NANO BIOACTIVE COMPOUNDS IN FOOD DELIVERY SYSTEM

Abstract

Bioactive compounds have immense health benefits and disease preventive characteristics due to the few limitations in delivering them into the targeted sites in the human body it is not effective as desired. In the past few years, there has been a growing compulsion with preparing effective food grade oral nano-delivery systems to improve the bioavailability of bioactive compounds such as bioactive lipids, bioactive proteins and bioactive carbohydrates. Encapsulation of bioactive compounds using Nano oral delivery systems like nano emulsions, nano liposomes etc has capability to enhance bioavailability of bioactive compounds. It can reach to the targeted site of the human body and it can resist the high acidity and enzymatic activity in the stomach. This book chapter focused on the types of bioactive compounds and their limitation in controlled delivering in the human body and how can it be enhanced by using nano delivery systems.

Keywords: Bioactive nano-delivery systems bioactive lipids,

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Demand of food products with potential benefits to health had increased the scope for identification, extraction and development of products with bioactive compounds called nutraceuticals. The health benefits of these nutraceuticals are in several areas which include immune response, diabetes, cancer, aging, mental health etc. The mechanism and benefits of these compounds in health generally include anti-oxidants and anti–inflammatory activity, inhibition or detoxifying carcinogens and enzyme activity. The present science and industry are interested in designer foods which have these potential compounds with high stability. In the last decade nanotechnology field emerged into fabrication of new forms of nano-sized bioactive compounds with anticipated applications like encapsulation of bioactive compounds with higher stability and bioavailability by the customized release of compounds. Undeniably, the most thrust area of food nanoscience research is stability of bioactive compounds in developing designer foods and deliver of these compounds from food into human body when consumed. The key advantages of nano-nutraceuticals chemistry are improved bioavailability of bioactive compounds and increasing stability of these compounds in foods.

Nutraceuticals were bioactive functional compounds present in natural and processed foods which have positive health outcomes. In recent trends there was enormormous awareness in public on health and drugs. This made a shift in research from pharmaceuticals to nutraceuticals. The functional bioactive components have numerous health benefits directly and indirectly. Recently nanomaterial's captured importance in different fields of research, because of its small size and important physico-chemical characteristics. The applications of nanoparticles in the food industry encompass enhancements in the sensory attributes of foods, such as improving color, flavor, and texture. They also extend shelf life through Nano preservation methods without altering the inherent characteristics of the food. Additionally, nanoparticles are employed to enhance the absorption of functional compounds present in the food or through fortification, utilizing structured and targeted delivery systems. Nano materials are high performance materials which have many opportunities for the creation of high performance target delivery systems of encapsulated bioactive systems. Many bioactive/functional food components including vitamins, minerals, and other constituents like colors, preservatives, flavors, antimicrobials etc., can have better performance when encapsulated and also by appropriate delivery system.

Nutraceuticals or pharmaceuticals intended for oral ingestion sometimes have poor bioavailability of bioactive compounds due to number of physiological and physicochemical reactions like less permeability across the cell, absorption in gastrointestinal tract, enzymatic and chemical reactions etc. Oral consumption of lipophilic nature bioactive compounds shows less bioavailability. The efficacies of these compounds depend on the diet composition through which they are consumed. Hence the potentiality of these compounds can be increased through food-based delivery systems.

The present article focuses on important bioactive compounds that are present in food and, their therapeutic benefits. Some of the lipophilic bioactive agents are:

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I. BIOACTIVE LIPIDS

Acylglycerols, fatty acids, phytosterols, phospholipids, carotenoids and fat-soluble vitamins are some of bioactive lipids which exert positive health effects. The reviews of health benefits of some of these bioactive compounds are presented in this paper are as follows.

