**NANO BIOACTIVE COMPOUNDS IN FOOD DELIVERY SYSTEM**

**Dr K V Sucharitha\* and M Kalavathi\*\***

**\*Associate Professor, \*\*Ph D Scholar, Food Technology Track,**

**Dept. of. Home Science, Sri Venkateswara University, Tirupati.**

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 are the classes of bioactive compounds found in natural and processed foods which have beneficial health effects. 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. Nano particle applications in food sector can be in improvement of sensory qualities of foods (color, flavor, texture enhancement), to increase shelf life by Nano preservation techniques without altering the nature of the food, to increase better absorption of bioactive compounds present in the food or by fortification or by structured targeted delivery system. 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., Most of the bioactive agents in foods that can be used for oral intake are highly lipophilic molecules with low and or variable bioavailability. The bioavailability of bioactive agents depend on composition of food that is ingested along with them, which gives a scope for designing food based delivery systems to improve the performance of these agents.

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

# BIOACTIVE LIPIDS

Lipids can have both positive and negative impacts on human health. Bio active lipidsincludeacylglycerols, fatty acids, phospholipids, carotenoids, phytosterols, and oil-soluble vitamins.Thesecompounds have some specific health benefits. The review of health benefits of some of these bioactive compounds are presented in this paper are as follows.

**Carotenoids**

Carotenoids are a group of 600 different compounds that contribute to the yellow to red colors present in many foods. Oxygen containing Carotenoids are known as xanthophylls For instance, oxygen-containing variants are referred to as xanthophylls (such as lutein and zeaxanthin), whereas those devoid of oxygen are categorized as carotenes (examples include lycopene and β-carotene). Research report says Carotenoids inhibit various free-radical-initiated diseases, such as atherosclerosis, cataract formation, age-related muscular degeneration, and multiple sclerosis β-Carotene, α-carotene, and β-cryptoxanthin are sources of provitamin A. Once converted to vitamin A, these compounds maintains the health of normal eye, epithelial function, embryonic development, and immune system function. Lycopene has potential effect on decreasing the development of prostate, cervical, colon, rectal, stomach, and other types of cancers. Lutein and zeaxanthin, are present in high amounts in the human eye, were reported to have beneficial age-related macular degeneration and cataracts. They also reduce the risk factors for coronary heart disease,

Stroke, and breast cancer, and may also improve skin health (Ribaya-Mercado & Blumberg 2004). The protective mechanisms exhibited by carotenoids include (*a*) antioxidant activity, (*b*) ability to absorb light (eye health), (*c*) anti-inflammatory activity, (*d)* in vivo metabolism into active compounds, and (*e*) participation in gap junction communication (GJC). Though carotenoids are antioxidants they do not exhibit the strong antioxidant properties when added to foods. The other functional challenge of using carotenoids as ingredients in functional foods is their high melting point, making them crystalline at food storage and body temperatures. Endogenous carotenoids in foods are generally stable. When carotenoids are used as food additives, they are relatively unstable in food systems because they are susceptible to light, oxygen, and auto oxidation. In addition, dispersion of carotenoids into ingredient systems can result in their rapid degradation. Carotenoids can be degraded by reactions that cause the loss of double bonds or the scission of the molecule. In addition, the double bonds in carotenoids can undergo isomerization to the *cis* configuration. Isomerization reactions could potentially have advantageous effects, as cis isomers of carotenoids, like lycopene, are believed to possess greater bioavailability and bioactivity, as indicated by Schieber and Carle in 2005. In food industry carotenoids can be used as natural colorants in the place of synthetic colors.

