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Cyclodextrin Based Nanoencapsule Applications In Foods

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HIGHLIGHTS

- Cyclodextrin-based nanoencapsulation can improve food shelf-life and stability depending on the encapsulated active compound.
- Food industry benefits from cyclodextrin nanoencapsulation for bioactive delivery.
- Cyclodextrin nanocapsules enhance the functionality of food products.
- Nanoencapsulation of bioactive compounds offers new trends in food applications.

Abstract

This research explores the significance of cyclodextrin-based nanoencapsulation applications in the food industry and the benefits that this technology offers. Nanoencapsulation represents a novel technique that offers protection and enables the controlled release of bioactive compounds from environmental influences. In particular, the effects on increasing stability and preserving the functional properties of sensitive substances such as vitamins, antioxidants and flavor components are discussed within the scope of this review. The amphiphilic nature of cyclodextrins with a hydrophobic inner cavity and a hydrophilic outer surface is vital for encapsulating ingredients and enhancing their shelf life. Cyclodextrin-based nanoencapsulation has a wide application potential in the food industry. This technology offers significant advantages in terms of maintaining and improving the quality of functional foods, as well as improving the sensory and nutritional properties of bioactive ingredients. Although it has some limitations such as high costs and production difficulties, it is predicted that this technology will make a significant contribution to improving the quality of food products with further development in the future.

Keywords: Bioactive Compounds; Cyclodextrin; Food Industry; Functional Foods; Nanoencapsulation

1. Introduction

Encapsulation refers to the process of enclosing one or more active ingredients in nano, micro or macro capsules, typically in liquid, gaseous, or solid form, which are surrounded by a protective coating material (Aloğlu and Öner 2010; Gökmen et al. 2012). This technology enables controlled release by protecting the active ingredients from undesired reactions by isolating them from the external environment. At the same time, it

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helps to maintain the stability of bioactive substances and prevent the occurrence of undesirable conditions in foods in order to stop or slow down the rate of degradation that may occur during food processing and storage (Lesmes et al. 2009). Encapsulation approach is used in the food, pharmaceutical, cosmetic and agricultural sectors for the protection, release control and stabilisation of active ingredients (Gökmen et al. 2012). In the food industry, it is widely preferred to preserve components such as vitamins, enzymes, antioxidants and flavouring agents and to increase their stability during processing processes (Madene et al. 2006; Gharsallaoui et al. 2007; Soyuçok et al. 2009).

Encapsulation types can be classified differently according to their size (Figure 1). This classification is divided into nanoencapsulation (smaller than 200 nm=0.2 μm), microencapsulation (0.2-5,000 μm) and macroencapsulation (larger than 5,000 μm) (King 1995). Nanoencapsulation is preferred to increase the bioavailability of active ingredients by using capsules smaller than 200 nm and to provide controlled release at the targeted site (Ribeiro et al. 2020). Microencapsulation is a common method to maintain the stability of active ingredients and avoid undesired interactions and has wide application especially in the food and pharmaceutical industry (Gouin 2004). Additionally, macroencapsulation, is used when larger components need to be protected and generally provides physical protection and full control of release (King 1995).

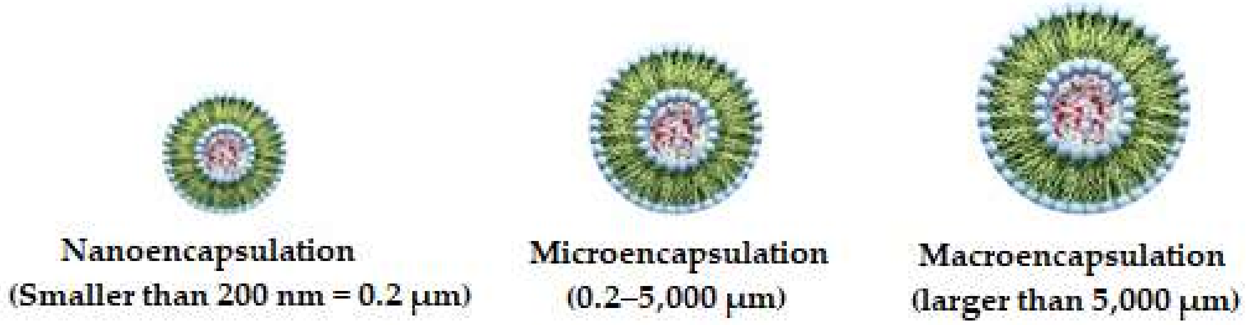


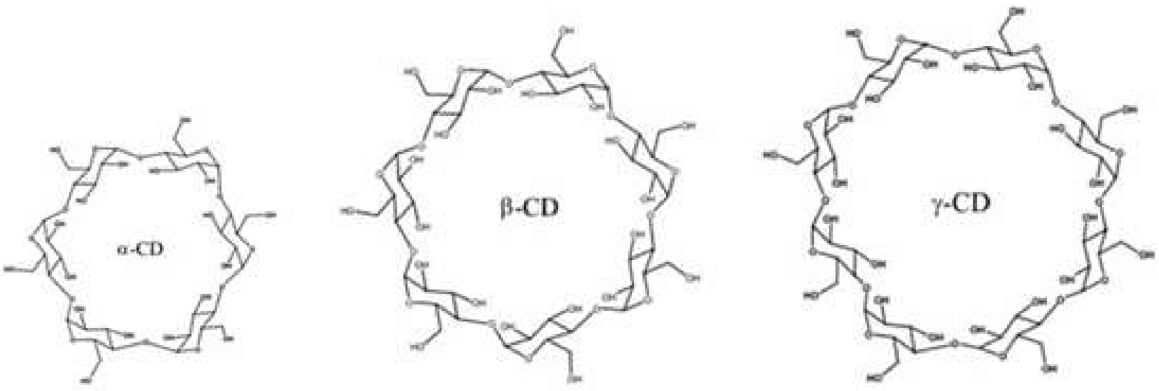
Figure 1. Types of capsules (King 1995).

