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# Chitosan, a multifunctional biopolymer: bridging technological innovation in Food Processing and sustainable health promotion (Review Article)

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**Abstract**: This review will focus on the nature of chitosan, its sources, extraction modes and its applications in food preservation and food packaging, its health and pharmaceutical applications. Chitosan is a cationic polymer of chitin, which is found in abundance in the exoskeletons of crustaceans, insects and arthropods and in certain other organisms like fungi. Chemical processes that are used to extract chitin include deproteinization and demineralization of proteins and minerals followed by deacetylation of the end product, to form chitosan. Other alternatives include enzymatic extraction, assisted by the use of enzymes such as papain, trypsin and pepsin or biological extraction through fermentation of microorganisms which is more in line with the concept of the sustainability. Chitosan is characterized by its biodegradability and biocompatibility, in addition to its antimicrobial properties and potent cationic nature, making it a promising material for food preservation and packaging applications. It is also used in the development of drug delivery systems, particularly in its nanoscale form, where its physical and chemical properties can be modified to improve the efficiency of loading and releasing therapeutic compounds. Studies also indicate that chitosan may contribute to improving certain indicators associated with metabolic disorders, such as cholesterol levels and glucose balance, especially when used in soluble nanoparticle formulations prepared using methods such as ionization and spray drying, which have shown promising results in animal models fed high-fat diets.

**Key words**: Chitosan, marine shellfish, Chitosan Production, Applications, Glucose Balance, Obesity Treatment.

## 1. Introduction

Chitin was first discovered by its name from the Greek word "chiton", which means "mail coat". It in fact is a polysaccharide comprised of acetyl-D-glucosamine monomers that occur naturally. In 1799, the first scientist to remove chitin was Hatchett who used the shell of mollusks (crabs and lobsters), prawns, and crayfish. Later in 1811, Henri Braconnot discovered chitin in the cell walls of mushrooms and called it "fungine". The biosphere has been found to be rich in chitin and chitosan, which are important substances in the exoskeleton of numerous organisms, and as by-products of the world seafood sector **(Iber *et al*., 2022).**

Chitosan is a natural biopolymer, a linear polysaccharide derived from chitin, consisting primarily of D-glucosamine units linked by β-(1→4) bonds **(Valachová & Šoltés,2021; Takeuchi *et al*., 2024)**. Chitosan is produced through the deacetylation of chitin, in which acetyl groups are removed from N-acetyl-D-glucosamine to form free glucosamine units **(Osemba *et al*., 2024).** It is also widely found in the exoskeletons of crustaceans and in fungal cell walls, making it one of the most abundant and widely used natural polymers in various biological fields **(Yadav *et al*., 2024)**. There is great scientific and practical interest in chitin and chitosan due to their unique properties such as biocompatibility, safety, biodegradability and adsorption performance of heavy metals and radionuclides **(Novinyuk *et al*., 2018)**, its production has increased significantly in recent years, and chitosan has been widely used in various fields of technology, medicine, and food manufacturing **(Tyliszczak *et al*., 2019)**. Its properties are greatly affected by its molecular weight, which ranges from 2 to more than 200 kDa, as well as the degree of deacetylation which affects its solubility in acid, if the degree is more than 55%, it is soluble in 1% acetic or hydrochloric acid **(Wang & Chen, 2014)**. The presence of reactive amino groups at C2 atom and hydroxyl groups at C3 and C6 atoms of chitosan which makes it useful in wide applications in various industries **(Al-Jbour *et al*., 2019)**. Recently, chitosan has received great attention in the biomedical field due to its valuable biochemical and physiological properties **(Ssekatawa *et al*., 2021)**.

### Chemical structure of chitin and chitosan

Chitosan is composed of β-(1,4)-d-poly-glucosamine after removing the polyacetyl group from chitin (β-(1,4)-N-acetyl-d-glucosamine) as shown in Figure (1).

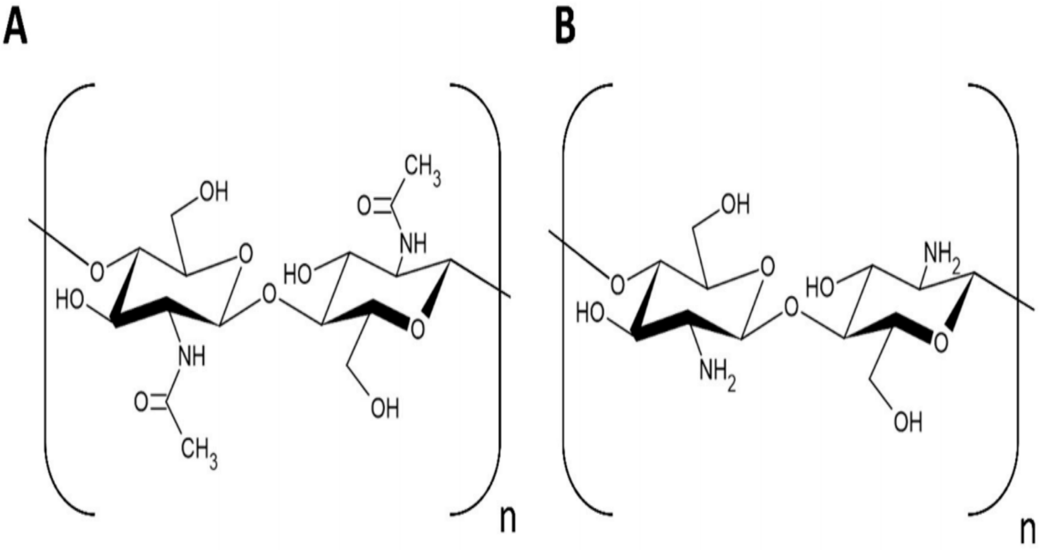


**Figure (1). Structure of: (A) chitin and (B) chitosan (Kozma *et al*., 2022)**

### Chitosan sources

Chitosan can be produced from the chitin of insects, yeast, fungi, the cell wall of fungi, and marine shellfish such as crabs, lobsters, squid, and shrimp as shown in Figure (2) and Table (1). In shellfish, chitin forms an outer protective layer as a network covalently linked to proteins, some minerals, and carotenoid residues **(Jo *et al*., 2011)**.

