Microencapsulation of Bioactive Compounds in Food Products

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Abstract

Bioactive compounds have therapeutic potential due to their antifungal, antioxidant, anti-inflammatory, and antimicrobial properties. Their demand has recently increased due to growing awareness and the COVID-19 pandemic. The stability, bioavailability, and scalability of bioactive compounds in foods face challenges due to temperature, pH variations, and extraction costs. Microencapsulation is a technique that involves entrapping substances in a matrix with particle sizes ranging from 1-5000 µm, and thus helps cater to the challenges regarding the stability and storage of bioactive compounds. Key factors like release kinetics and microencapsulation efficiency (MEE) are crucial for controlled release, processability, and environmental protection. Microencapsulation techniques include physical methods like spray drying, freeze drying, fluidized bed coating, extrusion, and liposome entrapment, each with specific advantages and limitations based on various factors. Chemical methods such as coacervation, interfacial and in situ polymerization, sol-gel, and molecular inclusion offer precise control over encapsulation efficiency, release properties, and stability, but may involve complex processes or safety concerns. It has been employed to preserve nutrients across various food products. Future research should prioritize sustainable technologies, safety compliance, and AI-driven advancements for improved encapsulation efficiency and industrial adoption.

Keywords: Microencapsulation, Bioactive compounds, Controlled release, Spray drying, Coacervation

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Introduction

Bioactive compounds are various components of food that are responsible for the beneficial attributes (therapeutic potential) of functional foods. These compounds are diverse in terms of their structure and sources, capable of interacting with various components of living tissues (Mu et al., 2014). These compounds are usually secondary and primary metabolites, which can reduce the risk or aid in the management of certain chronic diseases because of their antifungal, antioxidant, anti-inflammatory, and antimicrobial properties (Banwo et al., 2021). In previous years, due to increased awareness about the benefits of bioactive compounds and dietary supplements, the global supplement market has grown rapidly, with an expected worth of 300 billion US dollars in 2028 (Halder et al., 2021). The COVID-19 pandemic also increased the focus of consumers and industry towards supplements containing vitamins, minerals, and bioactive compounds due to their proposed benefits against infections and several diseases (Djaoudene et al., 2023).

There is no doubt in the increasing importance and demand of bioactive compounds, but at the same time, there are some challenges faced by industry for the incorporation of bioactive compounds into food products. Stability of bioactive compounds is a major issue since variations in temperature and pH may impact the structure, functions, as well as sensory attributes of bioactive compounds and respective foods containing those (Pateiro et al., 2021). The bioavailability of these compounds when incorporated into foods, along with optimization of extraction techniques, cost-effectiveness, and scaling up of procedures, are some other major issues (Bürck et al., 2024). There is a lack of standard regulations and legislation at the international level regarding the processing, extraction, incorporation, sustainability, and safety of these compounds (Vilas-Boas et al., 2021). For the issues regarding stability of bioactive compounds in different food products, targeted delivery, controlled release, and bioavailability, microencapsulation has emerged as a solution showing great potential. So this chapter highlights the importance of microencapsulation of various food byproducts to increase their stability, bioavailability, protection, and controlled release.

Microencapsulation

Microencapsulation finds its applications in various industries like cosmetics, paints, petroleum, textiles, food, agriculture, and pharmaceutical industries as microencapsulation-based technologies made into the scene in the middle of the twentieth century (Lobel et al., 2024). Microencapsulation is defined as the technique of entrapping substances (gas, liquid, or solid) in a continuous matrix (wall and shell) in such a way that the size distribution of particles ranges from 1-5000μm (Rashid, 2016). Release kinetics and microencapsulation efficiency (MEE) are two major parameters that have to be kept in mind while developing microcapsules through various techniques for enhancing processability, controlling release, and ensuring environmental protection (Huang et al., 2023).

Microencapsulation Techniques

Microencapsulation of bioactive compounds can be carried out through various physical, chemical, and physicochemical methods, some of which are discussed below and shown in Figure 1.

