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Encapsulation Unveiled: Exploring Techniques and Applications

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ABSTRACT

Encapsulation, the process of enclosing one substance within another, has garnered significant attention and importance in food processing industries. Encapsulation is a transformative process with profound implications in the realm of food processing. Encapsulation has redefined the preservation, enhancement of flavors and controlled release of sensitive and valuable components within food products. This technology has emerged as an anchor in maintaining the overall quality of food items, preventing oxidation and stability of omega-3 fatty acids, extending shelf life and precisely delivering flavors and nutrients to the consumer. By shielding sensitive elements like vitamins, minerals, flavors and bioactive compounds from external threats such as heat, moisture, oxygen and light, encapsulation ensures that these ingredients retain their efficacy and quality and also preserves their nutritional and sensory attributes. Furthermore, encapsulation enables the controlled and targeted release of these ingredients enhancing not only the taste and texture of products but also their nutritional benefits. The applications of encapsulation are myriad, ranging from fortifying foods with essential nutrients to concealing undesirable flavors, enhancing product stability and providing new frontiers in product development.

KEYWORDS

Controlled release, Nutrient protection, Flavor enhancement, Sensitive ingredients, and nutrients delivery

Introduction

Encapsulation is a process that involves trapping one substance within another substance, resulting in the creation of particles with sizes ranging from a few nanometers to several millimeters. The substance being encapsulated is often referred to as the core material, active agent, fill, internal phase, or payload phase. On the other hand, the substance that surrounds and encapsulates the core material is known as the coating, membrane, shell, carrier material, wall material, external phase, or matrix (Gibbs et al., 1999). Encapsulation in food involves the incorporation of active ingredients, such as flavors, vitamins, nutrients, aromas, colors, oils, or bioactive compounds, within a carrier material to form capsules, beads, particles, or coatings. The carrier material can be made from various food-grade substances, including polymers, lipids, proteins, or carbohydrates. There are two primary categories of encapsulates: reservoir-type and matrix-type (Zuidam et al., 2010). The reservoir type involves a protective shell surrounding the active agent. It's also known as a capsule, single-core, mono-core, or core-shell type encapsulate. When pressure is applied, the reservoir-type encapsulates can rupture, releasing their contents. In some cases, there are poly- or multiple-core encapsulates that contain multiple reservoir chambers within a single particle. In contrast, the matrix type of encapsulate disperses the active agent more evenly throughout the carrier material. The active agent in this type can exist as relatively small droplets or be distributed more uniformly within encapsulate. Furthermore, in matrix-type encapsulates, the active agents are often present on the surface, unless they have an additional protective coating.

Encapsulation helps protect sensitive or volatile food ingredients from exposure to environmental factors like oxygen, light, moisture, and temperature, which can degrade or alter their quality. Encapsulating certain ingredients can extend their shelf life, preventing spoilage or oxidation and preserving their sensory qualities and can control the release rate and timing of specific ingredients, ensuring a more prolonged and controlled flavor or nutrient release when consumed (De Vos et al, 2010). Encapsulation can also be used to mask undesirable tastes or odors of certain ingredients, making them more palatable to consumers. Food encapsulation techniques vary widely depending on the desired outcome and the specific food product being

developed. The choice of encapsulate material, the encapsulation method, and the encapsulated ingredient's properties are all considered during the design and development of encapsulated food products (Dziubla et al, 2008).

Carrier materials

In the food sector, microencapsulation is often accomplished using biomolecules, including carbohydrates (polysaccharides), proteins, and lipids, in addition to other biocompatible materials. These biomolecules serve as excellent encapsulation materials due to their biocompatibility, safety, and ability to provide controlled release and protection for various sensitive or active food ingredients (Soni et al., 2019). Here's an overview of each of these biological materials used for encapsulation:

Carbohydrates: Carbohydrates, primarily in the form of polysaccharides, make up a significant part of the dry weight of all living organisms, from plants and animals to microorganisms. These polymers are essential for structural support, energy storage, and various biological functions. Polysaccharides are natural polymers composed of sugar residues and their derivatives. They can be simple homopolymers or complex heteropolymers, depending on the arrangement of sugar units.Native polysaccharides exhibit remarkable diversity in terms of their structures and properties. Examples include cellulose, starch, chitin, pectin, and many others (King, W., Trubiano, P. and Perry, 1976). Each polysaccharide has specific functions in living organisms.Polysaccharides have immense economic importance. One of the primary sectors where polysaccharides are crucial is the food industry. They are used as thickeners, stabilizers, gelling agents, and emulsifiers in various food products, enhancing texture and quality (Bustos et al, 2003). Some main examples are:

- Polysaccharides: Carbohydrates like polysaccharides are widely used in encapsulation due to their biocompatibility and natural origin. Examples include (Gascon, A.D., 2001):
- Alginate: Alginate, derived from seaweed, is commonly used for encapsulating cells, probiotics, and bioactive compounds. It forms gel-like beads when combined with calcium ions (Connick, J. and William, 1983).
- Chitosan: Chitosan, derived from chitin (found in shellfish), is mainly used in

pharmaceuticals and wound care products for controlled drug release.

- Starch: Starch-based microcapsules are used in the food industry for encapsulating flavors, fragrances, and vitamins (Kaushik, 2016).
- Cyclodextrins: Cyclodextrins are cyclic oligosaccharides used to encapsulate hydrophobic compounds, improving their solubility and stability.
- β-Cyclodextrin: It's used to encapsulate flavors, fragrances, and pharmaceutical compounds (Thevenet F, 1995).

Proteins: Proteins are built from a sequence of amino acids, and the specific order and frequency of these amino acids determine a protein's unique structure and function. With 20 different amino acids to choose from, the potential combinations are virtually limitless, giving rise to a vast variety of proteins. Beyond their traditional roles in nutrition, proteins are finding applications in various non-traditional fields. These applications include biotechnology, where proteins are used in the development of biopharmaceuticals and enzyme-based processes (Jimenez, M., Garcia, H.S. and Beristain, 2004). They are also utilized in materials science to create biodegradable and environmentally friendly materials. Proteins used in encapsulation are:

- Gelatin: Gelatin, derived from animal collagen, is commonly used in the food and pharmaceutical industries for encapsulating drugs, vitamins, and sensitive food ingredients. Gelatin capsules are widely used in pharmaceuticals for oral drug delivery (Li et al., 1998).
- Whey Protein Isolate: Whey protein is used in food and beverage applications for encapsulating flavors and stabilizing emulsions (Sheu and Rosenberg, 1998).
- Soy Protein Isolate: Soy protein can be used for encapsulating bioactive compounds in food products (McClements, 2004).

Lipids: Lipids, including triglycerides, phospholipids, and fatty acids, are used to create lipid-based microcapsules for encapsulating lipophilic ingredients, such as oils, flavors, and vitamins (Wandrey et al., 2010).

Liposomes: Liposomes are spherical lipid bilayers used for encapsulating hydrophilic and lipophilic compounds. They find applications in pharmaceuticals, cosmetics, and drug delivery. Liposomal formulations

are used to deliver drugs like Doxorubicin (Fathi, et al, 2012).

- Solid Lipid Nanoparticles (SLNs): SLNs are lipid-based nanoparticles used for drug delivery and controlled release. Lipid-based coatings can be used to encapsulate flavors, nutrients, and bioactive compounds in food products. Encapsulation of fish oil within lipid-based coatings in omega-3 supplements is widely adopted.

These biological materials offer several advantages for encapsulation, including biocompatibility, low toxicity and the ability to create protective matrices or shells for sensitive compounds. The choice of material depends on factors such as the specific application, the nature of the core material to be encapsulated and the desired release profile (Ubbink, J. and Krüger, J. 2006).

Encapsulation Techniques

Encapsulation techniques are a set of processes used to enclose one substance or material within another, often in the form of a protective shell or coating. These techniques are employed in various industries, including pharmaceuticals, food science, cosmetics, and materials science, to achieve specific objectives such as protecting sensitive ingredients, controlling release rates, enhancing stability, and improving delivery systems (Mozafari et al, 2008). Many encapsulation processes involve the creation of droplets containing the active substance (which can be a gas, liquid, or powder), followed by the surrounding of these droplets with a carrier material through various physico-chemical processes. This approach is particularly effective for achieving controlled release, protection, and stabilization of the active substance (Eratte et al., 2018). Some common encapsulation techniques include-

Physical / Mechanical Methods: Spray-drying**,** Extrusion**,** Spray-cooling / chillingand fluidized bed coating.