2. Cyclodextrins

Cyclodextrins are ring-shaped cyclic oligosaccharides formed by the enzymatic breakdown of natural starch. These molecules are formed by linking glucose units and have a hydrophobic (water repellent) interior and a hydrophilic (water attractive) exterior. These properties allow cyclodextrins to form capsule-like structures that can take various molecules into them. Thus, cyclodextrins offer an effective solution for the protection and controlled release of active ingredients in areas such as pharmaceuticals, food, cosmetics and agriculture (Dhiman and Bhatia 2020).

The first scientific paper on the structure of cyclodextrins was published by Villiers in 1891. Villiers obtained 3 grams of crystallised substance from 1000 grams of starch with *Bacillus amylobacter* microorganism and defined the composition of this substance as $(C_6H_{10}O_5)_2$-$3H_2O$ and named it 'cellulosin' (Szejtli 1998).

Cyclodextrins are cyclic oligosaccharides consisting of 6 (α), 7 (β) or 8 (γ) glucose units (Figure 2). These glucose units are linked together by α-(1-4) glycosidic bonds and the resulting molecule takes the shape of a conical cylinder.



α-Cyclodextrin: Six glucose units **β-Cyclodextrin:** Seven glucose units **γ-Cyclodextrin:** Eight glucose units

Figure 2. Molecular structural representation of alpha (*α*), beta (β) and gamma (*γ*)-cyclodextrin (Li et al. 1992; Pinto et al. 2014a; Ju, 2023).

β-cyclodextrin is the most commonly utilized type, particularly favored in pharmaceutical and food industries because of its cost-effectiveness and extensive manufacture. The cyclodextrin molecule's cyclic arrangement of glycopyranose units and hydroxyl groups on the exterior confer water solubility, while its inner apolar structure is capable of establishing inclusion complexes through interactions with hydrophobic molecules. (Çetin 2014).

Schardinger discovered the interaction of cyclodextrins with ion solutions and observed that these compounds were produced by various microorganisms. In 1903, in his studies on bacterial species that can survive in food processes and cause food poisoning, he reported on microorganisms that break down starch to form two different crystallised products (Schardinger 1903). He also observed that crystallized dextrin's interacted with iodine or iodine solution to form characteristic iodine compounds and named the parent compound *α*-dextrin as a result of these findings. The difference between *α*- and β-dextrin was determined by iodine reaction; *α*-dextrin/iodine complex was blue when wet and grey-green when dry, while β-dextrin/iodine complex was red-brownish when wet and dry. Thus, the foundations of cyclodextrin chemistry were laid with these studies of Schardinger (Szejtli 1998). In addition, *γ*-cyclodextrin has a larger ring structure consisting of eight glucose units and the capacity to interact with larger molecules. It is especially preferred in the food and pharmaceutical sectors for stabilisation and solubility enhancement of large molecules (Del Valle 2004).

In the 1930s, Freudenberg et al. determined that the dextrins discovered by Schardinger consisted of maltose units and *α*-1,4 glycoside bonds. The first method for the purification of these substances was developed and their cyclic structure was identified in 1936. Between 1948 and 1950, *γ*-cyclodextrin was isolated and its structure was clarified. These cyclic structures consisting of six, seven and eight glucose units are named *α*, β and *γ*-cyclodextrin, respectively (Szejtli 1998; Bayrak 2006; Lima et al. 2016).

Cyclodextrins (CDs) are materials obtained by degradation of starch and widely used in the formation of inclusion complexes (Lima et al. 2016). Having a non-polar internal cavity and hydroxyl groups on their surface, CDs contain hydrophobic components, hydrophobic interactions between guest molecules and their inner walls. Furthermore, van der Waals forces and dipole-dipole interactions also play a role in this process (Li et al. 2017).

Many different carrier materials and techniques can be used in encapsulation; however, methods requiring advanced infrastructure and expensive carrier combinations increase costs. In contrast, the method of forming inclusion complexes with β-cyclodextrin offers advantages compared to many other methods. An agent-cyclodextrin complex is formed when the appropriate sized core material is placed in the hollow space on the inner surface of cyclodextrins. This structure gives cyclodextrin inclusion complexes water solubility (Çetin 2014). In addition, nano-sized encapsules can be produced by this method and thus the activity of the active material can be increased.

2.1. Importance of Cyclodextrins in Nanoencapsulation Applications

Cyclodextrins are integral to nanoencapsulation applications primarily due to the hydrophobic cavities within their molecular framework. These cavities enable hydrophobic molecules to embed themselves within cyclodextrins, enhancing their solubility in the surrounding medium and providing stability to bioactive substances. (Li et al. 2017). Nanoencapsulation is frequently used for the protection and controlled release of sensitive components such as volatile components and oils. Since the structure of cyclodextrins consists of glucose units arranged in a conical cylinder, this structure stands out as an effective tool for encapsulation of bioactive components. These properties cause cyclodextrins to be widely preferred in food and pharmaceutical sectors (Szejtli 1998; Bayrak 2006).

