

Chitosan-Based Biocomposites Integrated With Nanotechnology: A Comprehensive Scientific Review

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Abstract: Chitosan-based biocomposites have emerged as a highly versatile class of sustainable materials due to their biodegradability, biocompatibility, and chemical versatility. The integration of nanotechnology into chitosan matrices has led to significant advancements in mechanical performance, antimicrobial properties, thermal stability, and biological functionality. This extended review provides an in-depth examination of the structural characteristics of chitosan, the molecular mechanisms that govern its interactions with diverse nanomaterials, and the synthesis methodologies used for preparing advanced nanobiocomposites. Particular attention is given to polymer–nanofiller interfacial chemistry, nanoparticle dispersion behavior, physicochemical characterization techniques, and multifunctional applications across biomedical, pharmaceutical, environmental, agricultural, food packaging, and industrial fields. The review also analyzes safety considerations, toxicity issues, production challenges, and future research prospects. The discussion demonstrates that nanotechnology not only enhances the intrinsic properties of chitosan but also expands its application potential for next-generation smart materials, controlled-release systems, biosensors, and environmentally friendly technologies.

Keywords: Chitosan, biocomposites, nanotechnology, nanofibers, nanoclay, green materials, biomedical engineering, drug delivery, antimicrobial packaging, biodegradable polymers.

INTRODUCTION:

Chitosan is a naturally occurring linear polysaccharide that has attracted remarkable scientific interest for its unique structural, chemical, and biological characteristics. Derived primarily from chitin, chitosan represents one of the most abundant biopolymers on Earth, second only to cellulose. Over the last decade, there has been a rapid expansion in research related to chitosan-based biocomposites because of the global transition toward sustainable, biodegradable, and environmentally friendly materials. At the same time, the field of nanotechnology has matured and now provides new tools for modifying, strengthening, and functionalizing natural polymers at the molecular level. The convergence of chitosan chemistry and nanotechnology has opened new horizons for producing materials with exceptional performance in areas where conventional biopolymers fall short.

Native chitosan possesses numerous advantages, including non-toxicity, antimicrobial behavior, mucoadhesiveness, film-forming capacity, and a

substantial ability to bind metal ions or bioactive compounds. However, its mechanical strength, thermal stability, moisture sensitivity, and limited solubility under neutral conditions restrict its use in many high-performance applications. Nanotechnology provides a powerful platform to overcome these limitations. Incorporating nanoscale fillers—such as metallic nanoparticles, carbon nanomaterials, nanoclays, magnetic nanoparticles, or biogenic nanofibers—into the chitosan matrix significantly alters its structural organization, interfacial bonding, and functional capabilities. These improvements have led to a new generation of chitosan-based nanobiocomposites that are suitable for applications ranging from drug delivery and tissue engineering to environmental remediation, water purification, smart food packaging, and agricultural innovation.

This article presents a comprehensive and uninterrupted scientific discussion on chitosan nanobiocomposites, providing theoretical principles,

synthesis strategies, physicochemical characteristics, and application-oriented insights in a continuous, high-volume academic format.

Structural and Physicochemical Characteristics of Chitosan

Chitosan's molecular structure consists of β -(1 \rightarrow 4)-linked D-glucosamine and N-acetyl-D-glucosamine units. The relative proportion of these repeating units, defined as the degree of deacetylation (DDA), profoundly influences the polymer's solubility, crystallinity, charge distribution, and reactivity. Chitosan with a higher DDA contains more free amino groups, which become protonated under acidic conditions and impart a strong cationic nature to the polymer. This positive surface charge is critical for interactions with negatively charged nanoparticles, microbial membranes, nucleic acids, and various biomolecules. In addition to DDA, molecular weight (MW) is another key factor determining viscosity, film-forming capability, mechanical performance, and degradation profile.

The solubility of chitosan is limited under neutral and alkaline conditions. However, the protonation of amino groups in acidic environments enhances solubility and facilitates processing into solutions, gels, fibers, films, beads, microspheres, and hydrogels. The polymer's chemical versatility allows a wide range of modifications, including carboxymethylation, quaternization, phosphorylation, and graft copolymerization, leading to improved physicochemical properties that further enhance the performance of nanocomposites.

Chitosan's biological properties—biodegradability, biocompatibility, antioxidant capacity, hemostatic activity, and broad-spectrum antimicrobial behavior—make it a highly attractive biopolymer for biomedical and pharmaceutical fields. When combined with nanotechnology, these natural advantages are amplified and expanded, enabling multifunctional systems that outperform traditional biomaterials.

Integration of Nanotechnology into Chitosan Biocomposites

The incorporation of nanomaterials into chitosan matrices introduces significant reinforcement due to the extremely high surface-to-volume ratio and unique physicochemical properties of nanoscale fillers. Nanoparticles exhibit enhanced reactivity, improved dispersibility, and distinct quantum or interfacial phenomena that fundamentally alter the behavior of bulk composite materials. When embedded in chitosan, nanofillers enhance mechanical strength by facilitating uniform stress

distribution and forming hydrogen bonds, ionic linkages, or covalent interactions with chitosan chains. They also significantly improve the thermal stability of the composite by restricting polymer chain mobility and by serving as effective heat barriers.

