as shown in figure 3.

Micro-emulsions are highly versatile that they can deliver both hydrophobic and hydrophilic bioactive compounds.

Hydrophobic bioactives, such as curcumin or coenzyme Q10, which are poorly soluble in water, benefit from being incorporated into the oil phase of the micro-emulsion, improving their solubility and bioavailability (Ghoshal, 2024). On the other hand, hydrophilic compounds, like water-soluble vitamins and polyphenols, can be encapsulated in the aqueous phase of the micro-emulsion, enabling their controlled release and improving their stability (Valdes-Becerril et al., 2025).

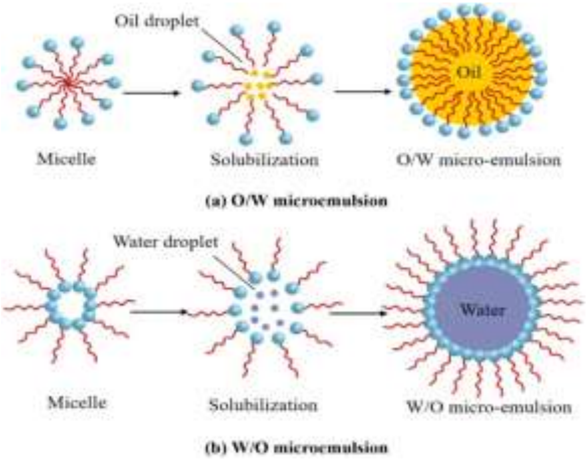

Figure 3. Advances in micro-emulsions applications (Zhu et al., 2022).

One of the key advantages of micro-emulsions is their ability to improve the bioavailability of poorly water-soluble bioactive compounds. The small size of the droplets allows for better absorption and faster release of the bioactives in the gastrointestinal tract, as demonstrated in recent studies (Loffredi & Alamprese, 2024). This makes micro-emulsions an ideal delivery platform for functional foods, nutraceuticals, and pharmaceutical applications. The successful application of micro-emulsions in encapsulating lipophilic bioactive compounds has been extensively documented in the literature. For example, curcumin, a well-known antioxidant with low bioavailability, has been encapsulated using micro-emulsion systems to improve its stability and absorption (Malik et al., 2023).

Similarly, essential oils derived from turmeric, ginger, and cinnamon, known for their significant health benefits, have been successfully incorporated into micro-emulsions to protect against oxidation and degradation (Pandita et al., 2024). These advancements underscore the versatility of micro-emulsions in preserving and enhancing the functional properties of sensitive bioactive compounds, thereby broadening their applicability in nutraceutical and functional food products.

In the food industry, micro-emulsions have been used to improve the delivery of nutrients in functional beverages and fortified foods. They are also gaining attention in the cosmetic and pharmaceutical industries for the delivery of active ingredients in creams, lotions, and transdermal patches.

3.3 Microcapsules

Microcapsules are structures in which a core material (e.g., bioactive compounds, drugs) is surrounded by a coating material. These coatings can be made from natural or synthetic polymers, proteins, or polysaccharides. Microencapsulation protects sensitive bioactives from external factors, such as light, oxygen, and moisture, while enabling controlled release in a targeted manner (Boostani & Jafari, 2021). They are highlighted as larger-scale delivery systems that provide controlled release and protect sensitive ingredients from environmental factors such as pH, temperature, or oxygen (Parente et al., 2022). In a typical process, a core material (e.g., bioactive compound) is dispersed into an emulsifier-containing solution under controlled stirring to form a water-in-oil (W/O) emulsion (Wang et al., 2024). The emulsifier stabilizes the core droplets, preventing coalescence during the encapsulation process (Galogahi et al., 2021; Marhamati et al., 2021). Subsequent crosslinking or solidification of the encapsulating material, achieved through thermal, chemical, or physical means, finalizes the formation of microcapsules. This method offers precise control over capsule size and shell properties, making it ideal for applications requiring stability and targeted delivery.

Microencapsulation techniques in food applications, figure 4 emphasizing the significance of emulsifiers in forming stable systems and achieving high encapsulation efficiency (Muhoza et al., 2022). Similarly, another study (Vieira et al., 2020) demonstrated the optimization of microcapsules using solvent evaporation for pharmaceutical and nutraceutical applications. These studies highlight the versatility of the W/O emulsion technique in encapsulating a wide range of bioactives effectively.