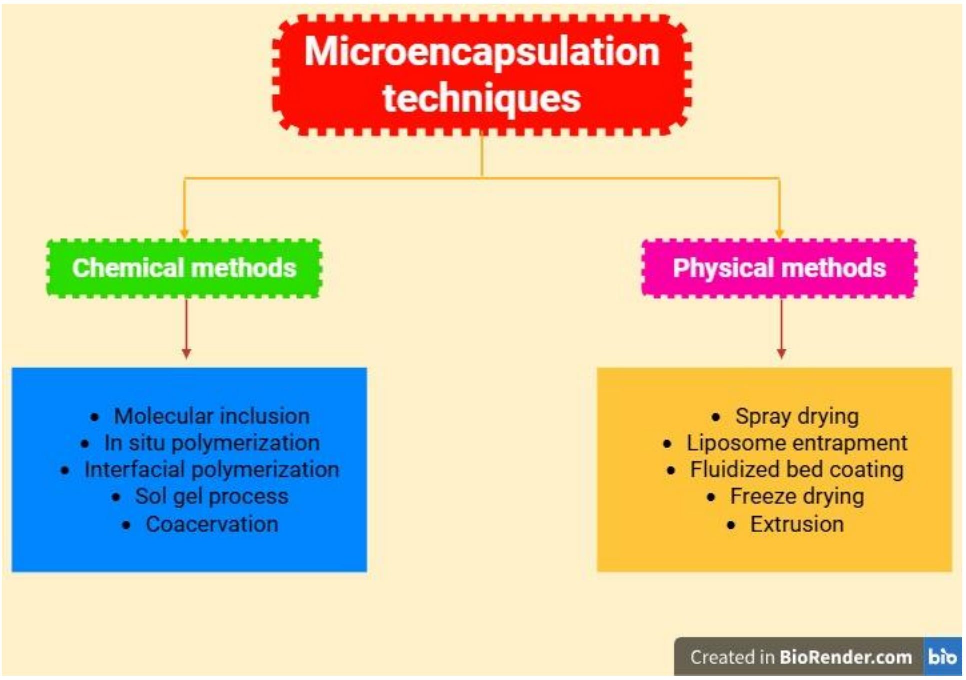

Fig. 1: Different techniques used for microencapsulation

Physical Methods

In spray drying, liquid is sprayed through an atomizer in a drying chamber where it is constantly divided into fine droplets. The interaction of these droplets with hot gas turns them into fine powder, vaporizing the liquid (Gil-Chávez et al., 2020). It is one of the most common and economical methods of microencapsulation that has been employed for the microencapsulation of flavors (soy sauce, green tea, orange), fragrances (lemon aroma, swiss cheese aroma), and oils (fish, algal, flaxseed, soy, walnut, oregano etc.) along with various bioactive compounds like vitamin C, curcumin, carotenoids, gallic acid etc. (Wianowska & Olszowy-Tomczyk 2023). Usually, a matrix-type microcapsule is formed with core material over the wall matrix, due to which the wall material should have good protection, film-forming properties, along with solubility in water (Zuidam & Shimoni 2010). Mulsification of bioactive compounds (core) is sometimes necessary to improve kinetic stability since some of these compounds are hydrophobic. The use of only permitted wall materials makes this technique less cost-effective in the food industry as compared to other industries (Furuta & Neoh, 2021). The use of high temperatures in spray drying makes it inefficient for heat-labile compounds (Jadhav et al., 2024). The use of modified spray, drying techniques like ultrasound (utilizing ultrasonic nozzles to produce consistent and smaller particles), pulse combustion (intermittent combustion eliminating the need for an atomizer), and multistage drying systems can improve the effectiveness of spray drying, but more research is required (Thakur et al., 2024).

