International Journal of
Analytical and Applied Chemistry

ISSN: 2582-5933
Volume 10, Issue 1, 2024
DOI (Journal): 10.37628/IJAAC

https://journalspub.com/journal/IJAAC/

Review IJAAC

Exploring the Boundless Applications of Chitosan: From Biomedical Marvel to Environmental Saviour

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Abstract

Chitosan has attracted much interest because of its versatile properties and possible numerous usages in diversified industrial applications. Chitosan is having poor solubility in neutral and basic media, and this is limiting its use. Chitosan is not a single polymer and do not have a defined structure. Chitosan is family of molecules with different composition, size & monomer units' distribution and these characteristics have effect on the biological & technological performance of Chitosan. Dedicated research work is underway to sort out the problems of its poor solubility and improving polymer properties. Chitosan is a derivative of chitin, has emerged as a versatile biomaterial with numerous applications across various industries. This article delves into the properties, production methods, and diverse applications of chitosan, ranging from biomedical to environmental fields. From wound healing to water treatment, chitosan's versatility and biodegradability makes it a promising candidate for medical, agriculture and food applications. This review article aims to throw light on the vast potential of chitosan and its role in shaping the future of multiple industries.

Keywords: Chitosan, chitin, biological activity, drug delivery, antioxidant, antimicrobial, aetallic nanoparticles, bio-catalysis

INTRODUCTION

Chitosan is a polysaccharide, that is derived from chitin which is the second most abundantly available polysaccharide in the world after cellulose. The amino groups in the chitosan can be protonated to improve its solubility in diluted aqueous acidic solutions. Several useful properties of chitosan may open doors for unique opportunities to develop various biomedical applications. The understanding of their mechanism will lead to a better applicability of chitosan in medical & pharmaceutical industries. The haemostatic activity of chitosan can be explained due to the presence of positive charges on chitosan backbone. Due to positive charges on its backbone, chitosan can interact with the negative part of cells membrane in turn leading to reorganization & opening of the tight junction proteins & enhance permeation property of this polysaccharide.

The polycationic nature of chitosan also contributes to chitosan analgesic effects. Chitosan biodegradability can be explained on the basis that this is a polymer bearing amino groups and is also a polysaccharide which contains breakable glycosidic bonds. Chitosan is degradable in vivo by several proteases mainly lysozyme.

As Chitosan is biocompatible & biodegradable and non-toxic, it can be used in medical applications as antimicrobial & wound healing biomaterials. It is used as chelating agent due to its capability to bind cholesterol, fats, proteins and metal ions [1].

Due to its biodegradability, natural occurrence, abundance, reactivity, etc., it has numerous

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Received Date: June 14, 2024
Accepted Date: June 20, 2024
Published Date: June 25, 2024

Citation: Sandeep Rai. Exploring the Boundless Applications of Chitosan: From Biomedical Marvel to Environmental Saviour. International Journal of Analytical and Applied Chemistry. 2024; 10(1): 1–8p.

potential applications like medical, agricultural, food processing, nutritional enhancement, cosmetics, and waste & water treatment etc.

It may be highlighted that the electrospinning of chitosan itself proved to be difficult, chitosan is mixed with other synthetic or natural polymers, such as PEO or PVA for making fibres by electrospinning.

Since chitosan nanofibers with (50-500nm diameter) are biocompatible & biodegradable, so they can find use as wound healing materials [2].

Chitosan, derived from the deacetylation of chitin, a naturally occurring polymer found abundantly in the exoskeletons of crustaceans, insects, and fungal cell walls, has garnered significant attention in recent years due to its remarkable properties and diverse applications. As a biocompatible, biodegradable, non-toxic, and renewable resource, chitosan has found its way into various fields, including biomedicine, pharmaceuticals, agriculture, food, cosmetics, and environmental remediation. [3–12].