1. **Carotenoids:** Carotenoids consist of approximately 600 diverse compounds responsible for imparting the yellow to red hues found in numerous food items. Carotenoids that contain oxygen atoms are commonly referred to as xanthophylls. Examples of oxygen-containing xanthophylls include lutein and zeaxanthin, while those lacking oxygen are classified as carotenes, like lycopene and β-carotene. The free radicals initiated diseases like atherosclerosis, cataract formation, age-related macular degeneration, and multiple sclerosis was inhibited by carotenoids. The sources of provitamin A are β-Carotene, α-carotene, and β-cryptoxanthin. After conversion into vitamin A, these bioactive compounds support in epithelial function, normal vision, embryonic development, and immune system function. Lycopene has the potential to reduce the incidence of prostate, cervical, colon, rectal, stomach, and various other forms of cancer. Lutein and zeaxanthin, which exist in significant quantities within the human eye, have been documented to provide advantages for age-related macular degeneration and cataract prevention They also diminish the risk factors associated with coronary heart disease, stroke, and breast cancer, and may additionally enhance skin health (Ribaya-Mercado & Blumberg 2004) The safeguarding mechanisms demonstrated by carotenoids encompass (a) ant oxidative properties, (b) light-absorbing capabilities for eye health, (c) anti-inflammatory attributes, (d) transformation into active compounds during in vivo metabolism, and (e) involvement in gap junction communication (GJC). Though carotenoids are antioxidants they do not exhibit the strong antioxidant properties when added to foods. Another functional hurdle when it comes to "utilizing carotenoids as components in functional foods is their elevated melting point, causing them to become crystalline at both food storage and body temperatures. Naturally occurring carotenoids within foods typically exhibit stability. When carotenoids are employed as food additives, they tend to be relatively unstable in food systems due to their vulnerability to light, oxygen, and auto-oxidation. Furthermore, the dispersal of carotenoids into ingredient systems can lead to their swift deterioration. Carotenoids may undergo degradation through reactions that result in the loss of double bonds or the cleavage of the molecule. Furthermore, the double bonds within carotenoids have the potential to undergo isomerization, adopting the cis configuration. Isomerization reactions may indeed yield favorable effects, as it is believed that cis isomers of carotenoids, such as lycopene, exhibit enhanced bioavailability and bioactivity, as noted by Schieber and Carle in 2005. In food industry carotenoids can be used as natural colorants in the place of synthetic colors.

2. **Phytosterols:** The emergence of phytosterol-enriched foods has gained popularity because phytosterols have the capacity to reduce total cholesterol levels and decrease low-density lipoprotein (LDL) cholesterol by inhibiting the absorption of dietary cholesterol, as indicated by Wong in 2001 and Ostlund in 2004. Phytosterols encompass a group of phytochemicals, including compounds like stigmasterol, β-sitosterol, and campesterol. Plant stanols, which occur naturally in smaller quantities than sterols, can be produced through the hydrogenation of phytosterols. In vegetable oils, the concentrations of phytosterols typically vary between 0.1% to 1.0%. The rise in the popularity of

fortified foods containing phytosterols is attributable to phytosterols capacity to impede the absorption of dietary cholesterol in humans, resulting in reductions in both total cholesterol and low-density lipoprotein cholesterol levels, as evidenced by studies conducted by Wong in 2001 and Ostlund in 2004. The absorption of dietary phytosterols in the intestine is minimal, thus posing no adverse health effects. Phytosterols can be integrated into foods, but the challenge lies in their high melting point and propensity to form insoluble crystals. Initially, phytosterols were introduced into high-fat foods, such as margarine, where solubilization and dispersion are relatively straightforward. After consuming phytosterol esters, lipases break down the attached fatty acid, leading to the liberation of unbound phytosterols. Encapsulation of phytosterols can prevent oxidation when introduced into products and increase the oxidative stability. Encapsulated Phytosterols can be introduced into aqueous products.

3. **Polyunsaturated Fatty Acids:** Polyunsaturated Fatty Acids (PUFAs) play a vital role in maintaining overall well-being, as they cannot be naturally synthesized by the human body. Hence PUFAs should be supplied through diet only. The two main important PUFAs are Omega-3 fatty acids and Omega-6 fatty acids.

   - **n-3 PUFA :** Among the dietary n-3 PUFAs, notable examples include α-linolenic acid (ALA, C18:3), eicosapentaenoic acid (EPA, C20:5), and docosahexaenoic acid (DHA, C22:6). n-3. PUFAs have undergone extensive research due to their potential to reduce cholesterol levels, as elevated LDL cholesterol is associated with the onset of cardiovascular disease (CVD). In the last trimester of pregnancy and the initial year of life, high concentrations of DHA can be found in the cell membranes of both the brain and the retina. In a study by Clandinin et al. (1980), and a review conducted by McCann & Ames (2005) on various types of research, it was determined that increases in brain DHA levels were linked to improvements in cognitive or behavioral performance. Both epidemiological observations and experimental findings have provided substantial evidence supporting the advantages of augmenting dietary n-3 PUFAs. These benefits encompass protection against various conditions such as colon, breast, prostate, and pancreatic cancers, as well as stress, anxiety, cognitive decline, mood disorders, diabetic nephropathy, inflammatory bowel disease, Alzheimer's disease, and numerous other ailments.