Freeze drying method of microencapsulation uses the principle of sublimation, allowing the preservation and encapsulation of bioactive compounds that are heat-labile and therefore cannot be spray-dried (Meena et al., 2023). Advantages of this method include protection against oxidation, but at the same time, maintenance of low temperature for long periods makes this process costly and therefore unsustainable (Song, 2002). It has been used to encapsulate polyphenols from red wine, wastewater, cloudberry, red onion, yellow onion, and blackberry etc. (Buljeta et al., 2022). Freeze drying involves freezing moisture to ice, after which primary and secondary drying is carried out, pulling moisture through direct conversion of ice into vapor, where parameters such as pressure and temperature play a critical role. Recent studies employing microwave-assisted freeze drying and applying a 280-watt power supply to magnetrons have been found to reduce operational cost and time, respectively (Eikevik et al., 2012). Some studies also attempt to combine spray and freeze drying, which not only reduces time and cost but also improves retention. This process involves three major steps, i.e., spraying of liquid through atomizers, freezing droplets, and drying through sublimation. Similarly, infrared and freeze-drying have also been shown to rapidly reduce time (up to 70%) and electric energy (Kandasamy & Naveen, 2022).

Fluidized bed coating is another method of microencapsulation that involves spraying coat material onto the core through top, bottom, and tangential sprays, resulting in 5-50% microcapsules (Frey, 2023). The inlet temperature of the air, humidity, atomization pressure (nozzle), and velocity, along with feed rate (coating), are some parameters that critically impact the efficiency of microencapsulation (Choudhury et al., 2021). This process can be carried out either continuously or in batches. The coating material is usually an aqueous solution of substances like proteins, gums, dextrins, etc. that must form a thermally stable film of appropriate viscosity (El-Sayed et al., 2024). This process has been employed to encapsulate bioactive compounds like menthol, β-carotene, and choline bitartrate using starch sodium octenyl succinate, hydroxypropyl cellulose, and hydrogenated soybean oil, along with Tween 80 and PEG 400 as wall substances, respectively, using an inlet temperature ranging from 60-80 °C (Zabot et al., 2022). Due to its low energy needs, controlled particle size, up scalability, and low cost, along with continuous production, it has the potential to carry out microencapsulation of certain bioactive compounds at a larger scale (Huang et al., 2023). Rotary side sprays, down sprays, Wurster bed coating, and spouted beds are some other types of fluidized bed coating methods of encapsulation. Rotary side spray bed method has been employed using sodium caseinate and sodium alginate to create a multiple-layer coating on chlorophyll extracts with a production yield of 96.71% and 96.98%, respectively, showing 94.27% and 30.11% release in the intestine and stomach (stimulated gastrointestinal fluid) (Yang et al., 2022). Wurster fluidized bed coatings involve a Wurster cylinder where downflow beds (powder flowing state) with expansion/coating chambers (fluidized state) improve the homogeneity of coating. This process has been used to produce liquid medicines with sustained release (Mohylyuk et al., 2020).

Extrusion can also be employed for the microencapsulation of bioactive compounds, but high operational temperatures (80-150 °C) may be a disadvantage (Bamidele & Emmambux, 2021). High-density products with good protection to core material (bioactive compounds) are some characteristics of extrusion coating. Both core as well as coating material are pumped through a concentric orifice separately and coextruded, after which the extruded material breaks into tiny particles forming microcapsules due to centrifugal force that propels it (Alu'datt et al., 2022). Mostly, the temperature for extrusion is rarely 115 °C at less than 100psi pressure. It has been employed for the encapsulation of proteins, probiotics, flavors, antioxidants, oils, bacteriocin compounds, and probiotics due to its ability to prevent oxidation, improve stability, and ensure controlled release, along with versatility and low cost. This technique creates droplets by vibration overlay as the core and coating pass through the extruder under controlled conditions, making droplets that are incorporated into the gelling bath for the formulation of microcapsules (Rani & Kamble, 2024). Different types of extrusion methods i.e. electrospinning (*Lactobacillus acidophilus, Bifidobacterium infantis* and carqujaa extract), melt injection (lemon flavor, orange oil, cherry durarome, cherry, peppermint flavor and D-limonene), hot-melt (lemon oil, orange oil, quercetin, carvedilol and ascorbic acid), centrifugal (canola oil, kenaf oil seed, *L. casei, L. reuteri, L. plantarum and L.* paracasei) as well as particle form gas saturated solution (flax oil, phytosterol, lavandin oil, cinnamaldehyde, caffeic acid, olive leaf extract, vitamin K3 and D3) have been used for the microencapsulation of bioactive compounds (Bamidele & Emmambux, 2021; Zabot et al., 2022).

