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Nanoencapsulation in food industry: technology, applications and challenges; a review

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ABSTRACT

Nanocapsulation, as an innovative technology in the food industry, has great potential to improve the quality, safety, and stability of food products. This technology prevents the degradation of bioactive compounds such as vitamins, antioxidants, and antimicrobial agents by encapsulating them at the nanoscale, protecting them from environmental factors like light, temperature, and oxygen, while facilitating their controlled and targeted release. This feature enhances the shelf life and efficacy of active compounds in food products. Additionally, nanocapsules can improve consumer experiences through the gradual release of nutrients and flavorings. However, the use of nanocapsulation in the food industry faces challenges, including high production costs, safety concerns related to nanoparticles, and their long-term effects on human health. This article reviews various nanocapsulation technologies, including physical, chemical, and biological methods, and their applications in enhancing the stability and quality of food products. Furthermore, the existing challenges in this technology, including environmental issues and economic limitations, will be evaluated. Despite the numerous advantages, further research is needed to assess the safety and long-term impacts of nanoparticles so that the safe and effective use of this technology can be expanded in the food and pharmaceutical industries.

1.Introduction

In recent years, significant transformations in lifestyle and dietary patterns, coupled with increasing public awareness of the role of nutrition in disease prevention, have led to a growing demand for functional foods enriched with bioactive compounds. Substances such as vitamins, antioxidants, omega-3 fatty acids, polyphenols, flavonoids, bioactive peptides, probiotics, and natural antimicrobial agents have garnered considerable attention in scientific and industrial research due to their potential roles in preventing and managing non-communicable diseases, including diabetes, cardiovascular diseases, cancer, and inflammation [1–5].

However, the effective utilization of these compounds in food systems is challenged by their low stability under environmental conditions (light, oxygen, heat, pH), poor solubility in aqueous media, susceptibility to oxidation, and limited bioavailability in the gastrointestinal tract [6–7]. Consequently, the development of strategies to enhance their stability, control their release, and improve their bioavailability has become imperative in the advancement of modern food products.

In this context, nanotechnology—and particularly nanoencapsulation—has emerged as a novel and multifunctional technology offering new opportunities for improving the quality, safety, and stability of food ingredients [8]. Nanoencapsulation involves the entrapment of bioactive compounds within structures smaller than 1000 nanometers, typically consisting of an active core (functional compound) and a protective shell (such as biocompatible polymers, lipids, or proteins) [9]. These structures can safeguard the active compounds from environmental degradation, enable targeted or controlled release within the gastrointestinal system, and ultimately enhance their bioavailability [8].

Among the key advantages of nanoencapsulation are the gradual release of bioactive ingredients such as nutrients, flavorings, and preservatives. This feature not only improves their efficacy and stability in the final product but also enhances the sensory experience for consumers [10]. Additionally, nanocapsules play a critical role in preventing undesirable reactions such as oxidation, preserving delicate flavors and aromas, and extending the shelf life of food products [11].

Despite these benefits, the application of nanocapsules is also accompanied by certain challenges. Technical complexities in formulation design, high production costs, limited scalability in industrial processes, the absence of clear regulatory frameworks, and safety and toxicity concerns regarding nanoparticles are among the main obstacles to the widespread commercialization of this technology [12–13]. Therefore, comprehensive evaluation of the technological, functional, safety, and environmental aspects of nanoencapsulation is essential for its sustainable development within the food industry.

2. Technologies and Methods of Nanoencapsulation

2.1 Nanoencapsulation Technology

Nanocapsules are small, nanoscale vesicular systems in which bioactive compounds are enclosed within a protective shell. These nanocapsules have a core–shell structure, where the core contains the active substance and the shell is made of materials such as biodegradable polymers, lipids, or proteins [14].

Encapsulation helps protect sensitive compounds from environmental factors and facilitates the targeted and controlled release of active substances [15].