PRODUCTION OF CHITOSAN

It involves extracting chitin from crustacean shells, which is then converted into chitosan. This process includes several steps: demineralization to remove calcium carbonate, deproteinization to eliminate proteins, and deacetylation to transform chitin into chitosan. The resulting chitosan is a versatile biopolymer with numerous applications in various industries due to its biocompatibility, biodegradability, and antimicrobial properties.

CHITOSAN CHEMICAL STRUCTURE

Chitosan is produced by deacetylating chitin, a natural polymer found in the exoskeletons of crustaceans like crabs and shrimp. The process involves treating chitin with an alkaline substance, typically sodium hydroxide, to remove acetyl groups, resulting in the conversion of chitin to chitosan. This biopolymer is valued for its biocompatibility, biodegradability, and non-toxicity, making it useful in a variety of applications, including medical, pharmaceutical, agricultural, and industrial fields. The degree of deacetylation and molecular weight can be controlled during production to tailor the properties of chitosan for specific uses (Figure 1).

PROPERTIES OF CHITOSAN

Chitosan possesses several unique properties that contribute to its wide-ranging applications:

1. *Biocompatibility and Biodegradability:* Chitosan exhibits excellent biocompatibility, making it suitable for various biomedical applications such as tissue engineering, drug delivery, and wound healing. Moreover, its biodegradability ensures environmental sustainability, minimizing ecological impacts.
2. *Antimicrobial Activity:* Chitosan demonstrates inherent antimicrobial properties, attributed to its cationic nature. This antimicrobial activity makes it an ideal candidate for applications in food preservation, wound dressings, and antimicrobial coatings.
3. *Film-Forming Ability:* Chitosan can form films with desirable mechanical properties, barrier properties, and biodegradability, making it useful for packaging materials, wound dressings, and controlled drug release systems.
4. *Chelation and Adsorption:* Chitosan exhibits chelating and adsorption capabilities, allowing it to remove heavy metals, dyes, and other pollutants from water and wastewater. This property has significant implications for environmental remediation and water treatment (Figures 2 and 3).

Chitosan is primarily produced through the deacetylation of chitin, which involves the removal of acetyl groups from chitin molecules. The production process typically entails several steps, including demineralization, deproteinization, and deacetylation, followed by purification and drying. Various sources of chitin, such as crustacean shells, fungal mycelia, and insect exoskeletons, can be utilized for chitosan production, offering flexibility and sustainability.

