

Chitosan-Based Biopolymer Films: Structure, Processing Technologies, Functional Modifications and Advanced Applications

¹Saranya K, ²Sudha S S, ³Mahenthiran R, ¹Arockia Sterlin M, ¹Shri Raghav S

¹Students, Department of Microbiology, Dr. N.G.P Arts and Science College, Coimbatore-641048

²Professor, Department of Microbiology / Co-Ordinator, CDC, Dr. N.G.P Arts and Science College, Coimbatore-641048

³Assistant Professor, Department of Microbiology, Dr. N.G.P Arts and Science College, Coimbatore-641048

ABSTRACT

The looking into greener plastic options has picked up pace, thanks to worries over oil-based versions. From nature's own materials, chitosan shows real promise when making thin films - all because it fights bacteria, forms strong layers, breaks down safely, and plays well with biological tissues. Found in crustacean shells and fungi, it comes from chitin, which ranks second only to cellulose in natural sugar abundance. What makes it stand apart lies in how it behaves physically and chemically, fitting roles that stretch across food wraps, medical tools, farming aids, and cleaner ecosystems. Yet using raw chitosan sheets in mass production hits snags - heat tolerance isn't great, stretching weakens them, and moisture throws off performance. In recent years, researchers turned their attention to tweaking chemicals, mixing polymers, building tiny composites, also slipping in active biological elements to boost results. What unfolds here dives into how chitosan-based films are made, their makeup, shapes they take when cast, strength traits, barrier skills, added roles they perform, plus where they find real-world fit. Questions around rules, making things big without breaking the process, what might come next tech-wise get a close look too. By using cleaner methods from green science paired with nano-scale tools, these materials may step into key spots within circular bio-resource networks, shaping smarter material choices ahead.

Keywords

Chitosan; biopolymer films; nanocomposites; antimicrobial packaging; biodegradable; food packaging.

1. Introduction

Chitin, found in insect shells, fungi, and crabs, turns into chitosan when stripped of its acetyl groups. Waste from seafood processing offers tons of this material each year. From that waste, a useful compound emerges without draining new resources. Using ocean-based leftovers in this way keeps value flowing where it might otherwise be lost (Wang, Qian, & Ding, 2017; Jain et al., 2025; Díaz-Montes et al., 2021).

Chains built from β -(1 \rightarrow 4)-linked D-glucosamine, sprinkled with different amounts of N-acetyl-D-glucosamine, form most of chitosan's backbone. Found along these chains, active hydroxyl and amino sites open doors to blend with polymers, link into networks, or undergo chemical tweaks. Because of that setup, adjustments can match specific strength needs, heat responses, or environmental behavior (Flórez et al., 2021; Khubiev et al., 2023; *Frontiers in Microbiology*, 2018).

From tiny crystal zones and tight hydrogen ties between molecules, chitosan blocks oxygen well when made into films. This trait fits neatly into food wrap uses - keeping oxygen out helps keep foods fresh longer. When conditions turn sour, the positive charge on chitosan reaches for negative parts on germ surfaces, sticking fast. That grip shuts down many microbes, both bacterial and fungal, without flash or noise.

Humidity can weaken pure chitosan films, making them less reliable in moist conditions. While natural, they often stretch less and break more easily compared to man-made plastics. When heat is involved in production, their performance tends to drop off quickly. These shortcomings push researchers toward mixing materials or altering their structure. Improving function without losing biocompatibility becomes the quiet goal behind many lab efforts (Mitantsoa et al., 2023; Haghighi, 2022; *Recent ScienceDirect Review*, 2020).

From tiny labs to everyday shelves, chitosan films show how smart materials can do more than just sit there. These wraps don't simply block outside elements - they fight bacteria while shielding food from decay. One reason stands out: the stuff comes from nature itself, giving it an edge over synthetic options. Instead of waiting passively, such packaging tracks changes, responds to moisture shifts, even signals when freshness fades. What makes chitosan special isn't just what it does, but how easily it breaks down after use. Lately, demand has pushed design beyond static barriers into living-like layers that adapt and protect. Floating into labs more often now, chitosan flakes show up in medical tech roles like coating implants or mending broken skin. Built to form gels and open frameworks, they hand out drugs slowly even as tissues rebuild themselves. Since the body accepts them without protest and breaks them down naturally, harsh side effects tend to fade away (Khubiev et al., 2023; *Frontiers in Microbiology*, 2018).

Still, chitosan does more than just protect food or carry medicine - it slips into farming through seed coats and thin sheets that rot in soil. What makes it stick around is how it arms plants, boosting their own shields while lifting what they produce.