The main idea behind nanocapsule technology is to enclose bioactive compounds in a nanoscale carrier to improve their stability, bioavailability, and effectiveness.

The functions of the protective shell surrounding the core include protection, controlled release, and targeted delivery.

The shell materials protect the encapsulated compounds against degradation caused by

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environmental factors such as light, heat, oxygen, or pH changes [16].

Nanocapsules are designed to provide controlled or sustained release of active substances. The release rate can be adjusted based on the shell composition and environmental conditions, which is very important in food applications to maintain freshness and potency over time [17].

In some cases, nanocapsules are engineered to release their contents at a specific site or under specific conditions, thereby improving the efficacy of bioactive compounds and increasing their absorption in the human body [18].

2.2 Physical Methods

Various methods, including physical, chemical, and biological techniques, are used to produce nanocapsules, each with its own advantages and disadvantages.

Physical methods include high-pressure homogenization, spray drying, and ultrasonic techniques.

In the high-pressure homogenization method, a mixture of bioactive compounds and polymer is homogenized under high-pressure conditions.

This process breaks large droplets into nanoparticles and helps produce nanocapsules with uniform size.

This method is particularly effective for encapsulating hydrophobic compounds and can enhance the stability of nanocapsules [19].

Spray drying is also one of the most common and cost-effective methods for producing nanocapsules.

In this process, the liquid mixture containing the active compound is transformed into a spray and sprayed into a heated chamber in the form of fine droplets.

With the rapid evaporation of the solvent, nanocapsules are formed.

This method has the capability for large-scale production of nanocapsules and can effectively encapsulate bioactive compounds [20].

In ultrasonic methods, ultrasonic waves are used to produce nanocapsules.

Ultrasonic waves can help generate acoustic shocks that lead to better mixing and homogenization of the materials.

This method is particularly suitable for encapsulating heat-sensitive substances and can improve the solubility and bioavailability of compounds [21].

These methods are widely used due to their ability to produce nanocapsules with specific size and characteristics and their potential for optimization in various food industry applications.

2.3 Chemical Methods

Chemical methods for producing nanocapsules are of special importance due to their precise control over nanocapsule properties and selection of appropriate raw materials.

Chemical methods include in situ polymerization and the formation of nanoparticles using biocompatible materials.

The in situ polymerization method involves carrying out polymerization inside an emulsion or solution, leading to the formation of nanocapsules.

In this process, monomers are converted into polymers under specific conditions (such as temperature and time), which form the core of the nanocapsules.

Due to their special structure, nanocapsules have the capability for controlled release of bioactive compounds and can effectively enhance the stability of food materials [22].

Also, the formation of nanoparticles using biodegradable materials is done; in this method, natural and biocompatible materials (such as natural polymers) are used to produce nanoparticles.

These nanoparticles are usually suitable for food and pharmaceutical applications due to their biocompatibility and lack of toxicity.

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This process can include various methods such as precipitation or extraction [23].

These methods not only affect the stability of the compounds but can also help increase the efficacy and bioavailability of food ingredients.

2.4 Biological Methods

Biological methods for producing nanocapsules have gained considerable attention in recent years due to the use of natural and sustainable materials, which include the extraction and utilization of natural sources to create biocompatible nanocapsules.

Biological methods include the use of natural polymers and microbial techniques.

In the method using natural polymers, natural polymers such as chitosan, gelatin, and pectin are used to produce nanocapsules.

Due to their biocompatibility and water solubility properties, these polymers are suitable options for encapsulating food and pharmaceutical compounds.

These nanocapsules are commonly used in the food and pharmaceutical industries due to their specific features such as controlled release and high stability [24].

In addition, in microbial techniques, microorganisms (such as bacteria and yeasts) are used to produce nanocapsules.

Microorganisms can act as producers of biopolymers, which are then used to encapsulate bioactive compounds.

This method can help reduce production costs and increase the stability of nanocapsules [25].