Chemical Methods: Coacervation**,** Molecular-inclusion**,** Co-crystallization.

Physical methods:

1. Spray-Drying

Spray-drying is one of the oldest and most widely used processes for encapsulating active agents (Madene et al, 2006). It is a commercial process widely used in large scale production of encapsulated flavors & aromas and it is so common in the food industry that the encapsulated form, such as spray-dried aroma, may not always be

recognized as an encapsulate. It is used for heat sensitive materials as short drying time is required. The key steps in spray drying for encapsulation are as follows (Gharsallaoui et al., 2007):

Preparation of Active Agent and Carrier Material: The process begins with the preparation of the active agent and the carrier material. The active agent can be a liquid, solid, or powder that needs to be encapsulated. It is often dissolved, emulsified, or dispersed in an aqueous solution of the carrier material.

Atomization and Spraying: The prepared mixture of the active agent and the carrier material is then atomized into fine droplets. This atomization is typically achieved using spray nozzles or other atomization devices. The mixture is sprayed into a hot chamber or drying tower.

Drying Process: Inside the hot chamber, the sprayed droplets are exposed to hot air or a drying gas. This rapid exposure to high temperatures causes the solvent (usually water) within the droplets to evaporate quickly.

Formation of Dry Particles: As the solvent evaporates, the carrier material solidifies around the active agent, forming dry, microencapsulated particles. These particles are typically in powder form and contain the encapsulated active agent within them.

Collection and Packaging: The microencapsulated particles are then collected from the drying chamber, and any remaining traces of solvent are removed. These encapsulated particles can be packaged and stored for various applications.

The liquid's viscosity, the pressure drop and the spray velocity affect the size (Turton and Cheng, 2005). The choice of carrier material must fulfill a range of requirements, including safeguarding the active ingredients, exhibiting high water solubility, possessing excellent film-forming characteristics, demonstrating effective emulsifying properties, and being cost-effective. Various examples include proteins like dairy proteins (Keogh et al., 2001), soy proteins, carbohydrates (maltodextrins and cellulose derivatives), lipids, and/or natural gums (Petrović et al., 2007). Spray drying is a versatile and widely used process with several advantages, making it a popular choice in various industries. Some of the key advantages of spray drying are Efficient Drying, Particle Size Control, Preservation of Active Ingredients, High Product Quality,

Easy Handling and Storage and Improved Solubility and Scalability (Kailasapathy, K., 2002)

2. Fluidized Bed Coating

Fluidized bed coating is a widely used industrial process in which a fine powder or granular material is coated with a liquid or solid coating material while suspended and fluidized in a stream of air or gas. This technique is employed in various industries, including food processing, chemicals, and materials science.

Schematics of a fluidized-bed coater (Dewettinck, K. and Huyghebaert, 1999)

a) Top spray fluidized bed coating system.

b) Wurster system (bottom spraying fluidized bed coating system)

c) Side or tangential spray/ rotary system

Key Components of a Fluidized Bed Coating System:

Fluidizing Chamber: This is the primary chamber where the powder or granular material to be coated is placed. It contains a distribution plate or grid that allows for the even distribution of air or gas.

Air or Gas Supply: A source of compressed air or gas is used to fluidize the powder or granules in the chamber. The controlled flow of air or gas is crucial for maintaining the fluidized state.

Coating Material Supply: The coating material, which can be in the form of a liquid or solid, is introduced into the fluidized bed chamber. Liquid coating materials are typically atomized into fine droplets before being sprayed onto the particles.

The fluidized bed coating process typically involves the following steps:

Fluidization: Compressed air or gas is introduced into the fluidized bed chamber through the distribution plate at a controlled velocity. This causes the powder or granular material to become suspended and fluidized, forming a "fluidized bed" of particles.

