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Nanoencapsulation in Food Systems: Techniques, Applications, Challenges and Future Perspectives

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Abstract

One of the many diverse and quickly embraced nanotechnology in the food business is nano-encapsulation. It is an emerging technology that involves the encapsulation of active ingredients or bioactive compounds and could be suitable for delivering such protected compounds to target biological systems within nanometer- scale carriers. This review also focuses on different methods, which have been used for encapsulation purposes such as coacervation, ionic gelation, nano-precipitation, nano spray drying and ultra-sonification. In addition to improving food's nutritional value and overall health, nanotechnology can also improve food's sensory qualities, storage, and target distribution, as this study explored. Current state of knowledge, limitations of these techniques, and recent trends are also discussed. Finally, safety and regulatory issues in the nano encapsulation of bioactive compounds are also highlighted.

Keywords: Nanoencapsulation, nanotechnology, bioactive compounds, coacervation, target delivery

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Introduction

Nanotechnology has developed as one of the most encouraging scientific field of research and has been touted as the next revolution in many industries, including agriculture and food industry over the most recent couple of decades Subramani *et al*. [1]. The surface-to-volume ratio rises when particle size is reduced to the nanoscale range, which subsequently enhances reactivity several times with modifications in mechanical, electrical, and optical properties. It deals with the manufacture, processing, and uses of materials smaller than 1,000 nm [2].

Therefore, the design and manufacture of materials, tools, and systems with control at nanoscale dimensions is referred to as nanotechnology. Food production, processing, storage, and the development of novel components, products, and applications have all been transformed by nanotechnology. The application of nanotechnology to the food sector could generate innovation in the macroscale characteristics of food, such as texture, taste, other sensory attributes, coloring strength and stability during shelf-life, leading to a great number of new products. Furthermore, nanotechnology can enhance bioactive compounds' oral bioavailability, thermal resistance, and water solubility [3]. The primary applications of nanotechnology in food science include controlling the release of food ingredients, creating new flavors and sensations, encapsulating food components or additives, encapsulating bioactive chemicals with nanocarriers by nanotechnology can change the textures of food items and/or increase the bioavailability of nutritional ingredients and is a promising approach to increase the solubility, stability, and bioavailability of these molecules.

Nano encapsulation

Encapsulation has prospective applications in many scientific and technological domains, particularly in the food industry. It is a technique by which the sensitive ingredients are packed within a coating or wall material. The wall material protects the sensitive ingredients against adverse reaction and controls release of the ingredients [4]. The food sector already commonly uses the encapsulation process to preserve organic substances which impart flavor and odor after these molecules typically possess smaller molecular weights and can easily volatilize during food processing/manufacturing and storage [5]. The aim of encapsulation is mainly protecting the labile and sensitive bioactive agents from the undesirable circumstances. A capsule is made up of a small sphere encased in as solid shell. The wall of the capsule might be referred to as the shell, coating, wall material, membrane shell, carrier material, encapsulating agent, external phase, or matrix, while the substance within is referred to as the core material, internal phase, encapsulant, payload phase, or fill [6]. Encapsulation can help foods contain more stable bioactives by better controlling their release at the physiological site of action [7].

Specifically, nanoencapsulation provides particles of <100 nm, the encapsulated particles can be classified as nanocapsules (<0.2 µm), microcapsules (0.2–5000 µm) and macrocapsules (>5000 µm). Nanocapsules can be classified into two basic categories of single-core or multicore and each one in a form of single-wall or multiwall One of the main benefits of applying nano encapsulation is the homogeneity it imparts, resulting in better encapsulation efficiency and suitable physical and chemical properties. For functional food components that significantly affect product stability, bioavailability, and process ability, this approach offers a convincing alternative [8].

Advantages of nano encapsulation

- Increasing the bioavailability of food ingredients.
- Masking the unpleasant aromas and tastes, such as the undesirable taste of fish oil.
- Preventing the unnecessary interactions with other chemical structures, for example, micro-encapsulation of organic acids, such as citric acid and ascorbic acid to maintain the proper physicochemical properties and nutrient level of foods.

Techniques

Coacervation

In the coacervation procedure, one or more polyelectrolytes are separated from a solution by phase separation, and the newly created coacervate phase is then deposited around the active component. Moreover, a hydrocolloid shell can be cross-linked with the help of an appropriate chemical or an enzymatic cross-linker, such as transglutaminase or glutaraldehyde, primarily to strengthen the coacervate [9].

