REVIEW

CHITOSAN IN NEXT-GENERATION FUNCTIONAL FOODS: TECHNOLOGICAL, NUTRITIONAL, AND SUSTAINABLE PERSPECTIVES

Rita Paola Debri[1,a], Antonino De Lorenzo[2,b], Raffaele Conte[1,3,4,c,*], Gianfranco Peluso[1,3,d]

[1] – Faculty of Medicine and Surgery, Saint Camillus International University of Health Sciences, Via di Sant'Alessandro 8, 00131 Rome, Italy
[a] – 0009-0006-8791-5474, [c] – ORCID: 0000-0002-6266-4991,
[d] – ORCID: 0000-0003-4352-9484
[2] – Department of Biomedicine and Prevention, University of Rome "Tor Vergata" Via Montpellier 1, 00133 Rome, Italy
[b] – ORCID 0000-0001-6744-0850
[3] – Research Institute on Terrestrial Ecosystems (IRET)-CNR, Via Pietro Castellino 111, 80131 Naples, Italy
[4] – National Biodiversity Future Center, Piazza Marina 61, 90133 Palermo, Italy
**corresponding author: raffaele.conte@unicamillus.org*

Abstract

Chitosan, a naturally derived cationic polysaccharide obtained through the partial deacetylation of chitin, has emerged as one of the most versatile biopolymers in food science. Owing to its biodegradability, biocompatibility, non-toxicity, and multifunctional biological activities, chitosan has found increasing application in the development of functional foods. Beyond its traditional role as a food preservative or coating material, chitosan is now widely studied as a technological and bioactive ingredient that can improve nutritional value, the bioavailability of functional compounds, gut health, and metabolic outcomes. This review focuses on its use in the formulation of functional foods. Special emphasis is placed on emerging food technologies, including encapsulation systems, probiotic and nutraceutical delivery, nano- and micro-structured foods, and sustainable processing strategies. Current challenges, regulatory aspects, and future perspectives for chitosan-based functional foods are also discussed.

Keywords: *chitosan, functional foods, nutraceutical delivery, nanofood technologies, bioactive compound encapsulation, sustainable food innovation*

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1. Introduction

The global food industry is currently undergoing a profound and irreversible transformation, largely driven by increasing consumer awareness of the close relationship between diet, health, and overall well-being [1]. Modern consumers are no longer satisfied with foods that merely provide basic nutrition; instead, there is a growing demand for products that can actively contribute to the prevention of chronic diseases, support physiological functions, and promote long-term health [1]. This consideration has significantly accelerated the development and commercialisation of functional foods, a category broadly defined as foods that exert beneficial effects on one or more target functions in the body beyond their conventional nutritional value [2].

The rise of functional foods is closely linked to major global challenges, including the increasing prevalence of non-communicable diseases such as obesity, cardiovascular disorders, diabetes, and gastrointestinal dysfunctions. At the same time, demographic changes, population ageing, and lifestyle-related health issues have further reinforced the need for innovative dietary strategies to support metabolic health, immune function, and gut homeostasis [3]. Within this framework, food science has progressively moved toward an interdisciplinary approach that integrates nutrition, biotechnology, materials science, and advanced processing technologies.

In this context, natural biopolymers have attracted considerable interest as both functional ingredients and enabling technological platforms for the design of health-oriented food products. Biopolymers derived from renewable sources are particularly appealing due to their biodegradability, biocompatibility, and alignment with clean-label and sustainability trends [4]. Unlike synthetic additives, natural biopolymers are generally perceived as safer and more acceptable by consumers, thereby facilitating market uptake and regulatory approval [4]. Moreover, their structural versatility enables them to serve multiple roles in food systems, including texture modification, stabilisation, encapsulation, and the controlled release of bioactive compounds [5].

Among the wide range of biopolymers explored for food applications, chitosan stands out due to its unique combination of technological functionality and intrinsic biological activity. Chitosan is a cationic polysaccharide obtained through the partial deacetylation of chitin, a naturally abundant polymer found in the exoskeletons of crustaceans, insects, and the cell walls of fungi [6]. While initially investigated primarily for medical and pharmaceutical applications, such as wound healing, drug delivery, and tissue engineering, chitosan has progressively gained relevance in food science and technology over the past two decades [6].

The growing interest in chitosan for food applications derives from several distinctive features. From a technological perspective, chitosan exhibits excellent film-forming ability, emulsifying capacity, and water-binding properties, making it suitable for a wide range of food matrices [7]. From a biological and nutritional perspective, chitosan exhibits antimicrobial, antioxidant, hypocholesterolemic, fat-binding, and microbiota-modulating activities that are directly relevant to the formulation of functional and nutraceutical foods [8]. Importantly, chitosan is one of the few dietary polysaccharides with a positive charge under physiological conditions, enabling strong electrostatic interactions with negatively charged molecules such as fatty acids, bile salts, proteins, and bioactive compounds [9].