2.2 Encapsulation Applications of Cyclodextrins in Food Industry

Cyclodextrins have found widespread applications in the stabilization of essential oils and the protection of volatile compounds. In particular, β-cyclodextrin forms complexes with various essential oils, protecting these components from oxidation and extending their shelf life (Wang et al., 2016). Furthermore, such encapsulations can mask aroma and taste components in foods and prevent unwanted odors and flavors. In the food industry, cyclodextrins are utilized in many areas, such as enhancing the solubility of certain vitamins and colorants, extending shelf life by protecting heat-, light-, and oxygen-sensitive components, and stabilizing flavors and essential fatty acids.

For example, the use of 1.5% β-cyclodextrin in bread-making has been shown to delay staling by preserving the hardness and elasticity of the bread. Studies have demonstrated that complexing with cyclodextrins is more effective than other methods in protecting volatile and sensitive components (Avcı and Dönmez, 2010). The most significant advantage of complexing with cyclodextrins compared to traditional methods is that encapsulation can occur at the molecular level, effectively protecting each flavor component in multicomponent food systems and preventing intermolecular interactions in natural or synthetic components such as flavor concentrates, essential oils, and oleoresins (Szente and Szejtli, 2004).

Recent studies have further highlighted the versatility of cyclodextrins in food applications. For instance, Li et al. (2022) demonstrated the encapsulation of curcumin, a bioactive compound, using β-cyclodextrin to enhance its bioavailability and protect it from environmental factors such as heat and light. Similarly, Wang et al. (2019) studied the encapsulation of lycopene with cyclodextrins, showing that the complexes significantly improved the stability and antioxidant activity of lycopene during storage, making it more effective for use in functional food products.

Further research has also explored the encapsulation of probiotics using cyclodextrins to enhance their survival and activity under harsh gastrointestinal conditions. Rajam ve Subramanian (2022) evaluated the encapsulation of probiotic strains in α-cyclodextrin, reporting improved viability during storage and enhanced resistance to acidic environments, which is crucial for their use in functional dairy products.

Additionally, Iskineyeva et al. (2022) investigated the use of cyclodextrins in the encapsulation of polyphenols such as resveratrol. Their findings indicated that the cyclodextrin-polyphenol complexes not only enhanced the stability of these compounds but also improved their bioavailability and antioxidant capacity, making them ideal candidates for incorporation into health-promoting beverages.

In the case of flavor protection, Shi et al. (2023) encapsulated volatile lemon oil using cyclodextrins to prevent loss of aroma during food processing. The study showed that cyclodextrin encapsulation could significantly prolong the shelf life of lemon-flavored products without altering their sensory properties.

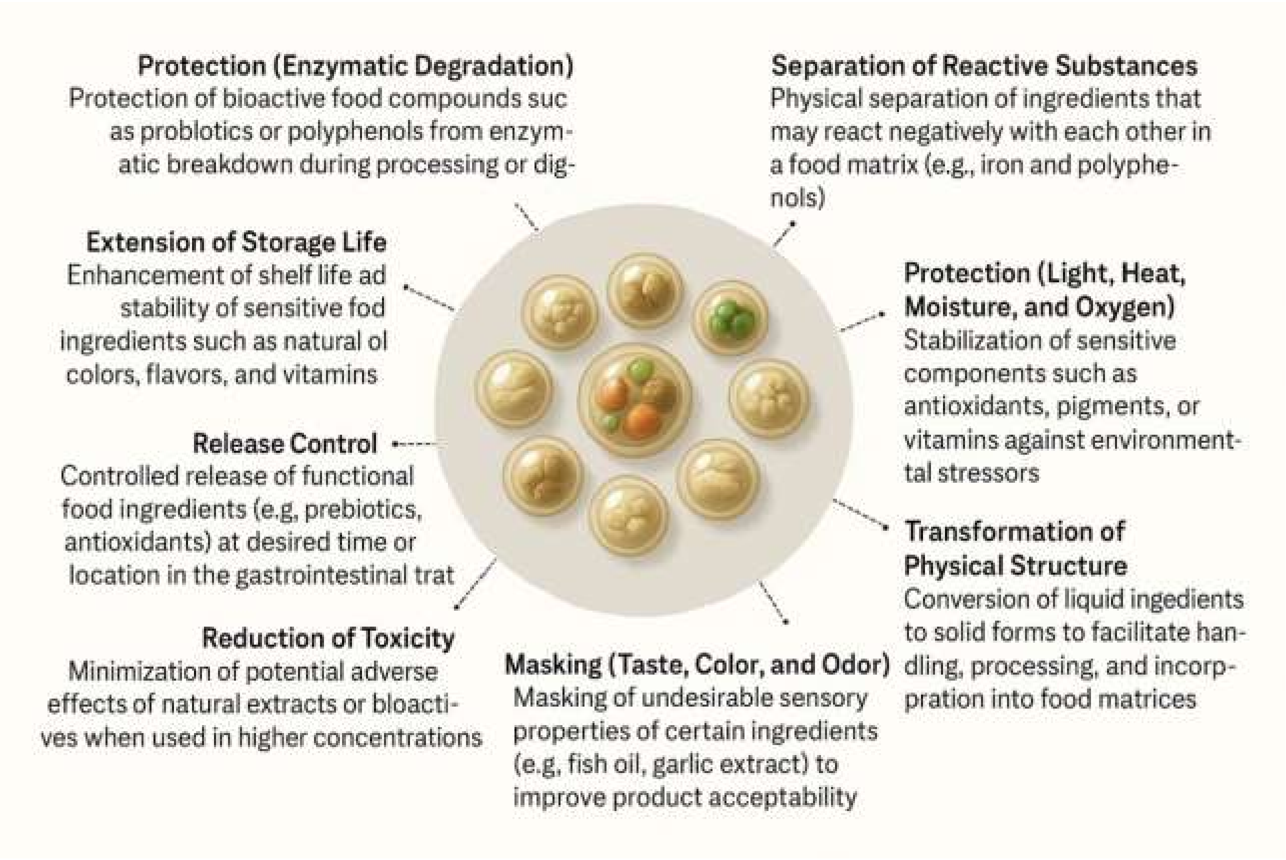
The interest in cyclodextrin complex formation continues to grow due to its technological advantages. These complexes provide more stable structures and help maintain the quality of the products, a significant benefit for both the food and pharmaceutical industries (Szente and Szejtli, 2004). Moreover, cyclodextrin complexes in powder form allow for precise dose adjustments, enhancing their practical application. The reduction in packaging and storage costs further contributes to economic savings in production processes