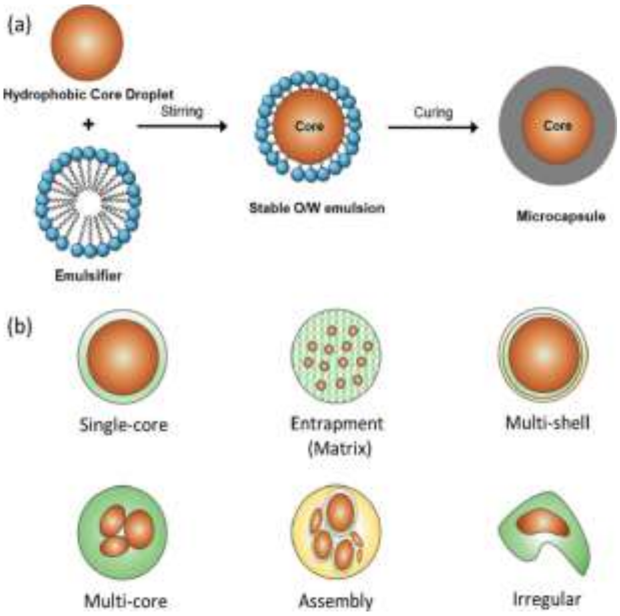

Figure 4. Microencapsulation for food applications (C. Yan et al., 2022).

Microcapsules provide critical advantages for bioactive compound delivery, particularly in food and pharmaceutical applications as given in figure 5. They effectively protect sensitive compounds like antioxidants and probiotics from environmental stressors, enhancing stability and reducing degradation.

Additionally, their coatings can be designed for controlled release, enabling targeted delivery in specific conditions, such as the stomach or intestines (Boostani & Jafari, 2021). Their versatility in encapsulating a wide range of materials, from vitamins to probiotics, using natural or synthetic polymers, allows for tailored applications, making microcapsules indispensable for improving the efficiency and functionality of bioactive delivery systems.

Microcapsules are widely used in the food industry for the controlled delivery of functional ingredients such as probiotics and vitamins (Wang et al., 2022). They are also used in the pharmaceutical industry for the targeted delivery of drugs.

Figure 5. Microencapsulation applications in food Industry (Arenas-Jal et al., 2020).

3.4 Nanoparticles

Nanoparticles are a class of nano-scale delivery carriers used for encapsulating bioactive compounds (Luo et al., 2020). These systems range from 1 to 100 nm in size and can be fabricated using lipids, proteins, or synthetic polymers (Alu'datt et al., 2022). Nanoparticles can enhance the bioavailability, stability, and solubility of bioactive compounds, especially those that are poorly water-soluble. The small size of nanoparticles allows them to interact at a molecular level, making them highly effective for controlled and targeted delivery (Mitchell et al., 2021). Figure 6 shows the schematic diagram for targeted delivery of nanoparticles.

Nanoparticles have been successfully used to encapsulate a variety of bioactives, including antioxidants, essential fatty acids, and vitamins. Their applications extend to both functional foods and drug delivery, with growing interest in personalized nutrition. While significant progress has been made in the development of these delivery systems, several challenges remain. The scalability of production methods, regulatory hurdles, and the need for more sustainable, eco-friendly materials are areas that require continued research and innovation. Additionally, the integration of these systems into bio-manufacturing processes, where cost-effectiveness and large-scale production are essential, remains an ongoing challenge.

Encapsulation strategies involve various chemical and physical processes to achieve stability and functionality. For example, click chemistry, a highly selective and efficient chemical reaction, is often used in the synthesis of nanoparticles. This reaction facilitates the attachment of functional groups or bioactive compounds to nanoparticle surfaces, enhancing their stability and delivery efficiency(Arslan et al., 2019). Additionally, crosslinking reactions using agents such as glutaraldehyde or genipin are employed to stabilize encapsulating materials in microcapsules, ensuring controlled release and protection of the encapsulated compounds (Huang et al., 2023).

Future research in encapsulation and delivery systems is expected to focus on several critical areas. One key direction involves scaling up production from laboratory to industrial levels, addressing challenges such as cost-efficiency and maintaining consistency in large-scale manufacturing processes. Additionally, sustainability has become a priority, with efforts concentrated on developing eco-friendly and biodegradable materials to minimize the environmental footprint of encapsulation technologies. Another promising avenue lies in the creation of multifunctional delivery systems designed to encapsulate multiple bioactive compounds, enabling synergistic effects and enhancing the efficacy of functional ingredients in diverse applications (McClements, 2020). These advancements have the potential to further expand the role of encapsulation technologies in modern food systems and bio-manufacturing processes.