These interaction capabilities make chitosan a strategic material for next-generation food systems, where the effectiveness of functional ingredients is strongly influenced by their stability, bioaccessibility, and controlled release within the gastrointestinal tract. Chitosan-based systems can be engineered to protect sensitive nutraceuticals from degradation, enhance their solubility and intestinal uptake, and modulate their release in

response to environmental stimuli such as pH or enzymatic activity. As a result, chitosan acts not only as a passive carrier but also as an active contributor to the physiological effects of functional foods [10].

In parallel with its bio-functional properties, chitosan has gained attention in the context of emerging food technologies. Advances in nano- and micro-structuring, encapsulation techniques, and precision processing methods, such as microfluidics and self-assembly, have enabled the development of highly sophisticated chitosan-based delivery systems [11–13]. These technologies support the formulation of functional foods with improved efficacy, reduced dosage requirements, and minimal impact on sensory attributes, addressing some of the key limitations traditionally associated with health-oriented food products [14].

The present review aims to provide a comprehensive and updated analysis of chitosan as a key material in functional food formulation. Compared to previous reviews published over the last five years, this work provides a more integrative and forward-looking perspective by combining technological, nutritional, and sustainability aspects of chitosan within a unified framework. In particular, this review uniquely emphasises: (i) the role of chitosan in next-generation delivery systems (nano/microstructured foods), (ii) its application in synbiotic and multifunctional food systems, and (iii) the emerging transition toward sustainable and green extraction strategies. Additionally, unlike prior reviews that primarily focus on isolated biological effects, this work critically connects physicochemical properties (e.g., molecular weight and degree of deacetylation) with functional performance in complex food matrices and real-world applications.

2. Systematic Methodology

This review was conducted following a structured literature selection approach. Scientific databases, including Scopus, Web of Science, PubMed, and Google Scholar, were systematically searched for relevant articles published between 2015 and 2025. Keywords included “chitosan”, “functional foods”, “nutraceutical delivery”, “bioavailability”, and “food applications”. Inclusion criteria comprised peer-reviewed articles, reviews, and clinical studies focusing on chitosan in food systems. Exclusion criteria included non-English publications, studies lacking experimental validation, and works unrelated to food applications. Priority was given to recent studies (last 5–7 years) and high-impact journals to ensure scientific rigour and relevance.

3. Functional Foods: Concepts and Technological Challenges

Functional foods are designed to modulate specific physiological functions and contribute to the maintenance of health or the reduction of disease risk beyond the provision of basic nutrition [15]. These foods target a wide range of biological processes, including digestion, lipid metabolism, glycaemic regulation, immune response, oxidative balance, and gut microbiota homeostasis [15]. Despite their growing market relevance, the development of functional foods remains technologically challenging. One of the primary limitations lies in the intrinsic instability of many bioactive compounds, including polyphenols, vitamins, carotenoids, polyunsaturated fatty acids, and bioactive peptides. These compounds are often sensitive to processing conditions, including heat, oxygen, light, and pH variations, as well as to interactions with other food components [16]. As a result, significant losses in bioactivity may occur during processing, storage, and digestion, compromising the efficacy of the final product [17]. Another critical challenge in

functional food formulation is the low bioavailability of many health-promoting compounds. Even when bioactives are present in sufficient quantities in the food matrix, their poor solubility, rapid degradation, or limited intestinal absorption can severely reduce their physiological effectiveness [17]. Consequently, enhancing bioaccessibility and controlled release have become central objectives in functional food research. Moreover, sensory quality is an additional, often underestimated barrier to the successful development of functional foods. Many bioactive ingredients impart undesirable tastes, odours, or textures that negatively affect consumer acceptance. Bitterness, astringency, or changes in mouthfeel can limit the inclusion levels of functional ingredients and reduce the commercial viability of health-oriented products [18]. Therefore, modern functional food design must balance physiological efficacy with sensory optimisation [18]. Furthermore, complex interactions between functional ingredients and the food matrix can alter both technological performance and biological activity. Proteins, lipids, carbohydrates, and minerals can interact with bioactive compounds through physical or chemical mechanisms, affecting their stability, release behaviour, and intestinal absorption [19]. In particular, chitosan interacts with complex food matrices through electrostatic interactions, hydrogen bonding, and hydrophobic associations. With proteins, chitosan forms polyelectrolyte complexes that can modify texture and gelation behaviour. In lipid systems, it stabilises emulsions by forming interfacial layers, reducing oxidation. Interaction with polysaccharides can lead to synergistic or antagonistic effects on viscosity and stability. Importantly, these interactions may influence sensory properties, such as mouthfeel, astringency, and viscosity, which are critical for consumer acceptance. Advanced strategies are necessary to effectively control these matrix effects, which are highly dependent on the formulation. In response to these challenges, food science has increasingly employed advanced delivery systems and structuring technologies that protect bioactives, improve their bioavailability, and minimise sensory drawbacks.