Preheating: In some cases, the powder or granules are preheated to a specific temperature before the coating process begins. This can improve adhesion and the uniformity of the coating.

Coating Application: The coating material, either in liquid or solid form, is introduced into the fluidized bed. If it's a liquid, it is typically atomized into fine droplets and

sprayed onto the fluidized particles. If it's a solid coating material, it's usually added in powder form. The bottom spray reduces the distance between the powder and the drops of coating solution, thereby reducing the risk of premature drying of the coating (Dubey et al., 2011).

Coating and Drying: As the coating material come into contact with the fluidized particles, it adheres to their surfaces. Simultaneously, the solvent or liquid carrier evaporates, leaving behind a solid coating. The coating thickness can be controlled by adjusting the process parameters.

Cooling: After coating and drying, the coated particles may be cooled to room temperature or to a specific temperature range to prevent agglomeration.

Final Product Collection: The coated particles are then removed from the fluidized bed chamber, and any excess coating material is separated for reuse or disposal (Anal and Singh, H., 2007). An aqueous solution comprising proteins, gums, cellulose derivatives, dextrins, and/or starch derivatives may be used as the coating material. The rate of spraying, the initial water content in the coating solution, the airflow, the humidity of the air entering the chamber, and the temperature of the coating solution affect how quickly the water content in solution evaporates (Teunou and Poncelet, 2005). Fluidized bed coating (FBC) offers several advantages in industrial processes like it provides a highly efficient and continuous method for achieving uniform coatings on particulate materials. FBC allows for precise control over coating thickness, minimizes the risk of particle agglomeration, and is versatile enough to be applied across various industries, including pharmaceuticals, food, and materials science. Its efficiency, versatility, and ability to produce consistent and controlled coatings make it a valuable technique in achieving desired product properties and quality (Desai and Park, 2005).

3. Melt Extrusion

Encapsulation via extrusion has been used for volatile and unstable actives inglassy carbohydrate matrices. It involves dispersion of the core material in a molten carbohydrate mass at a temp above 100°C (Schlameus, 1995). This mixture is forced through a die containing a dehydrating liquid which hardens the coating to trap the core material and form capsule in which active agent has relatively little mobility. The most common liquid used for the dehydration and hardening process is

isopropyl alcohol (Porzio 2004). The strands or filaments of hardened material are broken into small pieces.It is common to use screws of L/D ratio between 20:1 and 40:1.

The screw system combines oscillatory and rotational movements to assist material transport within the extruder. The incoming feed is efficiently homogenized by the screw operating at low pressure in the feed zone, where the process starts. The screw design is gradually improved to raise pressure as the material moves through successive zones, which causes the extrudate to melt. Uniform delivery of the molten material from the extruder is ensured by maintaining a constant high pressure in the barrel's last section through the use of a consistent screw design. The components used as extrudates may include proteins, lipids, starch, and/or gums (Schlameus, 1995).

4. Spray cooling/ chilling

It is the least expensive encapsulation process for encapsulation of aroma compounds & water soluble flavors. It is similar to spray drying- but does not involve the evaporation of solvent (Oxley, J.D., 2012) .Mixture of core and wall is atomized into the cooled or chilled air, which causes the wall to solidify around the core.In spray-cooling, the coating material is vegetable oils including fat with melting points of 45˚C - 72˚C. In spray-chilling, the coating material is typically a hydrogenated vegetable oil with a melting point in the range of 32˚C - 42˚C (Favaro-Trindade et al., 2015). In these processes, a melted lipid, above its melting point, is sprayed onto the core material and allowed to cool.Instant solidification of the lipid takes place yielding almost perfect spherical and free-flowing microcapsule powders.These two methods, which differ only in the melting point of the wall material used, are most often used to encapsulate solid materials such as vitamins, minerals or acidulants (Gouin, 2004).

