

Encapsulation Technologies For Active Food Ingredients And Food Processing



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 Springer

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encapsulation technologies for active food ingredients and food processing are revolutionizing the food industry, offering innovative solutions to enhance product quality, extend shelf-life, and improve consumer appeal. This comprehensive guide delves into the multifaceted world of encapsulation, exploring its critical role in protecting sensitive food components, controlling their release, and facilitating their incorporation into various food matrices. We will examine the diverse range of encapsulation methods, the types of active ingredients benefiting from these techniques, and the specific applications within food processing. Understanding these advancements is crucial for food scientists, product developers, and manufacturers seeking to leverage cutting-edge solutions for next-generation food products, including probiotics, vitamins, flavors, and colors, while also addressing challenges in bioavailability and stability.

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The Science Behind Encapsulation Technologies for Active Food Ingredients

Encapsulation in the context of food science is a sophisticated process involving the physical or chemical entrapment of active ingredients within a protective barrier or shell. This barrier, often referred to as the "carrier" or "wall material," serves multiple crucial functions. Primarily, it shields the core active ingredient from detrimental environmental factors encountered during food processing and storage. These factors can include oxygen, moisture, light, pH variations, and interactions with other food components. By forming a protective layer, encapsulation significantly mitigates degradation, oxidation, and loss of potency of sensitive compounds like vitamins, probiotics, and delicate flavor molecules.

The choice of wall material is paramount and dictates the success of the encapsulation process and the final product characteristics. These materials are typically edible and food-grade, such as carbohydrates (starches, maltodextrins, gums), proteins (whey, gelatin, casein), lipids (fats, waxes), and synthetic polymers (though less common in food applications due to regulatory considerations). The physical and chemical properties of the wall material, including its solubility, melting point, viscosity, and glass transition temperature, directly influence the encapsulation efficiency, particle size, and release profile of the encapsulated ingredient. Furthermore, the interaction between the core material and the wall material is critical to ensure stable and effective encapsulation.

The encapsulation process itself is designed to create a distinct micro- or nano-compartment around the active ingredient. This not only provides physical protection but also allows for controlled release. Controlled release mechanisms are a cornerstone of encapsulation technology, enabling the active

ingredient to be delivered at a specific time, location, or in response to particular stimuli within the food matrix or the consumer's digestive system. This targeted delivery enhances the efficacy and performance of the active ingredient, leading to improved nutritional profiles or sensory experiences in the final food product. The scientific principles underpinning these processes involve understanding material science, physical chemistry, and chemical engineering to optimize barrier properties and release kinetics.

Key Benefits of Encapsulation in Food Processing

The application of encapsulation technologies in food processing yields a multitude of benefits that directly impact product quality, functionality, and marketability. One of the most significant advantages is enhanced stability and shelf-life extension. By creating a protective barrier, encapsulation shields volatile or sensitive active ingredients from degradation pathways such as oxidation, hydrolysis, and photodegradation. This protection is critical for ingredients like omega-3 fatty acids, vitamins A, C, and E, and natural colors, which are prone to rapid deterioration under typical processing and storage conditions. Consequently, encapsulated ingredients maintain their potency and efficacy for longer periods, reducing product spoilage and waste.

Improved bioavailability is another compelling benefit. Many bioactive compounds, particularly those found in natural extracts or probiotics, have poor solubility or are susceptible to breakdown during digestion. Encapsulation can enhance their absorption and utilization by the body. For instance, encapsulating lipophilic vitamins can improve their dispersion in aqueous food systems and facilitate better absorption in the gastrointestinal tract. Similarly, encapsulating probiotics protects them from the harsh acidic environment of the stomach, ensuring a higher number of viable microorganisms reach the intestines where they can exert their beneficial effects.

Encapsulation also plays a vital role in masking undesirable flavors and odors. Many functional ingredients, such as certain amino acids, minerals, or plant extracts, possess bitter or unpleasant tastes that can detract from the palatability of food products. Encapsulation effectively creates a

physical barrier between these ingredients and the consumer's taste buds, rendering them imperceptible. This allows food manufacturers to fortify products with beneficial ingredients without compromising the sensory attributes that consumers expect, thereby expanding the range of acceptable functional foods and beverages.