The common driving force for this method is electrostatic attraction between oppositely charged molecules. Gelatin, gum of acacia and chitosan has been used as wall materials in this technique.

Advantages

- Coacervation is a distinctive and promising encapsulation technology because of the very high payloads achievable (up to 99 %) and the possibilities of controlled release which is beneficial foe sustained drug delivery, or gradual flavor and fragrance release.
- Many coacervation processes use biocompatible and biodegradable polymers, making it suitable for pharmaceutical and medical applications, where safety is concern.

Nanoprecipitation/ Solvent Displacement Method

The nanoprecipitation method is also called solvent displacement. In the aqueous exterior phase, the organic internal phase—which contains the dissolved polymer, drug, and organic solvent—emulsifies spontaneously. The process of nano precipitation entails the dispersion of the organic solvent in the aqueous medium and the precipitation of a polymer from an organic solution [10]. This process exploits the difference between solvent and non-solvent to induce the formation of nanoparticles. Organic solvent into the surrounding aqueous phase, together with the dissolved carrier material.

Advantages of Nanoprecipitation

- Compared to alternative techniques for creating nanoparticles, nanoprecipitation has the following benefits:
- Simplicity: There is not a requirement for advanced equipment or extreme reaction conditions because the procedure is really simple and straightforward.
- Gentle conditions: The procedure is suitable for heat-sensitive materials because it doesn't require the use of high temperatures or pressures and is completed at room temperature.

Challenges and Future Perspectives

Even with all of nanoprecipitation's benefits, there are still certain problems that require attention. Strategies for improving the characteristics of nanoparticles made via nanoprecipitation require further investigation.

Ionic Gelation

Ionic gelation uses ionic cross-linking of polyelectrolytes with multivalent ions to form a gel network. The most commonly used polymer in ionic gelation is chitosan that is cationic in nature. This techniqueis used to precipitate an anti-solvent [11]. Reagent toxicity and unwanted side effects are possible with physical crosslinking, which is based on electrostatic interactions among polymers and crosslinking agents. This method is simpler to implement because it uses the magnetic stirrer's kinetic energy at room temperature [12].

Advantages

- **Mild Processing conditions**: occur at mild temperatures and physiological pH levels, which preserves the stability of sensitive bioactive compounds, such as proteins and nucleic acids, that may degrade at high temperature.
- **Controlled release**: By forming a gel matrix, this method can help control the release of encapsulated compounds, making it deal for sustained drug delivery.
- **Biocompatibility**: Ionic gelation often uses biopolymers like chitosan, alginate which are naturally biocompatible and can reduce potential toxicity [13].

Nano spray drying

Nanocapsule formation by Nanospray drying

The process of spraying a fluid into a heated drying medium to turn it from a liquid into a dried particle form is known as spray drying. This one-step technique operates well for transforming a variety of liquid formulations-such as organic and aqueous solutions, emulsions, and suspensions—into dry powders. Spray drying provides a high degree of flexibility in controlling particle size and morphology through the optimization of process parameters and feed formulations [14].

Higher stability, improved resistance to environmental factors including oxidation, light, and temperature, ease of transportation and storage, and dispersibility in aqueous solutions are all advantages of the dried powder form [15].

Principle

There are 3 basic processes in the spray drying process:

- Atomization of the liquid feed,
- Drying of the sprayed droplets in the drying gas and formation of dry particles, and
- Separation and collection of the dry product from the drying gas. The nozzle atomizes the feed into droplets. A significant increase in surface area results from the lowering of particle size. The hot drying gas (often air or inert gas) continuously flows through the drying chamber, rapidly eliminating the solvent, which may be water, solvents made from organic material, or combinations of these. After getting separated from the gas stream by a cyclone, the dry solid particles are gathered in a collection tank.

By dissolving, emulsifying, or dispersing the core material in a carrier material solution, encapsulation is achieved. The combination is then sprayed into the heated drying chamber. There could be a liquid or solid form of the enclosed substance.

Encapsulation protects the bioactive compound from the surrounding environment, increases the product storage stability [16] and preserves their health-promoting [17]. Additionally, encapsulation is used to maximize bioavailability, control the release of the bioactive chemical, target particular areas, and cover up an ingredient's flavor.