Chitosan research pulls together knowledge from polymer science, tiny-scale tech, tiny life forms, what we know about food, plus how bodies interact with materials. Thanks to better nano-blend methods, chitosan films are almost ready for stores - they're stronger now, resist wear far better. Adding small particles, key plant layers, lab-grown extracts, and active biological mixes pushes what these items can do. Yet widespread market presence remains limited today. Hurdles include high making costs, shaky supply of base stuff, difficulty scaling up reuse, approval delays, and how well they last over time. Also, fine-tuning formulas must happen so toughness grows without hurting breakdown in nature.

Starting at the tiny building blocks, then moving through precise lab techniques, this piece dives into chitosan-based films. What lies ahead comes clear when fresh findings meet real-world hurdles - future paths take shape where progress stalls. Insight grows not just from success, but also from what remains unsolved (*Frontiers in Microbiology*, 2018; *Recent ScienceDirect Review*, 2020).

2. Chitosan Chemistry and Molecular Arrangement

Looking closely at chitosan-based films means diving into how their molecules are arranged. A chain of D-glucosamine units joined by β -(1 \rightarrow 4) bonds makes up chitosan - it's what gives the material its core shape. This substance comes from treating chitin so it loses some acetyl parts, but not all. How many amino groups stay exposed depends on the deacetylation level, called DD. That number quietly controls solubility, how stiff or flexible the film feels, whether it forms tight crystal patterns, and even how it behaves in living systems. Much rides on that single measure, though it goes unnoticed (Wang, Qian, & Ding, 2017; Qiao et al.; *Scientific.Net*, 2014).

Starting off, chitosan stands apart from many natural sugars because it carries basic nitrogen units right in its structure. When placed into sour conditions, those nitrogen parts grab extra hydrogen atoms. That shift makes chitosan mix well in tainted small-chain acids like vinegar-based ones. Thanks to this mixing trait, pouring the solution lets thin layers form slowly as the liquid dries out (Politesi Thesis, 2024; Qiao et al.). Hydrogen sticking between molecules changes sharply when deacetylation shifts. More amino bits show up if DD drops, boosting germ-fighting power along with electric pull effects. Yet too much stripping away acetyl parts weakens crystal order, dragging down toughness. To keep films working right across tasks, tuning DD becomes unavoidable.

Molecular weight plays a key role too. When chitosan has longer polymer chains, it tends to show stronger mechanics and forms films more easily. Yet shorter chains might respond faster within biological settings. Those lighter versions often move through systems with less resistance.

Water soaks into loose parts easily, yet tight zones resist stretching. Though stiff spots boost strength, they slow gas movement across the surface. How it acts overall comes down to how packed areas mix with open ones. Loose chains bend under moisture while firm segments hold shape tightly (*Scientific.Net*, 2014; Mitantsoa et al., 2023).

Water molecules link through fleeting ties that hold shapes together. Across the material, webs of attraction rise from OH and NH parts, bracing the whole setup. Even so, chitosan bits grab moisture from air - thanks to those very links pulling H₂O near.

Stiff in shape, chitosan fits many jobs. Because it carries active sites, changes like grafting or turning into nanoparticles can happen - yet still break down naturally. Its backbone stays tough even when tweaked. (Mitantsoa et al., 2023; Flórez et al., 2021).

3. Film Formation Methods and Production Techniques

Something shifts when chitosan turns from powder to film - solvent type matters, so do temperature and how molecules line up. Not just drying, but real rearrangement happens, held together by weak bonds and tangled chains slowly losing liquid. How it forms depends on more than heat alone, influenced heavily by how tightly strands stick and let go. Understanding what drives this change helps adjust texture and performance without guesswork (Qiao et al.; Politesi Thesis, 2024; Wang, Qian, & Ding, 2017).

Chitosan flakes often come from the result casting method. Here, impure organic acids - acetic acid most of the time - break down the chitosan. Once the amino groups take on protons, the polymer dissolves. Then, someone spreads the sticky mix across a flat surface. Drying happens slowly under controlled heat and humidity. When the detergent slowly disappears, polymer strands move closer. Because of this shift, hydrogen bonds begin to form between them. As more solvent leaves, the structure starts taking on a semi-ordered pattern. With less liquid present, the chains get entangled more easily. Their movement slows down just as connections grow stronger (Mitantsoa et al., 2023; Pereda et al., 2011).

How fast the detergent vanishes shapes how the film forms. If drying drags on, chains line up more neatly but turn out weaker when bent. When evaporation races ahead, hidden stresses get locked in, leading to fragile flakes. What happens to polymer strands as things dry depends heavily on warmth and dampness nearby. These factors twist the ending structure in big ways.