Liposome entrapment is another physical method that can be utilized for microencapsulation of bioactive compounds. Four major liposomes have been developed for delivery systems (conventional, ligand-targeted, sterically-stabilized, and a combination of the previous three) (Sercombe et al., 2015). Liposomes are amphiphilic double-layered closed vesicles that can encapsulate both hydrophobic and hydrophilic compounds, improving their stability. Liposomes are co-loaded with fish oil, folic acid, vitamin C, Vitamin B5, antioxidant peptides (flaxseed), medium chain fatty acids, lactoferrin and anthocyanins have been prepared and studied for their controlled release, improved functionality and oxidative stability (Wang et al., 2022).

Chemical Methods

The physicochemical method known as coacervation has been employed for the microencapsulation of beneficial compounds such as beta-carotene, broccoli, anthocyanins (from black raspberry), vitamin C, capsanthin, and astaxanthin (derived from shrimp waste). It generates microcapsules with high efficiency and facilitates controlled dispersion. The accumulation of elements with opposing charges results in coacervates, as this phenomenon essentially represents a colloidal system separation within the two phases of the liquid (Veis, 2011). Both simple and complex coacervation facilitate microencapsulation. Polymers are dissolved in a certain ratio of water and alcohol using a simple method; thereafter, additives and cross-linkers are incorporated with continuous stirring. Cooling the solution facilitates its solidification (Kolhe et al., 2022).

Complex coacervation is the dispersion of nuclei in an aqueous solution of anionic polymer, followed by the addition of a cationic solution to start a reaction among polyions (De Kruif et al., 2004). Changing temperature and pH as well as adding salts like electrolytes causes hardness and cross-linking, leading to coacervates with nuclei in their centre. Filtration or centrifugation desiccates these coacervates, producing the final product (Nezamdoost-Sani et al., 2024). Complex coacervation outperforms physical techniques in encapsulation efficiency, reaching up to 90-95% in certain situations. While thicker shells improve shelf life, using cross-linking agent's raises questions (Alu'datt et al., 2022).

A common method for microencapsulation, interfacial polymerisation creates a polymeric shell around the core material by means of a reaction at the interface of two immiscible liquid phases (Song et al., 2017). While the second phase is made up of a different monomer, the first phase's monomer must dissolve. The interaction of these phases causes polymerisation at the interface, therefore generating a protective shell around the enclosed item. Regulating capsule size, wall thickness, and permeability (Peanparkdee et al., 2016), this approach is best for pharmaceutical, food, and agricultural.

Factors such as monomer composition and reactivity, phase vehicle formulation, and temperature, among others, affect the polymerisation process. While interfacial polymerisation is a prominent technology in microencapsulation, offering effective protection and transport of sensitive substances, the rather harsh starting conditions and non-uniform coating may pose challenges for its industrial application (Dhanusha & Vijayalakshmi, 2023).

The term "sol-gel" describes the reaction involving any metalloid or metal which may create organic bridges when dissolved in a solution causing polymeric structures to form (Wang et al., 2022). The sol-gel solution mixed with the surfactant solution creates an emulsion that, besides catalysts, creates oxides that are washed and filtered. By means of diffusion control, the created microcapsules provide variable, regulated release (Trojer et al., 2015).

Microcapsules created using this method have rapid biodegradability, strong thermal stability, strength, biocompatibility, and more. In the food sector, encapsulating chemicals such as ascorbic acid, orange peel oil, fish oil, etc., have been used to preserve aroma and texture using this approach (Ashraf et al., 2015).