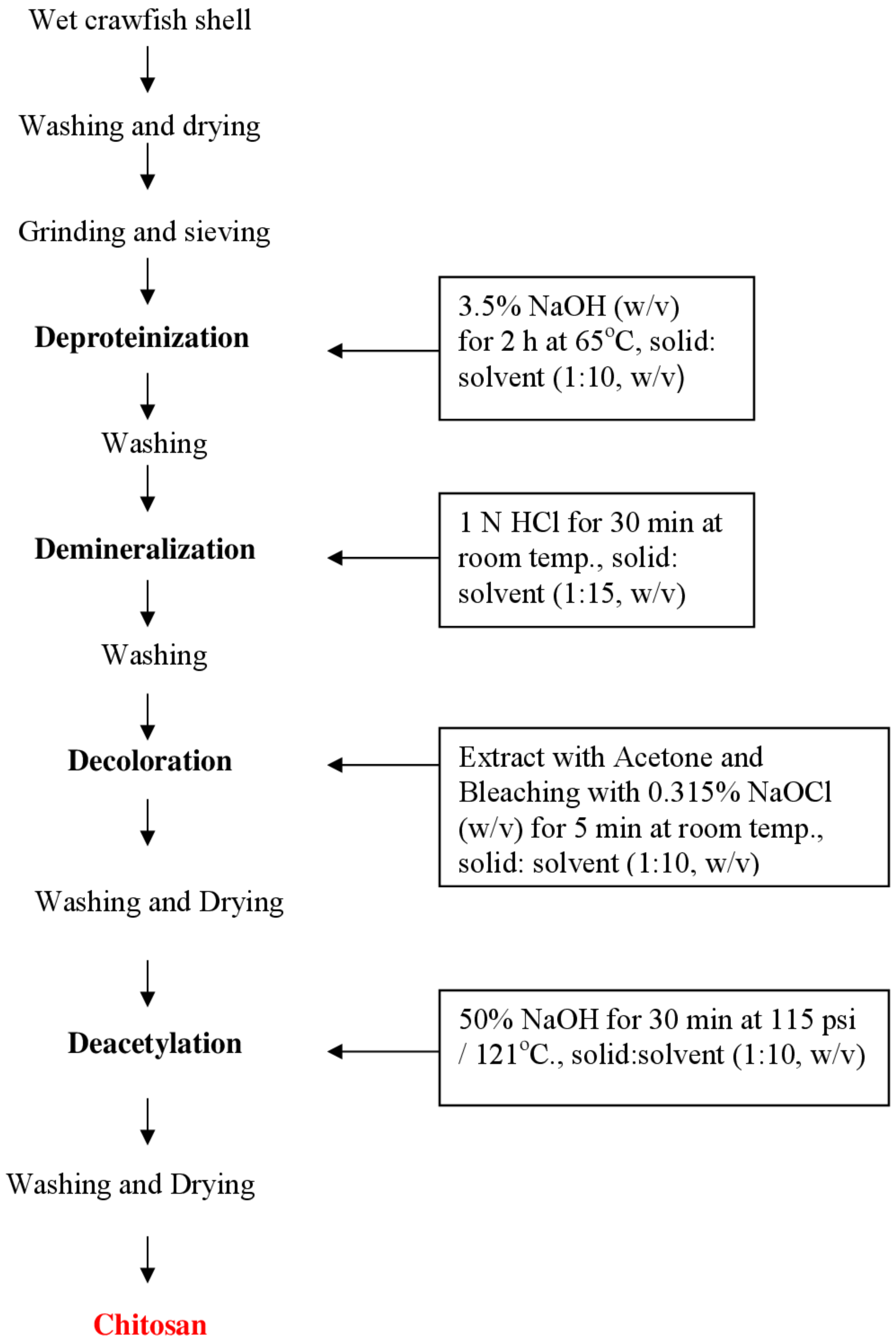

Figure 1. Process flow diagram for chitosan production.

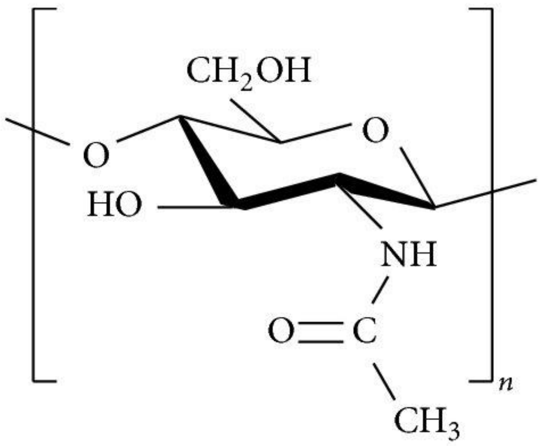

Figure 2. Chemical Structure of Chitosan [13].