Furthermore, encapsulation offers excellent control over ingredient release. This controlled or targeted release mechanism is invaluable for delivering specific sensory profiles or ensuring the gradual release of nutrients or active compounds over time. For example, encapsulated flavors can be designed to be released during chewing or at specific temperatures, providing a prolonged and dynamic taste experience. In functional foods, this controlled release can ensure a steady supply of nutrients or bioactive compounds throughout the day. This precision in delivery optimizes the performance of the active ingredient and enhances the overall consumer experience.

Finally, encapsulation can improve the processability and dispersibility of ingredients. Powdery or sticky ingredients can be transformed into free-flowing particles, making them easier to handle and incorporate into various food formulations. This is particularly beneficial for ingredients that tend to clump or settle, ensuring uniform distribution within the food matrix and preventing phase separation during processing or storage. The ability to create stable emulsions or suspensions of otherwise immiscible or poorly soluble compounds is another significant advantage, broadening the formulation possibilities for food scientists.

Types of Encapsulation Technologies for Active Food Ingredients

The diverse nature of active food ingredients and processing requirements necessitates a wide array of encapsulation techniques. These technologies can be broadly categorized based on the underlying physical, chemical, or physicochemical principles employed to create the protective barrier.

Physical Encapsulation Methods

Physical encapsulation methods rely on physical forces or phase transitions to form the protective shell around the core ingredient. These methods are often preferred for their simplicity, scalability, and ability to handle a wide range of core materials without significant chemical modification.

- **Spray Drying:** This is one of the most widely used and cost-effective encapsulation techniques in the food industry. It involves atomizing a liquid feed containing the core material and wall material into a hot drying chamber. The rapid evaporation of the solvent creates a solid shell around the active ingredient. Spray drying is suitable for heat-sensitive materials if process parameters are carefully controlled and offers excellent scalability for industrial production.
- **Fluidized Bed Coating:** In this method, solid particles of the core material are suspended in an upward stream of air. Coating material, typically in liquid or semi-liquid form, is sprayed onto these suspended particles, forming a continuous film. As the coating dries or solidifies, it encapsulates the core. This technique is effective for creating coatings with specific thicknesses and properties.
- **Coacervation (Simple and Complex):** Coacervation is a phase separation process where a polymer-rich phase separates from a liquid phase to form a continuous sheath around the core material. Simple coacervation involves the use of a single polyelectrolyte, while complex coacervation utilizes two oppositely charged polymers. This method is particularly effective for encapsulating water-soluble and oil-soluble materials, providing good protection and controlled release.
- **Extrusion:** This process involves forcing a mixture of the core material and wall material through a die under pressure. The resulting extrudate is then cut or broken into desired particle sizes. Extrusion can be used to form pellets, beads, or fibers, offering a versatile approach for encapsulating a variety of ingredients, including those that require higher temperatures or pressures.

- **Freeze Drying (Lyophilization):** While primarily a drying technique, freeze drying can be considered a form of encapsulation when used to form porous matrices that entrap active ingredients. The material is frozen, and then the ice is sublimated under vacuum. This process preserves the activity of heat-sensitive compounds and results in a porous structure that can be rehydrated, releasing the active ingredient.

Chemical Encapsulation Methods

Chemical encapsulation methods involve chemical reactions to form the protective barrier. These techniques often result in more robust and tailored encapsulation, suitable for ingredients requiring stringent protection.

- **Interfacial Polymerization:** This technique involves monomers that react at the interface between two immiscible phases to form a polymer shell. For example, oil-soluble monomers in an oil phase containing the core ingredient can react with water-soluble monomers in an aqueous phase to create a thin polymer membrane around the oil droplets. This method is effective for creating precisely controlled and impermeable capsules.
- **In-situ Polymerization:** In this method, polymerization occurs around the core material within a single continuous phase. Initiators trigger the polymerization of monomers, which deposit onto the surface of the core particle, forming a polymeric coating. This technique allows for the formation of well-defined and uniform capsules.