Film makers add softening agents right from the start so movies don't crack easily. Because chitosan strands hold things like sorbitol, PEG, or glycerin well, they weaken tight hydrogen links between chains while letting them move more freely. With these additives, films stretch further and bend easier - yet too much causes weaker edges and lower pull resistance. Getting just the right mix means balancing how strong it is against how flexibly it behaves (Recent ScienceDirect Review, 2020).

Heat sensitivity of chitosan restricts high-temperature methods because breakdown often happens before melting even begins. Extrusion, typically used for thermoplastics, might work for chitosan-based materials when adjusted with suitable plasticisers. Exploring alternative techniques helps improve thickness control and scaling potential along with output shaping. Because of this, fine-tuning the combination of heat and mechanical force becomes essential. Still, progress depends on careful balancing rather than broad application (Khubiev et al., 2023).

A thin stream of liquid gets stretched into fine threads when zapped with electricity - that's how chitosan mats take shape through electrospinning. Voltage pulls the goop until fibers form, each one tiny, full of surface space. These webs breathe well, interact closely with living tissue, thanks to open frameworks inside. Wound coverings rely on them just as much as scaffolds that guide new cell growth do.

Layer upon layer, alternating deposits of unevenly charged polyelectrolytes build up thin films step by step. Because chitosan carries a positive charge in acidic conditions, it pairs well with negative polymers like pectin or alginate. With this method, thickness, makeup, and performance of the coating come under close control. Such precision opens paths toward better barriers and timed delivery setups (Flórez et al., 2021; International Journal of Advanced Research, 2024).

Lately, new methods avoid solvents to reduce harm to nature. Instead of harsh chemicals, some approaches use ionic liquids or fluids under extreme pressure. These dissolve tough materials while skipping toxic cleaners. A few rely on lab results so far, yet point clearly elsewhere - toward making things that last without wrecking the planet. Most remain experimental, but the direction feels different now.

When everything settles, how chitosan films turn out depends on tiny movements inside molecules, how solvents behave, along with conditions applied during production. Because researchers can tweak each of those factors, lab results connect more smoothly to real-world uses through adjusted film formation speeds tailored to specific tasks (Politesi Thesis, 2024; Recent ScienceDirect Review, 2020).

4. Mechanical Thermal and Barrier Packages

Strength when pulled, how far it stretches before breaking, plus stiffness - these help measure how chitosan films behave under force. Pulling pure chitosan films leads to decent resistance because of tight hydrogen links across moist regions. Yet brittleness often shows up, stretching little, thanks to restricted motion between chains and crowded bonding patterns. How molecules are arranged matters a lot. So does how much acetyl group has been removed, along with size of the molecules themselves. Outside conditions during creation play a role too. (Scientific.Net, 2014; Mitantsoa et al., 2023).

Flexibility jumps when plasticisers push polymer chains apart, creating more open space within the material. Yet one thing gives way another - stretching ability rises even as the material weakens under

tension. Getting the balance right means tuning how much plasticiser mixes with the polymer, shaping its response without tipping too far in either direction (Pereda et al., 2011; Mitantsoa et al., 2023).

When tiny oxide bits, nanocellulose, or skin-like particles are mixed in, the material pulls apart less easily. These small fillers link up within the plastic base, helping spread force more evenly while slowing down crack growth. Because clumping of nanoparticles might harm strength and create odd bumps in structure, spreading them out well becomes key. Only when dispersion stays consistent does performance improve without weak spots forming.

Heat resistance matters a lot when working with storage or processing. Moisture tends to escape at cooler heats, while the material falls apart when things get too hot - these shifts show up often in chitosan. Around 250 to 300 °C, the links holding sugar units together start snapping, thinning out the chain structure. High-heat methods might hit limits because of this firmness, yet many wrapping tasks still fit within its range (Sutharsan et al., 2025; Basumatary et al., 2023; Bahar et al., 2023).

Crosslinked structures hold their shape better under heat because they restrict movement within the material. Instead of falling apart early, these modified versions resist breakdown longer than regular chitosan does. Heat tests show that adding nanoparticles helps even more. Films built with both links and tiny fillers stay stable when temperature climbs. Each measurement confirms a stronger performance under fire-like conditions.

Few materials block oxygen as well as chitosan films do. Since water-rich zones and tight hydrogen bonding slow gas movement, these wraps resist air flow. That slowness makes them useful. When protecting foods easily damaged by oxygen exposure, this trait turns out to matter a lot (Scientific.Net, 2014; Fiallos-Núñez et al., 2024).

