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Recent Developments in Nanoencapsulation of Plant Bioactives from Tea and Herbs

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Abstract: Consumers' increasing demand for natural and functional foods has led researchers to explore the potential of polyphenols found in tea and herbs, including flavonoids and phytochemicals. However, these compounds are inherently unstable and have poor bioavailability due to their susceptibility to degradation under various environmental conditions such as light, heat, and pH. This limits their utility in the food, pharmaceutical, and cosmetics industries. The advent of nanoencapsulation technology has provided a novel solution to address these challenges. This review article comprehensively examines recent advances in the nanoencapsulation of bioactive compounds from tea (Camellia sinensis) and various traditional medicinal substances. The critique encompasses a range of nanocarriers including Liposomes, Niosomes, Solid lipid nanoparticles (SLNs), Nanostructured lipid carriers (NLCs), polymeric nanoparticles, and Nanoemulsions. The discussion includes insights on formulation methods, encapsulation efficiency, stability, and controlled release mechanisms for each system. Furthermore, the review highlights the enhanced antioxidant, antimicrobial, and anti-inflammatory activities of bioactives achieved through nanoencapsulation. Case studies featuring green tea catechins, curcumin, quercetin, and essential oils from herbs illustrate the practical applications and outcomes of this technology. Lastly,the review addresses the current status of safety, regulatory considerations, and commercial viability of nanocapsulated plant bioactives, paving the way for the development of future functional products.

1. Introduction

The current shift towards preventive medicine and natural remedies has propelled plant-based bioactive components into the spotlight within both the scientific community and the consumer market. The focus on plant-derived substances is particularly prominent due to their rich composition of beneficial compounds. For instance, tea, originating from the leaves of Camellia sinensis, and various medicinal herbs contain a diverse array of chemical constituents such as polyphenols (like catechins in tea), flavonoids, terpenoids, and alkaloids. These bioactive compounds exhibit a wide range of health-promoting properties, including anti-inflammatory, anti-cancer, antibacterial, and antioxidant effects. Despite their therapeutic potential, the practical application of these bioactives faces significant challenges. Their chemical structures are susceptible to degradation when exposed to factors like oxygen, light, and temperature, leading to rapid deterioration. Additionally, these compounds often exhibit low water solubility, resulting in poor oral bioavailability. Furthermore, their metabolism primarily occurs in the liver and gastrointestinal tract, leading to limited systemic absorption within the body. To address these challenges, innovative delivery systems are required to protect these valuable molecules, enhance their bioavailability, and target their delivery to specific sites in the body. Nanoencapsulation, a technique that involves entrapping active substances within a carrier material at the nanoscale (> 1000 nm), has emerged as a highly promising and potentially transformative approach. This technology offers the exciting potential to stabilize plant bioactives and significantly enhance their biological activity, enabling their incorporation into functional foods, pharmaceuticals, or nutritional supplements for improved health benefits.

2. Nanocarrier systems, plant bioactives

Table 1 Comparison of Different Nanocarrier Systems for Encapsulation of Plant Bioactives

Nanocarrier System	Core Materials	Key Advantages	Key Limitations	Typical Bioactives Encapsulated
Liposomes	Phospholipids, Cholesterol	Biocompatible, can encapsulate both hydrophilic and lipophilic compounds, mimics cell membranes.	Low physical stability, potential for oxidation, relatively low encapsulation efficiency.	Green tea catechins, Quercetin, Resveratrol
Solid Lipid Nanoparticles (SLNs)	Solid lipids (e.g., tristearin)	High stability, controlled release, excellent protection against degradation.	Limited drug loading capacity, potential for drug expulsion during storage.	Curcumin, EGCG, Caffeine
Nanostructured Lipid Carriers (NLCs)	Blend of solid and liquid lipids	Higher drug loading than SLNs, reduced drug expulsion, improved stability.	More complex formulation, potential for lipid polymorphism.	Essential oils, Luteolin, Silymarin
Polymeric Nanoparticles	Natural or synthetic polymers	High stability, versatile surface modification, sustained release profiles.	Potential toxicity of some synthetic polymers, complex preparation methods.	Tea polyphenols, Berberine, Ginsenosides
Nanoemulsions	Oil, water, emulsifiers	High encapsulation efficiency for lipophilic compounds, enhances bioavailability, easy to scale up.	Kinetically stable but not thermodynamically, potential for Ostwald ripening.	Rosemary essential oil, Thymol, Carvacrol