Physicochemical Encapsulation Methods

Physicochemical encapsulation methods combine physical and chemical principles to achieve entrapment. These approaches leverage phenomena like self-assembly, phase transitions, and interactions between different molecules.

- **Emulsification:** This technique involves dispersing one immiscible liquid phase (e.g., oil containing the active ingredient) into another (e.g., water) with the help of an emulsifier. The dispersed droplets are then solidified or stabilized by various methods, such as cooling, gelling, or chemical cross-linking, to form capsules. It's a versatile method for encapsulating both oil-in-water and water-in-oil systems.
- **Liposome Formation:** Liposomes are spherical vesicles composed of one or more lipid bilayers enclosing an aqueous core. They are formed through the self-assembly of phospholipids. Liposomes are excellent carriers for both hydrophilic and hydrophobic compounds and are known for their biocompatibility and potential to enhance nutrient delivery and absorption.
- **Niosomes:** Similar to liposomes, niosomes are non-ionic surfactant-based vesicles. They offer similar advantages in terms of encapsulation and delivery but are often more stable and cost-effective to produce than liposomes.
- **Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs):** These are lipid-based colloidal carriers that encapsulate active ingredients within a solid lipid matrix. SLNs are formed from solid lipids, while NLCs are produced from a blend of solid and liquid lipids, creating imperfections in the crystal structure that can accommodate higher drug loadings and reduce expulsion during storage. They are particularly effective for encapsulating lipophilic compounds and enhancing their bioavailability.
- **Zein Nanoparticles:** Zein, a protein found in corn, can be used to form nanoparticles through various methods like antisolvent precipitation. These nanoparticles are stable, biodegradable,

and can effectively encapsulate lipophilic and hydrophilic ingredients, offering protection and controlled release.

Active Food Ingredients Benefiting from Encapsulation

A wide array of active food ingredients, essential for fortification, flavor enhancement, and functional properties, can be significantly improved through encapsulation. The protection and controlled release offered by encapsulation technologies make these ingredients more stable, bioavailable, and palatable within food matrices.

Vitamins and Minerals

Vitamins, especially fat-soluble vitamins like A, D, E, and K, and water-soluble vitamins like C and B vitamins, are highly susceptible to degradation from light, oxygen, heat, and moisture. Encapsulation shields these micronutrients, ensuring their potency during processing and storage. For instance, encapsulated vitamin C can withstand pasteurization temperatures in beverages, and encapsulated vitamin D can be evenly dispersed in dairy products without losing its efficacy. Similarly, minerals like iron, often prone to oxidation and metallic off-flavors, can be encapsulated to improve their stability and mask unpleasant tastes in fortified foods and supplements.

Probiotics and Prebiotics

Probiotic bacteria are live microorganisms that offer health benefits, but their survival through processing and transit in the gastrointestinal tract is a major challenge. Encapsulation, particularly using techniques like spray drying, extrusion, or forming alginate beads, provides a protective matrix

that shields probiotics from stomach acid and bile salts. This significantly increases the number of viable bacteria reaching the intestines. Prebiotics, which are non-digestible fibers that promote beneficial gut bacteria, can also be encapsulated to ensure their targeted delivery and efficacy.

Flavors and Fragrances

The delicate nature of flavor and fragrance compounds makes them highly vulnerable to loss through evaporation or degradation during food processing and storage. Encapsulation traps these volatile compounds, preserving their aroma and taste profiles. Techniques like spray drying, coacervation, and extrusion are commonly used to create encapsulated flavors that can be released gradually during consumption, offering sustained flavor release or triggered by specific conditions like heat or moisture. This also helps in masking off-notes from other ingredients.

Colors and Pigments

Natural food colors, derived from sources like fruits, vegetables, and algae, are often less stable than their synthetic counterparts. They can fade or change color due to pH variations, light exposure, and interactions with other food components. Encapsulating these natural pigments, such as anthocyanins, carotenoids, or curcumin, within a protective matrix like maltodextrin or gum arabic, significantly enhances their stability. This ensures vibrant and consistent coloration in a wide range of food products, from beverages to confectionery.