   - **n-6 PUFA:** The American Heart Association and numerous researchers recommend incorporating 5 to 10% of one's energy intake from n-6 PUFAs to enhance heart health, a topic explored in studies by Kris-Etherton and Harris, along with Ramsden et al. in 2010. Prominent among the dietary n-6 PUFAs are linoleic acid (LA; C18:2), its naturally occurring conjugated counterpart [conjugated LA (CLA)], and arachidonic acid (AA, C20:4). These n-6 PUFAs play a pivotal role in numerous physiological processes, with their derivatives participating in various molecular pathways. The adoption of vegetable oils as part of the diet has led to an upsurge in LA intake.

   - **Arachidonic Acid:** Arachidonic acid (AA) is an essential compound vital for the development of the mammalian brain and neural tissues, both in preterm and full-term human infants. From the onset of the third trimester until around the age of two years, there is a swift accumulation of arachidonic acid (AA) in the brain. Eicosanoid compounds, among which are prostaglandins, leukotrienes, and lipoxins, serve as precursor molecules to arachidonic acid (AA). These eicosanoids, originating from AA, exert influence over a broad spectrum of physiological processes. Numerous crucial elements of the immune response, including cytokine synthesis, antibody generation, cell maturation, proliferation, movement, and the display of antigens, are under the control of eicosanoids, as indicated by Harizi et al. in 2008. In healthy individuals, arachidonic acid (AA) can be produced through a series of desaturation and elongation reactions that take place within the cell's endoplasmic reticulum, starting from the conversion of linoleic acid (LA).Nevertheless, numerous investigations have documented a limited rate of conversion of AA from LA. At present, there exists no established daily recommended allowance for arachidonic acid (AA). Nevertheless, infant formulas enriched with AA are accessible in numerous countries due to mounting evidence indicating the vital necessity of preformed AA in the diets of both preterm and full-term infants.

II. BARRIERS IN THE DELIVERY OF BIOACTIVE LIPIDS

Important considerations in the delivery of bioactive compounds include:
The bioactive lipids should be active till they reach the site of action, because they undergo changes due to enzymes or acids in the site of their digestion that is in stomach. Another difficulty when integrating these compounds into foods is the poor water solubility of lipids, resulting in the formation of emulsions for delivery.

- The majority of bioactive lipids exhibit limited water solubility, necessitating their inclusion in a delivery system like micro emulsions or emulsions to ensure their efficient dispersion in water-based food products such as beverages, desserts, dressings, and sauces.

- In their pure state, certain bioactive lipids, such as carotenoids, exhibit a crystalline structure at room temperature. The crystalline characteristics of these lipids can pose manufacturing challenges for specific food products, potentially requiring the use of higher temperatures. Additionally, they may have the potential to adversely affect the long-term stability and sensory attributes of the final product.

- The bioactive lipid and its corresponding delivery system must be harmonious with the food matrix, ensuring that they do not detrimentally impact the product's visual appeal, texture, shelf stability, or taste. For instance, when a product contains a bioactive lipid within an emulsion, it may appear cloudy or opaque due to light scattering caused by the droplets. Conversely, when a product incorporates a bioactive lipid within a micro emulsion, it will maintain transparency because the particles are exceptionally small, minimizing light scattering.

- The lipids need to retain their inherent bioactivity throughout the entire lifecycle of the food product, encompassing its production, storage, transportation, and consumption phases. However, certain bioactive lipids are chemically unstable and their efficacy may be compromised by factors like light exposure, oxygen, or pro-oxidants (e.g., ω-3 fatty acids, β-carotene, or lycopene).

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- The lipids must retain their bioactivity within the human body until they reach their intended site of action. This may necessitate their ability to withstand the harsh conditions of the stomach, including high acidity and enzymatic activity.

III. ACTIVE PROTEINS, PEPTIDES, AND AMINO ACIDS WITH BIOLOGICAL EFFECTS

Proteins are indispensable dietary nutrients responsible for a range of vital biological functions, including growth, immune regulation, blood pressure control, antimicrobial activities, antioxidative effects, and modulation of food intake. These functions are executed by proteins, peptides, and amino acids.