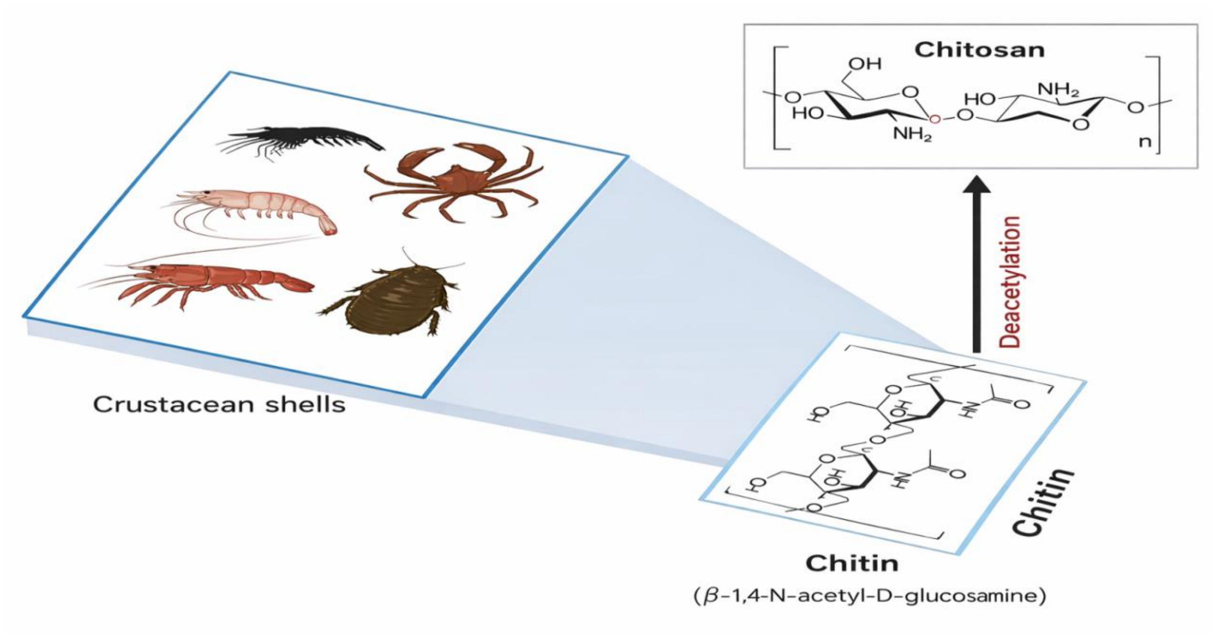
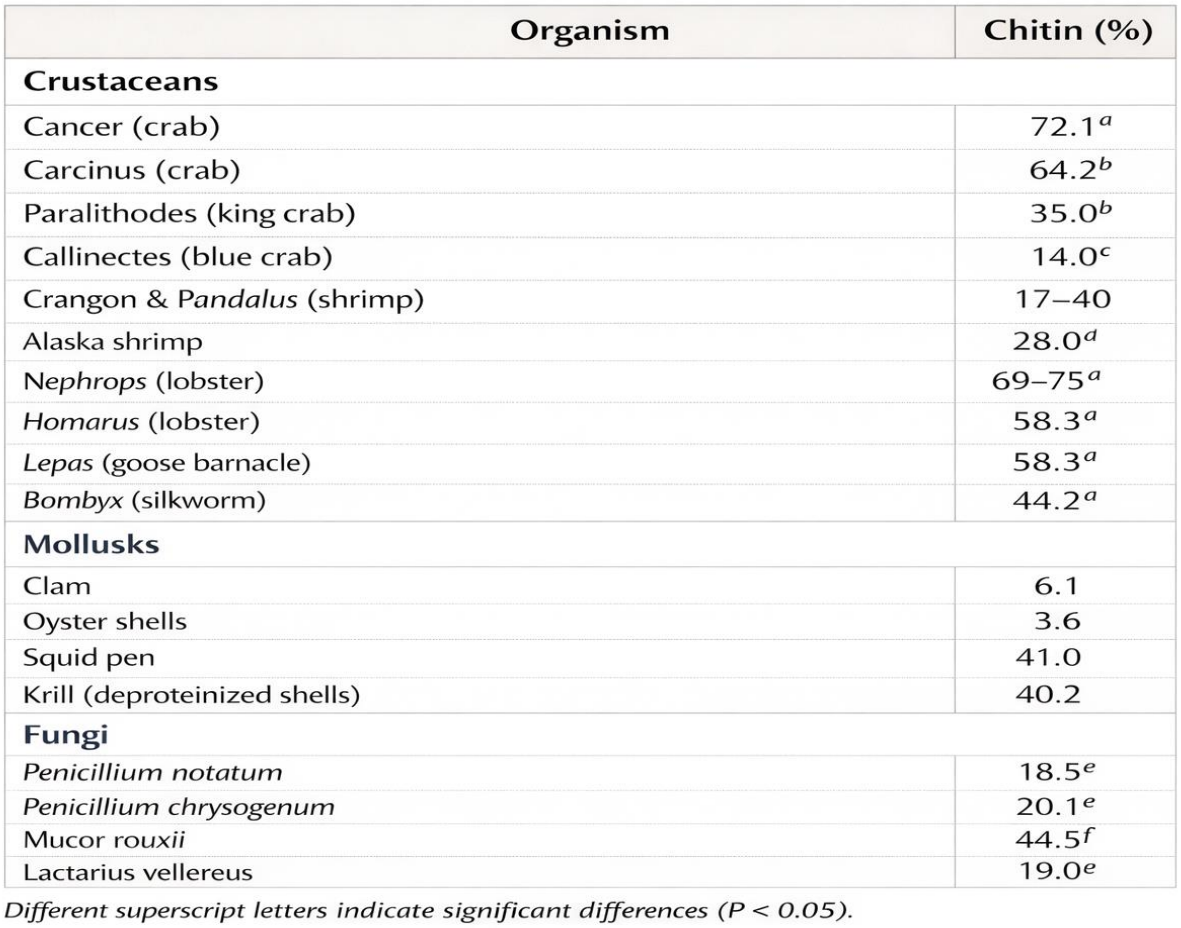


**Figure (2). Sources of chitosan (Abd El-Hack *et al.*, 2023)**



| Organism | Chitin (%) |
|---|---|
| **Crustaceans** | |
| Cancer (crab) | $72.1^a$ |
| Carcinus (crab) | $64.2^b$ |
| Paralithodes (king crab) | $35.0^b$ |
| Callinectes (blue crab) | $14.0^c$ |
| Crangon & *Pandalus* (shrimp) | 17–40 |
| Alaska shrimp | $28.0^d$ |
| *Nephrops* (lobster) | $69–75^a$ |
| *Homarus* (lobster) | $58.3^a$ |
| *Lepas* (goose barnacle) | $58.3^a$ |
| *Bombyx* (silkworm) | $44.2^a$ |
| **Mollusks** | |
| Clam | 6.1 |
| Oyster shells | 3.6 |
| Squid pen | 41.0 |
| Krill (deproteinized shells) | 40.2 |
| **Fungi** | |
| *Penicillium notatum* | $18.5^e$ |
| *Penicillium chrysogenum* | $20.1^e$ |
| Mucor rouxii | $44.5^f$ |
| Lactarius vellereus | $19.0^e$ |

