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Review Article

MICROENCAPSULATION OF BIOACTIVE COMPOUNDS

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Abstract

Microencapsulation has emerged as a key enabling technology for protecting bioactive compounds against degradation and for improving their stability, bioavailability and controlled release. Bioactive compounds such as phenolics, carotenoids, essential oils, vitamins, and bioactive lipids are highly sensitive to environmental factors including heat, oxygen, light, and pH. This review summarizes fundamental concepts of microencapsulation, commonly used wall materials, major encapsulation techniques, and release mechanisms, with a particular focus on food-related applications. Using selected recent literature, the advantages, limitations, and application potential of different microencapsulation strategies are discussed, highlighting current trends and future perspectives for the development of functional delivery systems.

Keywords: Microencapsulation, Bioactive compounds, Encapsulation techniques, Functional applications

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Introduction

Bioactive compounds derived from plant, animal, and microbial sources have attracted considerable scientific and industrial interest due to their demonstrated health-promoting properties, including antioxidant, antimicrobial, anti-inflammatory, and cardioprotective effects [1,2]. The growing consumer demand for functional foods, nutraceuticals, and natural health products has further accelerated research into the effective incorporation of these compounds into commercial formulations.

Despite extensive evidence supporting their biological efficacy, the successful application of bioactive compounds remains a significant challenge. Many of these compounds exhibit poor physicochemical stability, limited solubility, and low bioavailability, which restrict their functional performance in real systems [3]. Conventional formulation approaches often fail to provide sufficient protection against environmental and processing-related stresses, resulting in substantial losses of activity.

Microencapsulation has therefore emerged not only as a protective technique but also as a strategic tool for designing advanced delivery systems. By enabling controlled release, improved stability, and enhanced bioavailability, microencapsulation bridges the gap between laboratory-scale bioactivity and practical industrial application. Nevertheless, the selection of appropriate materials and techniques requires careful consideration of economic feasibility, regulatory constraints, and consumer acceptance. A critical discussion of these aspects is essential to fully exploit the potential of microencapsulation technologies [4].

Bioactive Compounds and Challenges in Their Utilization

Bioactive compounds encompass a wide range of naturally occurring molecules such as polyphenols, flavonoids, carotenoids, essential oils, vitamins, enzymes, peptides, and fatty acids [2,5]. These compounds are widely recognized for their positive physiological effects, including antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and anticancer activities. In food systems, bioactive compounds contribute not only to nutritional enhancement but also to improved oxidative stability, extended shelf life, and functional quality of products [3]. In pharmaceutical and nutraceutical formulations, they are increasingly used as active ingredients for disease prevention and health promotion.

Despite their well-documented benefits, the practical utilization of bioactive compounds faces significant challenges. Many bioactives are chemically unstable and highly sensitive to environmental factors such as oxygen, light, moisture, and temperature. During food processing operations such as heating, drying, extrusion, and storage, these compounds may undergo oxidation, volatilization, isomerization, or hydrolysis, leading to a substantial loss of bioactivity [3,6]. Furthermore, interactions with other food matrix components, including proteins, lipids, and minerals, can further reduce their effectiveness.

Another major limitation is the low bioaccessibility and bioavailability of several bioactive compounds following oral consumption. Poor water solubility, rapid degradation in the gastrointestinal tract, and limited intestinal permeability restrict their absorption and biological efficacy. Consequently, high concentrations are often required to achieve the desired functional effect, which may negatively affect sensory attributes such as taste, aroma, and color. Microencapsulation has therefore emerged as a promising strategy to protect bioactive compounds, enhance their stability, and improve their delivery efficiency [5].

Microencapsulation Systems and Structures

Microencapsulation systems can be broadly classified based on their internal structure into reservoir-type (core–shell) and matrix-type systems [1]. In reservoir systems, the core material is surrounded by a distinct coating layer, which acts as a diffusion barrier and controls release. In matrix systems, the bioactive compound is uniformly dispersed within a continuous polymer matrix, and release occurs through diffusion, swelling, or erosion mechanisms [7].