1. **Proteins:** Proteins derived from natural sources, including soy, dairy, fish, and meat proteins, have demonstrated bioactive properties. These bioactive effects encompass the inhibition of the angiotensin-converting enzyme (ACE), antimicrobial properties, antioxidant capabilities, anti-carcinogenic attributes, cholesterol-lowering effects, reduction in serum triglyceride levels, promotion of lean muscle mass, defense against pathogens, regulation of blood glucose levels, and satiety-inducing effects. For instance, within dairy proteins, substances like lactoferrin, lacto peroxidase, and immunoglobulins are believed to play pivotal roles in the human immune system, alongside their antibacterial, antiviral, anti-parasitic, and antifungal functions.

2. **Peptides:** Peptides are generated from proteins through processes such as hydrolysis, which can occur during the processing of protein-rich foods using methods like fermentation or enzymatic treatment. Alternatively, this process can also take place within the human digestive system post-food consumption, often catalyzed by acids or enzymes.

   For instance, casein phosphopeptides (CPP) represent a category of peptides known for their calcium-binding affinity. These specific peptides have exhibited diverse bioactive properties, including the protection of teeth against demineralization, as well as demonstrating antioxidant, antimicrobial, anti-cancer, and immuno-stimulatory effects. Additionally, peptides sourced from milk, plants, and fish have been scientifically validated for their ability to reduce blood pressure, as demonstrated by Muir in 2005.

3. **Amino Acids:** Amino acids" have demonstrated specific biological functions. Tryptophan and tyrosine are amino acids that serve as precursors for the synthesis of neurotransmitters such as serotonin and dopamine. Both of these amino acids are associated with mood alterations, with tyrosine, in particular, being linked to diminished stress responses in humans. Additionally, the branched-chain amino acids—leucine, isoleucine, and valine—play significant roles in various essential brain functions, including those related to tryptophan and tyrosine

   The primary obstacles related to the delivery of bioactive proteins, peptides, and amino acids within food matrices include: When integrating bioactive compounds into food products, it is crucial to ensure that they do not compromise the sensory qualities of the food. This is particularly important since specific bioactive peptides and proteins can impart a bitter or astringent taste sensation, which may restrict their use in certain food

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items. The bioactivity of particular proteins can diminish throughout the food production, storage, transportation, and consumption process, as well as during extraction, purification, or thermal treatment of food. The most important step is the delivery of the bioactive proteins or peptides at the action site with the potential form.

IV. BIOACTIVE CARBOHYDRATES

Dietary fibers represent the primary category of bioactive carbohydrates. The expression 'dietary fiber' encompasses a diverse group of substances, encompassing non-digestible carbohydrates and lignin. Soluble, non-digestible polysaccharides derived from natural sources like whole grains, fruits, and vegetables can be extracted and incorporated into food items, or they can be encapsulated for targeted delivery.

The functional benefits of bioactive compounds are presented in the above section. The challenges of utilization or bioavailability of these compounds depends on the food matrix along which they are consumed. The research says most of these substances are not effective due to inhibit activities of other nutrients. The Nano technology emerged as an effective mechanism for these substances as Nano sized and as controlled delivery systems through Nano encapsulation. The next section of this chapter concentrates on the review of different Nano delivery systems of bioactive compounds for therapeutic applications.

V. KINDS OF DELIVERY SYSTEMS

Nano delivery systems are categorized into liquid and solid forms. The liquid systems include Nano emulsions, Nano liposomes, and Nano polymerases and Solid systems include lipid nanoparticles, polymeric nanoparticles, and nanocrystals. Nanoemulsions consist of immiscible liquids stabilized by surfactants, while liposomes are lipid structures suited for hydrophilic and hydrophobic molecules. Polymersomes, similar to liposomes, use polymers for encapsulation. Nanocrystals boost solubility and interaction with cells. Solid Lipid Nanoparticles (SLNs)" and "Nanostructured Lipid Carriers (NLCs)" provide controlled release and stability, while polymeric nanoparticles include Nano spheres and Nano capsules, serving as protective carriers. These systems find applications in food and medicine, enhancing stability, solubility, and controlled release of bioactives.