(Avcı and Dönmez, 2010). The wide-ranging industrial applications of cyclodextrins are expanding rapidly due to their versatility.

However, cyclodextrins also have some limitations. Specifically, limited molecular interactions with certain bioactive compounds may prevent the desired effects from being fully realized. Additionally, the production costs of high-purity cyclodextrins can be high. In conclusion, while cyclodextrins offer substantial benefits in industrial applications, their potential drawbacks should be considered. Ongoing research and innovations in this field may enable cyclodextrins to have even broader applications, facilitating the development of more effective solutions.

3. Protection and Control Mechanisms Provided by Encapsulation

Encapsulation technology provides notable benefits, particularly by safeguarding vitamins, antioxidants, and other bioactive compounds against environmental influences. These substances are extremely vulnerable to degrading elements like light, heat, oxygen, and moisture. Through the encapsulation process, these compounds are enveloped in a protective outer coating, shielding them from the harmful impacts of environmental factors. Thus, the bioavailability of vitamins and antioxidants is increased, and they remain stable in food products for a long time (Figure 3). For instance, encapsulating light- and oxygen-sensitive compounds, such as vitamin C, helps protect these substances from oxidation during storage, preserving their effectiveness and stability. (Fathi et al. 2014). Similarly, antioxidants are also encapsulated, contributing to both the preservation of sensory quality and the continuity of nutritional properties (McClements 2014). This method is used in functional food products both to improve product quality and to provide consumers with healthy ingredients in the long term.



Protection (Enzymatic Degradation)
Protection of bioactive food compounds suc as problotics or polyphenols from enzymatic breakdown during processing or dig-

Extension of Storage Life
Enhancement of shelf life ad stability of sensitive fod ingredients such as natural ol colors, flavors, and vitamins

Release Control
Controlled release of functional food ingredients (e.g, prebiotics, antioxidants) at desired time or location in the gastrointestinal trat

Reduction of Toxicity
Minimization of potential adverse effects of natural extracts or bloactives when used in higher concentrations

Masking (Taste, Color, and Odor)
Masking of undesirable sensory properties of certain ingredients (e.g, fish oil, garlic extract) to improve product acceptability

Separation of Reactive Substances
Physical separation of ingredients that may react negatively with each other in a food matrix (e.g., iron and polyphenols)

Protection (Light, Heat, Moisture, and Oxygen)
Stabilization of sensitive components such as antioxidants, pigments, or vitamins against environmenttal stressors

Transformation of Physical Structure
Conversion of liquid ingedients to solid forms to facilitate handling, processing, and incorpration into food matrices

Figure 3. Protective and controlled effects of encapsulation (Estevinho, 2024)

4. Nanoencapsulation

Nanoencapsulation is a technology used to protect active ingredients (vitamins, antioxidants, enzymes, etc.) from external environmental conditions and increase their bioavailability by placing them in nanoscopic capsules (Figure 4). This technology is realized through nanospheres and nanocapsules. Nanospheres are typically solid polymers containing active ingredients embedded in the polymer matrix, while nanocapsules are a shell with an internal cavity loaded with the component of interest (Orive et al. 2009; de Vos et al. 2009). The capsules possess dimensions within the nanometre range (typically 1-1000 nm), facilitating efficient transport and controlled release of active compounds to designated targets. Within the food industry, nanoencapsulation serves as a crucial technique for preserving the stability of bioactive components and for enhancing the production of functional foods. (Fathi et al. 2014).

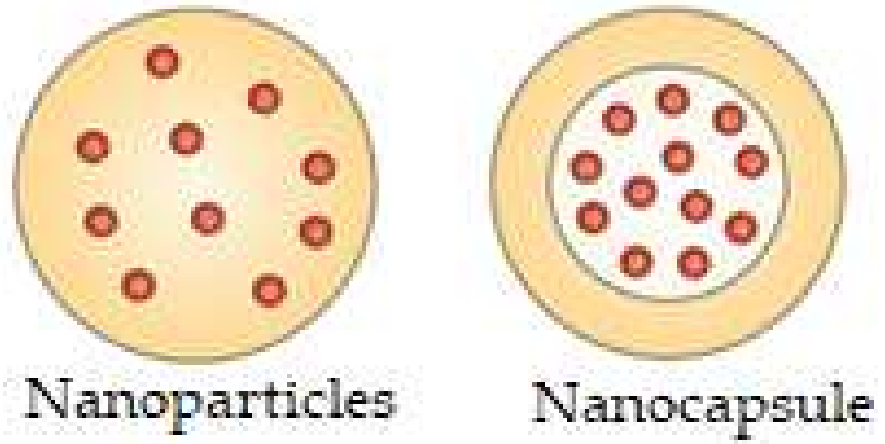


Figure 4. Nanospheres and Nanocapsules (Orive et al. 2009).