Biological methods for producing nanocapsules using natural polymers and microbial techniques have become increasingly popular in the food and pharmaceutical industries due to their biocompatibility and sustainability.

These methods not only help reduce negative environmental impacts but can also improve the quality and efficacy of final products.

2.5 Materials Used in Nanoencapsulation

In nanoencapsulation processes, various materials are primarily used to create nanostructures, including biodegradable polymers and lipids.

Biodegradable polymers are widely used in nanoencapsulation due to their biological degradability and environmental compatibility.

Polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) can act as encapsulation matrices that protect bioactive compounds from environmental degradation.

These polymers can facilitate controlled release of nutrients and help maintain the quality and stability of food products [26].

Lipids are also used as encapsulating materials in nanoencapsulation.

They can act as matrices for encapsulating hydrophobic compounds such as vitamins and antioxidants.

Due to their specific characteristics, such as the ability to form micelles and bilayers, these materials can contribute to the stability of nanocapsules.

Additionally, natural substances like starch and proteins can also be used as biocompatible carriers in the nanoencapsulation process [27].

These materials not only help improve the quality and stability of food products but are also more environmentally friendly.

3. Applications and Benefits of Nanocapsules in the Food Industry

Nanocapsulation plays a significant role in the food industry by protecting and enhancing the stability of bioactive compounds and contributes in various ways to preserving the nutritional value of food products.

3.1 Enhancing Stability and Protecting Sensitive Compounds

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Many bioactive compounds, such as vitamins A, D, E, and K, and antioxidants like polyphenols and flavonoids, are vulnerable to degradation by environmental factors.

Encapsulating these compounds in protective particles such as liposomes or nanogels enhances their chemical stability and helps reduce unwanted reactions [28–29].

3.2 Controlled and Targeted Release

Nanotechnology can enable the gradual release of bioactive compounds at specific sites within the gastrointestinal tract.

This feature is particularly important in improving the effectiveness of dietary supplements and nutraceutical products, as it allows nutrients to be absorbed at the right time and location for better efficacy [30].

Additionally, this technology aids in preventing the growth of pathogens and reducing food spoilage through controlled release of antimicrobial agents.

For example, nanocapsules can be used to control the release of antimicrobial substances such as essential oils and metallic nanoparticles so that these agents are gradually released and maintain their protective effects over time [28–29].

Encapsulated antimicrobial compounds in nanoparticles ensure that these agents attack harmful microorganisms in a targeted and effective manner without altering the sensory or nutritional properties of the food product.

This feature is especially beneficial in fresh products, dairy, meat, and packaged foods to prevent contamination and extend shelf life [31].

For instance, converting St. John's Wort extract into nanocapsules enhances its antimicrobial effect through gradual release and can help extend the shelf life of cheese and other food products [32].

3.3 Improving Bioavailability

The bioavailability of active compounds, meaning the extent and rate at which they are absorbed in the body, is a major challenge in developing nutritious food products.

Nanocapsulation improves solubility and bioavailability of such compounds, thereby enhancing their absorption and efficacy.

For example, hydrophobic compounds like carotenoids and curcumin can be transformed into more absorbable forms through this technology [33].

3.4 Application in Dairy Products and Beverages

In dairy and beverage products, using nanocapsules to add active compounds such as probiotics is very useful, without causing undesirable changes in taste and texture.

This facilitates the production of nutrient-enriched beverages with extended shelf life.

According to a study by Emtiazo and colleagues, it was shown that milk enriched with nanocapsules had no significant difference compared to control milk, indicating that nanocarriers can be effectively used for milk fortification without negatively affecting its sensory properties [34].

3.5 Increasing Shelf Life and Food Safety

Nanoencapsulation, by using nanoparticles, enables the slow release of antimicrobial compounds at targeted sites.

This method helps maintain freshness and prevents food spoilage, offering longer-lasting antimicrobial effects [35].