4. Biological Activities of Chitosan Relevant to Functional Food

Chitosan is a naturally occurring polysaccharide derived from chitin, the second most abundant biopolymer on Earth after cellulose [20]. Chitin is widely distributed in nature and is a key structural component of the exoskeletons of crustaceans such as shrimp, crabs, and lobsters, as well as of insect exoskeletons and fungal cell walls [20]. Industrially, chitosan is obtained through the partial deacetylation of chitin under alkaline conditions, a process that converts *N*-acetyl-D-glucosamine units into D-glucosamine, yielding a copolymer composed of both monomeric forms [21]. The extent of this deacetylation profoundly influences the physicochemical, biological, and functional properties of the resulting chitosan [21]. Structurally, chitosan is a linear polysaccharide linked by β-(1→4) glycosidic bonds, similar to cellulose but distinguished by the presence of amino groups at the C-2 position [22]. The functional behaviour of chitosan in food systems is governed by several key parameters, including molecular weight, degree of deacetylation, crystallinity, and solubility. Among these, the presence of free primary amino groups represents the most distinctive feature of chitosan, conferring a positive charge under acidic and mildly neutral conditions [22]. This cationic nature distinguishes chitosan from most other dietary polysaccharides, which are typically neutral or negatively charged. The positive charge of chitosan enables strong electrostatic interactions with a wide range of negatively charged molecules, including fatty acids, bile salts, proteins, polysaccharides, and bioactive compounds [23]. These interactions play a central role in determining the technological functionality of chitosan in food matrices, such as

emulsification, stabilisation, and encapsulation, but they are also directly linked to its physiological and biological effects once ingested [23]. As a result, chitosan occupies a unique position at the interface between food structure and biological function.

One of the most extensively studied biological activities of chitosan in relation to functional foods is its hypocholesterolemic and lipid-binding effect. Chitosan can bind dietary lipids and bile acids in the gastrointestinal tract through electrostatic and hydrophobic interactions, reducing lipid absorption and promoting faecal excretion of cholesterol [24]. In addition to lipid modulation, chitosan exhibits significant antimicrobial activity against a broad spectrum of foodborne pathogens and spoilage microorganisms. This antimicrobial effect is primarily attributed to interactions between the positively charged chitosan chains and negatively charged microbial cell membranes, leading to increased membrane permeability, leakage of intracellular components, and inhibition of microbial growth [25]. Chitosan and its low-molecular-weight derivatives, such as chitosan oligosaccharides, have also demonstrated prebiotic-like effects, supporting the growth of beneficial gut bacteria and contributing to intestinal homeostasis [26]. Furthermore, chitosan exhibits antioxidant activity through multiple mechanisms, including free radical scavenging, metal ion chelation, and the stabilisation of oxidative-sensitive compounds [27]. This antioxidant potential enhances the functional value of chitosan-containing foods by contributing to oxidative stress reduction, a key factor in the prevention of chronic diseases such as cardiovascular disorders, neurodegeneration, and metabolic syndrome [27]. In food formulations, chitosan's antioxidant activity also supports the stabilisation of bioactive ingredients and lipid-rich matrices, reinforcing its dual technological and nutritional role. Beyond its intrinsic bioactivities, chitosan serves as an exceptional carrier material for functional ingredients [28]. Its mucoadhesive properties enhance residence time in the gastrointestinal tract, while its pH-responsive solubility enables site-specific release of encapsulated compounds [28]. These characteristics, summarised in Figure 1, are particularly advantageous for the delivery of nutraceuticals, probiotics, enzymes, and plant-derived bioactives, allowing chitosan-based systems to act as multifunctional platforms rather than as inert excipients.

Figure 1. Multifunctional food applications of chitosan, highlighting its biocompatibility and eco-friendly nature.

In addition, the biological activity of chitosan is strongly dependent on its molecular weight (MW) and degree of deacetylation (DD). Low-MW chitosan and chitosan oligosaccharides exhibit higher solubility and bioavailability, resulting in enhanced

antioxidant and antimicrobial effects. Conversely, high-MW chitosan demonstrates stronger film-forming and lipid-binding properties. Similarly, a higher DD increases the density of free amino groups, enhancing electrostatic interactions with negatively charged molecules such as bile acids and fatty acids, thereby improving hypocholesterolemic effects. Table 1 summarises the relationship between MW/DD and biological activity.

Table 1. Relationship between chitosan weight and biological activity.

Chitosan MW/DD	Low MW	High MW	High DD	Low DD
Solubility	High	Low	Moderate	Low
Lipid binding	Moderate	High	High	Moderate
Antimicrobial	High	Moderate	High	Lower
Bioavailability	High	Lower	Moderate	Lower

5. Chitosan as a Functional Ingredient in Food Formulation

Chitosan, formulated as a functional food, can simultaneously fulfil technological and physiological roles. This dual functionality distinguishes chitosan from conventional food additives. From a technological perspective, chitosan contributes to structuring food systems by modifying texture, enhancing water-holding capacity, stabilising emulsions, and improving the physical integrity of complex food matrices [29]. From a physiological perspective, chitosan actively participates in the modulation of lipid metabolism, glycaemic response, gut microbial balance, and nutrient bioavailability, thereby directly supporting functional health claims [29].