Nanoencapsulation was first reported in the early 1980s in a study on 'encapsulation of drugs and pharmaceuticals in nanoscale systems' (Couvreur et al. 1995). This technology offers a variety of structural forms while ensuring the preservation and efficient delivery of bioactive components.

Nanoencapsulation not only ensures the preservation of biologically active ingredients in the food industry, but also improves product quality by increasing the stability of nutrients. Nanoencapsulation is applied in different food formulations to increase the nutritional value of foods and improve product quality (Kawashima 2001; Adeyeye and Fayemi 2019).

4.1 Nanoencapsulation: Innovative Approaches for the Preservation of Bioactive Components

As seen in the diagram, nanoencapsulation protects bioactive components from external factors and increases the activity of the core material. This method has the potential to improve product quality by increasing the stability of nutrients (Figure 4). In particular, applications such as obtaining transparent emulsions and facilitating the dissolution of essential oils with low solubility increase the importance of nanoencapsulation in the food industry.

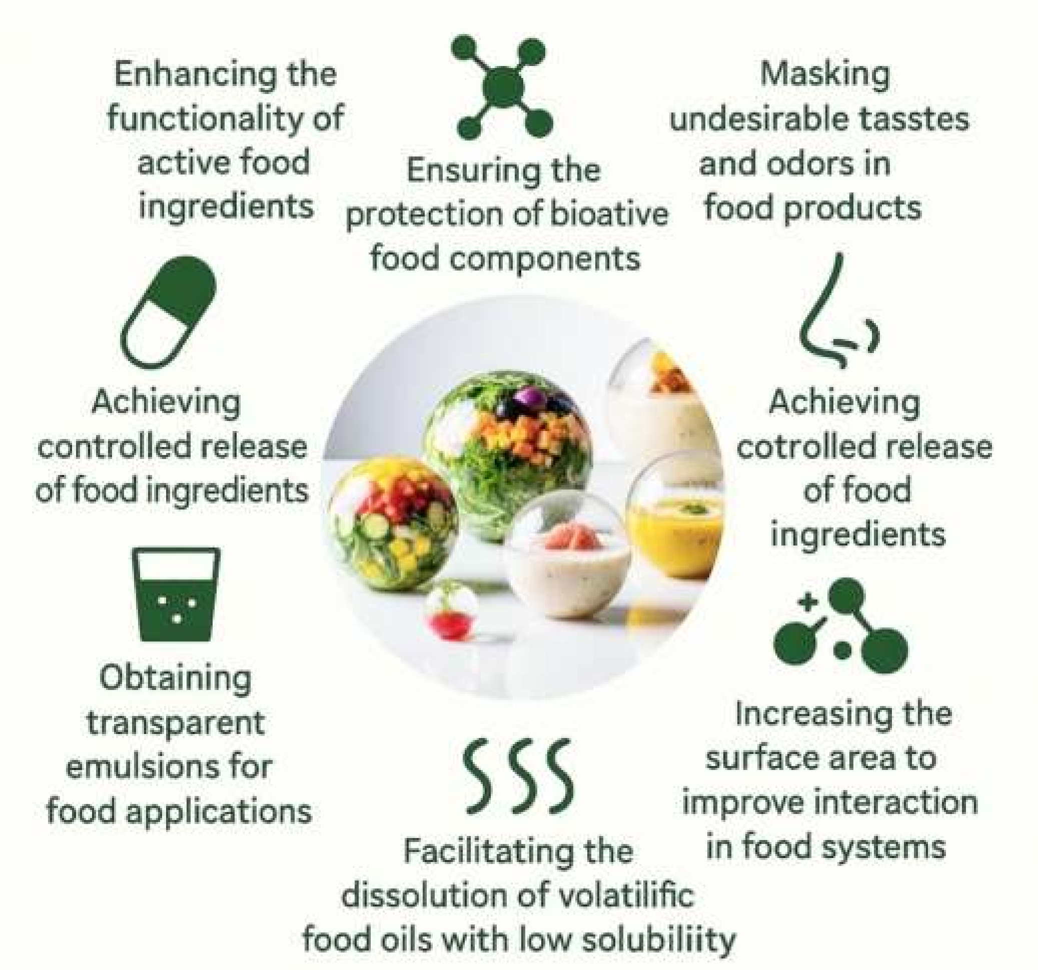


Figure 4. Importance of nanoencapsulation (Fathi et al. 2014)

Nowadays, nanoencapsulation is increasingly being used to protect active ingredients and improve functional properties in a wide range of products (Fathi et al. 2014). This technology is employed in a range of products, including dairy products, beverages, convenience foods, and functional snacks, to enhance the stability of bioactive ingredients and prolong shelf life. (McClements 2014). Active ingredients such as vitamins, minerals, probiotics and antioxidants are protected against environmental factors and controlled release is achieved (Donsì et al. 2011).