Notable examples include the use of silver nanoparticles and nanocapsules containing essential oils such as thyme and rosemary, whose antibacterial properties are effectively applied in food packaging to prevent microbial growth. This technology helps ensure food safety even at low storage temperatures and increases product shelf life [36].

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Seyed Hajizadeh and colleagues demonstrated that using rosemary essential oil nanocapsules can effectively extend the shelf life of perishable fruits such as apricots [37].

Nevertheless, this technology still faces challenges such as the safety of nanoparticles and their environmental impact, which require further research to ensure the long-term safety of using nanocapsules.

3.6 Preservation and Enhancement of Flavor and Aroma

Nanocapsulation traps aromatic and flavor compounds within nanoscale structures, preventing their direct exposure to environmental factors and reducing the likelihood of degradation and oxidation.

Another advantage of this method is increasing the solubility of aromatic compounds in aqueous environments, leading to their gradual release over time and creating a more stable and pleasant flavor and aroma.

Some studies have shown that nanocapsules enhance the bioavailability and durability of aromatic compounds in food systems, offering consumers a more enjoyable product experience [38].

This technology is particularly useful for protecting natural and sensitive compounds like essential oils and herbal aromas that are otherwise rapidly degraded.

With nanocapsules, these compounds can be gradually and controllably released, thereby providing lasting aroma and flavor throughout consumption [39].

3.7 Enhancing Nutritional Properties

This technology can help deliver micronutrients, vitamins, minerals, and probiotic compounds more effectively and with higher stability.

Micronutrients and probiotics are typically sensitive to adverse environmental conditions such as temperature, pH, and light, and are easily degraded or lose their biological activity.

Nanocapsulation encloses these compounds in protective nanoparticle shells, preventing their degradation while increasing their bioavailability.

This innovative technology has led to the production of high-performance food supplements and offers a solution to combat micronutrient deficiencies and promote public health.

For example, encapsulating vitamin D in nanocapsules increases its absorption and stability in the body and positively affects bone health and the immune system [40].

Alizadeh and colleagues showed that zein hydrolysate-based nanocapsules can be successfully used as a nanocarrier system for fortifying orange juice with vitamin D3 [41].

3.8 Reducing the Need for Artificial Preservatives

Artificial preservatives are typically used to prevent spoilage and extend the shelf life of food, but their long-term consumption may have negative health effects.

The nanocapsulation industry offers a natural and effective solution to preserve food quality and safety, potentially reducing the need for artificial preservatives and eliminating their adverse effects [42].

According to a study by Yeganeh and Reyhanipour, astaxanthin-loaded nanocapsules coated with maltodextrin and sodium caseinate demonstrated high potential to replace part of sodium nitrite in sausage formulations and possibly other meat products [43].

4. Challenges and Limitations

4.1 Safety and Health Concerns

Nanoencapsulation and the use of nanoparticles in the food industry have gained much attention due to their many advantages in improving food

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quality, extending shelf life, and enhancing nutrient efficiency.

However, the use of nanoparticles in foods has also raised concerns about their safety and potential effects on human health.

Due to their nanoscale dimensions, nanoparticles can easily cross biological barriers and accumulate in different organs of the body, which may pose unexpected risks and adverse effects [44].

4.2 Potential Effects of Nanoparticles on Human Health

4.2.1 Accumulation and Toxicity of Nanoparticles

One of the main concerns regarding the use of nanoparticles in the food industry is their potential to accumulate in body tissues.

Because of their small size and large surface area, nanoparticles can pass through physiological barriers such as the skin, digestive tract, and even the blood-brain barrier.

Some studies have shown that nanoparticles may accumulate in various cells and tissues, causing inflammation, oxidative stress, and even DNA damage, which could lead to chronic diseases such as cancer [45].

4.2.2 Gastrointestinal Toxicity of Nanoparticles

Nanoparticles, being exposed to the digestive system, may interfere with nutrient absorption.

Some research suggests that nanoparticles can damage the gastrointestinal mucosa and negatively affect the immune system.

