Nanoencapsulation Techniques in Food Biotechnology

Trupti Taori, Assistant Professor, Ajeenkya D Y Patil University, Pune
trupti.taori@adypu.edu.in

Tejal Dilip Nandankar,
Student, Department of B.Tech Biomedical Engineering, Ajeenkya D Y Patil University, Pune.

Abstract

Nanoencapsulation, a frontier in food biotechnology, is revolutionizing the way we enhance and preserve the quality of food products. This sophisticated technique involves the incorporation of nanoparticles to encapsulate food ingredients, enzymes, flavors, or other bioactive compounds. The primary objective of nanoencapsulation is to protect these compounds from adverse environmental conditions, control their release, and thereby increase their stability and effectiveness within food products. At the core of nanoencapsulation is the use of nanoscale materials to create capsules that are often only a few nanometers to a few hundred nanometers in size. This incredibly small scale allows for a high surface-to-volume ratio, significantly improving the efficiency of encapsulation. The encapsulated materials are shielded from factors like light, oxygen, and moisture, which can degrade sensitive ingredients. This protection is particularly crucial for maintaining the potency of vitamins, antioxidants, and probiotics that are vulnerable to environmental stressors. Another significant advantage of nanoencapsulation is the ability to control the release of encapsulated substances. This controlled release can be engineered to occur at specific times, under certain conditions, or in particular parts of the gastrointestinal tract. Such precision ensures that the bioactive compounds maintain their functionality and deliver the intended health benefits more effectively. Moreover, nanoencapsulation can enhance the bioavailability of nutrients, making them easier for the body to absorb and utilize. This is especially important for compounds that are naturally less bioavailable or degrade rapidly in the digestive system. By encapsulating and protecting these compounds, nanoencapsulation can ensure a higher uptake of essential nutrients. In addition to enhancing the nutritional value of foods, nanoencapsulation also opens up possibilities for innovation in flavors and textures. Flavor compounds can be encapsulated to prevent their loss during processing or to create novel taste experiences, such as flavors that are released upon chewing

Keyword: Nanoencapsulation, Bioavailability, Controlled Release, Food Biotechnology, Nutrient Stability, Flavor Preservation, Nanoscale Materials

1.Introduction

Nano encapsulation is a cutting-edge technique in the field of nanotechnology, primarily used in pharmaceuticals, food technology, and various other industries. This process involves encapsulating substances at a nanoscale, creating tiny capsules that can range from a few nanometers to several hundred nanometers in size. The core idea is to encase a small quantity of an active ingredient within a carrier material. This encapsulation enhances the stability, bioavailability, and controlled release of the active substance. In pharmaceuticals, nano encapsulation is used to improve the delivery of drugs, particularly those that are poorly soluble or have limited bioavailability. By encapsulating these substances at a nanoscale, it's possible to alter their physical and chemical properties, improving their absorption in the body and allowing for targeted drug delivery. This means the drug can be delivered directly to a specific site in the body, reducing side effects and increasing efficacy.

In the food industry, nano encapsulation is used to incorporate vitamins, antioxidants, and other nutrients into food products. This not only enhances the nutritional value of the food but also can improve taste, texture, and shelf-life. For example, sensitive nutrients that might be degraded by exposure to light, air, or heat can be protected through nano encapsulation. Additionally, nano encapsulation is being explored in the cosmetic industry for the controlled release of fragrances and in agriculture for the delivery of pesticides and fertilizers.

Nano encapsulation offers a promising approach to improve the effectiveness and efficiency of various products, from medicines to food items, by protecting active ingredients, enhancing their stability, and controlling their release.

Table 1: Nanoencapsulation of Various Food Bioactive Substances

No.	Bioactive Components	Encapsulation Techniques	Applications	Key Studies
1	Phenolics (e.g., Quercetin, Tea Catechins, Folic Acid, Thymol, Resveratrol, Anthocyanins)	Freeze, Spray, and Microwave Drying	Targeted delivery, enhancement of antioxidant properties, addition of new functionalities	Grgić et al., 2020;
2	Essential Fatty Acids (DHA, Linolenic Acid)	Spray Drying	Stability enhancement, improved solubility, volatility reduction, lower dosage requirements, sensory quality enhancement	Geranpour et al., 2020;
3	Vitamins (Vitamin D3, B9, B2, Riboflavin, Thiamine)	Spray Drying, Solvent Evaporation	Protection against oxidation	Mujica-Álvarez et al., 2020