**Phytosterols**

The development of phytosterol fortified foods has become popular due to the ability of phytosterols to lower overall cholesterol levels and reduce low-density lipoprotein (LDL) cholesterol by hindering the absorption of dietary cholesterol, as suggested by Wong in 2001 and Ostlund in 2004.Phytosterols are a group of phytochemicals that include compounds such as stigma sterol, *β*-sitosterol, and campesterol. Plant stanols, occurring naturally in lesser amounts compared to sterols, can be synthesized through the hydrogenation of phytosterols. In vegetable oils phytosterols concentrations range from 0.1 to 1.0% .The popularity of fortified foods with phytosterol increasing due to the ability of phytosterols to inhibit the absorption of dietary cholesterol in humans, leading to reductions in total and low-density lipoprotein cholesterol, as demonstrated by research conducted by Wong in 2001 and Ostlund in 2004. The absorption of dietary phytosterols in intestine is very low so dietary phytosterols do not have adverse effects on health. Phytosterols can be incorporated into foods the difficulty is with their high melting point and their tendency to form insoluble crystals. Phytosterols were originally added to high fat foods (e.g. margarine) where solublization and dispersion are relatively simple. 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.

**Polyunsaturated Fatty Acids.**

PUFAs are essential for human health because they are not synthesized by humans. Hence PUFAs should be supplied through diet only. The two main important PUFAs, are the n-3 and the n-6 fatty acids.

***n-3 PUFA.***

Three primary dietary n-3 PUFAs are recognized: α-linolenic acid (ALA, C18:3), eicosapentaenoic acid (EPA, C20:5), and docosahexaenoic acid (DHA, C22:6). n-3 PUFA have been widely studied for cholesterol lowering effects, since higher LDL cholesterol has a role in the development of CVD. During final trimester and first year of life DHA is present in high levels in cell membranes of brain and retina. (Clandinin et al. 1980). McCann & Ames (2005) reviewed the potential for cognitive beneﬁts of DHA in several types of studies, and concluded that changes in brain concentrations of DHA were positively associated with changes in cognitive or behavioral performance. Epidemiological and experimental evidence have also shown that increasing n-3 PUFAs in the diet has beneﬁts against cancer, including colon, breast, prostate, and pancreatic cancers, stress, anxiety, cognitive impairment, mood disorders, diabetic nephropathy, inﬂammatory bowel disease, and Alzheimer’s disease as well as many more.

**n-6 PUFA**

American Heart Association and many scientists advise consumption of at least 5 to 10% of energy as n-6 PUFA to improve heart health studies conducted by Kris-Etherton and Harris, as well as Ramsden et al. in 2010, have examined this matter. The main dietary n-6 PUFAs are linoleic acid (LA; C18:2), its naturally occurring conjugated derivative [conjugated LA (CLA)], and arachidonic acid (AA, C20:4). n-6 PUFAs are important in many physiological functions, and their derivatives are involved in various molecular pathways. The consumption of vegetable oils increased the intake of LA.

**Arachidonic acid**

AA is a critical compound for growth in mammalian brain and neural tissues in preterm and term human infants. It rapidly accumulates in the brain from the beginning of the third trimester to approximately two years of age. Eicosanoid molecules, including prostaglandins, leukotrienes, and lipoxins are precursor molecules of AA. These eicosanoids derived from AA impact a wide range 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. AA can be synthesized in healthy individuals by the conversion of LA after successive desaturation and elongation reactions occurring in the endoplasmic reticulum of the cell. Nevertheless, numerous investigations have documented a limited rate of conversion of AA from LA. There is currently no recommended daily allowance for AA. However, infant formula fortiﬁed with AA is available in many countries because increasing evidence shows that a dietary supply of preformed AA is essential for preterm and term infant

**Challenges to Delivery of Bioactive Lipids**

The significant challenges to be considered while delivering bioactive compounds are:

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 challenge in incorporating these compounds into foods is that lipids are poorly soluble in water; hence, they form emulsions that can be delivered.