The adaptability of chitosan allows its incorporation into a wide range of food matrices, including functional beverages, fermented dairy products, dairy alternatives, bakery goods, cereal-based products, pasta, nutritional bars, and plant-based meat analogues [30]. Numerous studies have demonstrated that chitosan can be integrated with these matrices without compromising product acceptability, while simultaneously enhancing the delivery and efficacy of functional ingredients [30].

One of the most extensively documented applications of chitosan in functional foods concerns its lipid-binding properties and its use in products targeting cardiovascular health. Several studies have reported that chitosan-enriched dairy products, such as yoghurts and fermented milk beverages, are effective in reducing serum total cholesterol and low-density lipoprotein (LDL) levels in both animal models and human intervention trials [31]. In these formulations, chitosan interacts with bile acids and dietary lipids, leading to reduced intestinal absorption and increased faecal excretion of cholesterol [31, 32]. Moreover, this polysaccharide acts as a technological, bactericidal and fungistatic agent [32]. Similarly, incorporating chitosan into bakery products has been shown to impart antimicrobial activity. Low- or medium-molecular-weight chitosan added to bread and biscuits has been shown to increase their resistance to mould while maintaining acceptable texture and sensory properties [33]. In some studies, composite formulations combining chitosan with soluble dietary fibres, such as β-glucans or pectins, further enhanced cholesterol-lowering effects, suggesting synergistic interactions between functional ingredients [34].

Functional beverages and nutritional bars enriched with chitosan have also been investigated as natural preservatives due to chitosan's antimicrobial and antioxidant properties [35].

Beyond cardiovascular health, chitosan has gained increasing attention for the development of functional foods aimed at glycaemic control and management of metabolic syndrome. Multiple studies have demonstrated that chitosan-enriched cereal-based products, including pasta, noodles, and breakfast cereals, are associated with a reduced postprandial glycaemic response compared to conventional formulations [36]. These effects have been attributed to delayed starch digestion, partial inhibition of digestive enzymes, and physical entrapment of carbohydrates within the chitosan-containing matrix [36].

In bakery applications, chitosan-fortified bread and cakes have been shown to lower glycaemic index values while preserving desirable sensory characteristics. Moreover, chitosan oligosaccharides and chitosan affect the rate of staling and the properties of bread crumb and crust [37]. In some formulations, chitosan has been combined with plant proteins or resistant starches, resulting in further improvements in glycaemic regulation and satiety-related outcomes. These composite systems highlight chitosan's potential to act synergistically with other functional ingredients commonly used in metabolic-health-oriented foods.

Protein-enriched functional foods, including meal replacement products and nutrition bars designed for individuals with impaired glucose tolerance, have also incorporated chitosan as a matrix-forming and bioactive component [38]. Experimental studies suggest that such formulations can attenuate glucose absorption and improve sensitivity of insulin markers, reinforcing the relevance of chitosan-based systems in metabolic health strategies [38].

Gut health represents a third major application area in which chitosan has demonstrated significant functional potential. Although chitosan is not classified as a classical fermentable prebiotic, numerous studies have shown that chitosan and chitosan oligosaccharides exert prebiotic-like effects by selectively modulating gut microbiota composition. *In vitro* and *in vivo* studies have reported that chitosan can inhibit pathogenic bacteria such as *Escherichia coli* and *Clostridium* species while promoting the growth of beneficial genera, including *Lactobacillus* and *Bifidobacterium* [39, 40].

Fermented dairy products and dairy alternatives enriched with chitosan demonstrated improved microbial viability during storage and enhanced survival through simulated gastrointestinal conditions. In these systems, chitosan acts both as a protective matrix for probiotic cells and as a modulator of microbial interactions in the gut environment [41, 42].

Synbiotic food formulations combining chitosan with probiotic strains and complementary prebiotic substrates have also been explored in the literature. Such systems have shown promising effects on gut barrier function, immune modulation, and inflammatory markers in preclinical models [42]. In plant-based fermented foods, chitosan has been reported to improve texture and microbial stability while supporting the functional performance of starter cultures [43]. The cited examples are summarised in Table 2.

Although numerous *in vitro* and *in vivo* studies support the biological activities of chitosan, the level of clinical evidence remains heterogeneous. Lipid-lowering effects are supported by both preclinical models and a limited number of human intervention studies, whereas evidence for glycaemic control is primarily derived from preclinical and small-scale clinical trials. Therefore, while the functional potential of chitosan is well-established, further large-scale randomised clinical trials are required to substantiate health claims and support regulatory approval.

Table 2. Chitosan as a functional ingredient.