Even so, letting water vapor through stays tricky. Since chitosan likes moisture, damp air gets soaked up, softening the layer and weakening how strong it holds together. To fight wetness, one way is making it more oil-friendly, mixing in materials that repel water better, or adding tiny fillers that block passage by creating winding trails hard to cross.

Fine at cutting down how much moisture moves through Nanocomposite setups stand out. Take melted skin-like films - they slow particles by making them wind along tougher routes. Besides that, tiny supports built from cellulose crystals or graphene oxide boost barrier strength. What helps even more is how small parts reshape the way stuff spreads (Flórez et al., 2021; Mitantsoa et al., 2023).

Light plays a big role in how packaging feels to the eye. Most chitosan films carry a soft, pale hue - nothing bold - and let light through easily. Seeing what's inside gets easier when the wrap lets images blur through gently. Still, tossing in certain tiny particles can mess with clear looks. Keeping things visually pleasing means thinking hard before mixing anything new.

Even so, chitosan shifts how materials handle stress, heat, plus resistance, walking a line where strength meets limited flexibility. Thanks to nano-scale tweaks and mixing polymers, its performance range now stretches much wider. That progress nudges it nearer to swapping out standard plastic stuff across certain uses (Gülpınar et al., 2024; Basumatary et al., 2023).

5. Functional Variations and Nanocomposite Engineering

Even though native chitosan films block oxygen well, break down easily in nature, and fight bacteria on their own, they crack under stress and soak up moisture too fast - this gets in the way of real-world uses. To fix these issues, researchers have explored different tweaks that boost strength while keeping the eco-friendly edge. Starting from a basic shellfish extract, altering its structure opens doors: suddenly it bends instead of breaks, fits specific needs, yet stays kind to the planet (Gülpınar et al., 2024; Basumatary et al., 2023).

Chemical changes offer a neat way to tweak chitosan's traits. Thanks to the hydroxyl spots at C-3 and C-6 - also the amino bits at C-2 - fine adjustments can happen. Controlled reactions allow shifts in how it dissolves, its surface charge, thickness when flowing, water affinity, plus links between chains. Each step shapes how the material behaves, nothing more (Khubiev et al., 2023).

Carboxymethylation is a changes how the polymer behaves in water across different acidity levels, simply by attaching new chemical bits along its chain. When moisture shows up, the material puffs outward more than before - a shift that also tightens how films hold together. Pairing with other water-friendly chains gets smoother too, thanks to this tweak on chitosan's structure (De Carli et al., 2022; Recent ScienceDirect Review, 2020). Humidity movement matters in living coatings; here, the modified version does better without question.

With neutral or just-alkaline conditions, antimicrobial action kicks in when amino groups get quaternized, bringing extra positive charge. Because of this shift, quaternized forms stay active across different pH levels, unlike natural chitosan that only works when acid environments provide protons. Activity shows up more reliably now, thanks to these tweaks. When it comes to food coating jobs, such adaptability matters - pH shifts happen often there.

Humidity resists better when chitosan gets hydrophobic tweaks through acylation or alkylation - water attraction drops as a result. Attaching oily chains to the main structure lets scientists craft molecules that grab onto oil-loving active ingredients, such as key plant oils, much more easily. These tweaks also boost how well moisture barriers work, an important shift when building layered protective materials.

One key change in material design involves linking molecules together. Instead of just sitting apart, they form bridges - citric acid and genipin create strong bonds that build a firm 3D structure, making films tougher and less likely to dissolve. On another note, using charged particles like multivalent anions forms links that can break and reform, which keeps the material able to decay naturally while still resisting water. Depending on how these connections are made, the result shifts - hardness, bendability, even how fast it breaks down - all depend on the type of bridging chosen (Fiallos-Núñez et al., 2024; Pereda et al., 2011). Not long ago, mixing materials became more than just altering chemicals - it turned practical, even scalable. Thanks to how hydrogen sticks and static charges behave, chitosan teams up with different natural polymers like gelatin, starch, modified cellulose, or polyvinyl alcohol. These pairings create effects where the whole works better than the parts alone. Take one example: chitosan fights bacteria quite well, while gelatin adds flexibility and helps films resist bending too much. In another case, polyvinyl alcohol builds tight bonds between molecules, making structures steadier and stronger when pulled. (Jain et al., 2025; Mitantsoa et al., 2023; Nashed et al., 2026; Springer et al., 2024).

When settings mix wrong, machines might not work together. Film layers split apart if materials refuse to blend. Drying too fast often ruins strong bonds between parts. Special helpers keep films smooth when elements resist each other.