* Most bioactive lipids have a low water-solubility and so they must be incorporated into some kind of delivery system (e.g., micro emulsions or emulsions) to make them readily dispersible in aqueous-based food products, such as beverages, desserts, dressings, and sauces.
* Most bioactive lipids have a low water-solubility and so they must be incorporated into some kind of delivery system (e.g., micro emulsions or emulsions) to make them readily dispersible in aqueous-based food products, such as beverages, desserts, dressings, and sauces;
* Some bioactive lipids are crystalline at room temperature in their pure form, e.g., carotenoids. The crystalline nature of these lipids may provide challenges in the manufacture of certain types of food products (e.g., it may be necessary to use elevated temperatures), or they might potentially have a negative impact on the ultimate product's extended stability or sensory qualities.
* The bioactive lipid and associated delivery system should be compatible with the food matrix, i.e., it should not adversely affect the appearance, texture, stability, or flavor of the product. A bioactive lipid contained within an emulsion will cause a product to appear turbid or opaque due to light scattering by the droplets. On the other hand, a bioactive lipid contained within a micro emulsion will appear trans- parent because the particles are so small that they do not scatter light strongly;
* The lipids should maintain their potential bioactivity within the food product during its manufacture, storage, transport, and utilization. Some bioactive lipids are chemically labile and their activity may be adversely affected by light, oxy- gen, or pro-oxidants (e.g., *ω*-3 fatty acids, *β*-carotene, or lycopene);
* The lipids should maintain their bioactivity within the human body prior to being delivered to the desired site-of- action, e.g., they may have to resist the high acidity and enzyme activity of the stomach

# BIOACTIVE PROTEINS, PEPTIDES, AND AMINO ACIDS

Protein is an essential nutrient in the diet, a number of biological functions such as growth and immune regulatory functions, antihypertensive agents, antimicrobial agents, antioxidants, food intake modifiers, are performed by proteins, peptides, and amino acids.

**Proteins**

Proteins from natural sources have been shown to be bioactive, including soy, dairy, fish, and meat proteins. These bioactivity affects include inhibition of the angiotensin-converting enzyme (ACE), antimicrobial activity, antioxidant activity, anti-carcinogenic activity, hypocholesterolemic effect, reduced serum triglycerides, increased lean muscle mass, protection against pathogens, regulation of blood glucose levels, and satiety effects. For example, dairy proteins, such as lactoferrin, lactoperoxidase, and immunoglobulin, are believed to be important mediators of the human immune sys- tem, as well as having antibacterial, antiviral, anti-parasite, and antifungal properties.

**Peptides**

Peptides are derived from proteins by hydrolysis. This happens o during processing of protein foods like fermentation methods or enzymatic methods or it may take place within the human digestive system after food consumption (e.g., by acids or enzymes). To provide an illustration, casein phosphopeptides (CPP) are peptides with a propensity to bind calcium. These particular peptides have been shown to possess various bioactive capabilities, including safeguarding teeth against demineralization and exhibiting antioxidant activity, anti-microbial activity, anti-cancer properties, and immuno-stimulation. Additional peptides sourced from milk, plants, and fish have been proven to possess the ability to lower blood pressure, as demonstrated by Muir in 2005.

**Amino Acids**

Amino acids have proved to exhibit specific biological activities. Tryptophan and tyrosine are amino acids which are precursors of neurotransmitter synthesis serotonin and dopamine. Both amino acids are linked with mood changes and particularly tyrosine is also linked to reduced stress responses in humans. The branched-chain amino acids, leucine, isoleucine, and valine, participate in a variety of important biological functions in the brain including those from tryptophan and tyrosine.

The main challenges associated with delivering bioactive proteins, peptides, and amino acids in food matrices are: When the bioactive compounds are incorporated into food they should not interfere with the sensory attributes of the food because certain types of bioactive peptides and proteins have a bitter or astringent mouth feel that limits their application in certain foods. The bioactivity of certain proteins will be lost during the production, storage, transport, and utilization and during extraction, purification, or thermal processing of food. The most important step is the delivery of the bioactive proteins or peptides at the action site with the potential form.

# BIOACTIVE CARBOHYDRATES

Dietary fibers are the major class of bioactive carbohydrates. The term “dietary fiber” refers to a complex class of materials that includes non-digestible carbohydrates and lignin. The soluble non digestable polysaccharides from natural foods such as whole grains, fruits and vegetables can be isolated and used into food products or can be encapsulated and delivered at the site.