*Different superscript letters indicate significant differences ($P < 0.05$).*

**Table (1). Chitin contents in various commercially important organisms (Kurita, 2006; Jo *et al.*, 2011)**

## Physical and Chemical Properties of Chitosan

The chitosan solution extracted from crab shells showed a yellow color after the removal of the acetylated and mineral components, and the water binding capacity was about 69%, while the lipid binding capacity was about 56%. Chitosan extracted from these crab shells exhibited an 89.5% deacetylation (DD), which was found to be effective and efficient in reducing and stabilizing silver nanoparticles from silver ions. These values were consistent with previous studies using shrimp shells in the synthesis of silver nanoparticles **(Osemba *et al*., 2024)**. The widespread use of chitosan in the preparation of nanoparticles is attributed to its properties of low toxicity and biocompatibility **(Spósito *et al*., 2024)**, as well as its biodegradability and environmentally friendly nature, in addition to its cationic nature and ease of chemical modification, making it a versatile material in industrial, food and environmental applications **(El-Araby *et al*., 2024)**. Chitosan contains active functional groups, such as a primary amino group at carbon C2, and primary and secondary hydroxyl groups at carbons C6 and C3. It also includes glycosidic bonds and acetamide groups. These functional groups allow for extensive chemical modifications, leading to the formation of polymers with distinctive properties and behaviors **(Edo *et al*., 2025)**. Chitosan is a pH-sensitive polymer. It is practically insoluble in neutral or basic solutions due to the amino groups remaining in their unionized form ($-NH_2$), resulting in chain convergence and aggregation. However, it dissolves in acidic solutions due to the protonation of these groups, transforming them into the charged form ($-NH_3^+$). This increases the hydrophilicity of the chains, leading to their dissociation and diffusion through electrostatic repulsion **(Sikorski *et al*., 2021)**. This behavior is related to chitosan's pKa value of approximately 6.5. It becomes soluble when about 50% of the amino groups are protonated. A higher pH leads to deprotonation and a decrease in positive charge, which enhances the interactions between the chains, causing them to aggregate and resulting in decreased solubility or precipitation **(Aranaz *et al*., 2021; Liu *et al*., 2023)**. This change in ionization state is also reflected in the interactions between the chains and the rheological properties. Solubility does not depend solely on pH, but is also affected by the degree of deacetylation and molecular weight, as it increases with increasing degree of deacetylation and decreasing molecular weight **(Araújo *et al*., 2025)**. Chitosan is insoluble in alcohols such as methanol or ethanol, or in acetone alone. However, chitosan can be dissolved in acidic aqueous solutions. This solubility is primarily due to the proteation of the amine groups in its structure, which causes it to acquire a positive charge and transform into a soluble polymer **(Yadav *et al*., 2023)**. Furthermore, a study by **Huaytragul *et al*. (2021)** demonstrated that using water-ethanol mixtures enhances chitosan solubility in membrane-forming systems. The molecular weight of chitosan varies within a wide range depending on its source and extraction conditions, typically ranging from 100,000 to 1,200,000 Daltons, with the possibility of extending to lower or higher values depending on the degree of processing. This variation directly affects its solubility and behavior in solutions **(Román-Doval *et al*., 2023)**.

## Chitosan Production

### 1- The chemical method

The key processes in the production of chitosan include the extraction of chitin in crustacean shells, such as demineralization, deproteinization, and deacetylation (Figure 3-A) **(Reshad *et al*., 2021; Kou *et al*., 2021)**. Washing, drying, and grinding of the residue are the initial stages to make the raw material **(Kandile *et al*., 2018)**. Hydrochloric acid and sodium hydroxide are then used to perform the demineralization process, and semi-pure chitin is obtained **(Hisham *et al*., 2021; Hosney *et al*., 2022)**. Chitin is then converted to chitosan through deacetylation with sodium hydroxide in alkaline and high-temperature conditions as **Varun *et al*. (2017)** reported a maximum of 50 percent concentration of alkali and 70-90C or higher temperatures. It will also demand a deacetylation of about 70-90% to produce chitosan with desirable characteristics but this procedure is dependent on severe operating conditions and can be damaging to the environment **(Mersmann *et al*., 2025)**. Conversely, recent research has revealed that with the application of sophisticated methods like enzymatic or microwave-assisted chitosan synthesis, low molecular weight chitosan with high solubility and bioactivity is produced as opposed to conventional methods. These techniques also contribute to reducing reaction time and improving product purity and functional properties, thus enhancing its suitability for food and pharmaceutical applications **(Younes & Rinaudo, 2015; Mersmann *et al*., 2025)**.

### 2- The Biological Method

A new approach to chitosan production is the biological method that is a variation of the chemical one. It is based on the application of microorganisms or enzymes under controlled operating conditions, thereby limiting the utilization of harsh chemicals and eliminating the environmental impacts related to production processes **(Younes & Rinaudo, 2015)**. The enzymatic method and the fermentation method are the two primary routes in which this method can be adopted **(Reshad *et al*., 2021)**.

### Two methods can be used in the biological method

### A- The Enzymatic Method:

The enzymatic technique is based on the substitution of chemicals employed in the process of removing proteins and minerals with special enzymes like papain, trypsin, alcalase and pepsin. The enzymes are essential in degradation of the proteins attached to the raw material. They are then followed by additional procedures, such as inactivation of enzymes, then centrifugation is performed to isolate the components. The protein is concentrated in the liquid (supernatant) and freeze-dried (Figure 3-B). and the chitin is concentrated at the base. The resulting precipitate is washed using water, ethanol and acetone to get pure chitin and the filtrate which contains many hydrolyzed proteins can be used in the production of peptides that have a nutritional or functional use. This technique is distinguished by a reduced level of chemical consumption when compared to the traditional technique, and it can entail more operation stages **(Reshad *et al*., 2021)**.

### B- Fermentation Method

The fermentation method for producing chitosan relies on the use of microorganisms such as Lactobacillus plantarum, Bacillus subtilis, and Pseudomonas aeruginosa, among others. These organisms are used to biologically process crustacean waste. The process begins by collecting and grinding shrimp or crustacean waste, then mixing it with distilled water and a suitable carbon source. This mixture is then incubated under conditions conducive to microorganism growth, typically at around 37°C, for two to three days. During fermentation, the microorganisms produce organic acids, such as lactic acid, which react with the calcium carbonate in the shells to form removable calcium lactate, thus removing minerals. Proteins are partially removed through autolysis or by enzymes produced by the microorganisms, a phenomenon common in fish and crustacean waste. After the fermentation period, the mixture is filtered to isolate the protein-containing filtrate, and the solid product, which contains chitin, is obtained, thoroughly washed to eliminate impurities, and converted to chitosan by deacetylation (Figure 3C). Compared to the chemical method, it is more environmentally friendly and may slow down but this method demands a high level of control over the operating conditions **(Reshad *et al*., 2021; Huq *et al*., 2022)**. Lastly, chitin is converted to chitosan by the removal of acetyl groups by enzymatic or mildly alkali-based processes which is used to conserve the molecular structure of the polymer. Although this bioprocessing method offers numerous benefits to the environment, its use in industry is limited because of the low reaction rate, and the operating conditions are hard to control in comparison to the traditional chemical counterparts **(Younes and Rinaudo, 2015)**.