Chemical Methods:

Coacervation: It is known as original method of encapsulation. The technology of coacervation and its use in encapsulation have a notable historical background. It was developed by the National Cash Register Co. (NCR) in the 1950s and played a pivotal role in the creation of carbonless copy paper.Carbonless copy paper, often referred to as NCR paper, was one of the first commercial products to utilize microencapsulation. In this application, coacervate-based microcapsules containing colorless reactants were used to create

copies by reacting with an impact or pressure. In coacervation, phase separation occurs when conditions such as temperature, pH, or the addition of specific salts or polymers cause the colloidal molecules or polymers in a solution to aggregate (Jyothi et al, 2010). This aggregation leads to the formation of a dense, liquid-rich phase called the coacervate phase and a lean, supernatant phase.The coacervate phase contains a concentrated solution of the colloidal molecules or polymers, and it can encapsulate other substances, including drugs, flavors, or fragrances. Depending on the number of polymer types involved, the coacervation process can be categorized as simple or complex coacervation.

Simple Coacervation: In simple coacervation, only one type of polymer is present in the system. This single polymer undergoes phase separation, leading to the formation of the coacervate phase.In simple coacervation, sodium alginate is dissolved in water and the active compound that needs to be encapsulated, which is usually oil, is mixed into it and the emulsion formed is released in drops. Simple coacervation gives products with size from 20 to 500 μm.

Complex Coacervation: Complex coacervation, on the other hand, involves the presence of two or more types of polymers with opposite ionic charges. These oppositely charged polymers interact through electrostatic forces, leading to phase separation and the formation of the coacervate phase.Complex coacervates are commonly made from an o/w emulsion with gelatin and gum arabic at a 1:1 w/w ratio and at a 2–4% of each polymer dissolved in the water phase via adjusting the pH from neutral to about 4 under turbulent conditions in a stirred vessel at >35°C, a temperature above the gelation temperature of gelatin.This creates three immiscible phases and the polymer rich phase droplets will deposit on the oil surfaces because of interfacial sorption (Timilsena, 2019). The diameter size range expected in complex coacervation is 1 to 500 μm. Complex coacervates are highly unstable so, chemical agents, such as glutaraldehyde, are necessary to stabilize them (Lemetter et al., 2009).

1. Molecular Inclusion

Cyclodextrins are enzymatically modified starch molecules that are useful for entrapping molecules. These cyclodextrins have three primary forms: α, β, and γ with diameters of roughly 14, 15, and 17 Å and containing six, seven, or eight glucose

molecules, respectively (Pagington, J.S. 1986). The cyclodextrin molecule's external surface is hydrophilic, while its interior cavity produces an environment that is comparatively hydrophobic. A suitable sized active molecule can be reversibly entrapped in an aqueous environment within the lipophilic inner pocket of cyclodextrin, which has dimensions of 5 to 8 Å (Dziezak, 1998).

One possible way to load active chemicals into cyclodextrins is to knead the complex into slurry of up to 45% partially dissolved cyclodextrin or use a paste that has around 20–30% water in it. After the resultant solid is dried under vacuum, it is cleaned with a tiny amount of solvent to get rid of any remaining particles. According to Hedges (1998), the molecular weight, shape, and chemical functionality of the entrapped material, as well as the polarity of the core material, can all affect how long compounds stay inside the cyclodextrin's cavity.

2. Co-Crystallization

Co-crystallization involves spontaneous cryztallization or precipitation, in which actives can be entrapped. Spontaneous crystallization of supersaturated sucrose syrup is achieved at high temperature (above 120 °C) and low moisture. Aroma compounds can be added at the time of spontaneous crystallization. Crystal structure of sucrose incorporates the actives by entrapment. It enhances flavour stability and the granular product has a low hygroscopicity. Co-crystallization products retain as much volatile oil as spray-dried and extruded products. During the process, the liquid actives are transformed into dry granules and some heat-sensitive compounds may be degraded (Madene et al., 2006). Although the product has a free-flowing property, the addition of a strong anti-oxidant is necessary to retard development of oxidized flavours during storage.

Encapsulation in Seafood industry

Encapsulation plays a significant role in the fish industry, offering various benefits related to the preservation, flavor enhancement, and value addition of seafood products (Khoshnoudi-Nia et al., 2022). Here are some key applications of encapsulation in the fish industry:

Flavor and Aroma Enhancement: Encapsulation is frequently used to preserve and enhance the flavors and aromas of seafood products. Encapsulated flavors can be added to seafood dishes, such as sauces

and marinades, ensuring consistent and long-lasting sensory experiences.