4. Challenges and Opportunities

The encapsulation and delivery of food functional factors via advanced carrier platforms such as Pickering emulsions, micro-emulsions, microcapsules, and nanoparticles hold transformative potential in food science. However, significant challenges must be addressed to unlock their full potential. This section discusses key technical, regulatory, and application-related aspects.

4.1 Technical Challenges

4.1.1 Scalability

One of the most pressing challenges in utilizing micro- and nano-scale delivery systems is the difficulty of scaling up production from the laboratory to industrial levels. Techniques such as high-pressure homogenization or ultrasonication, commonly used for producing these systems, often require costly equipment and considerable energy inputs (Qayum et al., 2023). Moreover, maintaining uniformity and consistency in particle size and distribution across large batches remains a significant obstacle. These challenges are particularly pronounced for Pickering emulsions, where consistent preparation of stabilizing particles at scale is critical.

4.1.2 Stability

Ensuring the physical and chemical stability of encapsulated compounds during processing, storage, and digestion is another technical hurdle (Hamed et al., 2023). Encapsulation systems must protect sensitive bioactive compounds from environmental stresses such as oxygen, light, and high temperatures. However, many delivery platforms, including micro-emulsions, may destabilize under extreme pH levels or ionic conditions (Garavand et al., 2021). This is especially problematic in food systems where processing involves varying pH levels or thermal treatments, such as pasteurization.

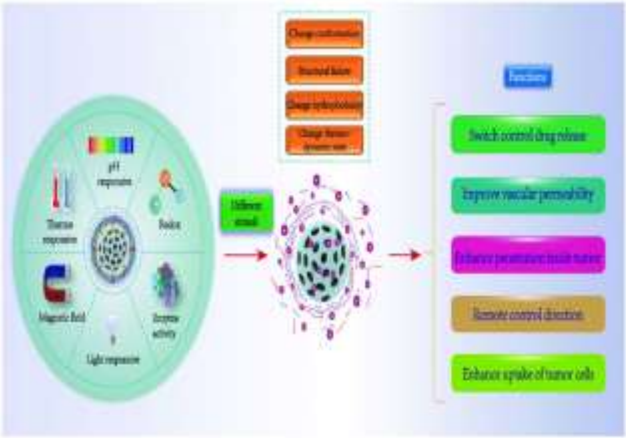

Figure 6. Schematic Diagram for Targeted delivery (Karimi et al., 2016).

4.1.3 Controlled release mechanism

Achieving precise control over the release of bioactive compounds remains an ongoing challenge. Current delivery systems are often unable to finely tune release rates, which can result in either premature degradation or delayed absorption in the gastrointestinal tract. Research into stimuli-responsive carriers-delivery systems that release compounds in response to pH, temperature, or enzymatic triggers-has shown promise but is still in its infancy in commercial applications (Garavand et al., 2021).

4.2 Regulatory Considerations for Nano-Scale Delivery Systems

The use of nano-scale delivery systems in food and nutraceuticals raises complex regulatory issues. In many regions, including the United States and Europe, nano-scale materials must undergo stringent safety evaluations before being approved for use in food products (Vlaicu et al., 2023). These regulations focus on aspects such as:

- **Toxicity:** Nanoparticles' small size may result in unique interactions with biological systems, potentially causing unforeseen toxicological effects.
- **Bioaccumulation Risks:** Regulatory bodies are concerned about the potential for nanoparticles to accumulate in tissues over time, posing long-term health risks (Warheit, 2018).
- **Transparency:** Many consumers are wary of nano-engineered ingredients, leading to calls for clearer labeling and public education about their safety and benefits.

Navigating these regulatory landscapes requires manufacturers to demonstrate not only the efficacy of nano-scale delivery systems but also their safety through rigorous testing and transparent reporting.

4.3 Potential Applications in Functional Foods and Nutraceuticals

The integration of advanced delivery systems, such as micro- and nano-encapsulation technologies, into functional foods and nutraceuticals is transforming the food industry. These systems address the limitations of traditional delivery methods, enhancing the stability, bioavailability, and functionality of bioactive compounds.