Antioxidants and Bioactive Compounds

Many plant-derived extracts and functional ingredients possess antioxidant and other health-promoting bioactive properties. However, these compounds, like polyphenols, flavonoids, and omega-3 fatty acids, are often prone to oxidation and have poor solubility or bioavailability. Encapsulation protects

these sensitive molecules from degradation, improves their dispersibility in food systems, and can enhance their absorption in the body. This is crucial for the development of functional foods and nutraceuticals aiming to deliver targeted health benefits.

Enzymes

Enzymes are biological catalysts used in various food processing applications, such as baking, brewing, and cheese making. Their activity can be compromised by harsh processing conditions, including high temperatures and extreme pH. Encapsulation can protect enzymes from these adverse environments, maintaining their functional integrity and allowing for controlled release, thereby optimizing their performance and extending their shelf-life. For example, encapsulated enzymes can be added to dough to control its properties during baking.

Applications of Encapsulation Technologies in Food Processing

The versatility of encapsulation technologies allows for their widespread application across numerous food product categories, enhancing sensory attributes, nutritional value, and overall product performance. These applications are constantly evolving as new materials and techniques are developed.

Beverages

In the beverage industry, encapsulation is used to deliver a range of active ingredients. Encapsulated vitamins and minerals are incorporated into functional drinks and juices to boost their nutritional content while preventing sedimentation or flavor degradation. Encapsulated flavors provide sustained or triggered flavor release, offering novel taste experiences in carbonated beverages, teas, and coffee.

products. Probiotics are encapsulated for use in probiotic drinks, ensuring their viability and efficacy. Furthermore, encapsulated natural colors help maintain the visual appeal of beverages throughout their shelf life.

Dairy Products

Dairy products, such as yogurt, milk, and cheese, are excellent matrices for encapsulated ingredients. Encapsulated probiotics are widely used in yogurts and fermented milk drinks to enhance gut health. Vitamins A and D are encapsulated to fortify milk and other dairy products, ensuring consistent nutrient delivery. Encapsulated flavors can add variety to yogurts and desserts, providing unique taste sensations. Encapsulated omega-3 fatty acids can also be added to dairy products to increase their nutritional value without imparting a fishy taste.

Bakery and Confectionery

The bakery and confectionery sectors benefit immensely from encapsulation. Encapsulated flavors are crucial for creating chocolates with long-lasting or melting-release flavors. In baked goods like bread and cakes, encapsulated leavening agents or enzymes can control the dough's properties and texture. Encapsulated vitamins and minerals can fortify breakfast cereals and snack bars, while encapsulated colors are used to create vibrant candies and desserts. Encapsulated acidic agents can also be used in confectionery to provide a sour burst upon consumption.

Meat and Poultry Products

In processed meats and poultry, encapsulation technologies can be employed to enhance safety, flavor, and nutritional profile. Encapsulated antimicrobial agents can be incorporated to extend shelf-life and improve food safety. Encapsulated flavors and spices can provide a more uniform and sustained

taste experience in processed meats, sausages, and marinades. Additionally, encapsulated antioxidants can help prevent lipid oxidation, preserving the color and flavor of meat products during storage.

Sauces and Dressings

Sauces, dressings, and condiments often contain sensitive ingredients like oils, flavors, and vitamins that can degrade over time. Encapsulation protects these components, improving the stability and shelf-life of the products. Encapsulated flavors provide consistent aroma and taste, while encapsulated acidulants can offer a controlled sourness. For instance, encapsulated omega-3 fatty acids can be added to salad dressings without affecting their flavor or texture. Encapsulated emulsifiers can also help stabilize these complex food systems.

Functional Foods and Nutraceuticals

The growing market for functional foods and nutraceuticals relies heavily on encapsulation to deliver targeted health benefits. Bioactive compounds, antioxidants, herbal extracts, and probiotics are encapsulated to enhance their bioavailability, protect them from degradation, and mask undesirable flavors. This allows for the development of products like fortified bars, health drinks, and dietary supplements that offer specific physiological effects, such as improved immunity, enhanced cognitive function, or better cardiovascular health.