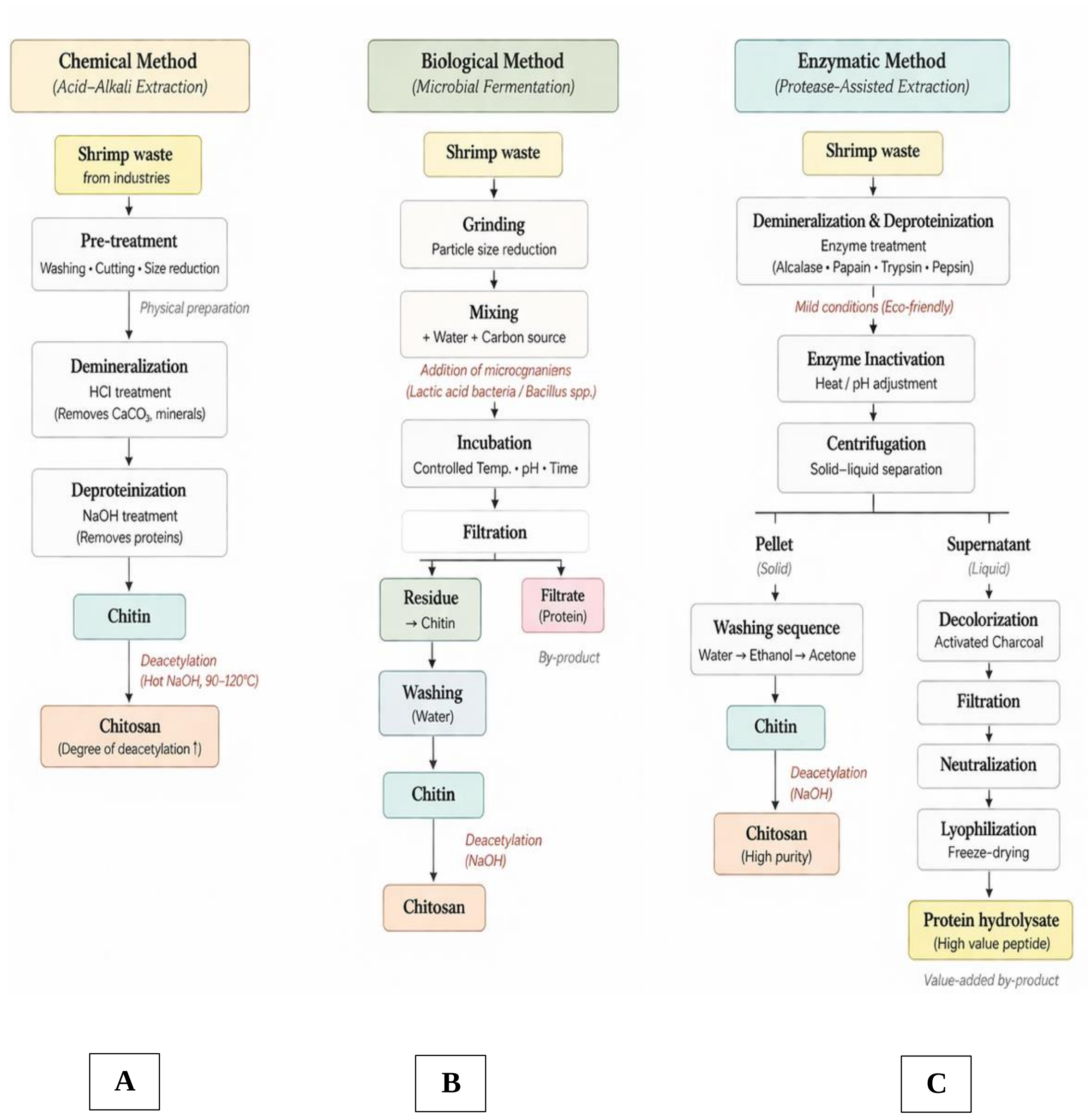


**Figure (3). A: Production flowchart of chitin and chitosan by chemical method. B: Production flowchart of chitin and chitosan by enzymatic method. C: Production flowchart of chitin and chitosan by fermentation method (Reshad,2021).**

## 3- Modern, Environmentally Friendly Chitosan Production Methods

In recent years, there is an increasing concern in the development of modern and environmentally friendly approaches to the production of chitosan. This is to minimize the environmental impact of the conventional ways of using harsh acids and bases, and the physical and chemical properties of the recovered polymer. This method has been recently shown to be in line with the principles of green chemistry and industrial sustainability, especially in food and medical use, where safe and biodegradable materials are required **(Pellis *et al*., 2022; Mohan *et al*., 2022)**.

Another application of ultrasonic processing is in the production of chitosan. This is based on the principle of the acoustic cavitation phenomenon that helps to dissolve the solid structure of chitin and makes the solutions more permeable to the polymer structure. This enhances efficiency of protein removal and deacetylation and minimizes the severity of chemical processing. Nevertheless, the method is mostly applied as a supplementary tool and not regarded as a separate production method **(Younes & Rinaudo, 2015)**. Similarly, recent evidence has demonstrated that energy-assisted technologies, e.g., ultrasound and microwaves, are helpful in enhancing mass transfer and breaking down cellular structures. This results in less time of extraction and less solvent and chemical use and does not compromise the biological activity of the compounds. These results indicate that it could be possible to exploit these physical principles to increase the extraction efficiency of biopolymers, such as chitosan, when used under appropriate operating conditions **(Liu *et al*., 2023)**.

Subcritical water has also proved to be an encouraging alternative in chitin purification and minimizing chemical contaminants, especially in high purity applications. Subcritical water has become an attractive alternative to chitin purification and reduction of various contaminants as it is defined by the capacity to eliminate bioactive substances like proteins under environmentally friendly circumstances. Research has also indicated that the process can be implemented in processing steps to enhance extraction and quality of raw materials. Nevertheless, the alkali treatment is still necessary in the process of deacetylation, which means that it does not fully replace the traditional ones **(Matouri *et al*., 2024; Mersmann *et al*., 2025)**. Resting on the foregoing, it is evident that modern green technologies of chitosan manufacture are diverse, and thus products with different physical and chemical characteristics can be obtained. The type of technology to be used depends on the nature of the application and the purification degree needed. Research also shows that the adoption of these technologies is an encouraging trend towards having a more balanced approach to production, quality of products, and environmental sustainability **(Pellis *et al*., 2022; Mohan *et al*., 2022)**.