Matrix	Health effect	[Ref]
yoghurt, fermented milk drinks	cholesterol and LDL reduction; lipid-lowering; chitosan acts as a technological, bactericidal and fungistatic agent	[31, 32]
bakery products (bread, biscuits)	cholesterol-lowering; enhanced satiety; increased resistance to mould formation	[33]
composite formulations combining chitosan with soluble dietary fibres	cholesterol-lowering effects	[34]
functional beverages, nutritional bars	bioactive stabilisation	[35]
pasta, noodles, breakfast cereals	reduced postprandial glycaemic response; carbohydrate digestion modulation	[36]
bakery products (bread, cakes)	lower glycaemic index; enhanced satiety	[37]
protein-enriched bars / meal replacements	glycaemic control; improved insulin response	[38]
fermented dairy / dairy alternatives	gut microbiota modulation; improved probiotic survival	[41, 42]
synbiotic products (probiotics + prebiotics)	enhanced probiotic viability; gut barrier support; immune modulation	[42]
plant-based fermented foods	texture improvement; microbial stability; gut health	[43]

6. Chitosan-Based Delivery Systems for Functional Ingredients

A major challenge in the development of functional foods is the intrinsic instability and poor bioaccessibility of many nutraceuticals, vitamins, and antioxidant compounds [44]. Significant degradation and loss of bioactivity can occur during processing, storage, and digestion, limiting their physiological effectiveness [44]. Chitosan-based delivery systems have emerged as a versatile solution to these limitations, providing both protection and controlled release of bioactive compounds while simultaneously enhancing solubility, stability, and bioavailability [45].

Chitosan can be engineered into various delivery formats, including nanoparticles, nanogels, microcapsules, and composite hydrogels, each offering specific advantages depending on the food matrix and intended physiological effect. Nanoparticles composed of low- and medium-molecular-weight chitosan have been extensively studied for encapsulating polyphenols such as curcumin, catechins, quercetin, and resveratrol. These systems have been shown to markedly improve solubility and protect polyphenols from oxidation during storage and gastrointestinal digestion. For example, curcumin encapsulated in chitosan nanoparticles exhibited enhanced intestinal absorption and sustained antioxidant activity [46], overcoming one of the major hurdles in functional beverage and dairy formulations. Moreover, such devices were used for fibrosis prevention [47]. Similarly, chitosan-based nanocarriers for catechins [48] and resveratrol [49] have been reported to maintain bioactivity under simulated gastric and intestinal

conditions, as confirmed in multiple investigations, indicating the potential for incorporation into beverages, protein bars, and yoghurt-based functional foods.

Carotenoids, such as beta-carotene and lutein, are highly prone to degradation by light and oxygen, limiting their application in functional foods. Chitosan nanogels and microcapsules have been used to enhance the solubility of carotenoids in aqueous matrices and protect them from oxidative damage, as shown by Verardi *et al.* [50]. These systems maintain antioxidant activity and allow controlled release in the intestinal tract, making them suitable for incorporation into functional beverages, dairy alternatives, and bakery products designed for eye health or oxidative stress mitigation.

Vitamins, including water-soluble compounds like vitamin C and fat-soluble compounds such as vitamin D and tocopherols, also benefit from chitosan-based delivery. Microencapsulation and nanoparticle strategies have been shown to increase stability during thermal processing and storage, protect against oxidation, and improve intestinal absorption. For example, Desai *et al.* [51] produced vitamin C-encapsulated chitosan microspheres cross-linked with tripolyphosphate (TPP) using a new spray-drying process, intended for oral delivery of vitamin C in functional food. Similarly, chitosan interacted with DL-alpha-tocopherol via ultrasonication, forming positively charged nanoparticles able to deliver vitamins in food systems [52].

Chitosan has also proven highly effective in the delivery of omega-3 fatty acids, which are highly sensitive to oxidation and prone to developing off-flavours in food systems. Chitosan-based edible microspheres protect these lipophilic compounds, maintain stability, and enable gradual release in the gastrointestinal tract [53], demonstrating enhanced bioaccessibility and retention of physiological activity [53].

A key advantage of chitosan-based delivery systems lies in their pH-sensitive solubility and mucoadhesive properties, which enable targeted and controlled release along the gastrointestinal tract. Chitosan microcapsules and nanoparticles can remain stable in the acidic stomach environment and release bioactives in the neutral to slightly alkaline conditions of the small intestine or colon [54]. Examples of these nanoparticles were used to enhance the adsorption and bioavailability of tea polyphenols [54]. In addition, this property is particularly relevant to functional foods designed for colon health, immune support, or enhanced systemic bioavailability. For instance, chitosan-coated probiotics have been shown to improve survival under gastric conditions and enhance intestinal colonisation, as demonstrated by Edo *et al.* [55]. Table 3 recaps the described applications.

7. Chitosan-Based Systems for Probiotic and Synbiotic Foods

The maintenance of probiotic viability during food processing, storage, and gastrointestinal transit represents one of the most critical challenges in the development of functional foods targeting gut health [56]. Probiotic bacteria, including widely used strains such as *Lactobacillus acidophilus*, *Bifidobacterium bifidum*, and *Lactobacillus rhamnosus*, are highly sensitive to environmental stressors such as low pH, oxygen exposure, heat, and shear forces during manufacturing [57]. Loss of viability can significantly reduce the intended health benefits of probiotic products, making effective protection strategies essential [57]. In this context, chitosan has emerged as a highly promising material for the encapsulation and delivery of probiotics, combining biocompatibility, biodegradability, and functional bioactivity with technological versatility.

Table 3. Chitosan-based delivery systems for functional ingredients.