Challenges and Future Trends in Encapsulation for Food

Despite the significant advancements and numerous benefits offered by encapsulation technologies, several challenges remain in their widespread adoption and optimization within the food industry. One

of the primary hurdles is the cost-effectiveness of certain encapsulation methods, particularly those involving complex multi-step processes or high-value wall materials. For many industrial applications, achieving a balance between encapsulation efficiency, desired release properties, and production costs is a continuous pursuit. Ensuring the scalability of novel techniques from laboratory to industrial production also presents a significant engineering and economic challenge.

Another critical consideration is the sensory impact of the encapsulation process and the wall materials used. While encapsulation aims to mask undesirable flavors, the shell material itself can sometimes impart its own taste or affect the texture of the final food product. Developing biodegradable and edible wall materials that are tasteless, odorless, and do not compromise the mouthfeel or appearance of foods is an ongoing area of research. Furthermore, regulatory approval for new encapsulation materials and processes can be time-consuming and complex, requiring extensive safety and efficacy data.

Looking ahead, several exciting trends are shaping the future of encapsulation technologies in food processing. There is a growing interest in nanoencapsulation, utilizing nanocarriers like liposomes, solid lipid nanoparticles, and zein nanoparticles. These nanoscale structures offer enhanced surface area, improved encapsulation efficiency, and superior controlled release capabilities, leading to better bioavailability and targeted delivery of active ingredients. The focus on clean label and natural ingredients is also driving the development of encapsulation solutions using naturally derived polymers and polysaccharides, moving away from synthetic alternatives.

Advanced controlled release mechanisms are another frontier, with research focusing on stimuli-responsive encapsulation. This involves developing capsules that release their contents in response to specific triggers such as pH changes in the digestive tract, temperature fluctuations, enzymatic activity, or even mechanical forces like chewing. This level of precision in delivery optimizes the efficacy of active ingredients and opens up new possibilities for personalized nutrition and functional food design. The integration of encapsulation with other food processing technologies, such as high-pressure processing or pulsed electric fields, is also being explored to enhance the stability and functionality of encapsulated ingredients.

Frequently Asked Questions

What are the primary benefits of encapsulating active food ingredients?

Encapsulation protects sensitive active ingredients (like vitamins, probiotics, or antioxidants) from degradation during processing and storage, enhances their bioavailability, masks undesirable flavors or odors, and allows for controlled release at a specific time or location in the digestive tract or food product.

What are the most popular encapsulation techniques currently trending in the food industry?

Spray drying and coacervation remain highly popular due to their scalability and cost-effectiveness. Emerging trends include interfacial polymerization for creating robust shells, extrusion for creating structured delivery systems, and nanoencapsulation techniques for enhanced bioavailability and specific targeting.

How does encapsulation impact the shelf-life of foods containing active ingredients?

Encapsulation significantly improves shelf-life by creating a physical barrier that shields the active ingredient from oxygen, light, moisture, and reactive compounds present in the food matrix. This protection prevents oxidation, hydrolysis, and other degradation pathways, maintaining ingredient efficacy over time.

What are the key considerations when choosing an encapsulation material for food applications?

Key considerations include the nature of the active ingredient, the food matrix, desired release profile, processing conditions (e.g., temperature, pH), regulatory approval (GRAS status), cost, and sensory

impact. Common materials include hydrocolloids (e.g., alginate, gum arabic), lipids (e.g., waxes, oils), and proteins (e.g., whey, gelatin).

How is encapsulation used to improve the delivery of probiotics in food products?

Encapsulation protects probiotics from the harsh conditions of the stomach and processing steps like baking or extrusion. Materials like alginates and calcium salts form protective matrices that allow probiotics to survive transit to the intestines, where they can exert their beneficial effects.

What are the challenges associated with scaling up encapsulation technologies for industrial food production?

Challenges include maintaining consistent particle size and encapsulation efficiency, optimizing process parameters for large volumes, ensuring cost-effectiveness without compromising quality, and achieving uniform distribution of encapsulated ingredients within the food matrix. Equipment investment and process validation are also significant hurdles.

How does encapsulation contribute to 'clean label' food formulations?

Encapsulation can replace synthetic preservatives or functional additives by delivering natural or bio-based actives. By protecting ingredients and improving their efficacy, encapsulation can also reduce the need for higher concentrations of other ingredients, contributing to simpler ingredient lists.