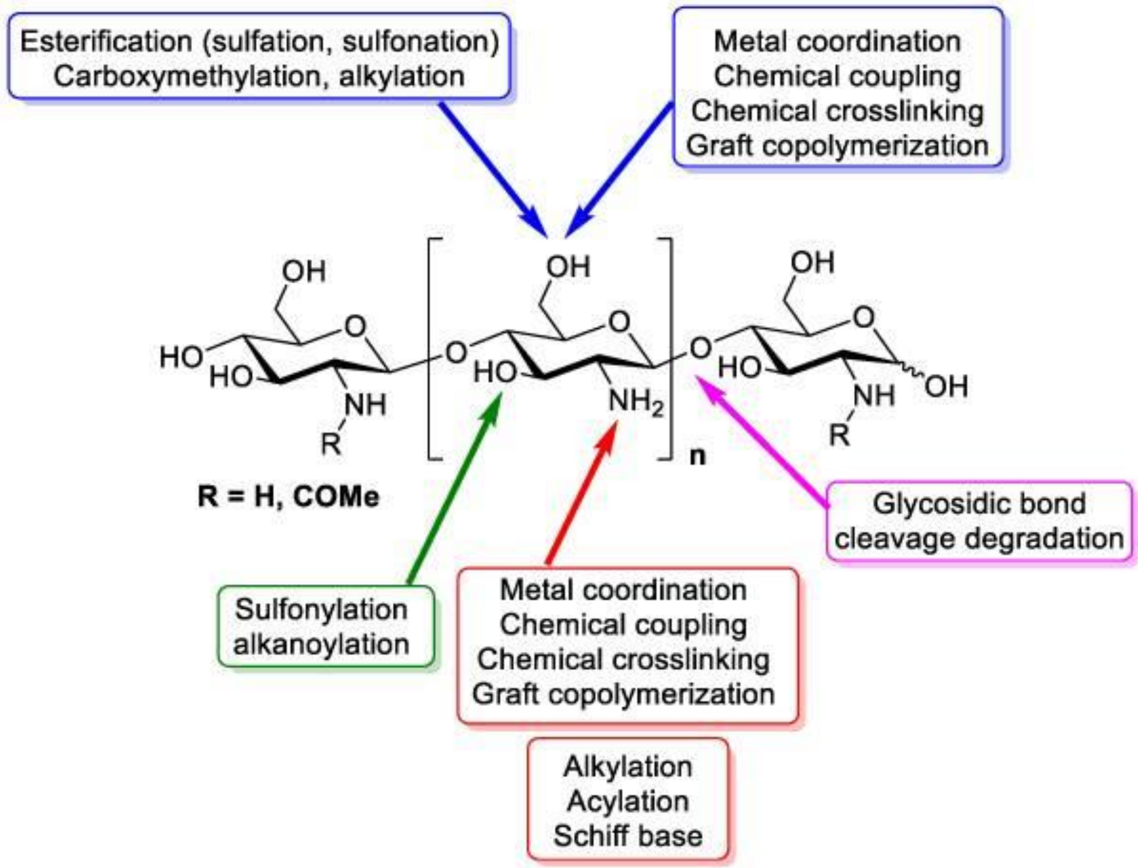

Figure 3. Functional groups in chitosan's structure used for chemical modification [14].

Chitin and its deacetylated derivative, chitosan, are a family of linear polysaccharides composed of varying amounts of (β1→4) linked residues of N-acetyl-2 amino-2-deoxy-D-glucose (glucosamine, GlcN) and 2-amino-2-deoxy-D-glucose (N-acetyl-glucosamine, GlcNAc) residues. Chitosan is soluble in aqueous acidic media via primary amine protonation. In contrast, in chitin, the number of acetylated residues is high enough to prevent the polymer for dissolving in aqueous acidic media.

Chitin is a very abundant biopolymer that can be found in the exoskeleton of crustacea, insect's cuticles, algae and in the cell wall of fungi. Chitosan is less frequent in nature occurring in some fungi

(Mucoraceae). Historically, commercial chitosan samples were mainly produced from chemical deacetylation of chitin from crustacean sources. More recently, chitosan from fungi is gaining interest in the market, driven by vegan demands. Moreover, these samples are better controlled in terms of low viscosity and exhibit a very high deacetylation degree [15]. Production from insect cuticles is also gaining interest, driven by the increased interest in protein production from these sources (Figure 3).