Out in the mix, tiny fillers boost how tough and heat-resistant chitosan films can be. Because these particles spread out so much, they link tightly with the base material. It's that close contact - thanks to massive surface reach - that sharpens performance across zones. Layered into the design, nano-reinforcements lift durability without weighing things down.

When tiny bits like titanium dioxide and zinc oxide go into materials, they bring germ-fighting and sun-blocking traits along. These particles weave through chitosan, making it harder for air and moisture to pass. Heat holds up better because the added pieces slow down how freely the material's strands can move.

From time to time, tiny particles in dishes let off charged bits that fight bacteria strongly. These work alongside chitosan's ability to disrupt cell walls, especially when mixed into chitosan strips. Action happens together, yet safety checks on how these move through tissues remain key. Even so, tests tracking movement and tissue response must happen first because health risks and approval rules raise concerns.

Gas movement slows down when tiny plate-shaped particles stack unevenly. These layers, often made of montmorillonite, block straight paths molecules might take. The zigzagging journey across bent barriers cuts how fast substances escape. That change in layout makes containers hold better. Structure shifts like these tweak how stuff flows through films.

Tiny plant-based fillers, like nano-sized fibers and crystals, deliver steady support. Because they bond well with chitosan through hydrogen links, things break down naturally yet stay stronger. These materials stretch further before snapping, their stiffness improves too. Rightly spread out, the cellulose bits let more light pass through. That clear look matters a lot on store shelves. Appearance shifts subtly when transparency rises.

From time to time, chitosan strips wake up once bioactives enter the mix. As it happens, the material holds tight to natural antioxidants, key oils, maybe even lab-made extracts - slowly letting go later on. Hidden inside are helpers: ones that fight rusting, others that block bad bugs, all aiming to stretch how long meals last. Yet release needs care. Sudden bursts might harm delicate items nearby (Sutharsan et al., 2025; Basumatary et al., 2023; Gülpınar et al., 2024).

Sticking well at the boundary, spreading evenly - these matter if changes need to work. How things link inside, what holds them up, gets clearer through methods such as wobbling tests under stress or zooming deep with electron eyes. Stiffness sits beside see-through quality; breaking down naturally goes hand in hand with staying tough. Each trait tugs against others when shaping a substance that serves its purpose.

Starting off quiet, chitosan shifts shape when touched by chemistry, mix-ins, or tiny built-up layers. It steps forward not as just another lab curiosity but as something able to respond to pressing environmental needs. Change comes through tweaks at the molecular level, teaming up with other substances, or structure tuned deep down small. Each move reshapes its role without shouting about breakthroughs. The material grows useful by bending to new forms rather than promising miracles (De Carli et al., 2022; MDPI/Elsevier Works, 2023).

6. Antimicrobials and Antioxidants Work

Chitosan-based films stand out because they actively fight bacteria. Rather than just blocking microbes like many other biopolymers do, chitosan gets involved through multiple methods. These approaches slow down microbial growth in clear ways. Knowing how it works helps shape better films for keeping food safe and aiding medical uses (Khubiev et al., 2023; *Frontiers in Microbiology*, 2018).

What gives chitosan its ability to fight bacteria mainly comes down to a positive charge it carries. When conditions turn acidic, amino groups gain protons - this lets them stick to microbial surfaces that are negatively charged. The bond pulls at the outer layer of microbes, shaking their structure loose. With the barrier weakened, key pieces inside start leaking into surrounding areas. Without these essential components, the microbe cannot survive.

Chitosan slips into microbes after tearing apart their outer layers, then sticks to genetic material inside. That sticking stops new RNA from forming, also blocks protein creation. Growth slows down because of these disruptions. Effectiveness depends heavily on two things: size of the molecule and where it lost acetyl groups. Bigger molecules crash harder against cell surfaces, causing more damage. Smaller ones slide easier across barriers, reaching deeper spots. Performance shifts based on those traits (*Frontiers in Microbiology*, 2018).

Chitosan grabs metal ions, stopping microbes from using them. Because of this, germs struggle to grow. Their enzymes falter without these elements. Food spoilage slows down as a result. The process weakens bacteria, molds, and certain pathogens alike. A shift happens in how cells manage essential minerals. Protection spreads across different types of harmful organisms.

Under different conditions, how well antimicrobials work can shift sharply. Chitosan's effectiveness ties closely to things like acidity, heat, what's on the surface, along with the kind of microorganism present. Because of their outer membrane structure, certain bacteria - like Gram-negatives - tend to stand up better than others. Even so, chitosan manages to block several harmful types linked to contaminated food.