1. **Nanostructured Approaches for Encapsulating Bioactive Lipids:** Nanotechnology offers a remedy for enhancing the management, durability, and efficiency of bioactive lipids via miniature delivery systems on the nanoscale. These nanoscale systems excel in some situations over traditional methods because of their small size and larger surface area. Numerous nanoscale delivery systems based on lipids have been created, each featuring distinctive designs aimed at protecting and conveying bioactive lipids. These systems vary in terms of their composition, structure, and functionality. Factors like size, shape, charge, composition, and how they group together can be customized for specific tasks. This context delivers into several commonly employed nanoscale delivery systems for bioactive lipids.

2. **Nano Emulsions:** Oil-in-water Nano emulsions comprise small oil droplets (typically under 200 nm in size) coated with emulsifying agents, dispersed within an aqueous solution. These droplets can entrap bioactive lipids either prior to or after the formation of the Nano emulsion. They are produced using food-grade oil, water, and emulsifiers

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through either low- or high-energy techniques. Low-energy processes result in the formation of small droplets as conditions are altered, whereas high-energy methods involve the use of devices such as homogenizers to disintegrate oil and water into tiny droplets. Various food-grade emulsifiers like proteins, polysaccharides, and biosurfactants prevent droplet merging. Nanoemulsions are resistant to separation, though they can enlarge through Ostwald ripening, especially with soluble oils. Careful design with ripening inhibitors is needed to counter this. Nanoemulsions and microemulsions share traits but differ in stability and preparation. Microemulsions are more stable but often rely on synthetic surfactants, which isn't ideal for food uses.

3. **Nanostructured Solid Lipid Particles and Lipid Carriers:** Lipid-based Nanoparticles are minuscule lipid particles enveloped by emulsifiers, giving rise to crystalline structures capable of safeguarding and managing the release of bioactive lipids. However, there's a risk of migration to the surface during crystallization, affecting stability. Also, shape changes can cause aggregation. Nanostructured lipid carriers (NLCs) overcome this challenge by employing a combination of solid and liquid lipids, enhancing the solubility and structural integrity of bioactive lipids Careful lipid and emulsifier choice is crucial for optimal performance.

4. **Nanoliposomes:** Nano liposomes are tiny lipid nanoparticles (below 200 nm) with concentric lipid bilayers formed by phospholipids in water. The polar heads face outwards, and the non-polar tails create hydrophobic areas that can hold bioactive lipids. Techniques such as "coating-solvent evaporation" and "homogenization" are employed to produce Nano liposomes, with the latter being more suitable for large-scale commercial production.

5. **Nanostructured Biopolymer Gels and Fibers:** Nanostructured biopolymer gels and fibers are created for the encapsulation of bioactive lipids. Nano gels refer to tiny particles rich in biopolymers dispersed in water. They form a network that captures water because of hydration and capillary forces. Bioactive lipids can be either directly enclosed or loaded into lipophilic Nano carriers within this interconnected structure. Nanofibers are thin crosslinked biopolymer fibers made through electrospinning, where bioactive lipids are incorporated in the biopolymer solution. These advancements improve the stability and delivery of bioactive lipids, finding applications in the fields of food processing and packaging.

6. **Emulsions Stabilized by Nanoparticles in the Pickering Style:** Pickering Emulsions of the Oil-in-Water Type comprise tiny oil droplets encased within food-grade nanoparticles, making them efficient carriers for bioactive lipids. Appropriate nanoparticles encompass Nano cellulose, Nano chitin, Nano-starch, protein-based nanoparticles, and SLNs. Bioactive lipids can be encapsulated within either the oil droplets or the stabilizing nanoparticles themselves. The creation of nanoscale delivery systems involves high- or low-energy techniques like homogenization, sonication, spontaneous emulsification, and phase inversion. Common systems like Nano emulsions, SLNs and NLCs can be produced using methods involving both high and low energy. Nano liposomes can be formed through a variety of processes, while alternative methods like Nano-spray drying and freeze drying produce powders loaded with nanoparticles.

Each of these systems comes with its own advantages and disadvantages that need to be taken into account for specific food applications.