Nutrient Protection and Fortification: Omega-3 fatty acids, vitamins, and other sensitive nutrients naturally found in fish are prone to oxidation and degradation. Encapsulation helps protect these valuable compounds from degradation due to light, oxygen, and moisture, ensuring the nutritional quality of fish-based products.

Controlled Release of Nutrients: Encapsulation allows for the controlled release of nutrients during cooking or consumption. For example, encapsulated omega-3 supplements can release their contents gradually, enhancing bioavailability and reducing the risk of fishy aftertastes.

Extension of Shelf Life: Microencapsulation can extend the shelf life of fish and seafood products by protecting them from spoilage and deterioration. Antioxidants and preservatives encapsulated in coatings can help prevent oxidation and microbial growth.

Sensitive Ingredient Protection: Encapsulation is used to protect sensitive ingredients in fish-based products. For instance, probiotics can be encapsulated to ensure their viability in seafood-based functional foods.

Reduced Off-Flavors: Encapsulation can mitigate off-flavors and odors associated with certain fish species. Encapsulated materials can absorb or mask unwanted flavors, improving overall product acceptability.

Encapsulation of Fish Oils: Fish oils, which are rich in omega-3 fatty acids, are commonly encapsulated to create dietary supplements. This ensures the stability and freshness of the oils and allows for convenient consumption (Shi et al., 2020).

Encapsulation for Value-Added Products:

Encapsulation can be used to create value-added seafood products, such as fish roe encapsulated in edible coatings, caviar substitutes, or flavored fish-based snacks.

Coatings for Seafood Products: Encapsulated coatings can be applied to seafood products to enhance texture, moisture retention, and flavor. These coatings can also provide a barrier against oil absorption during frying.

Encapsulation in Fish Feeds: In aquaculture, encapsulation is used to deliver essential nutrients and medications to

farmed fish. This ensures their health, growth, and overall quality.

Conclusion

Encapsulation's impact on the food industry extends beyond traditional preservation and flavor enhancement. It plays a pivotal role in the development of functional foods, dietary supplements, and personalized nutrition, aligning with evolving consumer preferences for health, convenience, and sensory delight. As the seafood industry continues to innovate, encapsulation remains a cornerstone technology, facilitating the creation of novel products that cater to a diverse and discerning global palate.In conclusion, encapsulation serves as a cornerstone of progress in the food industry, enabling the formulation of products that meet the demands of modern consumers for freshness, flavor, and health benefits. As research and development in encapsulation techniques continue to evolve, the future holds promise for an even broader array of functional and sensory-rich food innovations.

References

Anal, A.K. and Singh, H. (2007) Recent Advances in Microencapsulation of Probiotics for Industrial Applications and Targeted Delivery. Trends in Food Science & Technology, 18, 240-251.

Bustos, R., Romo, L., Yanez, K., Diaz, G. and Romo, C. (2003) Oxidative Stability of Carotenoid Pigments and Polyunsaturated Fatty Acids in Microparticulate Diets Containing Krill Oil for Nutrition of Marine Fish Larvae. Journal of Food Engineering, 56, 289-293.

Connick, J. and William, J. (1983) Controlled Release of Bioactive Materials Using Alginate Gel Beads. US Patents No. 4401456.

De Vos, P., Faas, M.M., Spasojevic, M. and Sikkema, J. (2010). Encapsulation for Preservation of Functionality and Targeted Delivery of Bioactive Food Components. International Dairy Journal, 20, 292-302.

Desai, K.G.H. and Park, H.J. (2005). Recent Developments in Microencapsulation of Food Ingredients. Drying Technology, 23, 1361-1394.

Dewettinck, K. and Huyghebaert, A. (1999). Fluidized Bed Coating in Food

Technology. Trends in Food Science & Technology, 10, 163-168.

Dubey, A., Hsia, R., Saranteas, K., Brone, D., Misra, T. and Muzzio, F.J. (2011) Effect of Speed, Loading and Spray Pattern on Coating Variability in a Pan Coater. Chemical Engineering Science, 66, 5107-5115.