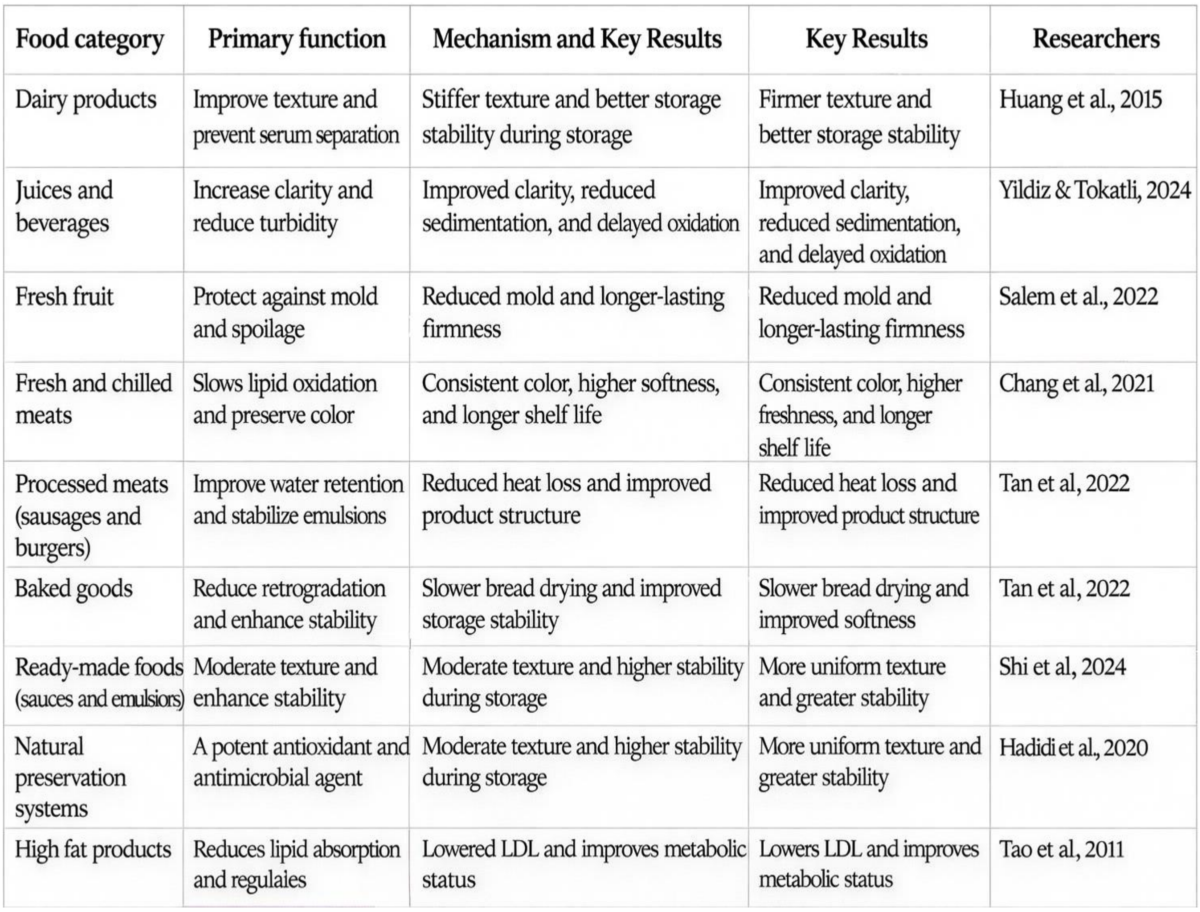
## Chitosan Applications in Food Preservation

Chitosan is a promising biopolymer in the field of food preservation due to its cationic nature and antimicrobial activity, making it effective in extending the shelf life of food products **(Hu & Gänzle, 2019)**. These properties are linked to its linear structure, which contains active functional groups, particularly amine ($NH_2$) and hydroxyl (OH) groups, giving it a high capacity for interaction with molecules and biofilms **(Al-Jbour *et al*., 2019)**. These groups also contribute to enhanced electrostatic interactions, hydrogen bonding, and hydrophobic interactions, in addition to chitosan's ability to chelate certain metals **(Wang & Chen, 2014)**. Chitosan can be used in food applications in various technical forms, such as solutions, powders, fibers, and biofilms, depending on the nature and purpose of the application **(Tan *et al*., 2022)**. It is also used in the development of biocompatible packaging materials due to its mechanical properties, such as tensile strength and elongation, making it suitable for improving the properties of polymer membranes **(Kumar *et al*., 2020)**.

It can be incorporated into composite systems or nanocarriers to enhance its functional properties and expand its applications **(Osorio-Alvarado *et al*., 2022)**. The antimicrobial effect of chitosan is attributed to its electrostatic interaction with the cell wall of microorganisms, leading to altered cell membrane permeability and disruption of vital functions **(Hu & Gänzle, 2019)**. It can also enhance membrane permeability and contribute to significant cell damage, as demonstrated in studies examining its effects on fungal cells **(Lo *et al*., 2020)**, Chitosan applications are detailed in Table 2.

Within the framework of nano systems, a research by **Ge *et al*. (2024)** has shown that chitosan-bound silver nanoparticles (CS-AgNPs) have strong antibacterial effects. These particles retained their spherical shape and size of about 20 nm with little influence by changes in the chitosan concentration over different preparation conditions and a higher chitosan concentration also substantially improved the antibacterial activity owing to its interaction with the peptidoglycan layer of the cell wall. The experiment established the effectiveness of these particles against Escherichia coli and Staphylococcus aureus and their capability to prevent bacterial growth through the use of biostaining/dead staining methods, meaning that they are broad-spectrum antibacterial agents.

**Table (2). Applied uses of chitosan in different food categories**



| Food category | Primary function | Mechanism and Key Results | Key Results | Researchers |
|---|---|---|---|---|
| Dairy products | Improve texture and prevent serum separation | Stiffer texture and better storage stability during storage | Firmer texture and better storage stability | Huang et al., 2015 |
| Juices and beverages | Increase clarity and reduce turbidity | Improved clarity, reduced sedimentation, and delayed oxidation | Improved clarity, reduced sedimentation, and delayed oxidation | Yildiz & Tokatli, 2024 |
| Fresh fruit | Protect against mold and spoilage | Reduced mold and longer-lasting firmness | Reduced mold and longer-lasting firmness | Salem et al., 2022 |
| Fresh and chilled meats | Slows lipid oxidation and preserve color | Consistent color, higher softness, and longer shelf life | Consistent color, higher freshness, and longer shelf life | Chang et al, 2021 |
| Processed meats (sausages and burgers) | Improve water retention and stabilize emulsions | Reduced heat loss and improved product structure | Reduced heat loss and improved product structure | Tan et al, 2022 |
| Baked goods | Reduce retrogradation and enhance stability | Slower bread drying and improved storage stability | Slower bread drying and improved softness | Tan et al, 2022 |
| Ready-made foods (sauces and emulsions) | Moderate texture and enhance stability | Moderate texture and higher stability during storage | More uniform texture and greater stability | Shi et al, 2024 |
| Natural preservation systems | A potent antioxidant and antimicrobial agent | Moderate texture and higher stability during storage | More uniform texture and greater stability | Hadidi et al., 2020 |
| High fat products | Reduces lipid absorption and regulaies | Lowered LDL and improves metabolic status | Lowers LDL and improves metabolic status | Tao et al, 2011 |

## Chitosan and Its Applications in Food Packaging

Biodegradable plastics are described as the materials, which could be broken down into simple compounds like water and carbon dioxide through the work of microorganisms, including bacteria, fungus and algae. This breakup is determined by the environmental conditions around it, the character of the raw material and the chemical structure and molecular makeup of the resulting polymer **(Haider *et al*., 2019; Letcher, 2020)**.