What role does encapsulation play in enhancing the functionality of plant-based proteins?

Encapsulation can improve the solubility, emulsification, and texture of plant-based proteins. It can also mask off-flavors associated with certain plant proteins and protect them from denaturation during processing, leading to more appealing and functional plant-based food products.

Are there any regulatory hurdles or considerations for using encapsulated ingredients in food?

Yes, regulatory approval is crucial. Encapsulation materials themselves must be food-grade and have the necessary regulatory approvals (e.g., GRAS in the US, E-numbers in the EU). The encapsulated ingredient also needs to meet all relevant food safety and labeling regulations. Novel encapsulation techniques or materials may require more extensive safety assessments.

Additional Resources

Here are 9 book titles related to encapsulation technologies for active food ingredients and food processing, following your formatting guidelines:

1. *Encapsulation of Active Food Ingredients: Innovations and Applications*

This book delves into the cutting-edge advancements in encapsulating various active food ingredients, such as vitamins, probiotics, and flavors. It explores the diverse range of encapsulation techniques available, from spray drying to coacervation, and their specific applications in improving food quality and shelf-life. Readers will gain insights into the challenges and future directions of this rapidly evolving field.

2. *Microencapsulation Techniques for Functional Foods*

Focusing on the practical aspects of microencapsulation, this title examines the methodologies used to protect and deliver functional food components. It details how encapsulation can enhance the stability, bioavailability, and sensory properties of bioactive compounds. The book also discusses the selection of appropriate carrier materials and encapsulation processes based on the specific functional ingredient and desired food product.

3. *Smart Encapsulation Systems for Controlled Release in Food*

This book explores the development and application of "smart" encapsulation systems that enable the controlled release of active ingredients within food products. It covers responsive materials and

mechanisms that trigger release in response to specific stimuli like pH, temperature, or enzymes. Understanding these systems is crucial for optimizing the efficacy and sensory experience of fortified and functional foods.

4. Edible Coatings and Encapsulation for Fruit and Vegetable Preservation

This specialized volume concentrates on the application of edible coatings and encapsulation technologies for extending the shelf-life and quality of fruits and vegetables. It discusses how these methods can reduce moisture loss, prevent oxidation, and incorporate beneficial active ingredients. The book provides a comprehensive overview of materials and techniques relevant to the post-harvest processing of produce.

5. Nanoencapsulation Strategies in Food Science and Technology

This title provides an in-depth look at the utilization of nanoencapsulation for food ingredients, highlighting the unique advantages offered by nanotechnology. It explores the creation of nanoparticles and their improved functionality in terms of stability, delivery, and absorption of active compounds. The book also addresses safety considerations and regulatory aspects associated with nanoencapsulated food products.

6. Encapsulation in Food Processing: From Bench to Industrial Scale

Bridging the gap between research and industry, this book covers the transition of encapsulation technologies from laboratory development to large-scale food processing. It discusses the engineering challenges, equipment, and optimization strategies required for successful industrial implementation. The content is invaluable for professionals seeking to integrate encapsulation into their production lines.

7. Encapsulated Probiotics and Prebiotics in Food Products

This book focuses specifically on the critical role of encapsulation in enhancing the survival and efficacy of probiotics and prebiotics in various food matrices. It details how encapsulation protects these sensitive microorganisms from harsh processing conditions and the gastrointestinal tract. The information is essential for the development of effective functional foods for gut health.

8. Flavor Encapsulation: Stability, Delivery, and Sensory Perception

Dedicated to the complex science of flavor encapsulation, this title examines the techniques used to preserve volatile flavor compounds. It discusses how encapsulation impacts flavor stability during processing and storage, and how it influences flavor release and perception by consumers. The book is a key resource for flavor chemists and food technologists.

9. Encapsulation of Vitamins and Minerals for Food Fortification

This book addresses the challenges and solutions for encapsulating essential vitamins and minerals used in food fortification programs. It explains how encapsulation improves the stability of these micronutrients against degradation and ensures their effective delivery in diverse food products. The content is vital for improving public health through fortified foods.

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