Dziezak, J.D. (1998). Microencapsulation and Encapsulated Food Ingredients. Food Technology, 42, 136-151.

Dziubla, T.D., Shuvaev, V.V., Hong, N., Hawkins, B.J., Madesh, M., Takano, H. and Muzykantov, V.R. (2008). Endothelial Targeting of Semi-Permeable Polymer Nanocarriers for Enzyme Therapies. Biomaterials, 29, 215-227.

Eratte, D., Dowling, K., Barrow, C.J. and Adhikari, B. (2018). Recent Advances in the Microencapsulation of Omega-3 Oil and Probiotic Bacteria through Complex Coacervation: A Review. Trends in Food Science & Technology, 71, 121-131.

F. Gibbs, Selim Kermasha, Inteaz Alli, Catherine N. Mulligan, B. (1999). Encapsulation in the food industry: a review. International journal of food sciences and nutrition, 50(3), 213-224.

Fathi, M., Mozafari, M.R. and Mohebbi, M. (2012) Nanoencapsulation of Food Ingredients Using Lipid Based Delivery Systems. Trends in Food Science & Technology, 23, 13-27.

Favaro-Trindade, C.S., Okuro, P.K. and Matos, J.F.E. (2015) Encapsulation via Spray Chilling/Cooling/Congealing. In: Mishra, M., Ed., Handbook of Encapsulation and Controlled Release, CRC Press, Boca Raton, 71-88.

Gascon, A.D., Zuritz, C.A., Bustamante, J.A., Borbon, L.D. and Oberti, G. (2001) A Study of Different Formulations of Wall Support Systems for Microencapsulation of Antioxidant Essential Oils. ISHS Acta Horticulturae, 503, 53-58.

Gharsallaoui A, Roudaut G, Chambin O, Voilley A, Saurel R (2007) Applications of spray-dryingin microencapsulation of food ingredients: an overview. Food Res Intern 40:1107–1121

Gouin S (2004) Microencapsulation: industrial appraisal of existing technologies and trends.Trends Food Sci Tech 15:330–347.

Hedges AR (1998) Industrial applications of cyclodextrins. Chem Rev 98:2035–2044

Jimenez, M., Garcia, H.S. and Beristain, C.I. (2004) Spray-Drying Microencapsulation and Oxidative Stability of Conjugated Linoleic Acid. European Food Research and Technology, 219, 588-592.

Jyothi, N.V.N., Prasanna, P.M., Sakarkar, S.N., Prabha, K.S., Ramaiah, P.S. and Srawan, G.Y. (2010) Microencapsulation Techniques, Factors Influencing Encapsulation Efficiency. Journal of Microencapsulation, 27, 187-197.

Kailasapathy, K. (2002) Microencapsulation of Probiotic Bacteria: Technology and Potential Applications. Current Issues in Intestinal Microbiology, 3, 39-48.

Kaushik, P., Dowling, K., McKnight, S., Barrow, C.J. and Adhikari, B. (2016) Microencapsulation of Flaxseed Oil in Flaxseed Protein and Flaxseed Gum Complex Coacervates. Food Research International, 86, 1-8.

Keogh, M.K., O'Kennedy, B.T., Kelly, J., Auty, M.A., Kelly, P.M., Fureby, A. and Haahr, A.M. (2001) Stability to Oxidation of Spray-Dried Fish Oil Powder Microencapsulated Using Milk Ingredients. Journal of Food Science, 66, 217-224.

Khoshnoudi-Nia, S., Forghani, Z., & Jafari, S. M. (2022). A systematic review and meta-analysis of fish oil encapsulation within different micro/nanocarriers. Critical Reviews in Food Science and Nutrition, 62(8), 2061-2082.

King, W., Trubiano, P. and Perry, P. (1976) Modified Starch Encapsulating Agents Offer Superior Emulsification, Film Forming, and Low Surface Oil. Food Product Development, 10, 54-57

Lemetter CYG, Meeuse FM, Zuidam NJ (2009) Control of the morphology and size of complexcoacervate microcapsules during scale up. AIChE Journal 55(6):1487–1496

Li, J.K., Wang, N. and Wu, X.S. (1998) Gelatin Nanoencapsulation of

Protein/Peptide Drugs Using an Emulsifier-Free Emulsion Method. Journal of Microencapsulation, 15, 163-172.