Particle size and morphology play a crucial role in determining encapsulation efficiency, release kinetics, and sensory perception, particularly in food applications where small particle sizes are preferred to avoid negative effects on texture [4].

Wall Materials for Microencapsulation

The selection of wall materials is a critical factor influencing the performance of microencapsulated systems. Ideal wall materials should be food-grade, non-toxic, biodegradable, and capable of forming stable matrices with the core material [1]. Commonly used wall materials include polysaccharides (alginate, starch, maltodextrin, pectin, chitosan), proteins (gelatin, whey protein isolate, casein), and lipids or waxes [3,8].

Polysaccharide-based materials are particularly attractive due to their biocompatibility, availability, and ability to form hydrogels that enable controlled release [9]. Protein–polysaccharide combinations are often used to improve encapsulation efficiency and mechanical strength through electrostatic interactions and complex coacervation [6].

Microencapsulation Techniques

A wide range of microencapsulation techniques has been developed to accommodate different types of bioactive compounds and application requirements. Among these, spray drying is the most extensively applied method in the food industry due to its economic feasibility, continuous operation, and scalability [3,10]. In this technique, a liquid feed containing the core and wall materials is atomized into a hot drying chamber, resulting in rapid solvent evaporation and formation of dry microcapsules. Spray drying is particularly suitable for relatively heat-stable bioactives; however, some degradation may occur for heat treatment resistant compounds.

Freeze drying is another commonly used technique, especially for heat-sensitive bioactive compounds. This method involves freezing the encapsulated system followed by sublimation of ice under vacuum conditions, producing porous structures with high retention of bioactivity [1]. Although freeze drying offers superior protection, its high energy consumption and long processing time limit large-scale industrial application. Other encapsulation techniques include complex coacervation, extrusion, fluidized bed coating, liposomal encapsulation, ionic gelation, and supercritical fluid technology [4,11]. Complex coacervation is particularly effective for encapsulating hydrophobic bioactives through electrostatic interactions between oppositely charged polymers. Extrusion and ionic gelation are widely used for hydrogel-based encapsulation systems, especially with alginate and other polysaccharides, allowing mild processing conditions and controlled release behavior [9]. Advanced approaches such as nanoencapsulation and hybrid delivery systems have gained increasing interest due to their ability to enhance bioavailability and achieve more precise control over release profiles [12].

Release Mechanisms and Bioavailability

The release behavior of microencapsulated bioactive compounds is a critical factor determining their functional performance. Release mechanisms are primarily governed by diffusion, swelling, erosion, or a combination of these processes, depending on the encapsulation structure, wall material composition, and environmental conditions [1,7]. In reservoir-type systems, the wall material acts as a diffusion barrier, while in matrix-type systems, release occurs through gradual diffusion of the bioactive compound from the polymer network.

Controlled release is particularly important to ensure that bioactive compounds remain protected during storage and processing, and are released at the desired location, such as specific regions of the gastrointestinal tract. Parameters such as wall thickness, porosity, hydrophilicity, and cross-linking density significantly influence release kinetics [7]. Environmental triggers including pH, temperature, and enzymatic activity can also be exploited to design smart delivery systems.

Numerous studies have demonstrated that microencapsulation significantly enhances the bioaccessibility and bioavailability of bioactive compounds by improving their solubility, dispersibility, and protection against degradation [2, 5]. Encapsulation systems based on biopolymers and hydrogels are particularly effective in maintaining bioactivity during digestion and facilitating sustained release, thereby improving the overall physiological impact of encapsulated bioactives.

Applications of Microencapsulated Bioactive Compounds

Microencapsulation of bioactive compounds has found widespread application across multiple industrial sectors due to its ability to enhance stability, functionality, and controlled delivery. The versatility of encapsulation systems allows tailoring of formulations according to specific application requirements, making this technology highly attractive for both commercial and research purposes.