4	Carotenoids (Tomato Lycopene, Crocins)	Freeze Drying, Nanodispersion, Nanoemulsion	Stabilization, controlled release, expanded industrial applications	Pateiro et al., 2021
5	Peptides and Enzymes (e.g., Natural Dipeptides, Nisin)	Nanoliposomes, Spray Drying	Boosted antioxidant and antibacterial effects, improved absorption	Pateiro et al., 2021;
6	Probiotics and Prebiotics (e.g., Lactobacillus casei, Bifidobacterium spp., Streptococcus thermophilus, Fructooligosaccharides)	Emulsification	Enhanced viability, promoting gastrointestinal health, effective incorporation into food products	Pateiro et al., 2021
7	Miscellaneous (Minerals, Colorants, Flavors, Buffers, Micronutrients)	Nanoemulsion, Nanoliposome	Enhanced homogeneity of food systems, regulated release, improved flavor, taste, and texture	Soni et al. 2020

2. Nanoencapsulation

Nanoencapsulation refers to the technique of encasing materials at the nanometer scale, including films, coatings, layers, or even basic microdispersions. Utilizing nanoparticles for encapsulation provides superior characteristics beneficial for encapsulation. These nanoparticles efficiently and effectively release bioactive substances and offer improved features related to encapsulation. The size of these particles plays a crucial role in the transportation of substances within an organism. Interestingly, it has been observed that nanoparticles can uniquely penetrate certain cell lines, giving them an advantage over larger microparticles, which tend to have lower absorption rates. Research indicates that nanoparticles not only enhance the compatibility with food matrices but also extend the shelf life and bioavailability of food products.

Bioavailability refers to the extent to which a substance or drug is completely accessible to its intended biological destination. Nanoencapsulation typically produces particles smaller than 100 nm. These encapsulated particles are further classified into nanocapsules (less than 0.2 µm), microcapsules (0.2 to 5000 µm), and macrocapsules (less than 5000 µm). The consistency provided by nanoencapsulation leads to enhanced efficiency and favorable physical and chemical properties. This method stands out as an excellent alternative for the innovation of intelligent food ingredients, which can significantly influence the processability, bioavailability, and stability of bioactive components. The choice of an appropriate and effective encapsulation process relies on both the core material and the desired attributes of the final product.

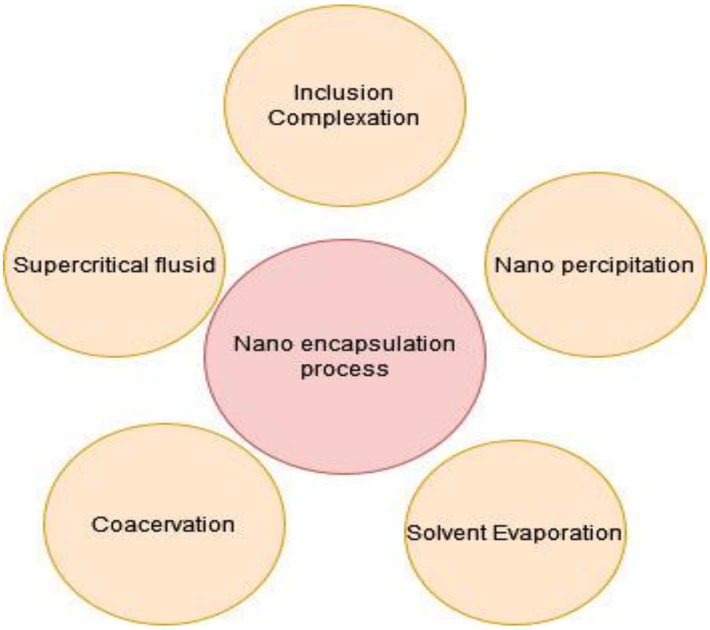

Figure 1: Nanoencapsulation technologies

3. Nanoencapsulation Materials

Nanoencapsulation is the technique of enveloping microscopic particles or droplets within a protective covering, forming nanocapsules that find applications across various industries. In the food sector, the wall materials used for encapsulation systems consist of polysaccharides, lipids, waxes, protein molecules, and safe synthetic compounds. Predominantly, polysaccharides and protein molecules constitute the primary wall materials employed in food encapsulation. This choice is rooted in the acceptability of these biopolymers for human consumption, their safety profile, and their ability to effectively entrap a wide range of bioactive substances.