From time to time, chitosan films show better germ-fighting power when mixed with essential oils or tiny particles. Oils mess up the fat layers in cell walls. Zinc oxide and silver specks make harmful oxygen bits that harm microbes. Because of this mix, the whole system hits more kinds of bugs than before (*Frontiers in Microbiology*, 2018).

Tiny bits that fight damage show up in chitosan flakes. When fats in food break down, they turn stale, taste strange, then lose value. Chitosan steps in by mopping up loose particles, holding tight to metal atoms. It slows spoilage because it grabs metals like iron, stopping them from speeding up decay.

From plant extracts to polyphenols, nature's touch boosts this effect in quiet ways. During storage, steady defense comes through slow escape from the material's web. Chitosan teams up with botanical shields, lifting function while skipping synthetic helpers. A slower fade means longer strength when tucked inside such wraps. No lab-made boosters needed where these two join forces behind the scenes (Basumatary et al., 2023; De Carli et al., 2022).

Crack healing gets help when germs stay away and cell damage drops, thanks to how these substances fight bacteria while soaking up stress. Wound coverings made with chitosan bits trigger clotting, slow microbes down, besides keeping the repair zone damp enough. Not just another wrapper - this material proves it can hold firm even beyond storage uses.

Even though things look good, checking antibiotics the same way every time matters a lot. Commercial use comes only after careful study of movement through tissues. Lasting effects need close watching too. Any chance of harmful byproducts. That gets examined first.

Flicks made from chitosan bring practical benefits, boosting protection while slowing spoilage thanks to germ-fighting and freshness-preserving traits. Their ability to support fabric recovery comes through natural reactivity, quietly enhancing durability over time. Safety edges improve not by chance but due to consistent interaction with microbes. Longevity shifts happen subtly, woven into daily use without fanfare.

Renewal of cloth surfaces emerges as a quiet side effect of routine exposure (Recent ScienceDirect Review, 2020).

7. Food Packaging Applications

A big claim today's food tech makes involves swapping oil-based plastics for materials that break down naturally. Thanks to strong germ-fighting traits, the ability to block oxygen, film-forming skills, and eco-friendly decay, films made from chitosan draw serious attention. Unlike old-style wraps that just sit there as passive shields, these chitosan layers jump into action - changing how food stays safe and lasts longer on shelves (Barik et al., 2024; Flórez et al., 2021).

Chitosan films slow down how fast oxygen moves through them - that helps keep food fresh longer. When foods meet air, they can lose color, nutrients, go rancid, or grow microbes more quickly. Hidden inside chitosan's layout, tiny crystal zones held together by hydrogen links put up a fight against oxygen passing by. This makes wrapping useful for items like cheese, cooked meals, and meats that spoil if left exposed. Even so, even though oxygen hardly gets through, water vapor often does - thanks to chitosan loving moisture too much. Fighting dampness has led scientists to try new paths: attaching water-repelling parts, mixing with less thirsty plastics, slipping in nanoparticle helpers (Basumatary et al., 2023; De Carli et al., 2022).

Spoilage in fish and meat often comes from fats breaking down or microbes taking hold. Because it carries a positive charge, chitosan can bind well with compounds such as plant-based phenols, boosting its ability to block bacteria. Instead of just slowing germs, this material tackles rancidity too - especially when blended with natural oils or lab-made extracts. Over time, samples wrapped in chitosan-coated wraps stay fresher inside cold storage compared to standard plastic coverings. On top of that, certain metal ions mixed into the wrap help prevent unwanted chemical reactions tied to decay. Through multiple trials, scientists noticed treated cuts held quality longer under refrigeration conditions. While not perfect, the method shifts how we think about preserving perishable protein sources.

Out in the open, milk products often face spoilage risks. Take waste bins, where dampness invites mold during storage. A shield formed from chitosan steps in quietly - blocking fungi, holding flavor steady. Moisture moves through it just enough, not too much, keeping things fresh without force (Basumatary et al., 2023; De Carli et al., 2022).

Now here comes smart wrapping, stepping in quiet but clear. Folks tinkering in labs found a way to paint warning signs onto films using earth-made dyes - think anthocyanins tucked into chitosan layers. As microbes stir and acidity shifts, the surface answers back with a hue flip, showing spoilage without words. These hues shift live, moment by moment, feeding eyes fresh clues about what lies beneath. Safety isn't shouted out loud - it's whispered through tint, meeting those who want truth on their plate.

Even though lab tests look good, real-world use faces hurdles. To keep liquids out during shipping and handling, the films need to hold up under stress. In damp storage conditions, moisture sensitivity becomes a problem. Before approval for food-related uses, thorough checks on toxicity and substance transfer are required - especially if tiny particles or base layers are involved. Right now, scientists continue working to close the gap in performance compared to regular plastic wraps.