Chitosan form	Bioactive compound	Delivery advantage	[Ref]
low- to medium-MW chitosan nanoparticles	curcumin	enhanced solubility, protection from oxidation, improved intestinal absorption	[46]
low- to medium-MW chitosan nanoparticles	curcumin	fibrosis prevention	[47]
chitosan nanocarriers	catechins	stabilisation during storage, controlled release, enhanced bioavailability	[48]
chitosan nanocarriers	resveratrol	stabilisation during storage, controlled release, enhanced bioavailability	[49]
chitosan nanogels	carotenoids (β-carotene, lutein)	protection from light and oxygen, improved water solubility, controlled intestinal release	[50]
chitosan microcapsules	vitamin C	thermal protection, oxidative stability, enhanced bioavailability	[51]
chitosan microcapsules	DL-alpha-tocopherol	thermal protection, oxidative stability, enhanced bioavailability	[52]
chitosan microspheres	omega-3 fatty acids	protection from oxidation, gradual release, improved bioaccessibility	[53]
chitosan microcapsules and nanoparticles	tea polyphenols	enhance absorption and bioavailability	[54]
chitosan coating	probiotic bacteria (*Lactobacillus*, *Bifidobacterium*)	enhanced gastric survival, mucoadhesion, improved colonisation	[55]

Chitosan-based microcapsules, nanoparticles, and coating systems have been extensively investigated for their ability to protect probiotics during storage and simulated gastrointestinal conditions. For example, studies by Ji *et al.* [58] demonstrated that probiotics encapsulated in chitosan-based microcapsules retained higher viability compared to free cells under both acidic gastric conditions and bile salt exposure. Chitosan coatings were shown to enhance microbial survival during freeze-drying, spray-drying, and other industrial processing methods, providing a stable delivery platform for functional foods such as yoghurts, fermented dairy alternatives, beverages, and nutritional bars [59].

One of the key advantages of chitosan in probiotic delivery lies in its pH-sensitive solubility and mucoadhesive properties. Orally administered chitooligosaccharides remain intact under acidic gastric conditions and undergo controlled swelling or degradation in the neutral to slightly alkaline environment of the small intestine, enabling the targeted release of probiotics where colonisation and activity are most effective [60]. Similarly, *L. rhamnosus* encapsulated in alginate/chitosan microgels has improved bioavailability, increased capacity to manipulate the gut microbiome, and ameliorates salt-induced hepatorenal injury [61].

Beyond protecting probiotics, chitosan is increasingly used in combination with prebiotics to create synbiotic foods that provide synergistic health benefits. The incorporation of chitosan with prebiotics such as inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), or resistant starch has been shown to enhance the survival and metabolic activity of encapsulated probiotics. These synbiotic formulations improved bacterial viability during storage, increased the production of beneficial metabolites, such as short-chain fatty acids, and supported the maintenance of intestinal barrier integrity in in vitro and in vivo models. Chitosan-prebiotic co-encapsulation strategies have been applied to yoghurt, kefir, fermented plant-based beverages, and probiotic-enriched snack bars, showing consistent improvements in both probiotic survival and functional efficacy. For example, Ismail *et al.* [62] produced functional yoghurt by adding chitooligosaccharides, either in their free or in nano/microencapsulated form. The chitooligosaccharides exhibited potent prebiotic and antioxidant activities. The stability of the yoghurt was enhanced when using the nano- or microencapsulated form.

Chitosan-based systems also offer opportunities for advanced probiotic delivery through nanotechnology. Chitosan nanoparticles, nanogels, and multilayered microcapsules created via electrostatic self-assembly or microfluidic techniques have been shown to further enhance probiotic stability, allow sustained release, and improve adherence to intestinal mucosa. Research by Febrian *et al.* [63] demonstrates that nanoencapsulation not only protects probiotics during gastric passage but also increases colonisation efficiency and enhances immunomodulatory effects. Similarly, Senthil Kumar *et al.* [64] found that chitosan-coated probiotic nanoparticles mitigate acrylamide-induced toxicity, making these systems highly relevant for the next generation of functional synbiotic foods.

Finally, chitosan-based delivery systems can be combined with other bioactive compounds to create multifunctional synbiotic products. For instance, probiotics encapsulated in chitosan along with polyphenols, vitamins, or omega-3 fatty acids benefit from the dual protection offered by the matrix, which stabilises sensitive bioactives while simultaneously enhancing probiotic survival [65]. Such composite systems improve both the physicochemical stability of the food matrix and the physiological functionality of the synbiotic product [65]. Table 4 summarises the cited studies.

8. Challenges and Future Perspectives

Despite the growing interest and numerous promising applications of chitosan in functional foods, several challenges remain that must be addressed to fully exploit its potential and to facilitate widespread industrial adoption. One of the primary limitations is the variability in chitosan properties arising from differences in source material, degree of deacetylation, molecular weight, and production methods. Chitosan derived from crustacean shells, although widely available, presents issues related to allergenicity, batch-to-batch variability, and environmental impact due to the chemical-intensive extraction and deacetylation processes [66]. In particular, chitosan derived from crustaceans may pose allergenicity risks in sensitive individuals due to residual proteins. However, highly purified chitosan typically shows minimal allergenic potential. Long-term dietary intake studies suggest acceptable tolerability, although excessive consumption may interfere with the absorption of fat-soluble vitamins and minerals. On the other hand, fungal-derived chitosan offers a more sustainable and hypoallergenic alternative, but large-scale production remains limited and more expensive, requiring the optimisation of fermentation and extraction technologies to achieve food-grade purity at competitive costs [67].