4.3.1 Enhancing Stability of Sensitive Compounds

Many functional ingredients, such as probiotics, vitamins, and polyunsaturated fatty acids, are sensitive to environmental factors like heat, light, and oxygen. Encapsulation provides a protective barrier, preserving their efficacy during processing, storage, and digestion. For example, encapsulated probiotics remain viable through acidic gastric environments, ensuring their delivery to the intestines for health benefits such as improved gut health and immune modulation (Bauer-Estrada et al., 2023).

4.3.2 Improving Bioavailability

The bioavailability of poorly soluble bioactives, such as curcumin, omega-3 fatty acids, and carotenoids, can be significantly enhanced through encapsulation (Saini et al., 2022). Nano-emulsions and microemulsions are particularly effective in improving the solubility and intestinal absorption of these compounds. Encapsulated curcumin, for instance, exhibits superior absorption, making it more effective as an anti-inflammatory and antioxidant agent (Rafiee et al., 2019).

4.3.3 Controlled and Targeted Release

Advanced delivery systems enable controlled and targeted release of functional ingredients, optimizing their efficacy. pH-sensitive coatings, for example, release nutrients in specific gastrointestinal regions, such as the intestine. This is crucial for compounds like enzymes or peptides that require localized action. Controlled release also ensures a sustained effect, reducing the need for frequent consumption (Adepu & Ramakrishna, 2021). Encapsulation systems can enable the targeted release of probiotics or prebiotics in the gut, where they have the greatest effect.

4.3.4 Fortification of Everyday Foods

Encapsulation technologies allow for the seamless integration of bioactives into common foods, including beverages, snacks, and dairy products (Liu et al., 2022). Fortified foods enriched with vitamins, minerals, or phytochemicals cater to consumer demands for health-oriented products. For instance, omega-3 fatty acids can be incorporated into baked goods or dairy without compromising taste or texture, thanks to microencapsulation (Feizollahi et al., 2018).

4.3.5 Development of Functional Ingredients

Functional beverages are a growing sector benefiting from encapsulation systems. Nano-encapsulation stabilizes hydrophobic compounds like resveratrol or caffeine in aqueous solutions, enabling their incorporation into clear beverages (Pateiro et al., 2021). Probiotic drinks also rely on encapsulation to maintain the viability of live microorganisms during shelf life. Recent studies have investigated the use of herbal and plant-based extracts in food products. A study on the combination of mint extract with animal and vegetable fats in ice cream, along with stabilizers such as guar gum and carboxymethyl cellulose, has been shown to enhance its sensory and quality attributes (Syed et al., 2022).

4.3.6 Nutraceuticals and Personalized Nutrition

In nutraceuticals, encapsulation enhances the efficacy and appeal of dietary supplements. Capsules or powders containing encapsulated vitamins, antioxidants, and phytochemicals ensure precise dosing and improved absorption (Chakraborty et al.; Panwar et al.; Rao et al., 2024). Additionally, advanced systems enable the creation of personalized nutrition solutions, where encapsulated bioactives are tailored to individual health needs (Ahmadzadeh et al., 2023).

4.3.7 Eco-Friendly and Sustainable Applications

The use of biodegradable and natural materials for encapsulation, such as alginate, chitosan, and plant-based proteins, aligns with the industry's shift toward sustainability. This approach reduces environmental impact while addressing consumer preferences for natural and eco-friendly products (Mondéjar-López et al., 2024). The potential to create innovative, health-enhancing products is driving investment and research in encapsulation technologies, setting the stage for significant growth in this sector.

5. Advanced Bio-manufacturing Applications

Encapsulation technologies represent a cornerstone of advanced bio-manufacturing, enabling breakthroughs in the sustainable and efficient production of functional foods. This section explores the role of these technologies in driving innovation and improving the efficiency of food manufacturing systems.

5.1 Role of Encapsulation Technologies in Advancing Food Bio-manufacturing

Encapsulation allows bioactive compounds, flavors, and nutrients to be incorporated into food matrices in a controlled and stable manner, thus supporting the production of high-quality, functional food products. For example, microencapsulation has been used to incorporate omega-3 fatty acids into baked goods without compromising taste or texture. Similarly, Pickering emulsions have been utilized to develop low-fat mayonnaise and salad dressings that maintain the sensory characteristics of their full-fat counterparts (Young, 2021).