The interest in chitin and chitosan relies on the myriad biological and technological properties exhibited by these polymers as depicted in Table 1. However, these properties are tightly related to the physicochemical properties of the polymers (mainly molecular weight and acetylation degree) [16]. Therefore, when working with chitin and chitosan a good and completed polymer characterization is mandatory. Several methodologies have been described to characterize chitin, chitosan and chit oligosaccharides, a description of which is far from the objective of this paper—but for interested readers, we recommend publications.

Table 1. The important properties of chitin and chitosan.

Property	**Remarks**
Mucoadhesive	Chitosan and its derivatives like thiolated chitosan, trimethyl chitosan, hydrophobically modified chitosan, etc are used to design of mucoadhesive drug delivery [17, 18].
Anti-inflammatory	Due to its versatile properties, hydrogel of Chitosan can provide an effective & novel anti-inflammation approach. Due to their high porosity, biocompatibility, biodegradability, and flexibility, hydrogels are considered to be an excellent choice for drug delivery [19].
Antioxidant	Antioxidant play a key role in scavenging the free radicals and thereby inhibit the oxidative damage caused by free radicals. Antioxidant mechanism of chitosan is due to functions which protect the host against oxidative stress related damages by interfering with the oxidation chain reaction [20].
Antimicrobial	Chitosan has exhibited to have fungicidal effects on various fungal pathogens in plants as well as in humans. Chitosan antifungal properties are mainly related to its interaction with the cell wall or cell membrane [21].
Antifungal	Chitosan has potential to inhibit growth of filamentous fungi (e.g., Aspergillus fumigatus) & yeast (e.g., Candida albicans) human pathogens. Chitosan under low nutrient (C and N) status has shown effective antifungal mode of action of this polymer on human pathogenic fungi [22].
Antihyperglycemic	Chitosan has potential to alleviate diabetic hyper glycemia by reducing hepatic gluconeogenesis and increasing skeletal muscle glucose uptake and utility [22].
Antitumoral	Chitosan is the second most abundantly available natural polysaccharide next to cellulose, and has excellent biocompatibility & good antitumor activity. Due to biodegradability, biocompatibility, biodistribution, nontoxicity and immunogenicity free characteristics of Chitosan, it is widely used polymer in the pharmacology [17–23].
Wound healing	Chitosan possesses bacteriostatic, fungistatic and film-forming properties which are very crucial to wound treatment. Chitosan has reparative nature which allows its use to restore or replace damaged tissue. Also, Chitosan usage is found to promote healing & producing less scarring [24].

APPLICATIONS OF CHITOSAN

Biomedical Applications

- *Tissue Engineering:* Chitosan-based scaffolds provide a three-dimensional environment for cell growth and tissue regeneration, making them valuable in tissue engineering applications.
- *Drug Delivery Systems:* Chitosan nanoparticles and microparticles serve as effective carriers for drug delivery, enhancing drug stability, bioavailability, and targeted delivery.
- *Wound Healing:* Chitosan-based wound dressings promote wound healing by providing a moist environment, absorbing exudates, and exhibiting antimicrobial properties.
- *Dental Applications:* Chitosan-based materials are used in dental products such as toothpaste, mouthwash, and dental implants due to their antimicrobial and remineralization properties (Table 1).

Pharmaceutical Applications

- *Controlled Drug Release:* Chitosan matrices enable controlled release of drugs, prolonging their therapeutic effects and reducing dosing frequency.

- *Gene Delivery:* Chitosan-based nanoparticles serve as vectors for gene delivery, facilitating gene therapy and genetic engineering applications.

Food and Agriculture

Due to abundance, biodegradability, nontoxic, and natural origin of chitosan, it can be safely used in agricultural applications. Few applications are seed coating, leaf coating, fertilizer, and sustain release of drug/ fertilizers are some of the emerging usages of Chitosan in agriculture. The use of chitosan in these areas has shown promising results to increase the number of crops produced by improving germination, rooting, leaf growth, seed yield, and soil moisture retention, and reducing the fungal infections and diseases in crops [25].