Advantages

- Controlled release of active compounds

  Due to increased hydrolysis, active chemicals enclosed in low molecular weight PLGA polymers release more quickly than those with a high molecular weight and degradation rate [18].
- Stability of active compounds during nano spray drying

  During the nano spray drying process, the active compound is exposed to several potential stress factors, such as fluid pumping, atomization into droplets, heat, and particle collection and recovery.

Challenges in nano spray drying

- Droplet formation may occur intermittently or perhaps cease entirely if certain fluids are too viscous to flow through the mesh system and suspensions block the mesh openings.
- The processing time may gradually increase. Sometimes the product may even build-up deposits on the vibrating mesh and reduce the product yield [19].
- Equipment designed for large-scale nano spray drying is yet to be developed and commercialized.

Future of nanoencapsulated food in human digestive tract

Human digestive tract has a linear form that might not be proper for the absorption of bioactive food components. Food ingredients can only be comfortably introduced by oral delivery and the processing of the food into a digestible form occurs in strict sequence thereafter. Thereafter, the bolus is swallowed and transferred into the stomach, where digestion takes place in the acid solution [20].

Safety and regulatory laws in food nanotechnology

Due to their miniature sizes and unique features there are underlying concerns about safety and possible negative effects, especially their persistence in ecosystems and possible bioaccumulation in living organisms. Another emerging concern relates to the ethical and societal implications of nanotechnology. Questions about the ethical development and application of nanoparticles as well as the fair distribution of advantages and hazards throughout society emerge when the boundaries between fiction and reality become progressively unclear. The potential for nanomaterials to exhibit unexpected behaviors, such as increased reactivity or bioavailability, poses serious challenges for risk management strategies [21].

By leveraging large datasets and machine learning algorithms, researchers can predict the toxicological properties of nanomaterials based on their physicochemical characteristics and biological interactions. These predictive models offer valuable tools for prioritizing the testing of high-risk nanomaterials and optimizing risk assessment strategies. Effective nanomaterial regulation requires including the public and encouraging communication among stakeholders. Regulations are greatly influenced by how the public views and accepts nanotechnology regulations and business practices. Thus, it is crucial to educate and enlighten the public about the advantages and dangers of nanomaterials [22].

Recent nanocarrier systems

1. **Liposomes**: are spherical vesicles composed of one or more concentric lipid bilayers, usually made of phospholipids similar to biological membranes. They can encapsulate hydrophilic compounds in their aqueous core and lipophilic compounds within the lipid bilayer. They are biocompatible and widely used in the food industry for flavor or nutrient protection
2. **Nanoemulsions**: are emulsions with extremely small droplet sizes, 20-200nm. They are not thermodynamically stable but have high kinetic stability. They are made of 2 immisible liquids with an emulsifier, but their droplets are so tiny that the mixture looks transparent. They are excellent for enhancing oral bioavailability of hydrophobic compounds, as their small size allows for rapid absorption.
3. **Cyclodextrins**: are a family of cyclic oligosaccharides with a unique structure i.e. a hydrophobic inner cavity and a hydrophilic outer surface. They form inclusion complexes by trapping a lipophilic guest molecule inside the cavity.

Conclusion

The food sector is undergoing a change due to nanotechnology, which provides innovative techniques for processing and preservation through nanoencapsulation. This technology greatly improves the stability, solubility, and bioavailability of sensitive bioactive chemicals by employing methods like coacervation, nanoprecipitation, ionic gelation, and nano spray drying. These techniques enable controlled release within the human digestive tract while shielding chemicals from external stress. However, there are significant obstacles to these inventions future use in terms of scale, possible toxicity, and regulatory safety. In the end, even if nanotechnology promises better functional food, effective commercial integration depends on the establishment of strict safety regulations and legal frameworks.

References

[1] Subramani,T and Ganapathyswamy, H An overview of liposomal nano-encapsulation techniques and its applications in food and nutraceutical. Journal of Food Science and Technology, 2020; 57: 1-11.