**TYPES OF DELIVERY SYSTEMS**

Nano delivery systems are divided into liquid and solid types. Among liquid systems are nano emulsions, nanoliposomes, and nanopolymersomes. 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) offer controlled release and stability, while polymeric nanoparticles encompass nanospheres and nanocapsules for protection. These systems find applications in food and medicine, enhancing stability, solubility, and controlled release of bioactives.

**Nanoscale Delivery Systems for Encapsulation of Bioactive Lipids**

Nanotechnology provides a solution to improve the handling, stability, and effectiveness of bioactive lipids through tiny delivery systems at the nanoscale. These nanoscale systems excel in some situations over traditional methods because of their small size and larger surface area. Various lipid-based nanoscale delivery systems have been developed with unique designs to safeguard and transport bioactive lipids. These systems differ in composition, structure, and function. By adjusting factors like size, shape, charge, composition, and how they group together, these systems can be customized for specific tasks. This context explores several widely used nanoscale delivery systems for bioactive lipids.

**Nanoemulsions**

Oil-in-water nanoemulsions consist of tiny oil droplets (less than 200 nm in diameter) coated with emulsifiers, dispersed within water. These droplets trap bioactive lipids, either before or after forming the nanoemulsion. They're made using food-grade oil, water, and emulsifiers through low- or high-energy methods. Low-energy techniques create small droplets when conditions change, while high-energy methods use devices like homogenizers to break down oil and water into small 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.

**Solid Lipid Nanoparticles and Nanostructured Lipid Carriers**

Solid lipid nanoparticles (SLNs) are tiny lipid particles coated with emulsifiers, forming crystalline structures that can protect and control 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) address this by using a mix of solid and liquid lipids, allowing better solubilization and shape stability for bioactive lipids. Careful lipid and emulsifier choice is crucial for optimal performance.

**Nanoliposomes**

Nanoliposomes 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. Methods like coating-solvent evaporation and homogenization create nanoliposomes, with the latter better for commercial production.

**Biopolymer Nanogels and Nanofibers**

Biopolymer nanogels and nanofibers are developed to encapsulate bioactive lipids. Nanogels are small biopolymer-rich particles in water, forming a network that traps water due to hydration and capillary forces. Bioactive lipids can be directly encapsulated or loaded into lipophilic nanocarriers within this network. Nanofibers are thin crosslinked biopolymer fibers made through electrospinning, where bioactive lipids are incorporated in the biopolymer solution. These technologies enhance stability and delivery of bioactive lipids, finding use in food processing and packaging.

**Nanoparticle-Stabilized Pickering Emulsions**

Oil-in-water Pickering emulsions consist of oil droplets surrounded by food-grade nanoparticles, serving as effective carriers for bioactive lipids. Suitable nanoparticles include nanocellulose, nanochitin, nano-starch, protein nanoparticles, and SLNs. Bioactive lipids can be enclosed within 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 nanoemulsions, SLNs, and NLCs can be made through both high- and low-energy methods. Nanoliposomes are generated using various procedures, and other techniques like nano-spray drying and freeze drying create nanoparticle-loaded powders. Each system has pros and cons, which must be considered for specific food applications.

**FOOD PROTEIN BASED NANO-DELIVERY SYSTEMS**

Food proteins, like caseins and whey proteins, possess valuable functional properties such as emulsification, gelation, and foaming, making them ideal candidates for creating nanocarriers to deliver safe 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.

**POLYSACCHARIDES BASED NANO-DELIVERY SYSTEMS**

Polysaccharides, integral components of various foods, offer a range of benefits due to their adaptable structures and site-specific digestion, making them suitable carriers for controlled and targeted drug or nutraceutical release in the gastrointestinal tract. 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 bioactives 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.

**POLYSACCHARIDES-PROTEIN (PEPTIDES) COMPLEX NANO-DELIVERY**

**SYSTEMS**

Food-derived proteins such as casein, gelatin, whey proteins (especially β-lactoglobulin), and casein phosphopeptides (CPP) hold potential as nanocarrier candidates due to their biodegradability, lack of antigenicity, nutritional value, and drug binding capabilities. However, their vulnerability to enzymatic digestion in the digestive system poses a challenge for oral delivery. Non-starch polysaccharides like alginate, pectin, dextran, and chitosan offer favorable attributes for oral delivery, including gastric stability, resistance to enzymes, and mucosal adhesion. Biopolymer nanoparticles can be engineered through controlled self-assembly driven by electrostatic interactions between oppositely charged protein and polysaccharide groups. 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.