Within the nanocapsule, the enclosed substance is referred to as the core or internal phase, while the surrounding material is known as the shell, coating, or membrane. The design of the wall material for nanocapsules is tailored to fulfill specific functions based on their intended use. Consequently, the wall material assumes paramount importance in the creation of nanocapsules, as it plays a critical role in protecting bioactive substances and food components from external conditions.

Furthermore, the wall material must possess key attributes, such as being non-reactive with the core constituents, stabilizing the core substance, being capable of forming a film, flexibility, neutrality in flavor, non-hygroscopic, exhibiting moderate viscosity, cost-effectiveness, and solubility in an aqueous environment. Additionally, the wall material can vary in flexibility, fragility, toughness, and thickness, offering precise control over the release of the encapsulated content in specific environments.

Safety precautions are essential during the development of nano-capsules, ensuring a proper and leak-free encapsulation process. The selection of coating materials involves considering a wide range of natural and synthetic polymers, focusing on properties necessary for the final product. Ideal coating materials for encapsulation should exhibit superior strength and durability, along with robust rheological properties at varying concentrations. Moreover, they should effectively retain and seal the active constituents within their structure during processing and long-term storage.

4. Materials

Nanoencapsulation Using Liquid-Based Methods

Nanoencapsulation through liquid-based approaches stands out as a highly effective strategy for the targeted delivery of nutraceuticals, even at the cellular scale. This section explores various liquid-based techniques adopted in research, along with a detailed analysis of their outcomes. Figure 1 illustrates diverse methodologies employed in this process.

Solvent Evaporation and Emulsification Method

This method involves creating an emulsion by blending a polymer solution into an aqueous environment, followed by the evaporation of the solvent. This leads to the formation of polymer nanoparticles. Recent work indicate that these nanoencapsulated particles are typically spherical. Factors like the viscosity of the organic or aqueous phases, stirring velocity, temperature, and the nature and quantity of dispersing agents significantly influence the size distribution of these nanoparticles. Commonly utilized polymers in this technique include polylactic acid (PLA).

Polylactic-co-glycolic acid (PLGA), cellulose acetate phthalate, ethyl cellulose, β-hydroxybutyrate, and polycaprolactone have been used in creating nanospheres, as noted by . These nanospheres are typically produced using methods like homogenization or high-speed ultrasonication, as indicated .The 'multiple emulsion' technique has been applied to encapsulate curcumin within a chitosan network cross-linked with tripolyphosphate, followed by freeze drying, resulting in spherical encapsulates of sizes 254–415 nm .

Another study focused on the solvent evaporation method for curcumin encapsulation, followed by freeze-drying (Li et al. 2015b). Prajakta et al. (2009) employed a similar approach, finding that curcumin encapsulates (< 135 nm) showed approximately a twofold increase in anticancer activity compared to curcumin alone in HT-29 cell lines (human colon adenocarcinoma). Smaller nanospheres (45 nm) of curcumin with higher loading capacity and sustained release, showing increased anticancer efficacy in human prostate cancer cell lines, were created using PLGA nanospheres. Emulsion evaporation technique also produced curcumin encapsulates with potent antimalarial activity in vivo. High-pressure emulsification effectively formed nanospheres of curcumin in PLGA, enhancing oral bioavailability by 22 times compared to non-encapsulated curcumin and the solubility of curcumin improved 640-fold when encapsulated in this manner .

Additionally, the 'single emulsion technique' was used to formulate a nanoencapsulate blend of PLGA and PLGA-PEG (< 200 nm) using sonication followed by freeze drying. These encapsulates exhibited 16 and 55 times higher bioavailability compared to non-encapsulated bioactives . PLA-based coatings in nanoencapsulation through the evaporation-emulsification method produced 130-nm-sized encapsulates with 97% entrapment efficiency of bioactives (Feng et al. 2018). Release studies showed an initial burst followed by sustained delivery, like quercetin releasing 88% in 72 hours and complete release in 96 hours The success of this method is highly dependent on the choice of emulsification and drying processes. In a different study, α-tocopherol encapsulated in nanospheres (90–120 nm) demonstrated a shelf life of about 3 months. Research also shows that processing parameters and the aqueous-to-organic phase ratio do not significantly impact the size and distribution of the resulting nanodispersions