Encapsulation technologies are integral to advancing food bio-manufacturing by addressing key challenges related to the stability, delivery, and bioavailability of bioactive compounds in food systems. These technologies enable the protection of sensitive ingredients, such as vitamins, antioxidants, and probiotics, from external factors (e.g., oxidation, moisture, and heat), ensuring their stability throughout processing, storage, and consumption. Furthermore, encapsulation methods allow for the controlled and sustained release of functional food ingredients, which enhances their effectiveness and bioavailability. As demand for functional foods, nutraceuticals, and health-promoting ingredients increases, these advanced technologies have become central to food manufacturing innovations.

5.1.1 Solid Particle Stabilized Emulsions

One promising encapsulation approach gaining attention is the use of solid particle-stabilized emulsions, commonly referred to as Pickering emulsions. Unlike conventional emulsions that rely on surfactants, This approach improves the stability of the emulsion, preventing phase separation and ensuring the protection of encapsulated bioactive compounds. Studies have shown that Pickering emulsions can successfully encapsulate a variety of bioactive ingredients, such as omega-3 fatty acids and curcumin, and maintain their stability during food processing. For instance, research by (KORKUT, 2021) demonstrated that plant protein-stabilized Pickering emulsions could effectively encapsulate omega-3 fatty acids, enhancing their bioavailability and stability. Similarly, Cahyana et al. (2022) (Cahyana et al., 2022) reported the successful encapsulation of curcumin in Pickering emulsions, improving its solubility and therapeutic efficacy. The unique structure of Pickering emulsions allows them to provide controlled release, offering potential benefits in functional foods aimed at improving consumer health.

5.1.2 Thermodynamically Stable Microemulsions

Microemulsions, another key encapsulation technology, have emerged as a versatile solution for encapsulating hydrophobic bioactives in water-soluble systems. Microemulsions are highly efficient in improving the solubility and bioavailability of compounds that are otherwise poorly soluble in water. For example, Mitsou et al. (2020) showed that microemulsions could encapsulate polyphenols, increasing their solubility and antioxidant activity (Mitsou et al., 2020). Microemulsions are also cost-effective and scalable, making them suitable for large-scale food manufacturing. Their ability to solvate hydrophobic bioactive compounds effectively makes them an ideal platform for delivering health-promoting ingredients, such as polyphenols and vitamins, in functional food formulations.

5.1.3 Nanoscale Emulsions for Enhanced Bioavailability

Nanoemulsions are particularly useful for encapsulating lipophilic bioactives like essential oils, antioxidants, and vitamins, which often face challenges in terms of solubility and bioavailability. Research by Choi et al. (2020) demonstrated that nanoemulsions could encapsulate antioxidants, enhancing their stability and bioavailability (Choi & McClements, 2020). Similarly, Wijekoon et al. (2023) reported that nanoemulsions could be used to encapsulate hydrophobic vitamins, improving their stability and ensuring more effective delivery in functional food applications (Wijekoon et al., 2023). The ability of nanoemulsions to improve the solubility and bioavailability of bioactive compounds makes them a valuable tool in the food industry, particularly for nutraceutical applications.

5.1.4 Controlled-Release Microencapsulation

Microencapsulation is a well-established technology that involves the encapsulation of bioactive compounds within a protective coating to protect the core ingredients and control their release. This technique is widely used in food bio-manufacturing to encapsulate sensitive bioactives, such as probiotics, vitamins, and omega-3 fatty acids. The core material is often surrounded by a polymer, lipid, or protein-based shell that can be designed to release the active compound under specific conditions, such as changes in pH, temperature, or enzymatic activity. Barajas et al. (2023) demonstrated the use of microencapsulation for enhancing the stability and viability of probiotics during gastrointestinal transit, protecting them from harsh conditions in the stomach and ensuring their controlled release in the intestines (Barajas-Álvarez et al., 2023). Comunian et al. (2022) also studied microencapsulation techniques for vitamins, showing that the encapsulated vitamins exhibited improved stability and controlled release profiles, ensuring their effective delivery in functional foods (Comunian et al., 2022). This technology offers the advantage of providing sustained release, allowing bioactives to be released gradually over time, enhancing their effectiveness in improving health outcomes.