Polylactic acid (PLA) is a biodegradable biopolymer used in food packaging applications. However, its functional properties can be enhanced by combining it with natural polymers such as chitosan. Studies have shown that incorporating chitosan into polymer systems imparts distinct functional properties, particularly antimicrobial activity and structural modification capabilities, thus improving the efficiency of bio-packaging materials **(Sharma *et al*., 2020; Santos *et al*., 2020)**. **Elsawy *et al*. (2016)** demonstrated that adding chitosan to a PLA matrix affects mechanical properties, exhibiting improvements in ductility and impact resistance. Other properties may also be affected depending on the addition percentage and the interaction between the components. Similarly, **Han *et al*. (2018)** indicated that combining chitosan with PLA results in the formation of membranes with a controllable porous structure, which impacts their functional properties, such as permeability and biodegradability. Therefore, combining chitosan with PLA is a promising approach to improving the performance of bio-coating materials, with the need to control the composition of the polymer system to achieve a balance between mechanical properties and biodegradability. Other studies have shown that incorporating chitosan with synthetic polymers such as polyethylene enhances biodegradability compared to conventional membranes. When using compatibility enhancers, e.g. polyethylene-graphite-maleic anhydride (PE-g-MA) enhances the homogeneity of the components in the polymer matrix, which contributes to balancing mechanical properties and biodegradability without severely affecting thermal stability **(Lizárraga-Laborin *et al*., 2018)**. As such, chitosan is a promising resource in the creation of sustainable food packaging materials, as it is an antimicrobial and biodegradable material, and also enhances the performance of other biopolymers, which is the direction towards the decrease in the use of the traditional plastics and the sustainability in the food industries **(Sharma *et al*., 2020; Santos *et al*., 2020)**.

**Chang *et al*. (2021)** made chitosan-polylactic acid (PLA) composite films by extrusion. The findings revealed that the chitosan/PLA films were very effective in preventing the growth of different microorganisms, decreasing the total volatile nitrogen (TVB-N) content, and increasing shelf life (around 15 days) of fresh shrimp when packaging the product with 1% chitosan without affecting the acceptable sensory and chemical properties. The effectiveness of these films is determined by a number of factors including the content of chitosan, the film thickness and the conditions of film preparation which subsequently influence the permeability of the film and its protective property.

Within the framework of creating bio-coating materials, **Tan *et al*. (2022)** suggested that it could be possible to enhance the mechanical characteristics of starch-based biofilms through chitosan reinforcement. The findings indicated a tensile strength and elongation at break increase, and a considerable reduction in water absorption in comparison to films prepared using pure starch, indicating a change in polymer network structure. This enhancement in the structure has a direct effect on degradation behavior. The same study showed that chitosan-reinforced films lost less weight during storage than pure starch and thus degraded relatively slower as shown in Figure 4.

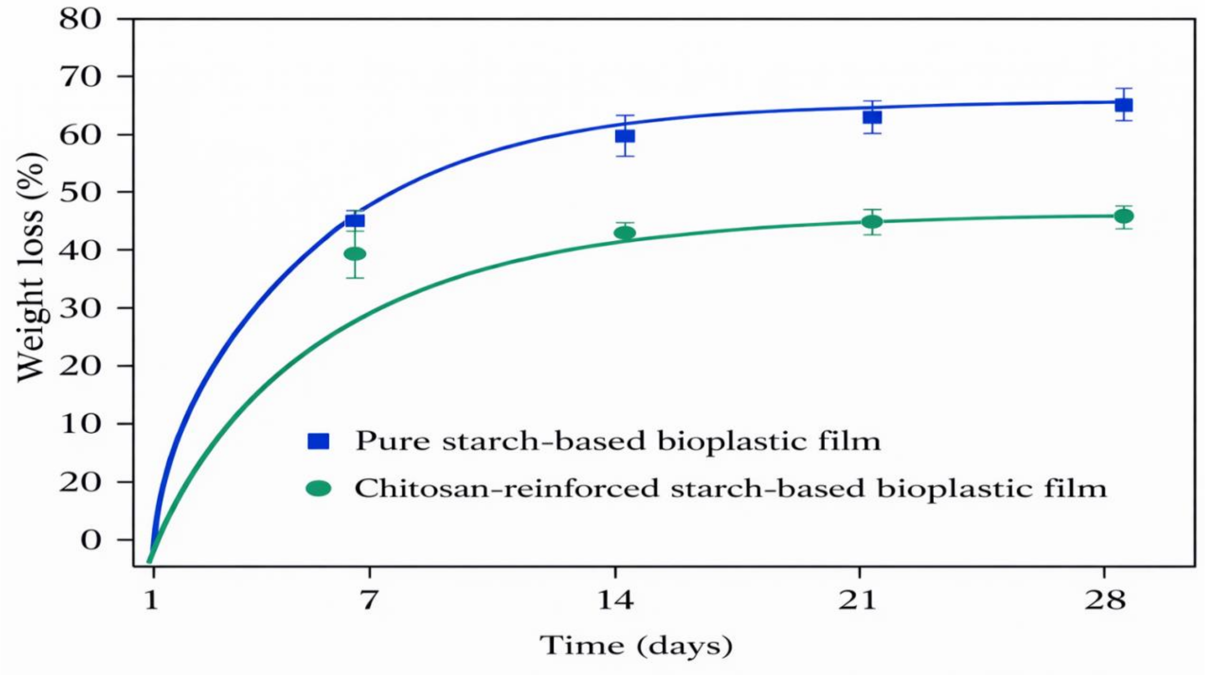


**Figure (4). Weight loss percentages of pure starch and chitosan-reinforced starch-based bioplastic films during storage period (Tan *et al*., 2022)**

This is attributed to the formation of a more cohesive network resulting from the interactions between starch and chitosan, which limits water permeability and reduces the ease of microbial penetration, thus delaying degradation without eliminating the material's biodegradability. These findings also support **Kumar *et al*. (2020)** assertion that incorporating chitosan into polymer films enhances their functional properties, particularly their antimicrobial activity, making them a promising component in modern food packaging materials. However, the rate of degradation depends heavily on the membrane composition and surrounding environmental conditions, such as humidity and microbial activity. The interaction between chitosan and starch may lead to the formation of a more cohesive polymer network, which limits water permeability and affects the rate of degradation without affecting the biodegradability of the material, as studies have shown that the structural properties of biofilms play an important role in determining their degrading behavior **(Correa-Pacheco *et al*., 2025; Tan *et al*., 2022)**.

## Health and Functional Applications of Chitosan

### 1. The role of chitosan in metabolic syndrome

Metabolic syndrome is a cluster of related disorders, including high blood glucose levels, dyslipidemia, and increased body fat accumulation, and is associated with an increased risk of cardiovascular disease. **Abd El-Hack *et al*. (2023)** indicated that chitosan and its derivatives may contribute to improving some components of this syndrome.