- *Food Preservation:* Chitosan coatings inhibit microbial growth and extend the shelf life of fruits, vegetables, and seafood, offering a natural alternative to synthetic preservatives.
- *Crop Protection:* Chitosan-based formulations enhance plant growth, suppress pathogens, and induce plant defence mechanisms, contributing to sustainable agriculture practices.
- *Cosmetics: Skin Care:* Chitosan is incorporated into skincare products such as creams, lotions, and masks for its moisturizing, anti-aging, and skin barrier-enhancing properties.

Environmental Remediation

- *Water Treatment:* Chitosan-based adsorbents remove heavy metals, dyes, and organic pollutants from wastewater, contributing to water purification and environmental remediation efforts.
- *Soil Amendment:* Chitosan improves soil structure, enhances nutrient retention, and promotes plant growth, making it valuable for soil amendment and rehabilitation in degraded ecosystems.

CHITOSAN MARKET-DRIVERS AND ROADBLOCKS

As per a market survey report [26] global market for Chitosan was USD 12.25 billion in 2023 and it is projected to be around USD 91.99 billion by 2033 [26]. Estimated growth rate [CAGR] of Chitosan is expected to be 22.31% due to its increased industrial usage as it has unique and useful properties with biodegradability.

Some of the main features regarding Chitosan Global Market are as follows:

Chitosan from shrimp has dominated the global market with 63% of total revenue generated in year 2023.

The biomedical segment has generated highest revenue of over 33.5% in year 2023. Further cosmetics application of Chitosan has generated 26% revenue share in year 2023. Asia Pacific region was having highest revenue share of approx. 46.91% in year 2023.

CHITOSAN MARKET GROWTH FACTORS

Waste water treatment & food & beverages industries are estimated to be drivers of growth for Chitosan Market. One of the important applications is Effluent Water treatment by chitin or chitosan. For the removal of dyes from industrial wastewater (e.g., textile wastewaters), as well as other organic pollutants such as organochloride pesticides, organic oxidized or fatty impurities, and oil impurities. The presence of highly reactive amino (–NH2) & hydroxyl (–OH) groups in the backbone of Chitosan are very effective in the wastewater treatment for removal of metals and other toxic impurities.

Excellent antioxidant and antimicrobial activity of Chitosan can be used to increase shelf life of foods. Chitosan's excellent emulsifying properties allow it to replace synthetic surfactants specially in food grade/contact applications. Chitosan can be used as a functional material against hypercholesterolemia, hypertension, and inflammations etc. It can also be used for nutrient encapsulation in functional food development. Increase in online retail in Food & Beverage which use biodegradable non-toxic packaging will create a positive impact on the chitosan market growth.

However, roadblocks in commercialization of Chitosan are the high production cost of chitosan, limited availability of raw materials, lack of standardization of quality and there is an urgent need for further dedicated research on Chitosan and its derivatives to fully utilize this versatile natural polymer.

CHALLENGES AND FUTURE DIRECTIONS

Despite its numerous advantages, chitosan faces challenges such as variability in properties, limited scalability of production methods, and cost constraints. Addressing these challenges requires continued research and innovation in chitosan processing, modification techniques, and applications. Future directions include the development of advanced chitosan-based materials, optimization of production processes, and exploration of novel applications in emerging fields such as nanotechnology, regenerative medicine, and environmental sustainability.

CONCLUSION

Chitosan stands as a remarkable biomaterial with unparalleled versatility and potential across diverse fields. From biomedical innovations to environmental solutions, the applications of chitosan continue to expand, driven by its unique properties and sustainable nature. As research advances and technology evolves, chitosan is poised to play a pivotal role in addressing contemporary challenges and shaping a more sustainable and healthier future for humanity and the planet.

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