[2] Neethirajan, S. and Jayas, D.S, Nanotechnology for the food and bioprocessing Industries. Food and Bioprocess Technology, 2011.; 4(1): 39-47.
[3] Silva, H. D., Cerqueira, M. A. and Vicente, A. A. Nanoemulsions for food applications: development and characterization. Food and Bioprocess Technology, 2012; 5: 854-867.
[4] Bakowska-Barczak.; A. M. and Kolodziejczyk, P.P. Black currant polyphenols: Their storage stability and microencapsulation, Industrial Crops and Products, 2011; 34(2):1301-1309.
[5] Saifullah, M.; Shishi, M. R. I.; Ferdowsi, R.; Rahman, M. R.T and Vuong, Q. Van Micro and nano encapsulation, retention and controlled release of flavor and aroma compounds: A critical review, Trends Food Science Technology, 2019; 86: 230-251.
[6] Jafari, S.M.; Assadpoor, E.; He, Y and Bhandari, B, Encapsulation efficiency of food flavours and oils during spray drying, Drying Technology, 2008; 26(7): 816-835.
[7] Jampilek, J.; Kos, J and Kralova, K, Potential of nanomaterial applications in dietary supplements and foods for special medical purposes, Nanomaterials, 2019; 9: 296.
[8] Human, C.; de Beer, D.; Van der Rijst, M.; Aucamp, M and Joubert, E. Electrospraying as a suitable method for nanoencapsulation of the hydrophilic bioactive dihydrochalcone, aspalathin. Food Chemistry, 2019; 276: 467-474.
[9] Zuidam, N. J. and Shimoni, E. 2010. Overview of microencapsulation use in food products or processes and methods to make them. In N. J. Zuidam and V. A. Nedovic (Eds.), Encapsulation technique for active food ingredients and food processing pp 3-29. NewYork: Springer.
[10] Galindo-Rodriguez, S.; Allemann, E.; Fessi, H and Doelker. Physicochemical parameters associated with nanoparticle formation in the salting-out, emulsification–diffusion and nanoprecipitation methods. Pharmaceutical Research, 2004, 21(8), 1428–1439.
[11] Joye, I. J and McClements, D.J. Production of nanoparticles by anti-solvent precipitation for use in food systems. Trends Food Science Technology, 2013, 34(2):109–123.
[12] Abdassah M. 2017. Nanopartikel dengan gelasi ionik. Jurnal Sains dan Teknologi Farmasi, 2017, 15(1):45-52.
[13] Indiarto, R.; Indriana, L.P.A.; Andoyo, R.; Subroto, E and Nurhadi, B. Bottom-up nanoparticle synthesis: a review of techniques, polyphenol-based core materials, and their properties. European Food Research and Technology, 2022, 248(1): 1-24.
[14] Nandiyanto, A.B.D. and Okuyama, K. Progress in developing spray-drying methods for the production of controlled morphology particles: from the nanometer to submicrometer size ranges. Advanced Powder Technology, 2011, 22: 1-19.
[15] Murugesan, R. and Orsat, V. Spray drying for the production of nutraceutical ingredients-a review. Food and Bioprocess Technology, 2012, 22:1-19.
[16] Celli, G. B.; Ghanem, A.; Brooks, M.S.-L. 2015. Bioactive encapsulated powders for functional foods-a review of methods and current limitations. Food and Bioprocess Technology, 2015, 8: 1825-1837.
[17] Quintanilla-Carvajal, M.X.; Camacho-Díaz, B.H.; Meraz-Torres, L.S.; Chanona-Pérez, J.J.; Alamilla-Beltrán,L.; Jimenéz-Aparicio,A and Gutiérrez-López,G.F, 2010. Nanoencapsulation: a new trend in food engineering processing. Food Engineering Reviews, 2:39-50.
[18] Panda, A. Meena, J. Katara, R. and Majumdar, D. K. Formulation and characterization of clozapine and risperidone co-entrapped spray-dried PLGA nanoparticles. Pharmaceutical Development and Technology, 2014, 7450: 1-11.
[19] Schmid, K., Arpagaus, C. and Friess, W. Evaluation of the nano spray dryer B-90 for pharmaceutical applications. Pharmaceutical Development and Technology, 2011, 16: 287-294.
[20] Jafari, S.M.; McClements, D.J. Nanotechnology approaches for increasing nutrient bioavailability. Advances in Food and Nutrition Research, 2017,81:1-30.
[21] Mitra, Rajendra N., Miles J. Merwin, Zongchao Han and Shannon M. Conley. Yttrium oxide nanoparticles prevent photoreceptor death in a light-damage model of retinal degeneration. Free Radical Biology and Medicine, 2014, 75: 140-148.
[22] Da Luz, Fernanda Santos, Fabio da Costa Garcia Filho and Maria Teresa Gomez Del-Rio.Graphene-incorporated natural fiber polymer composites: A first overview. Polymer, 2020, 12: 1601.

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