Additionally, direct contact of nanoparticles with intestinal cells may lead to allergic and inflammatory responses [46].

4.2.3 Cellular and Biological System Damage

Nanoparticles can easily interact at the cellular level and induce changes in cellular metabolism and the generation of free radicals.

This can lead to oxidative damage and inflammation, which over the long term may have harmful effects on human health.

Some nanoparticles, such as silica and silver nanoparticles, have been shown to damage cells and cause cell death [47].

4.2.4 Immune and Allergic Reactions

Contact with nanoparticles may trigger immune responses and cause allergies or hypersensitivity.

Due to their size and surface properties, nanoparticles may interact differently with the immune system compared to larger particles, potentially provoking allergic and inflammatory responses [48].

Despite the vast potential of nanoencapsulation in the food industry, further research is needed to more precisely assess their safety and potential effects on human health.

Such research must include detailed and long-term evaluations of nanoparticle toxicity, accumulation, and side effects in the human body to ensure this technology is safe for consumers.

4.3 Cost and Mass Production Limitations

Nanoencapsulation has attracted attention as an innovative technology with vast potential in the food, pharmaceutical, and chemical industries.

However, one of the major challenges in this field is the cost and scalability limitations.

Mass production of nanocapsules can face significant obstacles, requiring efficient and optimized solutions to enable widespread use of this technology across markets. One of the greatest challenges in nanocapsule production is the high cost of raw materials and manufacturing processes.

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The production of nanocapsules requires specific raw materials such as biodegradable polymers, lipids, and active compounds, which are often expensive.

In addition, many of the production processes, such as emulsification or precipitation, require specialized equipment and complex procedures, increasing overall production costs [49–50].

4.4 Environmental Impacts

Although the use of nanocapsules in various industries—especially food and pharmaceuticals—offers many benefits, concerns also exist regarding their environmental impact.

Because nanoparticles can disperse in the environment due to their microscopic size, it is essential to evaluate their effects on ecosystems and environmental health.

Moreover, using biodegradable materials for producing nanocapsules is being pursued to reduce the negative environmental effects of this technology [51].

4.4.1 Transport and Accumulation of Nanoparticles in the Environment

As the production and application of nanoparticles increase, their transport and accumulation in the environment have become important concerns in environmental research.

Nanoparticles may be absorbed by soil and water microorganisms and transferred through the food chain to higher organisms.

This can lead to bioaccumulation and biomagnification, which may have toxic effects on higher species such as fish, birds, and ultimately humans [52].

Due to their persistence and small size, nanoparticles can remain in the environment for long periods and disperse widely.

These properties may cause unpredictable changes in nanoparticle behavior and chemical reactions in the environment, leading to unknown biological and ecosystem effects [53].

4.4.2 Nanoparticle Biotoxicity

Biotoxicity of nanoparticles is a key topic in studies related to the use of nanocapsules in the food industry.

Research has shown that some nanoparticles can have negative effects on cells and body tissues, with the potential to cause toxicity and biological damage under certain conditions.

For instance, metal nanoparticles such as silver and titanium dioxide, once inside cells, can increase the likelihood of reactive oxygen species (ROS) production and cause oxidative stress, leading to cellular damage [54].

Some studies have also shown that certain nanoparticles may cross important biological barriers such as the blood-brain barrier and exert potential effects on the nervous system.

Moreover, in the digestive system, nanoparticles may impact the gut microbiome and disrupt its natural balance, potentially leading to gastrointestinal-related diseases [55].

However, the chemical and physical properties of nanoparticles—including size, shape, and surface composition—affect their toxicity level, showing that the degree and nature of toxic effects can vary by nanoparticle type.

Therefore, detailed evaluation of the biotoxicity of each type of nanoparticle is essential before their use in the food industry [56].

4.4.3 Effects on Soil and Water Microorganisms

Nanoparticles may affect microbial activity in soil and water.

These impacts can lead to changes in biological processes such as organic matter decomposition and the nitrogen and carbon cycles.