In addition, nanoencapsulation can increase the water retention capacity of ingredients added to foods, improve their sensory quality and increase their nutritional value (Donsì and Ferrari 2016). These advantages of nanoencapsulation enable products to become both nutritious and functional. For example, while the sensory properties of beverages containing nanoencapsulated antioxidants and vitamins are maintained, the bioavailability of bioactive components is also increased (Zhang et al. 2015). This technology can also be used as a fat replacer and stabiliser, thus playing an important role in the production of low-calorie and healthy food (McClements 2014).

The characteristics of nanocapsules are significantly influenced by their size, the materials comprising them, and the dimensions of the core particles. Due to their minute size, nanocapsules provide an extensive surface area, allowing them to function efficiently across diverse applications. Nanoscale particles are capable of displaying intricate structures, incorporating both an inner core and an external coating. These nanocapsules may either possess a microporous structure or be described as systems housing nanoscale core compounds, supported by an outer polymeric layer that encapsulates the core. (Quintanilla-Carvajal et al. 2010).

These structures have highly controllable properties and are coated with polymeric or lipid-based outer layers used to protect the core components from environmental conditions. The core part contains bioactive components in liquid or solid phase and the outer layer acts to protect these components against mechanical, chemical or biological degradation. As shown in Figure 5, nanocapsules are not limited to a single structure type but can exist in various forms, including core-shell, microporous structures, or a combination of these features (Quintanilla-Carvajal et al., 2010). The advantages of these diverse structural forms lie in their ability to provide tailored release mechanisms, enhanced stability, and improved bioavailability of encapsulated compounds. For instance, core-shell structures can protect sensitive active ingredients from degradation while allowing for controlled release, whereas microporous structures can facilitate the rapid release of smaller molecules, making them highly suitable for specific applications. Moreover, hybrid structures that combine both core-shell and microporous features can offer synergistic benefits, such as combining stability with a fast or sustained release profile, depending on the requirements of the particular application.

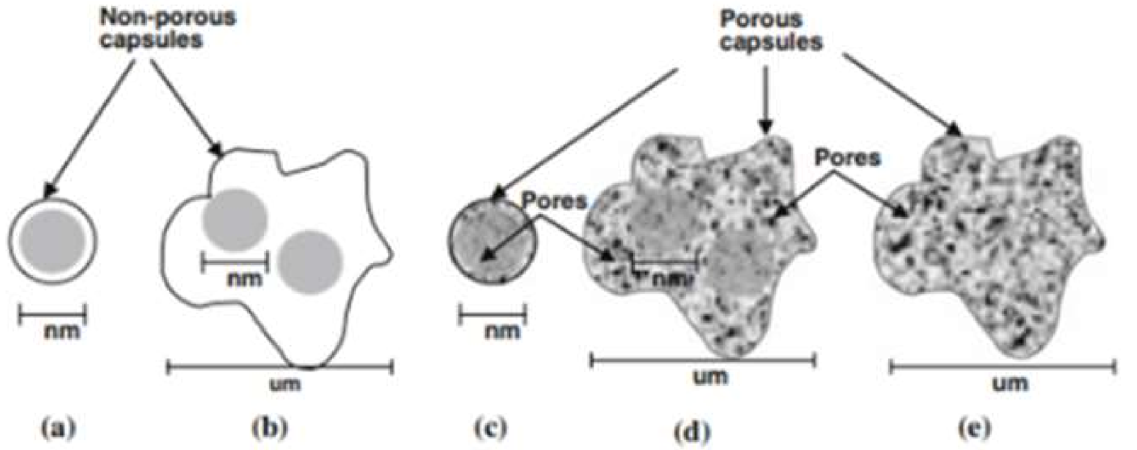


Figure 5. Proposal of different nanostructure patterns in capsules. a. Non-porous Nanocapsule (containing a nano-sized core): It has a nano-sized core and its outer layer is non-porous. b. Non-porous Microcapsule (containing a nano-sized core): Contains a nano-sized core, but the outer structure of the capsule is micro-sized and non-porous. c. Porous Nanocapsule (containing a nano-sized core): It has a nano-sized core and its outer layer is porous. d. Nanoporous Microcapsule (containing a nano-sized core): Contains a nano-sized core and the outer layers are nanoporous. e. Nanoporous Microcapsule: A microcapsule that does not contain a nano-sized core, but has nanopores in its outer structure (Quintanilla-Carvajal et al. 2010).

The structural variations of nanocapsules and microcapsules offer distinct advantages in the encapsulation and controlled release of active ingredients, providing versatility in a range of applications. Non-porous nanocapsules, characterized by a nano-sized core surrounded by a non-porous shell, offer superior protection for sensitive compounds. This structure ensures the stability of the encapsulated material by minimizing degradation due to environmental factors such as light, oxygen, or moisture. Additionally, the non-porous nature of the capsule facilitates controlled release over an extended period, making it particularly advantageous for applications requiring sustained or slow-release delivery (Sharma et al., 2021).

In contrast, non-porous microcapsules, which contain a nano-sized core but are encapsulated in a micro-sized non-porous outer layer, provide a balance between stability and controlled release. The micro-sized shell protects the core from external environmental stresses, while the nano-sized core enhances the encapsulation efficiency and ensures the effective release of the active ingredient.