Madene, A., Jacquot, M., Scher, J. and Desobry, S. (2006) Flavour Encapsulation and Controlled Release—A Review. International Journal of Food Science & Technology, 41, 1-21.

McClements, D.J. (2004) Protein-Stabilized Emulsions. Current Opinion in Colloid & Interface Science, 9, 305-313.

Mozafari, M.R., Khosravi-Darani, K., Borazan, G.G., Cui, J., Pardakhty, A. and Yurdugul, S. (2008) Encapsulation of Food Ingredients Using Nanoliposome Technology. International Journal of Food Properties, 11, 833-844.

Oxley, J.D. (2012) Spray Cooling and Spray Chilling for Food Ingredient and Nutraceutical Encapsulation. In: Garti, N. and McClements, D.J., Eds., Encapsulation Technologies and Delivery Systems for Food Ingredients and Nutraceuticals, Woodhead Publishing, Sawston, Cambridge, 110-130.

Pagington, J.S. (1986) β-Cyclodextrin and Its Uses in the Flavour Industry. In: Birch, G.G. and Lindley, M.G., Eds., Developments in Food Flavours, Elsevier Applied Science, London.

Petrović, T., Nedović, V., Dimitrijević-Branković, S., Bugarski, B. and Lacroix, C. (2007) Protection of Probiotic Microorganisms by Microencapsulation. Chemical Industry and Chemical Engineering Quarterly, 13, 169-174.

Porzio M (2004) Flavor encapsulation: a convergence of science and art. Food Technology 58(7):40–47

Schlameus, W. (1995) Centrifugal Extrusion Encapsulation. In: Risch, S.J. and Reineccius, G.A., Eds., Encapsulation and Controlled Release of Food Ingredients. ACS Symposium Series, Vol. 590, ACS Publications, Washington DC, 96-103.

Sheu, T.Y. and Rosenberg, M. (1998) Microstructure of Microcapsules Consisting of Whey Proteins and

Carbohydrates. Journal of Food Science, 63, 491-494.

Shi, M., Ying, D., Hlaing, M. M., Ye, J., Sanguansri, L., & Augustin, M. A. (2020). Oxidative stability of spray dried matcha-tuna oil powders. Food Research International, 132, 109050.

Soni, N., Shah, N.N. and Singhal, R.S. (2019) Dodecenyl Succinylated Guar Gum Hydrolysate as a Wall Material for Microencapsulation: Synthesis, Characterization and Evaluation. Journal of Food Engineering, 242, 133-140.

Teunou E, Poncelet D (2005a) Fluid-bed coating. In: Onwulata C (ed) Encapsulated and powderedfoods. CRC Press, Boca Raton, USA, pp 197–212

Thevenet F (1995): Acacia gums: natural encapsulation agent for food ingredients. In Encapsulation and Controlled Release of Food Ingredient, eds SJ Risch & GA Reineccius, pp. 51±59.

Timilsena, Y.P., Vongsvivut, J., Tobin, M.J., Adhikari, R., Barrow, C. and Adhikari, B. (2019) Investigation of Oil Distribution in Spray-Dried Chia Seed Oil Microcapsules Using Synchrotron-FTIR Microspectroscopy. Food Chemistry, 275, 457-466.

Turton, R. and Cheng, X.X. (2005) The Scale-Up of Spray Coating Processes for Granular Solids and Tablets. Powder Technology, 150, 78-85.

Ubbink, J. and Krüger, J. (2006) Physical Approaches for the Delivery of Active Ingredients in Foods. Trends in Food Science & Technology, 17, 244-254.

Wandrey, C., Bartkowiak, A. and Harding, S.E. (2010) Materials for Encapsulation. In: Zuidam, N.J. and Nedović, V.A., Eds., Encapsulation Technologies for Active Food Ingredients and Food Processing, Springer, New York, 31-100.

Zuidam, N.J. and Nedovic, V.A., Eds. (2010) Encapsulation Technologies for Active Food Ingredients and Food Processing. Springer Science + Business Media, LLC, New York.