7. **Nano-Delivery Systems Utilizing Protein from Food Sources:** Proteins derived from food sources, such as caseins and whey proteins, exhibit valuable functional attributes like emulsification, gelation, and foaming, rendering them excellent choices for developing Nano carriers for the safe delivery of drugs or nutraceuticals. These protein-based nanocarriers offer benefits like biodegradability, lack of antigenicity, and binding capabilities for various compounds. Caseins, forming micelles with unique structures, have been explored for encapsulating hydrophobic compounds, while whey proteins like β-lactoglobulin have shown potential for binding hydrophobic molecules. These proteins can be harnessed for oral delivery systems, exploiting their stability against digestion enzymes. Gelatin, derived from collagen, offers versatility and has been used to create nanoparticles for drug delivery. Overall, protein-based nanocarriers present promising options for delivering bioactive substances in food and pharmaceuticals.

8. **Nano-Delivery Systems Utilizing Polysaccharides:** Polysaccharides, which are essential constituents in various foods, provide a wide array of advantages owing to their flexible structures and the potential for digestion at specific sites. These characteristics render them suitable as carriers for precise and controlled delivery of drugs or nutraceuticals within the gastrointestinal system. Their attributes include biocompatibility, stability, and bioadhesion on mucosal surfaces, allowing specific delivery and extended retention. Polysaccharides like chitosan, derived from de acetylated chitin, stand out as effective carriers. Chitosan's cationic nature and biodegradability enable improved absorption of active compounds, making it valuable for applications in food, cosmetics, and pharmaceuticals. Chitosan nanoparticles have shown promise in efficient drug delivery, utilizing interactions with anions like tripolyphosphate to form microgel particles. Controlled release of bioactive like tea catechins and curcumin has been achieved using chitosan-based nanoparticles. Composite nanoparticles incorporating chitosan, alginate, and pluronic polymers have demonstrated cytotoxicity against cancer cells. Additionally, chitosan-based amphiphiles have been developed, presenting a structured network for potential applications. Overall, polysaccharide-based nanocarriers, particularly chitosan, offer a promising avenue for enhancing drug and nutraceutical delivery with potential implications across various fields.

9. **Nano delivery Systems Involving Complexes of Polysaccharides and Proteins (Peptides):**Proteins sourced from food, including casein, gelatin, whey proteins (particularly β-lacto globulin), and casein phosphopeptides (CPP), have the potential to serve as candidates for Nano carriers due to their biodegradability, absence of antigenicity, nutritional value, and drug-binding attributes. Nevertheless, their susceptibility to enzymatic breakdown within the digestive tract presents a hurdle when considering oral administration. On the other hand, non-starch polysaccharides such as alginate, pectin, dextran, and chitosan possess advantageous qualities for oral delivery, including resilience to gastric conditions, resistance to enzymatic degradation, and the ability to adhere to mucosal surfaces. Biopolymer nanoparticles can be created by orchestrating controlled self-assembly, primarily guided by the electrostatic attractions between protein and polysaccharide components with opposite charges. pH variations influence the complexation and phase separation of these biopolymer systems, offering the potential for controlled drug delivery. Strategies involving β-lg and chitosan or pectin

have demonstrated the formation of hydrogel particles with varying sizes and behaviors in response to different pH conditions. These approaches show promise for delivering water-insoluble and sensitive bioactive compounds within transparent liquid systems. Combining chitosan with proteins like α-lactalbumin or β-lg has also been explored as a means to create potential carriers for bioactive substances.

10. **Nanoparticles Combining Polysaccharides and Peptides:** Utilizing proteins for nano-complexes may raise allergy concerns, prompting the use of bioactive peptides as a safer alternative. An innovative nano-complex was developed from casein phosphopeptide (CPP), sourced from milk casein protein, and chitosan. CPP, resistant to digestion and possessing various benefits, formed hierarchical nanocomplexes with chitosan based on electrostatic interactions and hydrophobic bonding. These nanocomplexes offer potential as secure drug and functional food ingredient carriers. Additionally, CPP was employed to crosslink chitosan and bind with EGCG, resulting in well-dispersed nanoparticles that efficiently entrapped EGCG. This method demonstrated improved encapsulation efficiency and controlled release of EGCG compared to previous approaches. Protein-based nanoparticles are gaining traction for drug and bioactive delivery in the food industry, enhancing solubility, stability, and bioavailability of encapsulated compounds. These nanoparticles can extend residence time in the gastrointestinal tract and enable targeted delivery. Soy protein-based nanoparticles, due to their natural state and compatibility with bioactives, offer advantages such as ease of fabrication, controlled release, and cost-effectiveness, making them a promising choice for diverse applications.