Another chemical method of microencapsulation is molecular inclusion, which, as the name implies, microencapsulates by molecular-level interaction between the guest (bioactive chemicals) and host (Mehta et al., 2022). This process may include building polymer matrices with certain holes that can selectively bind and release target molecules using non-covalent interactions—e.g., hydrogen bonding, van der Waals forces—to generate self-assembled structures for encapsulation (Verma & Hassan, 2013). Because of their chemically and physically stable character, cyclodextrins are the most often used host material. Molecular inclusion has been used to trap bioactive chemicals including quercetin, carvacrol, chrysin and vanillin etc. (Ozkan et al., 2019)

Selecting Materials for Encapsulation

Choosing materials for microencapsulation calls for assessing the core component, encapsulant, and preferred capsule characteristics (Choudhury et al., 2021). Encapsulants are polymeric chemicals as well as non-polymeric materials like cellulose, ethylene glycol, and gelatin (Nagar & Sreenivasa, 2024). This material's voice is dictated by the qualities of the core material along with the preferred shape, size, and release mechanism of the capsules. Looking at capsule size, hydrophobicity, solubility, and mechanical qualities helps to improve the effectiveness of encapsulation (Choudhury et al., 2021).

Core Material

A method called microencapsulation builds a protective barrier around delicate, costly nutrients, hence promoting their manufacture. This allows for delivery under specific conditions, at a precise time, and a specified site (Choudhury et al., 2021). Complex food formulations—including volatile tastes in instant mixes, fatty acids, and dairy products—can also be protected via microencapsulation. Often encapsulated are several nutritional elements, including vitamins, probiotic bacteria, colourants, essential oils, antioxidants, and flavouring chemicals (Alu'datt et al., 2022). Core material manufacture has to guarantee its release at a specified time and place, therefore enhancing the effectiveness of microencapsulation. Core material characteristics, core-to-encapsulant ratio, and core-encapsulant interactions (Sonawane et al., 2020; Choudhury et al., 2021) define the core release.

Coating Material

Coating materials are chosen depending on their rheological characteristics, capacity to disseminate and stabilise the active component, inertness, and ability to hold the molecule (Touaiti et al., 2013). Examples include carbohydrates (starch, maltodextrin, modified starch, cyclodextrin, cellulose), lipids (wax, paraffin, beeswax, diacylglycerols, gums, gum acacia, agar, carrageenan), and proteins (gluten, casein, and gelatin). Coating materials affect capsule characteristics, including size, shape, porosity, hygroscopicity, hydrophobicity, surface tension, and thermal properties (Salawi, 2022). Microencapsulation protects sensitive nutrients by means of conditional release, hence preserving them (e.g., flavours in chewing gum released during mastication). Applications include the encapsulation of fatty acids in dairy products and volatile tastes in instant mixes to prevent auto-oxidation (Sonawane et al., 2020; Choudhury et al., 2021).

Application of Microencapsulation in Food Products

In the food industry, microencapsulation serves several goals, including safeguarding functional components and ingredients from processing conditions, improving sensory quality by hiding unwanted tastes and odours, and increasing food safety by preventing microbial development (Dias et al., 2015). Microencapsulation technology allows the administration of bioactive chemicals, improves product stability, and helps regulated nutrient release (Choudhury et al., 2021; Calderón-Oliver & Ponce-Alquicira, 2022). Its uses range from functional drinks to dairy products, bread, meat products, and nutraceuticals, providing creative answers to fulfil customer needs for health and convenience. Many uses of microencapsulation in the food sector are shown in Figure 2.