Porous nanocapsules, with a nano-sized core and a porous outer shell, enable the rapid and targeted release of encapsulated compounds. The porosity of the outer layer can be finely tuned to control the release rate, which is particularly beneficial in systems that demand fast bioavailability. Such structures are suited for applications where quick release of active compounds is critical, such as in drug delivery systems where immediate therapeutic effects are desired.

Nanoporous microcapsules, which combine a micro-sized shell with nanoporous characteristics, offer selective permeability, allowing specific molecules to pass through the nanopores while restricting others. This selective permeability is highly advantageous in targeted delivery systems, particularly within the pharmaceutical and food industries, where precise control over the release of active compounds is essential for both efficacy and safety.

These diverse structural configurations enable the fine-tuning of release profiles, offering significant advantages in terms of bioavailability, stability, and protection of sensitive compounds. By adjusting the porosity and size of the core and shell, these nanostructures can be optimized for a wide range of applications, from controlled drug release to functional food design (Elkalla et al., 2023).

Characterizing nanocapsules involves a comprehensive assessment of key physical properties, including their shape, size, surface morphology, and texture. This characterization is achieved through advanced techniques such as dynamic light scattering (DLS), electron microscopy (SEM/TEM), atomic force microscopy (AFM), and X-ray diffraction (XRD). Through these methods, attributes like homogeneity, surface charge, distribution, and physical stability of nanocapsules can be thoroughly examined (Awuchi et al., 2022). These characteristics are essential for evaluating the performance and stability of nanocapsules, playing a vital role in enhancing the bioavailability and controlled release of bioactive compounds, particularly within the food sector.

4.1.1 Advantages of Nanoencapsulation

Nanoencapsulation is an innovative technology widely used in the food, pharmaceutical and cosmetic industries. This method offers many important advantages by protecting active ingredients against environmental influences and providing controlled release at the desired site (Figure 6) (Couvreur et al. 2013). It also helps bioactive ingredients to be absorbed more effectively by the body, thus increasing their bioavailability (Torchilin 2006). When applied in food products, it increases the stability of the ingredients and prolongs shelf life by masking undesirable tastes and odours (Li et al. 2011). Thus, nanoencapsulation plays an important role in increasing the functionality and consumer acceptance of food products.

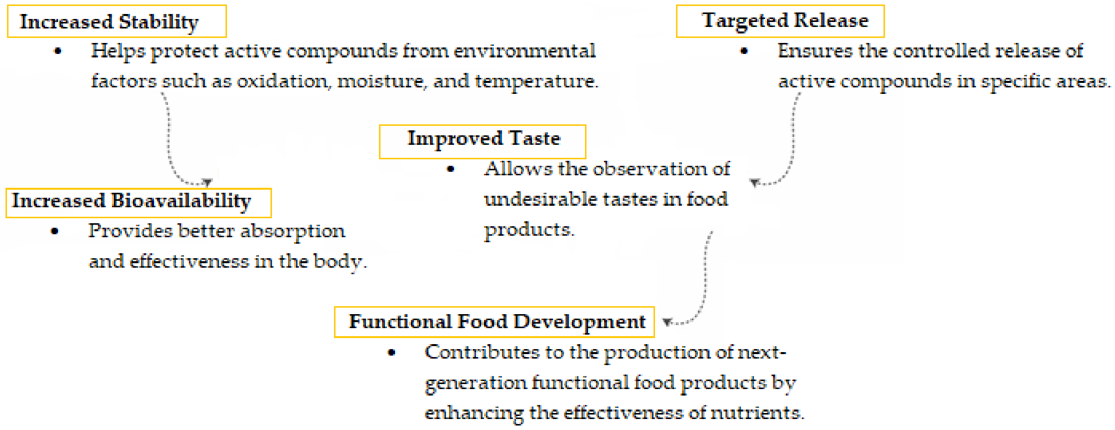


Figure 6. Advantages of nanoencapsulation (Quintanilla-Carvajal 2010; Fathi et al. 2014).

4.1.2 Disadvantages of Nanoencapsulation

Nanoencapsulation technology is a widely used method in the food and pharmaceutical industries and offers many advantages. However, there are some disadvantages and limitations encountered in the application of this technology. The disadvantages of nanoencapsulation may vary depending on the material used, process conditions and application area.

The first major disadvantage is the high cost. Nanoencapsulation processes can lead to increased costs, especially in large-scale production, due to complex equipment and high energy requirements. This is an important factor that may limit the widespread use of the technology. Especially in cases where advanced nanoencapsulation techniques are applied, production costs increase further (Neves et al. 2016).

Secondly, potential toxicity and biocompatibility issues are among the disadvantages of nanoencapsulation. It is of great importance that the nano-substances to be used in the food and pharmaceutical sectors are non-toxic. However, the lack of sufficient data on some nano-substances leads to uncertainty about the effects of these substances on human health in the long term. This situation poses a risk especially for consumer safety (Ravichandran 2010).

In addition, stability problems are another important disadvantage encountered in nanoencapsulation applications. Nanoencapsulated active ingredients may deteriorate over time due to external factors (such as heat, humidity, light). This may lead to the release of active ingredients in the capsule and decrease the efficacy, especially in products requiring long-term storage (Shah et al. 2014). Therefore, such stability problems are considered as an important factor limiting the use of nanoencapsulation technology.

Finally, low encapsulation efficiency is another disadvantage. Some nanoencapsulation techniques may not provide the desired levels of encapsulation efficiency. This may cause problems such as insufficient protection of the active ingredients or failure to provide controlled release. Therefore, low efficiency is seen as an important factor limiting the effectiveness of nanoencapsulation (Mozafari 2006).