A wide variety of nanomaterials have been successfully integrated into chitosan. Metallic nanoparticles such as silver, gold, zinc oxide, titanium dioxide, and copper oxide provide exceptional antimicrobial and catalytic activities. Carbon-based nanomaterials—including graphene oxide, reduced graphene oxide, fullerenes, carbon nanotubes, and nanodiamonds—impart electrical conductivity, mechanical reinforcement, and improved surface activity. Biogenic nanofillers such as nanochitin and nanocellulose contribute to excellent biodegradability and strengthen hydrogen bonding networks. Magnetic nanoparticles such as Fe₃O₄ or CoFe₂O₄ enable magnetically responsive systems used in targeted drug delivery, hyperthermia therapy, and advanced separation technologies. Nanoclays, including montmorillonite and halloysite nanotubes, enhance barrier properties, flame retardancy, and thermal resistance.

The choice of nanomaterial depends on the application and desired performance. Biomedical applications often require biocompatible or biodegradable fillers, whereas environmental applications may require high adsorption capacity, magnetic separability, or photocatalytic capability.

Molecular Interaction Mechanisms Between Chitosan and Nanomaterials

Interaction mechanisms play a pivotal role in determining the performance of nanobiocomposites. Chitosan's functional groups—particularly amino ($-NH_2$) and hydroxyl ($-OH$) groups—form hydrogen bonds, ionic linkages, or coordination complexes with nanoparticles. Negatively charged nanomaterials such as graphene oxide, nanoclays, or certain metal oxides interact strongly with protonated amino groups through electrostatic attraction. Metallic ions readily form chelation complexes with amino groups, leading to in situ growth of nanoparticles inside the chitosan matrix. These interactions improve nanoparticle stability, prevent aggregation, and increase interfacial adhesion.

Crosslinking agents such as glutaraldehyde, genipin, tripolyphosphate, or citric acid can further reinforce the structure by increasing crosslink density. Good interfacial bonding ensures improved mechanical properties, enhanced thermal stability, better dispersion, and superior functional behavior. Nanofillers act not merely as additives but as active

components that restructure the polymer matrix and generate synergistic effects.

Synthesis and Fabrication Techniques

Numerous fabrication techniques are used to prepare chitosan-based nanobiocomposites. Solution casting remains the simplest method, involving dispersion of nanoparticles in chitosan solution through mechanical stirring, sonication, or high-shear mixing. In situ nanoparticle synthesis inside the polymer matrix is widely used for metallic nanoparticles: metal ions are complexed with chitosan and subsequently reduced to stable nanoparticles with controlled size distribution.

Freeze-drying enables the creation of porous scaffolds suitable for tissue engineering, whereas electrospinning produces ultrafine nanofibers with high surface area and tunable morphology. The sol-gel method facilitates the growth of metal oxide nanoparticles within the polymer network. Advanced techniques such as microfluidics, spray drying, and 3D bioprinting allow further control over composite architecture and application-specific design.

Physicochemical and Structural Characterization

Characterization is essential to evaluate the properties of chitosan nanobiocomposites. Fourier-transform infrared spectroscopy (FTIR) identifies characteristic functional group interactions, confirming hydrogen bonding or coordination with nanoparticles. X-ray diffraction (XRD) provides insights into crystallinity, nanoparticle size, and structural alignment. Scanning and transmission electron microscopy (SEM/TEM) reveal the morphological features, dispersion quality, and nanointerfaces. Thermal analysis (TGA/DSC) evaluates thermal stability and degradation patterns. Mechanical testing assesses tensile strength, elasticity, and flexibility. Surface charge measurements through zeta potential analysis provide information about colloidal stability, which is crucial in drug delivery and water purification applications.

Future Perspectives

- Smart nanocomposites with stimuli-responsive behavior
- 3D bioprinting using chitosan nanocomposite inks
- Personalized medicine through nano-enabled drug delivery
- Large-scale green synthesis of nanoparticles using biological methods
- Hybrid nanostructures combining inorganic

and organic nanomaterials

Nanotechnology will continue to expand the applicability of chitosan into advanced fields such as nanoelectronics, flexible sensors, and regenerative medicine.

CONCLUSION

Chitosan-based nanobiocomposites represent a new generation of multifunctional, environmentally responsible materials with broad industrial and scientific applications. Nanotechnology significantly improves the structural, mechanical, antimicrobial, and biological properties of chitosan, transforming it into a high-performance material suitable for medicine, packaging, water purification, agriculture, and biotechnology. As research continues to advance, these composites will play a crucial role in sustainable material science and next-generation nanotechnology.

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