    Nanoparticles derived from soy protein, created using different methods, hold potential as vehicles to improve the solubility, stability, and bioavailability of bioactive compounds with low solubility, such as curcumin, phytosterols, coenzyme Q10, resveratrol, and vitamin D3. Nanostructured emulsions using soy proteins as stabilizers offer effective transport for lipophilic bioactives, displaying resistance to lipid oxidation. Protein-polysaccharide complexes have gained attention for their ability to protect and stabilize lipophilic ingredients, enhance bioavailability, and provide sustained release. Nanoemulsions enhance the bioavailability of encapsulated lipophilic compounds due to improved solubility and bio accessibility, offering benefits for compounds like vitamin E, vitamin D, resveratrol, and beta-carotene. Carbohydrates, particularly polysaccharides, hold potential as building blocks for delivery systems, originating from various sources like plants, animals, algae, and microbes, and can be tailored for specific application

11. **Starch:** Starch, the primary storage polysaccharide of plant origin, is composed of glucose units connected by α-d-(1→4) and/or α-d-(1→6) linkages. This biodegradable and biocompatible polymer is composed of amylose and amylopectin. Starch-based nanoparticles have been employed to encapsulate substances like insulin, flaxseed, unsaturated fatty acids, and flavors. To improve its capacity for encapsulating hydrophobic bioactive compounds, researchers have developed hydrophobic derivatives of starch, including dialdehyde starch and propyl starch nanoparticles. Starches that have undergone alterations, such as Octenyl Succinic Anhydride (OSA) modification and acetylation, are being employed for the encapsulation of food and pharmaceutical substances, taking advantage of their enhanced hydrophobic properties and increased stability. PEGylated starch acetate nanoparticles with a hydrophobic core are used for enhanced oral insulin delivery, showcasing improved encapsulation efficiency. These advancements highlight the versatility and potential of modified starch and carbohydrate-

based systems. Amylose molecules can form co-crystals with a range of lipophilic compounds, including long-chain alcohols, aromatic substances, lipids, and surfactants. In this process, amylose creates helical structures that contain hydrophobic pockets, which are well-suited for encapsulating water-insoluble food bioactives with particular molecular shapes. Recent research has emphasized that the characteristics of amylose complexes, including their structure, physicochemical properties, susceptibility to amylase digestion, and release patterns, are influenced by the chemical properties of the encapsulated molecules. Notably, starch stands out for its cost-effectiveness and relatively pure composition, avoiding the complex purification processes required by some other biopolymers. However, starch's susceptibility to acid degradation and enzymatic hydrolysis, especially in the oral cavity, is a notable limitation. Nevertheless, adjustments can be made to create starch variants that are resistant to acid or enzyme degradation.

12. **Cellulose:** Cellulose, a plentiful natural polysaccharide made up of glucose units connected by β-d-(1→4) bonds, can be subject to alterations to produce appropriate encapsulation structures, even though it naturally possesses limited water solubility and substantial dimensions. Nanocrystalline cellulose (NCC), obtained through acid hydrolysis, has garnered interest for its simple preparation and potential use of agricultural waste materials. Cellulose esters, divided into non-enteric and enteric categories, offer options for controlled release. Non-enteric esters such as acetate, acetate butyrate, and cellulose acetate propionate exhibit restricted water solubility, whereas enteric esters like cellulose acetate phthalate (CAP) or hydroxypropyl methyl cellulose phthalate (HPMCP) dissolve effectively in solutions with a slightly acidic to mildly alkaline pH range, making them suitable for targeted colon delivery. Enteric cellulose esters have been explored for nanocapsules to preserve bioactivity and prevent degradation of compounds like lutein. Pectin, another polysaccharide, has been utilized for nano-scale delivery systems; with pectin nanospheres produced using cross-linking agents. However, calcium pectinate carriers may have limitations in terms of entrapment efficiency and rapid release of bioactives. Techniques like high-intensity ultrasound have been proposed to enhance encapsulation efficiency.

13. **Guar Gum:** Guar gum, derived from the seeds of Cyamopsis tetragonolobus, is a water-soluble polysaccharide composed of mannopyranosyl units connected by 1→4 linkages and galactopyranosyl units connected by 1→6 linkages. It functions as a thickener, emulsifier, and retrogradation retardant in food. Guar gum possesses the ability to withstand enzymatic degradation until it reaches the colon, indicating its potential utility as a vehicle for drug delivery, as highlighted by studies. Modification is often needed due to native guar gum's high viscosity. De polymerization via methods like acid, enzyme, or heat hydrolysis, microwave degradation, and ultrasonication results in low molecular weight, water-soluble dietary fiber. Such depolymerized guar gum can improve flavor retention and be enhanced further by grafting with polyacrylamide to address hydration and thermal stability concerns.