4.2 Application Areas of Cyclodextrin-Based Nanoencapsulation

Cyclodextrin-based nanoencapsulation has emerged as a promising approach in the food industry due to its ability to enhance the solubility, stability, and bioavailability of various functional ingredients. Cyclodextrins, as cyclic oligosaccharides with hydrophobic inner cavities and hydrophilic outer surfaces, form inclusion complexes with a wide range of bioactive compounds, thus protecting them from environmental degradation factors such as light, oxygen, and pH fluctuations.

In food applications, cyclodextrin nanoencapsulation is particularly effective in stabilizing sensitive compounds such as essential oils, vitamins, antioxidants, and flavor compounds. For instance, the encapsulation of volatile flavors and aroma compounds using β-cyclodextrin has been shown to significantly reduce evaporation and oxidative degradation, ensuring sensory quality during processing and storage. Similarly, the inclusion of antimicrobial agents like thymol or carvacrol within cyclodextrin nanostructures enhances their controlled release, extending microbial protection throughout the shelf life of food products.

Moreover, cyclodextrins offer advantages in masking undesirable tastes or odors of certain bioactives, thereby improving consumer acceptability. Their ability to provide controlled release mechanisms also supports the development of functional foods with prolonged efficacy and targeted delivery.

Overall, cyclodextrin-based nanoencapsulation presents a versatile and efficient platform for the protection, stabilization, and functional enhancement of bioactive compounds in food systems (Awuchi et al. 2022).

4.2.1 Antimicrobial Applications

Cyclodextrin-based nanoencapsulation has shown considerable potential in enhancing the antimicrobial effectiveness of natural bioactive compounds by improving their solubility, stability, and controlled release. Cyclodextrins form inclusion complexes with hydrophobic antimicrobial agents such as essential oils (e.g., thymol, carvacrol) and phenolic compounds, protecting them from volatilization and degradation while enabling sustained antimicrobial activity. For instance, the encapsulation of thymol or eugenol in β-cyclodextrin has been reported to extend their antimicrobial efficacy in perishable foods by enabling gradual release throughout storage (Feng et al. 2016). This approach is particularly valuable in foods susceptible to microbial spoilage, such as dairy products, meat, and fresh produce, where maintaining microbial safety over extended periods is critical (Salgado et al. 2015). Cyclodextrin inclusion thus offers a natural, efficient strategy for prolonging shelf life while reducing reliance on synthetic preservatives.

4.2.2 Flavour and Aroma Control

Cyclodextrin-based nanoencapsulation plays a key role in preserving the stability and sensory quality of volatile flavour compounds in food systems. Due to their unique molecular structure, cyclodextrins can form inclusion complexes with aroma compounds, thereby protecting them from oxidation, volatilization, and interaction with other food components. This encapsulation not only prevents premature loss of flavour but also enables controlled release during storage or consumption, helping to maintain a consistent and desirable flavour profile over time. Studies have demonstrated that β-cyclodextrin complexes with compounds such as limonene, vanillin, or menthol enhance their stability and reduce flavour degradation during processing and storage (Szente & Szejtli, 2004). Therefore, cyclodextrin-based encapsulation offers a promising approach to improving flavour retention and shelf life in a wide range of food products.

4.2.3 Protection Of Functional Components

While probiotics are too large to be encapsulated at the nanoscale due to their cellular dimensions, cyclodextrin-based encapsulation can be effectively applied to protect smaller functional compounds such as prebiotics, enzymes, or bioactive metabolites that support probiotic function. For the probiotics themselves, microencapsulation techniques are widely used to enhance their survival in food matrices and gastrointestinal environments, especially in fermented dairy products such as yogurt (Agarwal et al. 2018; Huq et al. 2019). Although cyclodextrins are not used to encapsulate whole probiotic cells, they may contribute indirectly by stabilizing the food matrix or encapsulating synergistic molecules that promote probiotic viability. Therefore, while nanoencapsulation cannot be applied directly to probiotics, it still plays a complementary role in improving the functionality of probiotic-containing foods through targeted delivery of small supportive molecules.

5. Conclusions

Cyclodextrin-based nanoencapsulation offers targeted solutions for enhancing the stability, bioavailability, and sensory quality of sensitive food ingredients such as antioxidants, vitamins, and volatile flavour compounds. This review highlights that the unique amphiphilic structure of cyclodextrins enables the formation of stable inclusion complexes that effectively protect functional compounds against environmental degradation, particularly oxidation and heat.

In the food industry, this technology holds great promise for improving the shelf life and efficacy of bioactive ingredients in dairy products, beverages, and functional food formulations. Specifically, the encapsulation of flavour molecules and antioxidant compounds within cyclodextrin cavities can help maintain product freshness and nutritional quality throughout processing and storage. Additionally, cyclodextrins may serve as delivery carriers for synergistic molecules such as prebiotics or antimicrobial agents, contributing to the stabilization of probiotic systems.

Despite current limitations, including production cost and scalability, the development of more efficient encapsulation techniques and modified cyclodextrin derivatives could expand the commercial feasibility of this technology. Future studies should focus on optimizing encapsulation efficiency, evaluating release kinetics in complex food matrices, and exploring regulatory aspects for broader application. Cyclodextrin-based nanoencapsulation, therefore, represents a targeted and practical strategy for advancing functional food innovation and addressing consumer demands for quality, health-promoting products.

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