The selection of an appropriate nanocarrier is a critical determinant of the success of the nanoencapsulation process, significantly influencing encapsulation efficiency, stability, release properties, and other key aspects of the final product. A variety of nanocarriers with distinct physical and chemical characteristics have been developed, each tailored for specific applications. Among the prominent nanocarriers, lipid-based systems such as liposomes and Solid Lipid Nanoparticles (SLN) have garnered significant attention due to their biocompatibility and versatility in encapsulating both hydrophilic and hydrophobic compounds. Liposomes are lipid vesicles with a phospholipid bilayer structure, mimicking cell membranes and offering efficient encapsulation and delivery capabilities[1]. SLNs and their evolution into Nanostructured Lipid Carriers (NLCs) utilize solid lipids as the primary carrier, providing enhanced physical stability and controlled release features. Furthermore, polymeric nanocarriers such as chitosan, alginate, or polylactic-co-glycolic acid (PLGA) nanoparticles offer excellent defense mechanisms and customizable surface properties for targeted delivery applications. Nanoemulsions, characterized by kinetically stable oil-in-water dispersions at the colloidal scale, excel in encapsulating hydrophobic bioactives, enhancing their solubility and bioavailability. The selection among these nanocarrier systems is guided by various factors, including the chemical composition of the bioactive compound, desired release kinetics, application requirements, and processing considerations. Each system presents distinct advantages and limitations, as outlined in Table 1, necessitating careful consideration during the formulation process to optimize the encapsulation of medicinal properties from tea and herbs within these carriers.

3. Encapsulation of Bioactives from Tea (Camellia sinensis)

Teas, particularly green teas, are rich sources of bioactive catechins, with EGCG being the most abundant and pharmacologically potent compound. However, EGCG is highly unstable under neutral and alkaline conditions, leading to limited oral bioavailability. Nanoencapsulation has been explored as a strategy to address this challenge[2]. For instance, EGCG can be stabilized by loading it into TPP NPs, enhancing its stability against high temperatures and oxidation. The positive surface charge of chitosan promotes mucoadhesion in the gut, prolonging EGCG residence time and improving its absorption[3][4]. Incorporating EGCG into NLC also enhances its bioavailability. The lipid matrix of NLCs protects EGCG from degradation in the stomach and facilitates lymphatic absorption, bypassing first-pass metabolism in the liver, resulting in sustained and controlled release of EGCG into the bloodstream[5]. The effectiveness of these delivery systems is typically evaluated through a combination of in vitro and in vivo studies. These studies consistently demonstrate that nanoencapsulated tea catechins exhibit superior antioxidant properties and anti-proliferative effects compared to their free forms. Table 2 provides a summary of recent studies highlighting the enhanced stability and bioavailability of tea polyphenols achieved through various nanoencapsulation approaches. These findings underscore the transformative potential of nanotechnology in optimizing the delivery and efficacy of bioactive compounds, supporting the notion that nanotechnology has the capability to revolutionize the field.

Table 2 Selected Studies on Nanoencapsulation of Tea Bioactives

Bioactive Compound	Nanocarrier System	Key Findings	Reference
EGCG	Chitosan/TPP Nanoparticles	Encapsulation efficiency of ~80%. Enhanced stability against pH and temperature changes. Improved antioxidant activity.	Cheng et al[6]. (2020)
Green Tea Extract	Alginate/Pectin Nanoparticles	High encapsulation efficiency (>90%). Provided sustained release over 12 hours. Protected polyphenols from simulated gastrointestinal conditions.	Liang et al[7]. (2021)
Theaflavins	Whey Protein Isolate Nanoparticles	Improved water solubility and stability of theaflavins. Enhanced cellular uptake and anti-inflammatory effects in vitro.	Zhang et al[8]. (2019)
EGCG	Solid Lipid Nanoparticles (SLNs)	Increased oral bioavailability by 3.5-fold in rats compared to free EGCG solution. Enhanced thermal stability.	Pandita et al[9]. (2014)
Tea Polyphenols	Liposomes	Showed superior protection against UV degradation. Demonstrated better skin permeation for cosmetic applications.	Tomas et al[10]. (2017)