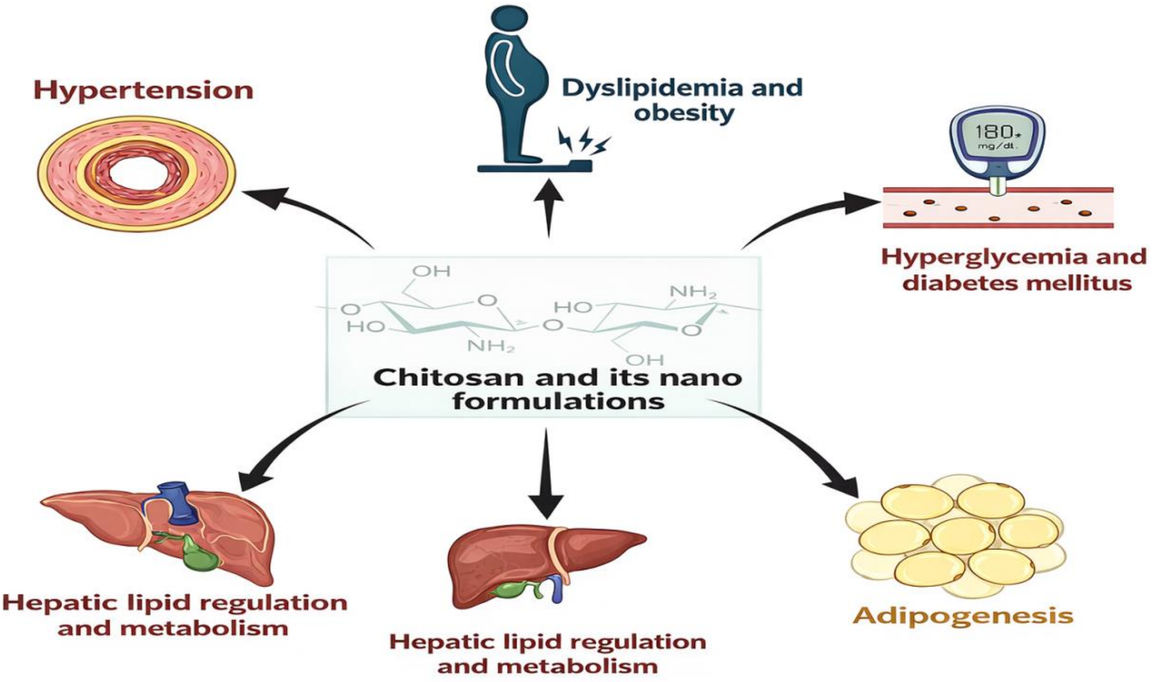


**Figure (5). Effects of chitosan and its nano-derived components on metabolic syndrome components (Abd El-Hack *et al*., 2023)**

Figure (5) illustrates the multiple effects of chitosan on the components of metabolic syndrome, which will be discussed in detail in the following paragraphs.

### 1. Reducing cholesterol levels

A study by **Tao *et al*. (2011)** showed that administering chitosan nanoparticles to Sprague–Dawley rats fed a high-fat diet resulted in a significant reduction in blood lipid levels, including total cholesterol and low-density lipoprotein cholesterol (LDL-C), as well as improved liver function tests compared to untreated animals. Gupta *et al*. (2018) also indicated that chitosan-based nanosystems are promising approaches for improving lipid reduction and mitigating the toxic effects associated with high cholesterol. Furthermore, **Zhang *et al*. (2025)** demonstrated that chitosan can inhibit fat digestion by influencing the activity of digestive enzymes and reducing the release of free fatty acids, thus contributing to its lipid-lowering effect.

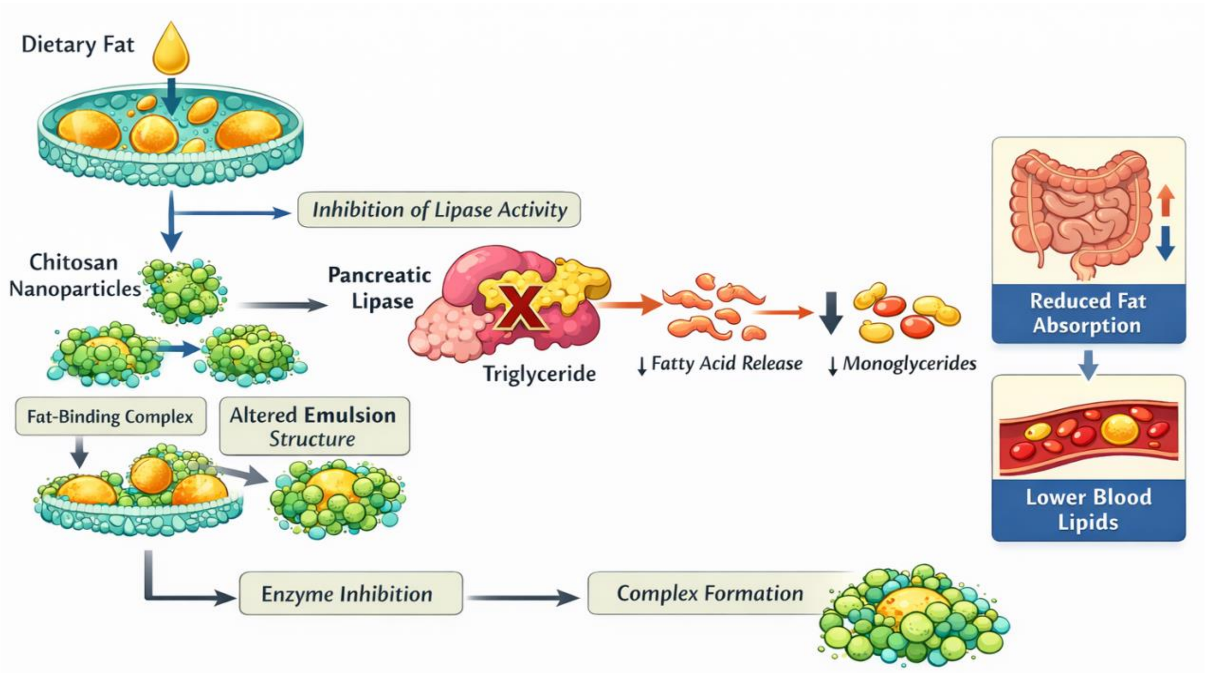


**Figure (6). The mechanism inhibition of lipid digestion using chitosan**

## 2. Regulating Glucose Balance

Chitosan and its derivatives may contribute to lowering blood glucose levels in animal models of diabetes, with studies showing a reduction in fasting blood glucose and improved glucose tolerance. Recent reviews also indicate that chitosan may help alleviate hyperglycemia by influencing certain metabolic pathways involved in glucose metabolism, including reducing hepatic gluconeogenesis and increasing its utilization in peripheral tissues **(Tzeng *et al*., 2022)**. Furthermore, recent studies have shown that chitosan and its derivatives may improve certain markers of metabolic syndrome associated with impaired glucose tolerance, including insulin resistance **(Abd El-Hack *et al*., 2023)**.

## 3. Obesity Treatment

Studies have confirmed the potential of chitosan in reducing obesity, demonstrating its effect in decreasing fat accumulation by inhibiting adipocyte differentiation, thus reducing fat storage within adipocytes. Chitosan use has also been associated with improved dyslipidemia and reduced body weight gain in animal models fed a high-fat diet **(Huang *et al*., 2015)**. Recent research has suggested that the anti-obesity effects of chitosan and its derivatives are associated with multiple metabolic pathways, such as effects on fat accumulation and metabolism, which may help to improve some of the indicators of obesity. It is necessary to mention that its efficacy can be different when it comes to individual derivatives and circumstances of application **(Shagdarova *et al*., 2023)**. Besides its ability to enhance the constituents of metabolic syndrome, chitosan has a variety of biological and pharmacological characteristics which can be utilized to increase its application in different medical and nutritional practice.

## Biological and pharmaceutical applications of chitosan

Since chitosan is the deacetylated compound of chitin, it has been widely utilized as nanocarrier to deliver therapeutic compounds because of its characteristic features such as biocompatibility, biodegradability and chemical modifiability. Physical or chemical methods can be used to engineer chitosan nanoparticles, whereby the nanoparticles can be designed to have the desired properties in diverse medical applications. They are usually synthesized in an appropriate nanoscale to allow them to interact efficiently with biological systems **(Gao and Wu, 2022)**.