Coacervation Process

The coacervation method achieves nearly 99% bioactive loading during encapsulation. This technique is based on the concept of phase separation, which involves separating a single polyelectrolyte or a mixture of polyelectrolytes from a solution, leading to the creation of a coacervate phase that encapsulates the core material. Enhancements in the coacervate's strength have been noted with the use of enzymatic or chemical cross-linkers like transglutaminase or glutaraldehyde. There are variations of this technique, such as simple and complex coacervation, utilizing one or multiple coating materials respectively. These methods have proven effective in encapsulating sensitive bioactives Additionally, the characteristics and robustness of the encapsulate can be tailored by altering the type and proportion of the biopolymer (including charge, flexibility, and molar mass), pH levels, ionic strength, and the hydrophobic interactions between biopolymers .

In particular, complex coacervation has shown efficacy in encapsulating capsaicin using gelatin and acacia. In this method, capsaicin is first treated with hydrolyzable tannins, then cross-linked with glutaraldehyde, and finally subjected to freeze drying.

Inclusion Complex Formation

Inclusion complexation stands as an effective encapsulation method, where a supramolecular connection between a ligand and a shell material (usually a cavity-bearing substrate) is formed. This process typically relies on an entropy-driven hydrophobic effect and van der Waals forces or hydrogen bonding. This technique has been applied using α and β-cyclodextrin, achieving encapsulation yields of 88% and 74% respectively Notably, encapsulating usnic acid in β-cyclodextrin resulted in an efficiency of 99.5% and a stability period of 4 months in suspension form. This method provided a more prolonged release of the encapsulated substance compared to usnic acid liposomes. Moreover, encapsulating docohexanoic acid in β-lactoglobulin (with low methoxy pectin) enhanced the shelf stability of the core by 80% compared to its free state). Researchers have suggested β-lactoglobulins and β-cyclodextrin as optimal coating materials, especially for volatile bioactives .

Encapsulation Utilizing Supercritical Fluid

Supercritical fluid encapsulation is characterized by the unique properties of supercritical fluids, which exhibit intermediate states between a liquid and a gas. These fluids have liquid-like density, gas-like viscosity, high penetrability, and greater solubility than gases, making them suitable for encapsulating thermolabile compounds .Commonly used supercritical fluids include carbon dioxide, propane, nitrogen, and water, with carbon dioxide being the most widely used. In this encapsulation process, a mixture of the active compound and a coating material (like a polymer) is exposed to the supercritical fluid and then allowed to expand through a nozzle, leading to the entrapment of the active core due to the supercritical phase behavior. This encapsulation is primarily driven by pressure, and variations in encapsulation can be achieved by adjusting the temperature (Duarte et al. 2015).

4. Conclusion

This comprehensive review highlights the advancements and efficacy of various encapsulation techniques in the field of nanotechnology, with a specific focus on the encapsulation of bioactive compounds. Techniques such as solvent evaporation and emulsification, coacervation, inclusion complexation, and supercritical fluid encapsulation have been explored, each offering unique benefits and suitability for different types of bioactives. The solvent evaporation and emulsification method is notable for its versatility in creating nanoparticles with controlled size distribution, significantly influenced by factors such as viscosity, temperature, and the nature of dispersing agents. Coacervation, on the other hand, excels in its high loading efficiency, making it ideal for the encapsulation of highly sensitive bioactives. Its effectiveness is enhanced through the use of cross-linkers, which improve the strength of the coacervate. Inclusion complexation emerges as a method particularly adept at encapsulating volatile bioactives, providing substantial protection and improved stability. This technique, utilizing the unique properties of substances like β-cyclodextrin, demonstrates high encapsulation efficiency and prolonged release profiles. Finally, supercritical fluid encapsulation stands out for its suitability in handling thermolabile compounds, leveraging the distinctive properties of supercritical fluids. This method is especially advantageous for its ability to modify encapsulation properties through temperature and pressure adjustments, catering to a wide range of bioactive compounds.

In conclusion, these encapsulation techniques represent significant strides in nanotechnology, offering tailored solutions for the effective delivery and stabilization of bioactive compounds. Their diverse applicability, efficiency, and ability to enhance the stability and bioavailability of encapsulated materials mark a pivotal advancement in the field, with promising implications for future research and applications in pharmaceuticals, food technology, and beyond.

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