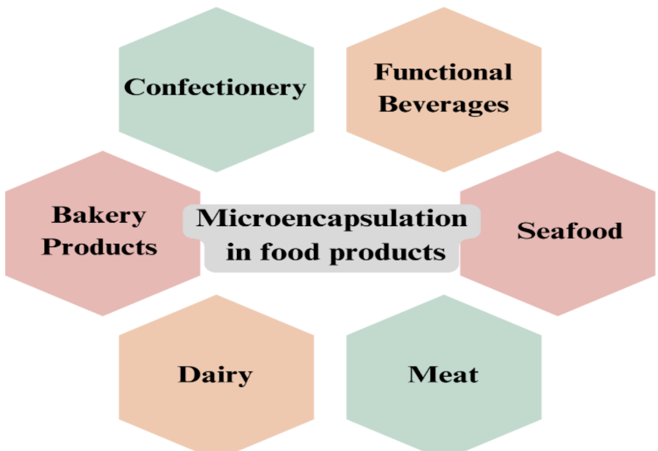

Fig. 2: Applications of microencapsulation in the food industry

Functional Beverages

Microencapsulation is essential in the development of functional beverages by improving the stability, sensory attributes, and bioavailability of bioactive compounds (Onwulata, 2013). The incorporation of fish oil into microcapsules via advanced coacervation has enabled the enrichment of fluids with fatty acids, hence increasing turbidity without compromising sensory attributes (Habibi et al., 2017). Microencapsulation facilitates the delivery of probiotics in juices, hence mitigating challenges such as low pH levels that may jeopardise microcapsule integrity and affect microbial viability during storage. Encapsulating beverages, bioactive compounds, and probiotics has facilitated the creation of functional powdered drinks with enhanced stability (Calderón-Oliver & Ponce-Alquicira, 2022). Table 1 illustrates the microencapsulation of some notable beverages.

Dairy Products

Microencapsulation may prove to be a transformative technology in daily products by enhancing their nutritional, functional, and sensory attributes. Additionally, microencapsulation allows the fortification of dairy products with essential nutrients like Omega 3 fatty acids, calcium, and iron, enhancing their stability under diverse storage conditions and improving mineral absorption (Calderón-Oliver & Ponce-Alquicira, 2022). Microencapsulation also contributes to masking undesirable flavors, enhancing flavor retention, and improving color stability in dairy products (Calderón-Oliver & Ponce-Alquicira, 2022). For instance, catechins encapsulated in cyclodextrin mask their flavor while preserving antioxidant properties in yogurt and milk (Szente et al., 2021). Similarly, lactase enzymes encapsulated in hydroxypropyl methylcellulose phthalate help in controlled release, making dairy products suitable for lactose-intolerant individuals. It also extends flavor stability as demonstrated with caramel microcapsules in milk with coffee, where flavored compounds persist longer compared to encapsulated counterparts (Koh et al., 2022). Table 2 gives microencapsulation of some of the dairy products used nowadays.

Table 1: Microencapsulation in functional beverages

	Product type	Encapsulated compounds	Key benefits	References
1.	Fortified juices	Vitamins (e.g., Vitamin C, Vitamin D), minerals (e.g., calcium)	Protection from degradation due to light exposure, oxygen and heat, enhanced nutrient stability, prolonged shelf life, improved bioavailability	(Calderón-Oliver & Ponce-Alquicira, 2022)
2.	Energy drinks	Caffeine, B vitamins, amino acids	Sustained energy release, Protection from oxidation, improved taste profile, enhanced stability	(Calderón-Oliver & Ponce-Alquicira, 2022)
3.	Sports drinks	Electrolytes (e.g., potassium, sodium), carbohydrates	Improved hydration and electrolyte balance, sustained energy release, and crystallization prevention	(Calderón-Oliver & Ponce-Alquicira, 2022)
4.	Functional water	Nutraceuticals (e.g., antioxidants, herbal extracts)	Enhanced bioactivity, improved consumer experience, longer shelf life, stable release, protection of bioactive compounds from light and oxygen	(Vieira & Souza, 2022)
5.	Tea and coffee-based beverages	Flavors, polyphenols, functional ingredients (e.g., probiotics)	Improved flavor, enhanced health benefits, improved stability during brewing and processing, and sustained release	(Vieira & Souza, 2022)
6.	Smoothies and meal replacements	Fiber, protein, vitamins (e.g., A, D)	Enhanced texture, nutrient stability, better digestion and absorption, controlled release	(Vieira & Souza, 2022)