Food Applications

In the food industry, microencapsulation is extensively employed to incorporate sensitive bioactive compounds into complex food matrices without compromising product quality. Encapsulated antioxidants, polyphenols, essential oils, carotenoids, and vitamins are commonly used to enhance nutritional value, delay lipid oxidation, and extend shelf life of food products [3,10]. Microencapsulation also plays a critical role in masking undesirable tastes and odors associated with certain bioactives, thereby improving consumer acceptability.

Furthermore, controlled release properties enable the gradual liberation of bioactive compounds during food storage or digestion, ensuring sustained functional effects. For example, encapsulated essential oils and antimicrobial compounds have been successfully applied as natural preservatives in active and functional foods. However, challenges remain regarding cost, large-scale production, and maintaining encapsulation efficiency during industrial processing.

Nutraceutical and Pharmaceutical Applications

In nutraceutical and pharmaceutical applications, microencapsulation enhances the stability, bioavailability, and targeted delivery of therapeutic compounds [3,12]. Many bioactive ingredients suffer from poor solubility and rapid degradation in physiological environments. Encapsulation within biopolymer-based matrices or lipid carriers protects these compounds and allows for controlled release in specific regions of the gastrointestinal tract.

Hydrogel-based systems, liposomes, and nanoencapsulation approaches have shown particular promise for oral delivery, enabling improved absorption and prolonged therapeutic activity. Despite these advantages, regulatory requirements, formulation complexity, and scalability continue to limit widespread commercialization.

Cosmetic and Personal Care Applications

In cosmetic and personal care products, microencapsulation is used to protect sensitive bioactive ingredients such as vitamins, antioxidants, fragrances, and essential oils from degradation caused by light, oxygen, and moisture [4]. Encapsulation enables sustained release upon application, improving long-term efficacy and sensory performance.

Additionally, encapsulated systems reduce skin irritation and enhance product stability, making them valuable for advanced skincare and dermatological formulations. The main challenges in this sector include ensuring consumer safety, compatibility with formulation ingredients, and cost-effective production.

Emerging and Other Applications

Beyond traditional sectors, microencapsulation is increasingly explored in agriculture, packaging, and biomedical fields. Encapsulated bioactives are being investigated for controlled release fertilizers, antimicrobial food packaging, and targeted biomedical therapies. These emerging applications highlight the expanding role of microencapsulation as a multifunctional delivery platform.

Conclusions

Microencapsulation has evolved into a sophisticated and versatile technology for improving the stability, bioavailability, and controlled delivery of bioactive compounds. As discussed in this review, the effectiveness of microencapsulation is strongly influenced by the choice of wall materials, encapsulation technique, and system design, all of which must be carefully optimized according to the intended application.

While significant progress has been made in developing efficient encapsulation strategies, several challenges remain. High production costs, scalability issues, and regulatory barriers continue to limit industrial adoption, particularly for advanced nanoencapsulation systems. Moreover, the interaction between encapsulated bioactives and complex food or biological matrices is not yet fully understood, necessitating further investigation.

Current research trends focus on the development of sustainable wall materials, green processing technologies, and smart delivery systems responsive to environmental stimuli such as pH and temperature. Integration of nanoencapsulation and biopolymer-based hydrogels is expected to further enhance the functionality and application scope of microencapsulation technologies.

Future research should focus on the development of sustainable and cost-effective wall materials, green processing technologies, and smart delivery systems capable of responding to environmental stimuli. Integrating microencapsulation with emerging technologies such as nanotechnology and biopolymer engineering is expected to further enhance functional performance. Overall, microencapsulation holds significant promise for advancing the application of bioactive compounds across food, nutraceutical, pharmaceutical, and cosmetic industries, provided that current limitations are addressed through interdisciplinary research and innovation.

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