5.1.5 Nanoparticle-Based Delivery Systems

Nanoparticles are particularly effective in encapsulating hydrophobic bioactives, such as polyphenols, vitamins, and essential oils, improving their solubility, stability, and bioavailability. One of the advantages of nanoparticles is their ability to be designed for targeted delivery, ensuring that the bioactive compound reaches the desired site of action in the body. For example, Maleki et al. (2022) used chitosan nanoparticles to encapsulate vitamins, enhancing their stability and providing controlled release in food systems (Maleki et al., 2022). Guo et al. (2021) also explored the use of nanoparticles for encapsulating polyphenols, improving their bioavailability and ensuring sustained release (Guo et al., 2021). Nanoparticles offer versatility in terms of encapsulation materials and can be tailored to meet the specific needs of different bioactive compounds, making them highly effective in food bio-manufacturing applications.

In addition, encapsulation technologies enable manufacturers to reduce waste and maximize the utilization of raw materials. For instance, encapsulation can extend the shelf life of volatile compounds, reducing spoilage and minimizing the need for synthetic preservatives.

(Table-1) shows the advanced bio-manufacturing applications of delivery carrier platforms in the food systems.

5.2 Impact on Sustainability and Efficiency in Food Processing

5.2.1 Reduced Environmental Footprint

The integration of encapsulation technologies into bio-manufacturing processes contributes to environmental sustainability. By encapsulating functional ingredients, manufacturers can reduce the amount of active ingredients required, lowering energy and resource inputs (Mukurumbira et al., 2022). Furthermore, natural and biodegradable materials used in Pickering emulsions and microcapsules align with the growing demand for eco-friendly packaging and ingredients.

5.2.2 Energy Efficiency

Encapsulation technologies improve energy efficiency by streamlining production processes. For example, using pre-encapsulated ingredients allows manufacturers to skip additional stabilization steps, reducing processing times and energy costs (Xu et al., 2024).

5.2.3 Innovation in Product Development

Encapsulation technologies also enable the creation of innovative food products that meet evolving consumer demands. From functional beverages fortified with bioavailable vitamins to plant-based meat alternatives enriched with encapsulated micronutrients, encapsulation expands the possibilities for product innovation (Halder et al., 2021). Probiotics have been increasingly incorporated into dairy products like yogurt to enhance their health benefits. For instance, a study on yogurt demonstrated that probiotic incorporation not only influenced its physicochemical attributes but also contributed to cholesterol assimilation during storage (Younas et al., 2024).

As food bio-manufacturing continues to evolve, encapsulation technologies will play an essential role in addressing the challenges of sustainability, efficiency, and consumer satisfaction (Jagtiani, 2022; M. R. Yan et al., 2022). Collaboration between researchers and industry stakeholders is essential to fully realize the potential of these advancements, as it fosters innovation and accelerates the adoption of cutting-edge solutions(Allioui & Mourdi, 2023). Moreover, encapsulation technologies not only enhance the functional capabilities of bio-manufactured foods, such as improved stability and nutrient delivery, but also contribute to sustainability and resource efficiency by reducing waste and optimizing production processes (Ullah et al., 2024). Various studies have focused on the role of bioactive compounds in maintaining food quality during storage. For instance, the enhancement of beetroot jam with stevia showed promising results in maintaining antioxidant activity throughout storage (Östbring et al., 2021). These innovations are poised to become a cornerstone of next-generation food systems, driving both environmental and economic benefits.

6. Future Directions and Predictions

The future of micro- and nano-delivery systems is marked by innovations aimed at improving functionality, scalability, and sustainability. One promising trend is the development of multifunctional delivery systems capable of encapsulating both hydrophobic and hydrophilic bioactive compounds. These systems could enable synergistic effects by delivering multiple bioactives simultaneously, enhancing their combined efficacy (Tan et al., 2021). Additionally, research is shifting toward the use of biodegradable and renewable encapsulating materials to address environmental concerns, aligning with global sustainability goals.

Advances in material science and nanotechnology are also driving the creation of stimuli-responsive delivery systems. These smart-systems can release bioactives in response to specific triggers such as temperature, pH, or enzymes, providing precise and efficient delivery. Furthermore, the application of computational modeling and artificial intelligence in the design and optimization of delivery systems is expected to accelerate innovation, reducing the time and cost associated with experimental trials (Tan et al., 2021).