One good thing about chitosan packaging is how well it fits into natural environments. Films made from this material show up more often now, simply because people want safer ways to wrap their food. Rules are shifting too, pushing makers toward materials that break down without harm. With demand rising, these thin layers stand out - quiet but steady alternatives building space in a changing market (Recent ScienceDirect Review, 2020).

8. Biomedical and Agricultural Uses

Chitosan films show up a lot in biomedical work. Their usefulness comes from how they interact with living tissue, fit well inside biological environments, stay stable yet break down naturally over time. Much like the sugars found in human tissues, chitosan shares a similar backbone structure. That likeness helps cells settle in more easily. As a result, repairs in skin, delivery of medicine, even healing cuts get support through its use.

A thin layer made from chitosan works like a shield when placed on splits in the skin. Moisture stays locked in, healing gets a boost, while germs find it hard to enter. Thanks to its natural pull toward red blood cells

- those carry oxygen - a gel form speeds up scab creation, slowing fluid loss fast. Fewer harmful bugs survive near this material, lowering risks linked to cuts that return often. Substances such as healing triggers, germ killers, or swelling fighters might nest inside these sheets, letting treatment unfold slowly where needed (Khubiev et al., 2023; *Frontiers in Microbiology*, 2018).

Tiny chitosan films help carry medicines inside the body thanks to their knack for turning into water-friendly gels with tiny tunnels. These open paths let drugs slip out slowly, shaped by how much liquid the film soaks up. The speed of release depends on the size of the molecules and how thickly linked the structure is - tuning these lets treatments match patient needs. When placed on skin, the sheets stick well due to clingy surface traits. That grip helps medicines push through outer layers more easily during patch-style use.

Tiny bits of chitosan help cells stick and grow inside engineered tissue. Because they act like the body's natural scaffolding, these porous forms support healing. With collagen mixed in, along with hydroxyapatite, the setup strengthens links in hard and soft structural tissues. While fresh tissue emerges, the chitosan quietly breaks down - vanishing because it dissolves naturally over time.

Tiny films made from chitosan help farming stay green. Instead of using plastic sheets that harm dirt, these break down naturally. When they rot, the land stays healthier. Plants grow better because chitosan wakes up their roots. Coating seeds with it helps them sprout faster while staying safe from bugs. Little shields form around young plants, keeping sickness away. From start to finish, the earth breathes easier (Nashed et al., 2026).

Chitosan layers slow down spoilage after harvest. When placed on produce, they block mold while delaying ripening. These coverings work two ways - spotting chemical changes and forming a barrier - that keep crops fresher longer without synthetic additives. Their job kicks in right after application, quietly improving storage outcomes.

One reason chitosan stands out? Its chemistry bends well to both farming and medical uses. Not like most natural polymers - it stays strong in shape even when sparking biological reactions. While many materials fall apart doing so, it holds firm, quietly active (*Frontiers in Microbiology*, 2018)

9. Challenges and scaling industry efforts

Even with progress in lab work, making chitosan-based films widely isn't straightforward yet. Because source materials differ, traits like molecular weight shift unpredictably. Deacetylation levels waver due to these inconsistencies. Consistency in manufacturing hinges on uniform processing methods. Without steady purification and preparation steps, repeatable results stay out of reach. Scaling up demands tighter control at every phase. Unexpected differences often emerge late in production. So far, stability remains a moving target. Small changes upstream ripple through the entire output. Until processes lock in place, large-scale efforts face hurdles.

Money matters just as much. Even though chitosan comes from plentiful ocean waste, turning it into a usable form often takes costly steps. For production to work long term, cleaner and smarter methods need to take shape (Haghighi, 2022; *Scientific.Net*, 2014).

Still tricky. Handling dampness in packaging meant for wet environments. Even with tweaks using chemistry and tiny blended materials, blocking moisture remains tough. Matching plastic's shield against water feels far off, despite progress made so far (Mitantsoa et al., 2023).

Even without official approval, moving forward brings serious hurdles. Equipment that contacts food has to follow tight safety rules. Testing for toxins becomes trickier if nanoparticles or chemical binders are part of the mix. Selling such items later demands well-defined regulatory standards (Mitantsoa et al., 2023).

Down the line, fresh breakthroughs might emerge as green chemistry meets nano-tech. New life could come to bio-based nanomaterials through large-scale extrusion without solvents. Shifts in how things are built layer by layer may reshape medical device designs. Printing objects bit by bit might redefine what's possible in healthcare tools (Mitantsoa et al., 2023).