Table 4. Chitosan-based systems for probiotic and synbiotic foods.

Chitosan form	**Probiotic / prebiotic**	**Delivery advantage**	**[Ref]**
chitosan microcapsules	*L. acidophilus*, *B. bifidum*	enhanced survival during storage and gastric passage	[58]
chitosan coating	*L. rhamnosus*	protection from acid and bile; improved intestinal colonisation	[59]
chitooligosaccharides	*L. acidophilus, B. bifidum*	enhanced survival during storage and gastric passage	[60]
alginate/chitosan microgels	*L. rhamnosus*	enhanced survival during storage and gastric passage	[61]
chitooligosaccharides	*L. acidophilus, B. bifidum*	synbiotic effect; improved storage stability and metabolic activity	[62]
nano-chitosan	multi-strain probiotics	protection under acidic conditions; sustained release	[63]
chitosan nanoparticles	multi-strain probiotics	protection under acidic conditions; sustained release	[64]
chitosan delivery systems	probiotics + bioactives	stabilisation of probiotics and bioactives; enhanced gut functionality	[65]

Another key challenge lies in the integration of chitosan into complex food matrices. Chitosan's solubility is strongly pH-dependent, and its cationic nature may interact with proteins, polysaccharides, and minerals, potentially altering texture, mouthfeel, and sensory perception. Formulating chitosan-containing functional foods thus requires careful optimisation to balance technological performance with consumer acceptability [67]. Additionally, while numerous *in vitro* and *in vivo* studies have demonstrated the health-promoting effects of chitosan, including lipid-lowering, glycaemic control, antioxidant activity, and modulation of the microbiota, translating these effects into consistent clinical outcomes remains challenging. Factors such as dosage, molecular weight, degree of deacetylation, and food matrix interactions critically influence bioavailability and physiological efficacy, emphasising the necessity of standardised formulations and clinical validation [68].

Advanced food processing technologies offer promising avenues to overcome these challenges. Techniques such as microfluidic-assisted encapsulation, electrostatic self-assembly, nano- and microencapsulation, and layer-by-layer coating can significantly improve the stability, solubility, and targeted delivery of chitosan and its co-encapsulated bioactives [69]. These strategies enhance functional performance and enable the design of "smart" foods with controlled release, site-specific delivery in the gastrointestinal tract, and synergistic combinations with other bioactives such as polyphenols, vitamins, and probiotics [70]. Nevertheless, the large-scale implementation of these technologies remains challenging, particularly in ensuring cost-effectiveness, food safety, and regulatory compliance. A key limiting factor is the variability in regulatory frameworks governing chitosan across different regions. In the European Union, chitosan falls under the Novel Food Regulation, with its use subject to restrictions based on source and intended application, alongside stringent evaluation of health claims by EFSA. In contrast,

in the United States, chitosan is generally recognised as safe (GRAS) for certain applications, although any associated health claims require approval from the Food and Drug Administration (FDA). In several Asian countries, including Japan and China, chitosan enjoys broader acceptance in functional foods and nutraceutical products, supported by more established and flexible regulatory pathways. These regional discrepancies represent a significant barrier to the global commercialisation and market expansion of chitosan-based functional foods.

In parallel, sustainability considerations are becoming central to the future of chitosan-based functional foods. Traditional chitosan production from crustacean shells relies on aggressive chemical treatments and generates significant waste streams, raising environmental concerns [71]. Green extraction methods, including enzymatic deacetylation, subcritical water processing, deep eutectic solvents, and microbial fermentation, are being actively explored as sustainable alternatives [71]. These methods minimise the use of chemicals, reduce energy consumption, and enable the valorisation of marine and agricultural by-products, contributing to circular-economy approaches in food production [72, 73]. Additionally, integrating chitosan-based formulations with eco-friendly food processing technologies, such as high-pressure processing, pulsed electric fields, ultrasound-assisted emulsification, and spray-freeze drying, can improve bioactive retention and functional efficacy while lowering the environmental footprint [74]. While these approaches significantly reduce environmental impact and chemical waste, their industrial scalability remains limited due to higher costs, longer processing times, and lower yields. Therefore, further optimisation is required before large-scale implementation. As a result, several research and development directions are crucial to increase the potential of chitosan in functional foods. These include: (i) systematic evaluation of the structure-function relationships of chitosan with respect to molecular weight, degree of deacetylation, and source, (ii) development of standardized, scalable, and green production processes for high-purity, food-grade chitosan, (iii) integration of chitosan with cutting-edge encapsulation, nano-delivery, and synbiotic technologies for multi-targeted functional foods, (iv) comprehensive *in vivo* and clinical studies to validate health claims, and (v) exploration of synergistic combinations with other bioactive compounds to enhance efficacy and sensory acceptance. Overall, the challenges and perspectives of chitosan in food products are presented in Figure 2.