Table 2: Microencapsulation in dairy products

Product type	Encapsulated compounds	Key benefits	References
Yogurts	Probiotics (*Lactobacillus, Bifidobacterium*)	Improved viability of probiotics, targeted release in the gut	(Calderón-Oliver & Ponce-Alquicira, 2022)
Probiotics-enriched milk	Vitamins (e.g., Vitamin D), minerals (e.g., calcium), or omega-3 fatty acids	Enhanced nutrient stability, reduced degradation, improved shelf life	(Calderón-Oliver & Ponce-Alquicira, 2022)
Flavored dairy drinks	Flavors, bioactive compounds (e.g., antioxidants)	Sustained flavor profile, improved consumer experience, controlled release of nutrients	(Calderón-Oliver & Ponce-Alquicira, 2022)
Cheese	enzymes, probiotics, or antimicrobial agents	Enhanced shelf life, better functionality in ripening, uniform distribution, and release over time	(Koh et al., 2022)
Ice-Creams and frozen desserts	Nutraceuticals, antioxidants, or vitamins	Improved functionality and nutrient retention during freezing and thawing	(Koh et al., 2022)
Dairy-based spreads	Omega-3 fatty acids, plant sterols	Enhanced spreadability, better nutritional profile, oxidation prevention, and texture maintenance	(Koh et al., 2022)

Meat and Seafood Products

Microencapsulation has been extensively employed in meat and seafood products to enhance the stability and efficacy of bioactive compounds (Gómez et al., 2018). The efficacy of the fungicidal action has been enhanced through the microencapsulation of clove oil in beta-cyclodextrin and starch (Calderón-Oliver & Ponce-Alquicira, 2022). Microencapsulation in meat and fish products extends the stability of fatty acids and antioxidants. Microencapsulation of omega-3 fatty acids in fish oil has been shown to enhance stability and reduce oxidation. Microencapsulation has been utilised to incorporate prebiotics and probiotics into meat products, such as cooked sausages, enhancing their stability and nutritional value (Calderón-Oliver & Ponce-Alquicira, 2022). Table 3 elaborates microencapsulation in meat and seafood products.

Table 3: Microencapsulation in meat and seafood products

Product type	Encapsulated compounds	Key benefits	References
Meat (beef, chicken)	Omega-3 fatty acids, minerals, antioxidants	Enhanced flavor stability, reduced rancidity, improved nutritional profile, controlled release, oxidation prevention	(Calderón-Oliver & Ponce-Alquicira, 2022)
Fish (salmon, tuna)	Omega-3 fatty acids, antioxidants	Improved flavor retention, better oxidative stability during storage and cooking, enhanced health benefits	(Calderón-Oliver & Ponce-Alquicira, 2022)
Seafood (shrimp, crab)	Omega-3 fatty acids, antioxidants	Enhanced nutritional value, improved shelf life, better texture, controlled release	(Calderón-Oliver & Ponce-Alquicira, 2022)
Processed meat products (e.g., sausages)	antioxidants, flavor enhancers	Longer shelf life, improved taste and texture, reduced spoilage	(Calderón-Oliver & Ponce-Alquicira, 2022)
Canned fish and seafood	Omega-3 fatty acids, vitamins, antioxidants	Retained nutritional value, prolonged shelf life, improved consumer appeal	(Calderón-Oliver & Ponce-Alquicira, 2022)
Fish oil supplements	Omega-3 fatty acids, vitamins	Enhanced bioavailability, improved stability of omega-3s, reduced oxidation, controlled release	(Calderón-Oliver & Ponce-Alquicira, 2022)

Bakery and Confectionery

Essential oils are widely used to enrich various products including bakery goods, chocolates, candies, and gum (Casalini & Peri, 2024). The confectionery industry, particularly soft confectionery is rapidly growing due to its appeal to all age groups especially children. These products are highly valued for their unique textures, flavors and visual appeal. However, consumer preferences are shifting towards more natural ingredients, fewer synthetic components, lower calorie content and active ingredients with health benefits (Calderón-Oliver & Ponce-Alquicira, 2022). The microencapsulation of bakery items are given in the Table 4.