Working through these hurdles means material experts must team up with food specialists, medical innovators, and oversight groups. Biodegradable options could see a sharp rise in need once environmental concerns grow stronger alongside tighter plastic regulations spreading worldwide (*Recent ScienceDirect Review*, 2020).

10. Conclusion

From shrimp shells and fungi, chitosan emerges - a natural substance shaping eco-conscious materials. Its backbone supports films that resist bacteria while breaking down safely in nature. Though weak when wet, science now strengthens it through mix-ins and molecular tweaks. Lab work combines it with nanoparticles, altering its behavior under stress. Even damp settings become manageable after smart adjustments. Once limited, today's versions hold up better thanks to layered innovation behind the scenes. (Flórez et al., 2021; Khubiev et al., 2023; Recent ScienceDirect Review, 2020).

One way chitosan flakes help is by extending how long food stays fresh through natural antioxidant traits - working alongside germ-fighting effects. Because they come from nature and break down easily, these materials often outperform lab-made versions in medical uses and farming tasks. Yet their wider adoption runs into hurdles like high production costs and difficulty scaling up output reliably. Approval pathways remain unclear, while fine-tuning effectiveness across conditions hasn't been fully settled yet.

Future research might dig into plant-based nano additives, green manufacturing methods, yet also smart wrapping solutions. Chitosan-made films could play a key role in boosting circular economy plans while supporting earth-safe substance discovery, especially as global demand shifts toward lasting materials.

Reference

1. Fiallos-Núñez et al. — Eco-Friendly Design of Chitosan/Gelatin Biopolymer Films: Optimisation and Properties (2024)
2. Gülpınar et al. — Chitosan film incorporated with silver-loaded organo-bentonite: Synthesis and characterisation (2024)
3. Barik et al. — Evaluation of chitosan-based packaging film for food shelf-life extension (Journal of Agriculture & Food Research, 2024)
4. Sutharsan et al. — Chitosan/agar/TiO₂ biopolymer nanocomposite film for antibacterial & food preservation (2025)
5. Jain et al. — Sustainable chitosan-gelatin composite films from marine processing byproducts (2025)
6. Mitantsoa et al. — Starch-chitosan bioplastic films: mechanical and barrier properties (2023)
7. Nashed et al. — Multiscale analysis of plasma-modified chitosan/silk fibroin films (2026)
8. Wang, Qian & Ding — Emerging chitosan-based films for food packaging (J. Agric. Food Chem., 2017)
9. Flórez et al. — Chitosan for food packaging: active and intelligent films (review) (2021)
10. Díaz-Montes et al. — Trends in chitosan edible films and coatings (PMC review)
11. Zhao et al. — Functional biopolymers for food packaging with chitosan films (2023)
12. Khubiev et al. — Chitosan-based antibacterial films review (biomedical & food) (2023)
13. Haghghi — Recent advances on chitosan-based films: literature overview (review)
14. Jamróz — Composite biopolymer films based on furcellaran-chitosan complex (2021)
15. Basumatary et al. — Chitosan composite films with active agents & ZnO nanoparticles (2023)
16. De Carli et al. — Production of chitosan active films enriched with propolis extract (2022)
17. Martínez-Camacho et al. — Chitosan composite films with antifungal properties (2010)
18. Pereda et al. — Chitosan-gelatin composite and bi-layer films (2011)
19. Bahar et al. — Edible films: gelatin/chitosan/ZnO composites (2023)
20. Qiao et al. — Chitosan films' structure & properties vs. solvent type (cited in literature)
21. Springer et al. — Chitosan/PVA/chitooligosaccharides/gallic acid hydrogel films (2024)
22. Politesi thesis — Chitosan film formulation with acid vs CO₂ dissolution (2024)
23. Scientific.Net — Chitosan film structural & mechanical properties (AMR 979)
24. Frontiers in Microbiology — Chitosan triple action: eliciting, antimicrobial, film-forming (2018)
25. Recent ScienceDirect review — Chitosan films for sustainable food packaging (2020)
26. International Journal of Advanced Research — Chitosan film with pectin/cellulose reinforcement (2024)

27. Research on chitosan adsorption film mechanics (surface properties) — Bureau et al. (2025)
28. Chitosan nanoparticles & films (various synthesis/functional studies) – (general literature)
29. Other films incorporating plant extracts/active compounds — cited across recent MDPI/Elsevier works
30. Many cited review articles cover hundreds of individual studies — good sources to identify more works (e.g., Haghighi, Flórez, Díaz-Montes)



Copyright & License:

© Authors retain the copyright of this article. This work is published under the Creative Commons Attribution 4.0 International License (CC BY 4.0), permitting unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.