**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.

Soy protein-derived nanoparticles, produced through various approaches, show promise as carriers for enhancing solubility, stability, and bioavailability of poorly soluble bioactives like 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 bioaccessibility, 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 applications

**Starch**

Starch, the predominant plant-based storage polysaccharide, consists of glucose units linked by α-d-(1→4) and/or α-d-(1→6) bonds. 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 enhance its capabilities in encapsulating hydrophobic bioactives, hydrophobic starch derivatives have been developed, such as dialdehyde starch and propyl starch nanoparticles. Modified starches like Octenyl Succinic Anhydride (OSA) and acetylated starch have found use in encapsulating food and pharmaceutical agents, benefiting from improved hydrophobicity and stability. PEGylated starch acetate nanoparticles, with a hydrophobic core, have been utilized for oral insulin delivery, showcasing enhanced encapsulation efficiency. These advancements highlight the versatility and potential of modified starch and carbohydrate-based systems. Amylose molecules exhibit the capability to co-crystallize with various lipophilic substances, including long-chain alcohols, aromatic compounds, lipids, and surfactants. Through this process, amylose forms helical structures with hydrophobic pockets suitable for encapsulating water-insoluble food bioactives with specific molecular shapes. Recent studies highlight that the properties of amylose-complexes, such as structure, physicochemical attributes, susceptibility to amylase digestion, and release profiles, are influenced by the chemical characteristics of guest 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. Nonetheless, modifications can be applied to develop acid- or enzyme-resistant starch variants

**Cellulose**

Cellulose, the abundant natural polysaccharide composed of glucose units linked by β-d-(1→4) bonds, can undergo modifications to create suitable encapsulating structures despite its inherent low water solubility and large 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 like acetate, acetate butyrate, and cellulose acetate propionate have limited water solubility, while enteric esters like cellulose acetate phthalate (CAP) or hydroxyl propyl methyl cellulose phthalate (HPMCP) dissolve in mildly acidic to slightly alkaline solutions, suitable for 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.

**Guar gum**

Guar gum, sourced from Cyamopsis tetragonolobus seeds, is a water-soluble polysaccharide with β-d-(1 → 4) mannopyranosyl and α-d-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.

**Chitosan**

Chitosan, derived from chitin through deacetylation, is a biocompatible and biodegradable polymer with versatile applications in the food industry, including antimicrobial and antioxidant properties. It can bind dietary fats and extend residence time in the gastrointestinal tract, making it useful for controlled release. 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.

**Alginate**

Alginate, derived from brown sea algae, forms a gel-like structure in the presence of divalent cations. Alginate beads cross-link through an egg-box-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.

**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. Despite promise, reports on nanoencapsulation of food bioactives using modified dextran are limited.

**Cyclodextrins**

Cyclodextrins (CDs) are cone-shaped oligosaccharides with hydrophilic exteriors and lipophilic central cavities, making them effective for encapsulating poorly soluble, temperature-sensitive, or unstable bioactives. α-, β-, and γ-CDs offer varying capacities for encapsulation. They have been applied to encapsulate antimicrobials, antioxidants, essential oils, and flavors. Modifications like hydroxypropyl β-cyclodextrin (HP-β-CD) enhance water solubility and biocompatibility. Novel polysaccharides from unconventional sources, e.g., Balangu and wild sage seeds, show potential for encapsulation. These polysaccharides exhibit both hydrophobic and hydrophilic attributes, suitable for encapsulating various food bioactives. Further exploration is needed to understand their structural properties and potential for tailored delivery systems.

**Carbohydrate Combinations**

To enhance functional properties, carbohydrate combinations are often utilized. Blends of alginate and chitosan utilize the mucoadhesive properties of chitosan and the acid resistance of alginate to achieve targeted delivery to the colon, as demonstrated in previous 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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