Table 4: Microencapsulation in bakery and confectionery

Product type	Encapsulated compounds	Key benefits	References
Cakes and pastries	Nutrients (e.g., vitamins, minerals), flavorings	Improved nutrient retention, enhanced flavor, release during consumption	(Calderón-Oliver & Ponce-Alquicira, 2022; Gunes et al., 2022)
Cookies	Nutrients (e.g., fiber, antioxidants), flavors	Increased shelf life, stable flavor profile, nutrient retention	(Calderón-Oliver & Ponce-Alquicira, 2022; Gunes et al., 2022)
Bread	Omega-3 fatty acids, enzymes, and probiotics	Enhanced nutritional value, better shelf life	(Calderón-Oliver & Ponce-Alquicira, 2022; Gunes et al., 2022)
Chocolate and sweets	Bioactive compounds (e.g., antioxidants), flavors	Enhanced stability, controlled release of flavors and bioactive compounds, and oxidation prevention	(Calderón-Oliver & Ponce-Alquicira, 2022; Gunes et al., 2022)
Gummies and candies	Vitamins, probiotics, or minerals	Improved nutrient stability, extended shelf life	(Calderón-Oliver & Ponce-Alquicira, 2022; Gunes et al., 2022)
Chewing gum	Sweeteners, flavors, functional ingredients	Prolonged flavor release, improved consumer experience, controlled release	(Calderón-Oliver & Ponce-Alquicira, 2022; Gunes et al., 2022)

Nutraceuticals and Dietary Supplements

The encapsulation of bioactive compounds, including those with nutraceutical claims, has been extensively investigated in recent years. Various encapsulation technologies and materials have been employed to deliver bioactive molecules such as resveratrol, quercetin, and curcumin, which have recognized anti-cancer potential (Chavda et al., 2022). Encapsulated polyphenols and vitamins can be added to various edible products, maintaining their stability (Fang & Bhandari, 2010). Additionally, the encapsulation of folic acid with silica particles has been successfully applied in commercial citrus juices protecting them during processing and storage as shown in the Table 5. These compounds have been encapsulated into nano-liposomes and bio-compatible polymeric nanoparticles demonstrating improved solubility, absorption, bioavailability and anti-cancer potential (Reque & Brandelli, 2021).

Table 5: Microencapsulation in nutraceuticals and dietary supplements

Product type	Encapsulated compounds	Key benefits	References
Capsules	Nutrients (e.g., vitamins, minerals, omega-3 fatty acids)	Improved bioavailability, enhanced stability, controlled release, protection from light, air, and moisture	(Reque & Brandelli, 2021; Li et al., 2023)
Tablets	Herbal extracts, probiotics, and vitamins	Improved nutrient stability, targeted delivery	(Reque & Brandelli, 2021; Li et al., 2023)
Powders	Nutraceuticals (e.g., protein, antioxidants, probiotics, vitamins)	Enhanced nutrient absorption and retention, prolonged shelf life, and rehydration	(Reque & Brandelli, 2021; Li et al., 2023)
Soft gels	Fish oils, essential oils, and vitamins	Easier consumption, better bioavailability, protection from degradation	(Reque & Brandelli, 2021; Li et, al., 2023)
Chewable tablets	Probiotics, vitamins, minerals	Enhanced consumer compliance, targeted health benefits, masking unpleasant taste, controlled release	(Reque & Brandelli, 2021; Li et al., 2023)

Conclusion

In short, Microencapsulation may play a vital role in the food industry by enhancing the stability, bioavailability, and controlled release of bioactive compounds, ensuring that sensitive nutrients and functional ingredients retain their efficacy, improving food quality, and extending shelf life. Its application in various food products, from dairy and meat to functional beverages and nutraceuticals, underscores its significance in promoting human health and well-being. Future research must focus on sustainable technologies, including green processing methods and energy-efficient systems, and ensure the safety of microencapsulation procedures through rigorous regulatory compliance and risk assessment for widespread industrial adoption. Advances in AI, material science, and smart manufacturing also hold great promise for refining encapsulation techniques driving the future of microencapsulation making it a cornerstone of food technology.

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