Particularly, some nanoparticles may directly harm microorganisms or alter the microbial community structure [57].

Although nanocapsules offer significant advantages for the food and pharmaceutical industries, their environmental and biotoxic impacts remain serious concerns.

Due to their persistence and small size, nanoparticles can remain in the environment, enter the food chain, and accumulate at various levels, potentially causing toxic effects to ecosystems and organisms.

Negative effects on soil and water microorganisms and potential disruptions in biological processes require careful management and further research.

Ultimately, using biodegradable nanocapsules and conducting comprehensive evaluations are essential for reducing the environmental consequences of this technology.

5. Conclusion

Nanoencapsulation technology, as one of the most innovative approaches in the food industry, plays an unparalleled role in improving the quality, shelf life, and safety of food products.

By utilizing nanoscale structures, this technology enables the encapsulation of bioactive compounds, protects them against environmental factors, and allows for controlled release at specific times and locations.

The findings presented in this article show that nanocapsules can offer multiple advantages such as enhanced bioavailability, improved nutritional properties, protection of flavor and aroma, and reduced reliance on artificial preservatives.

However, challenges such as high production costs, scalability complexity, and concerns related to the safety of nanoparticles on human health and the environment remain major obstacles to the widespread development and acceptance of this technology.

To overcome these challenges, it is essential to conduct more comprehensive studies on nanoparticle toxicity, improve the materials used for nanoencapsulation, and develop sustainable and cost-effective methods.

Overall, nanoencapsulation holds significant potential to shift the food industry toward producing higher-quality and more sustainable products, but achieving this goal requires interdisciplinary collaboration, investment in research and development, and the establishment of safety policies and strict standards.

Attaining these objectives can pave the way for the full utilization of the capabilities of this novel technology.

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مقاله علمی_پژوهشی

مروری بر نانوکپسول سازی در صنایع غذایی: فناوری، کاربردها و چالش‌ها

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چکیده

نانوکپسول‌سازی به عنوان یک فناوری نوین در صنایع غذایی، توانایی بالایی در بهبود کیفیت، ایمنی و پایداری محصولات غذایی دارد. این فناوری با محصور کردن ترکیبات زیست‌فعال مانند ویتامین‌ها، آنتی‌اکسیدان‌ها و مواد ضد میکروبی در مقیاس نانو، از تخریب آن‌ها در برابر عوامل محیطی مانند نور، دما و اکسیژن جلوگیری می‌کند و به آزادسازی کنترل‌شده و هدفمند آن‌ها کمک می‌کند. این ویژگی باعث افزایش ماندگاری و اثرگذاری ترکیبات فعال در محصولات غذایی می‌شود. همچنین، نانوکپسول‌ها می‌توانند بهبود تجربه مصرف‌کننده را از طریق آزادسازی تدریجی مواد مغذی و طعم‌دهنده‌ها فراهم کنند. با این حال، استفاده از نانوکپسول‌سازی در صنایع غذایی با چالش‌هایی روبه‌رو است، از جمله هزینه‌های تولید بالا، نگرانی‌های ایمنی مرتبط با نانوذرات و اثرات بلندمدت آن‌ها بر سلامت انسان. مقاله حاضر به بررسی فناوری‌های مختلف نانوکپسول‌سازی، شامل روش‌های فیزیکی، شیمیایی و زیستی، و کاربردهای آن در بهبود پایداری و کیفیت محصولات غذایی می‌پردازد. علاوه بر این، چالش‌های موجود در این فناوری، از جمله مشکلات زیست‌محیطی و محدودیت‌های اقتصادی، مورد ارزیابی قرار می‌گیرد. با وجود مزایای فراوان، تحقیقات بیشتری برای ارزیابی ایمنی و تأثیرات نانوذرات در بلندمدت مورد نیاز است تا استفاده از این فناوری به طور ایمن و مؤثر در صنایع غذایی و دارویی گسترش یابد.

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