**Saravanakumar *et al*. (2022)** have shown that L-lysine α-oxidase-polyethylene glycol (PEG)-modified chitosan nanoparticles have high specific targeting of HER2/neu breast cancer cells, which is an overexpressed growth receptor in some breast cancers. This helps in increasing the efficacy of treatment and reducing the toxicity on normal tissues. Recent reviews have indicated that chitosan nanoparticles hold promise to be used as platforms in the development of advanced drug delivery systems. They have the potential to enhance drug loading performance, stability and release control, and bioavailability and decreased systemic toxicity, especially in complex therapeutic uses like cancer therapy **(Stefanache *et al*., 2025)**. Moreover, it is possible to manipulate chitosan at the nanoscale to engineer smart drug delivery systems, including pH-responsive or targeted systems in the body, to enhance treatment efficacy and decrease side effects. These results indicate that chitosan nanoparticles will become an increasingly important ingredient in the future of the development of highly efficient drug delivery systems.

### The Role of Chitosan as a Bio-Carrier Matrix in Enhancing Antioxidant properties

Chitosan exhibits antioxidant activity attributed to its amine and hydroxyl groups, which are capable of reacting with free radicals and reducing oxidative stress. However, this activity is relatively limited compared to phenolic compounds and is influenced by factors such as molecular weight and degree of deacetylation **(Rinaudo, 2006; Aranaz *et al*., 2021)**. In food applications, chitosan is used as a bio-matrix carrying active compounds, such as essential oils and phenolic compounds. These compounds, when incorporated into the polymer structure, impart antioxidant and functionally enhanced properties to the membranes, thereby improving the antioxidant efficacy of dietary systems **(Flórez *et al*., 2022; Casalini & Giacinti Baschetti, 2023)**.

### Tissue Engineering and Wound Dressing

The high porosity and absorbency of chitosan make it a promising material for wound dressing applications. **Basit *et al*. (2020)** reported the development of curcumin-loaded chitosan nanoparticles for burn treatment, demonstrating improved healing properties due to their antioxidant and antimicrobial effects. **Deng *et al*. (2021)** also showed that thymine-modified chitosan derivatives exhibit broad-spectrum activity against wound pathogens, along with good biocompatibility and the ability to accelerate wound healing.

### Toxicity and Safety

Chitosan is a biopolymer characterized by its low toxicity and biocompatibility, making it suitable for use in food and pharmaceutical applications. However, its biological properties are highly dependent on its chemical structure, such as molecular weight and degree of deacetylation, which influence its biological behavior and safety profile **(Aranaz *et al*., 2021)**. Studies have also shown that chitosan nanoparticles may exhibit different behavior compared to conventional forms, potentially leading to cellular or physiological effects that depend on size, dose, and duration of exposure. This necessitates careful toxicity assessment before its adoption in various applications **(Kean & Thanou, 2010)**.

## Conclusions

Chitosan is a biopolysaccharide that is a deacetylation product of chitin to different extents. It is characterized by its biodegradability, biocompatibility, and environmental friendliness. Chitin can be chemically or biologically synthesized, and chitosan of various structural and functional characteristics can be produced. The use of chitosan has an extensive variety of applications especially in the biological, food and medical industries, because of its antimicrobial nature and its capability to react with other compounds or be used as a functional carrier. Chitosan is also applicable in drug delivery systems development, such as nanotechnology development and enhancement of some indicators of metabolic disorders, like blood glucose and lipid levels. Chitosan is hence a promising material that will act as a bridge between health and environmental applications. Nevertheless, its characteristics and safety should be considered depending on its type and construction when utilized in various applications. Lastly, on a global front, chitosan will become an everyday connection between human health, environmental protection and healthy ways of living.

## Recommendations

1 .It is advisable that more effort is put in the study of low molecular weight chitosan and nanochitosan as it has great potential in enhancing functional properties as well as biological uses in food and pharmaceutical industries.

2 .There is a need to create active food packaging systems with chitosan and supplemented with natural antioxidants to prolong the shelf life of products and minimize the use of plastics and conventional preservatives.

3 .It is recommended to use crustacean waste as a local and sustainable option of chitin and chitosan to develop principles of the circular economy and minimize pollution of the environment.

4 .It is advisable to widen applied research on actual food products in an industrial manufacturing and storage environment to make the evaluation of chitosan efficacy realistic and practical.

5 .It is important to support the utilization of modern, environmentally friendly technologies, especially enzymatic ones in the manufacture of high-purity chitosan with a minimum of using of harsh chemicals.

6. To establish the health and regulatory properties of chitosan and its derivatives in food, it is necessary to record and comply with international standards and ensure the safety of consumers.

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# الكايتوسان، بوليمر حيوي متعدد الوظائف: الربط بين الابتكار التكنولوجي في تصنيع الأغذية وتعزيز الصحة المستدامة (مقال مراجعة)

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## الملخص

ستركز هذه المراجعة على طبيعة الكايتوسان ومصادره وطرق استخلاصه وتطبيقاته في حفظ الأغذية وتغليفها، بالإضافة إلى تطبيقاته الصحية والصيدلانية. الكايتوسان بوليمر كايتوني من الكيتين، الموجود بكثرة في الهياكل الخارجية للقشريات والحشرات والمفصليات وفي بعض الكائنات الحية الأخرى كالفطريات. تشمل العمليات الكيميائية المستخدمة لاستخلاص الكيتين إزالة البروتينات والمعادن، متبوعةً بإزالة مجموعة الأسيتيل من المنتج النهائي لتكوين الكايتوسان. تشمل البدائل الأخرى الاستخلاص الأنزيمي، بمساعدة إنزيمات مثل البابايين والتربسين والبيبسين، أو الاستخلاص البيولوجي من خلال تخمير الكائنات الدقيقة وهو ما يتماشى بشكل أكبر مع مفهوم الاستدامة. يتميز الكايتوسان بقابليته للتحلل الحيوي وتوافقه الحيوي، بالإضافة إلى خصائصه المضادة للميكروبات وطبيعته الكاتيونية القوية، مما يجعله مادة واعدة لتطبيقات حفظ الأغذية وتغليفها. يُستخدم الكايتوسان أيضًا في تطوير أنظمة توصيل الأدوية، لا سيما في شكله النانوي، حيث يمكن تعديل خصائصه الفيزيائية والكيميائية لتحسين كفاءة تحميل وإطلاق المركبات العلاجية. وتشير الدراسات أيضًا إلى أن الكايتوسان قد يُسهم في تحسين بعض المؤشرات المرتبطة بالاضطرابات الأيضية، مثل مستويات الكوليسترول وتوازن الكلوكوز، خاصةً عند استخدامه في تركيبات الجسيمات النانوية القابلة للذوبان المُحضّرة باستخدام طرق مثل التأين والتجفيف بالرش والتي أظهرت نتائج واعدة في النماذج الحيوانية التي تتغذى على أنظمة غذائية غنية بالدهون.