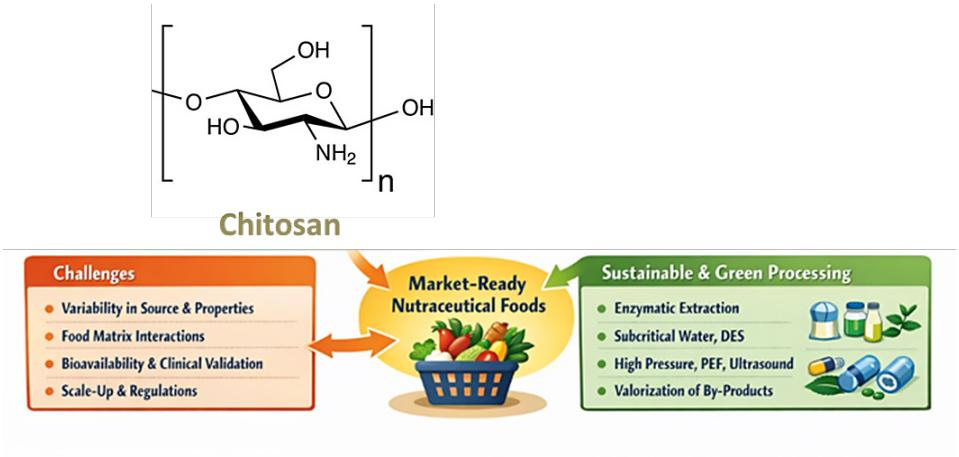

Figure 2. Chitosan in functional foods: challenges and perspectives.

9. Conclusions

Chitosan has emerged as a highly versatile and multifunctional biopolymer with significant potential in the development of next-generation functional foods. Its unique combination of physicochemical properties, including cationic charge, mucoadhesiveness, pH-responsive solubility, and biocompatibility, enables a wide range of applications, from lipid-lowering and glycaemic control to gut health modulation and antioxidant delivery. The ability of chitosan to interact with proteins, polysaccharides, lipids, and bioactive compounds allows for the design of functional foods that not only enhance nutritional profiles but also improve the bioavailability and targeted delivery of physiologically active ingredients. Moreover, chitosan's role as a carrier for probiotics, synbiotics, and nutraceutical compounds leads to the creation of complex food. The research highlighted in this review demonstrates that chitosan-based delivery systems, including nanoparticles, nanogels, microcapsules, and multilayered coatings, can significantly enhance the stability, solubility, and controlled release of bioactives, ensuring their efficacy in diverse food matrices such as beverages, dairy products and bakery goods. Encapsulation of vitamins, polyphenols, carotenoids, omega-3 fatty acids, and probiotics in chitosan matrices has consistently been shown to protect these sensitive compounds from degradation, improve their gastrointestinal survival, and facilitate targeted release at specific sites within the intestine. Furthermore, the incorporation of chitosan with prebiotics into synbiotic formulations provides synergistic health benefits, enhancing microbial colonisation, modulating gut microbiota composition, and contributing to immune system support.

Despite its activities, the use of chitosan in functional foods is not without challenges. Variability in source material, degree of deacetylation, and molecular weight can affect its technological performance and bioactivity, while interactions with complex food matrices can influence sensory properties and consumer acceptability. Additionally, further clinical validation is required to standardise dosages, confirm health claims, and ensure consistent outcomes across populations. The adoption of sustainable, green food-processing technologies is a critical direction for the future development of chitosan-based functional foods. Innovations such as enzymatic extraction, microbial fermentation, deep eutectic solvents, and subcritical water processing provide environmentally friendly alternatives to traditional chemical-based production. Integration with advanced processing techniques, including high-pressure processing, ultrasound-assisted emulsification, and microfluidic encapsulation, enables the production of stable, high-quality functional foods while aligning with the principles of circular economy and clean-label manufacturing. Moreover, the integration of chitosan into personalised nutrition and targeted dietary interventions will lead to the creation of nutraceutical-grade foods that deliver precise physiological effects.

In conclusion, chitosan represents a unique biopolymer that combines technological versatility, physiological functionality, and sustainability potential. Its integration into functional food design not only enhances the stability and bioactivity of key nutrients and probiotics but also supports the development of innovative, eco-conscious, and health-promoting food products. As research continues to expand, chitosan-based functional foods will play a central role in shaping the future of nutrition.

10. Author Contributions

Conceptualisation, R.C., R.P.D., and G.P.; methodology, R.P.D. and A.D.L.; resources, A.D.L. and G.P.; data curation, R.C. and G.P.; writing—original draft preparation, R.P.D.

and R.C.; writing—review and editing, R.P.D., R.C., and G.P.; visualisation, A.D.L.; supervision, R.C. and G.P.; project administration, A.D.L. and G.P.; funding acquisition A.D.L. and G.P. All authors have read and agreed to the published version of the manuscript.

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