14. **Chitosan:** Chitosan, obtained by deacetylating chitin, is a biocompatible and biodegradable polymer with a wide range of uses within the food industry. It possesses both antimicrobial and antioxidant attributes. Furthermore, it has the capacity to bind to dietary fats and prolong its presence in the digestive system, thus proving valuable for controlled release applications. Chitosan's pH-dependent solubility (acidic $pH < 6.5$)

allows for modification through physical or chemical means. An ionic-gelling method produces chitosan-tripolyphosphate particles for controlled bioactive release. Amphiphilic chitosan derivatives encapsulate hydrophobic materials, while glycol chitosan (GCH) nanoparticles enhance water solubility and release properties, especially for acid-sensitive bioactives. These advancements enhance chitosan's potential as a versatile carrier.

15. **Alginate:** Alginate, sourced from marine brown algae, undergoes gelation when exposed to divalent cations, resulting in a structure reminiscent of a gel. Alginate beads cross-link through a grid-like configuration, with applications in delivering acid-sensitive bioactives. Hydrogel nanoparticles composed of alginate are generated through modified techniques. Alginate calcium particles have encapsulated lipid nanoparticles, lipase, and turmeric oil, while challenges include leaching and rapid dissolution. Combining alginate with chitosan nanoparticles addresses burst release in intestinal conditions.

16. **Dextran:** Dextran, a bacterial glucan polysaccharide, possesses hydroxyl groups for attaching organic functional groups. Modified dextran with adjusted degree of substitution forms self-organized nano-scale particles, offering potential for encapsulating substances with varying hydrophobicities. However, biodegradability decreases with hydrophobic group substitution, although ester links promote degradation in biological environments. While there is potential, there is a scarcity of literature on the utilization of modified dextran for nanoencapsulation of food bioactives.

17. **Cyclodextrins (CDs):** Cyclodextrins (CDs) are ring-shaped oligosaccharides with hydrophilic outer surfaces and hydrophobic inner cavities, making them effective for enveloping bioactive compounds that are poorly soluble, sensitive to temperature, or prone to instability. α-, β-, and γ-CDs offer varying encapsulation capacities. These versatile compounds have found application in the encapsulation of antimicrobial agents, antioxidants, essential oils, and flavor compounds. Modifications such as hydroxypropyl β-cyclodextrin (HP-β-CD) have been developed to enhance water solubility and biocompatibility. Additionally, novel polysaccharides sourced from unconventional origins, such as Balangu and wild sage seeds, exhibit potential for encapsulation. These polysaccharides possess a combination of hydrophobic and hydrophilic properties, making them suitable for encapsulating a wide range of food-related bioactive compounds. However, further investigation is necessary to fully comprehend their structural characteristics and explore their potential in tailored delivery systems.

VI. EFFECTIVE CARBOHYDRATE COMBINATIONS

To improve the functional attributes, carbohydrate pairings are frequently employed. Combinations of alginate and chitosan harness chitosan's mucoadhesive characteristics and utilize alginate's resistance to acidity, as evidenced in prior research studies. Researchers investigated the layer-by-layer encapsulation of probiotic Lactobacillus acidophilus using chitosan and carboxymethyl cellulose as a strategy to enhance viability within the gastrointestinal environment. Carbohydrates serve as coatings for nanocarrier systems, as seen with chitosan-coated nanostructured lipid carriers for hesperetin encapsulation. Coated liposomes with cationic chitosan and anionic pectin were used to enhance protection and stability of polyphenolic grape seed extract.

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Nano sized bioactive compounds and Nano delivery systems are emerging fields of Nano food science research. The above review describes the effect of different bioactive compounds on different diseases. The challenge is how these compounds are delivered effectively to the target area with out loosing the efficacy of the functions of the bioactive compounds. The Nano structured delivery systems like Nano emulsions, Nano structured lipid, protein, carbohydrate carriers and combination of these carriers, and Nano encapsulations are proved to be the better ways of delivering these compounds.

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