4. Encapsulation of Bioactives from Medicinal Herbs

Nanoencapsulation is a versatile technology that extends beyond tea to encompass various medicinal plants, facilitating the extraction of beneficial compounds. Curcumin, derived from turmeric (Curcuma longa), is a notable example where nanoencapsulation has been employed to enhance its therapeutic potential[11]. Despite its anti-inflammatory properties, curcumin faces challenges related to poor water solubility and rapid metabolism. Through nanoencapsulation using polymer nanoparticles, nanoemulsions, and other carriers, the delivery of curcumin is significantly improved. Encapsulation enhances the solubility of curcumin and elevates its bioavailability in animal models by over twentyfold, enabling the achievement of therapeutic levels at lower doses[12]. Similarly, essential oils from herbs like oregano, thyme, and rosemary possess potent antimicrobial properties but suffer from instability and volatility[13]. Incorporating these oils into nanoemulsions or chitosan-based carriers helps to stabilize them, prevent degradation, and facilitate their incorporation into water-containing foods, enhancing their utility in food preservation applications. For instance, nanoemulsified oregano essential oil has demonstrated enhanced efficacy against foodborne bacteria such as E.coli and Listeria monocytogenes when applied to food packaging films or directly integrated into food matrices[14].Table 3 presents a diverse array of successfully encapsulated herbal bioactives, illustrating the versatility and utility of nanotechnology in harnessing the potential of naturally occurring substances for various industrial applications.This highlights the significant impact of nanotechnology in enhancing the functionality and applicability of herbal bioactives across different sectors[15].

Table 3 Examples of Nanoencapsulated Bioactives from Various Herbs

Herbal Source	Bioactive Compound(s)	Nanocarrier System	Enhanced Property/Application
Turmeric (Curcuma longa)	Curcumin	Polymeric Micelles	Increased solubility, >10-fold increase in bioavailability, anti-cancer therapy[11].
Milk Thistle (Silybum marianum)	Silymarin	Liposomes	Improved hepatoprotective effects, enhanced skin penetration for topical use[16][17].
Ginseng (Panax ginseng)	Ginsenosides	Niosomes	Enhanced bioavailability and improved anti-fatigue and neuroprotective effects[18].
Oregano (Origanum vulgare)	Carvacrol, Thymol	Chitosan Nanoparticles	Controlled release, enhanced antimicrobial activity in food preservation[19].
Grape Seed (Vitis vinifera)	Proanthocyanidins	Nanoemulsion	Improved antioxidant stability, application in functional beverages[20].
Rosemary (Rosmarinus officinalis)	Carnosic acid, Rosmarinic acid	NLCs	Protection against oxidation, enhanced antioxidant capacity for meat products[21].

5. Conclusion and Future Perspectives

Nanoencapsulation is an innovative technology that addresses the challenges associated with utilizing bioactive components extracted from tea and herbs. By encapsulating these sensitive molecules in nano-sized carriers, issues related to stability, solubility, and bioavailability are significantly mitigated, enabling easier processing by the body and expanding their applications in various fields. Studies have highlighted diverse nanocarriers such as lipids, polymers, and emulsions that provide a protective shield around compounds like EGCG, curcumin, or essential oils, preventing their degradation and enhancing their absorption in food, pharmaceuticals, or cosmetics. Moreover, precise control over the release kinetics allows for sustained and optimized delivery of these bioactive compounds, maximizing their therapeutic benefits over an extended period. However, transitioning from laboratory-scale research to industrial-scale production and commercialization presents challenges. Future research efforts should focus on cost-effective and scalable manufacturing processes that are environmentally sustainable. Comprehensive safety assessments and regulatory compliance are essential to ensure the long-term safety and effectiveness of nanoencapsulated products. Furthermore, the development of “smart” nanocarriers capable of responding to specific physiological cues, such as pH or enzymatic activity, holds promise for tailored and personalized therapeutic interventions. Overcoming these challenges is crucial to fully harness the potential of nanoencapsulated plant bioactives and usher in a new era of highly efficient and personalized health products derived from nature.

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