Encapsulation has emerged as a cornerstone technology in functional food delivery, offering a reliable solution to key challenges such as the stability, bioavailability, and targeted release of bioactive compounds. By protecting sensitive ingredients from degradation and ensuring their controlled release, encapsulation enhances the efficacy of functional foods in delivering health benefits. It also enables the incorporation of a wide range of bioactives into food systems, expanding product possibilities and catering to consumer demands for nutritious and functional options. Moreover, encapsulation supports the development of customized delivery solutions tailored to individual dietary needs, paving the way for personalized nutrition (Mehta et al., 2024). This adaptability highlights its critical role in advancing functional food innovation and improving public health outcomes.

The integration of encapsulation technologies into advanced bio-manufacturing is poised to revolutionize food processing by combining scientific

Table 1. Advanced Bio-manufacturing key findings and Applications of Delivery Carrier platforms in Food System

Encapsulation technology	Key Findings	Applications	References
Pickering Emulsions	Investigated the use of plant protein-stabilized Pickering emulsions for encapsulating omega-3 fatty acids, enhancing stability and bioavailability.	Omega-3 fatty acid delivery in functional foods	(KORKUT, 2021)
	Investigated the potential of Pickering emulsions for encapsulating bioactive compounds such as curcumin, improving its stability and bioavailability.	Curcumin encapsulation for enhanced bioavailability.	(Cahyana et al., 2022)
Microemulsions	Examined the use of microemulsions for encapsulating fish oil, improving its oxidative stability and providing a sustained release profile.	Fish oil encapsulation for improved stability and delivery.	(Yang et al., 2024)
	Focused on the formulation of microemulsions for encapsulating polyphenols, enhancing their solubility and bioavailability.	Polyphenol encapsulation for improved solubility and bioavailability.	(Mitsou et al., 2020)
Nanoemulsions	Investigated nanoemulsions for the delivery of bioactive compounds, such as antioxidants, improving both stability and controlled release.	Antioxidant delivery for nutraceutical applications.	(Choi & McClements, 2020)
	Studied the encapsulation of hydrophobic vitamins in nanoemulsions, improving their stability and bioavailability.	Vitamin delivery for improved bioavailability.	(Wijekoon et al., 2023)
Microcapsules	Investigated microcapsules for encapsulating probiotics, enhancing their stability and survival in the gastrointestinal tract.	Probiotic delivery in functional foods.	(Barajas-Álvarez et al., 2023)
	Studied the use of microcapsules for encapsulating vitamins,	Vitamin	(Comunian et

	improving both their release profile and shelf-life.	delivery and shelf-life enhancement.	al., 2022)
Nanoparticles	Discussed chitosan nanoparticles for encapsulating vitamins, enhancing stability, and providing controlled release in food systems.	Vitamin delivery in food and nutraceutical applications.	(Maleki et al., 2022)
	Studied the use of nanoparticles to encapsulate bioactive compounds such as polyphenols, improving their bioavailability and stability.	Polyphenol delivery for nutraceutical applications.	(Guo et al., 2021)

precision with sustainability. By enhancing the efficiency of ingredient utilization, reducing waste, and facilitating the production of innovative functional foods, encapsulation aligns with the growing demands for more sustainable and efficient food production systems (Bazzaz et al., 2024). These technologies support the creation of foods with improved bioactive delivery, addressing consumer preferences for healthier and eco-friendly options.

As research continues to explore new materials, mechanisms, and applications, encapsulation technologies will remain integral to advancing functional food development. Their role in bridging the gap between scientific advancements, industrial applications, and consumer needs will drive innovation in the food industry, fostering a more sustainable, health-conscious food system.

7. Conclusion

In conclusion, encapsulation technologies have emerged as a vital component in the advancement of functional food delivery systems, offering solutions to improve the stability, bioavailability, and controlled release of bioactive compounds. Platforms such as Pickering emulsions, microemulsions, microcapsules, and nanoparticles have proven instrumental in enhancing the functionality of food products, making them more efficient in delivering health benefits. These innovations not only meet consumer demands for functional foods but also align with sustainability goals through the use of biodegradable and eco-friendly materials. As the field continues to evolve, the integration of encapsulation technologies into advanced biomanufacturing processes will further optimize production efficiency and contribute to the development of personalized nutrition solutions. Ultimately, encapsulation remains a critical tool in the pursuit of a sustainable, health-focused food system, offering new possibilities for both research and industry applications.

Acknowledgment

I sincerely thanks to all colleagues for their support and express my gratitude to my mentor for her invaluable guidance.

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