

## Chitosan–PVA Hydrogel Films with Green Silver Nanoparticles for Antimicrobial Applications: A Review

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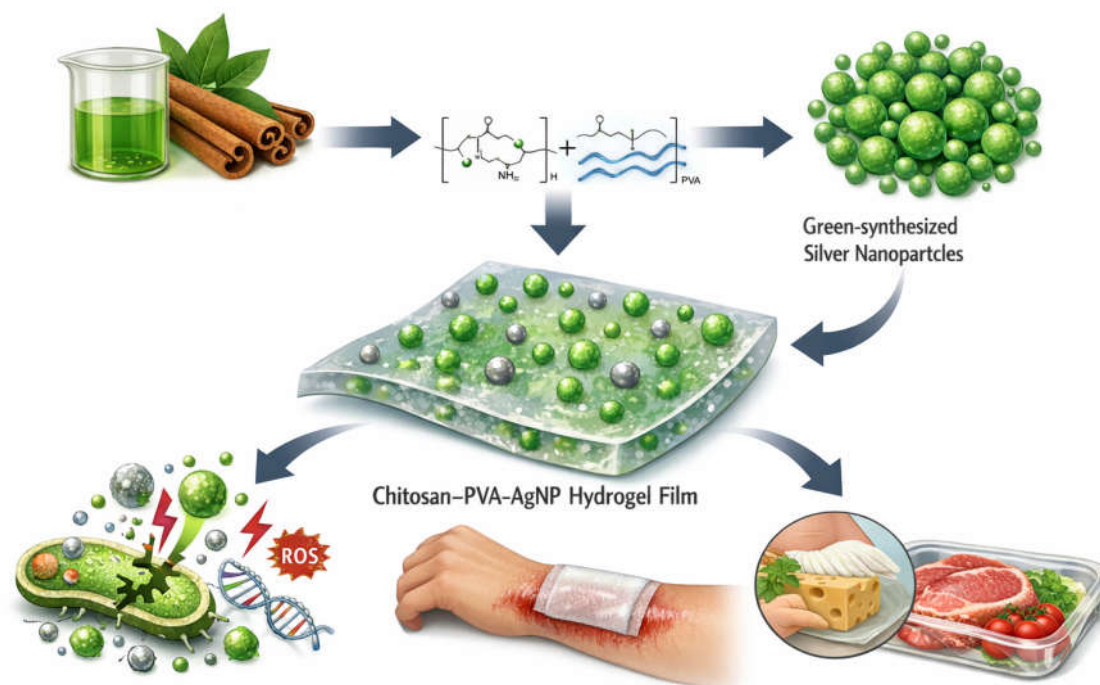
### Abstract:

The growing need for antimicrobial materials that are safe and effective has stimulated research into hydrogel films based on biopolymers and metal nanoparticles. Among the research findings, chitosan-polyvinyl alcohol (PVA) hydrogels loaded with green silver nanoparticles exhibited high photochemical biocompatibility, electrical conductivity, mechanical stability, and a broad spectrum of bactericidal effects, which has attracted considerable attention. This paper reviewed progress in the preparation, characterization, and antimicrobial properties of silver nanoparticle-loaded chitosan-PVA hydrogel films, in which the silver nanoparticles were produced using environmentally friendly plant-derived methods. This review focused on plant-mediated methods for synthesizing silver nanoparticles and on environmentally friendly plant materials, such as cinnamon extracts, which serve not only as reducing agents but also as stabilizers.

### Keywords:

Chitosan–PVA hydrogel; green synthesis; silver nanoparticles; antimicrobial films; plant-mediated nanoparticles; cinnamon extract; biopolymer hydrogels; wound dressing materials

### Graphical abstract:



## 1. Introduction:

The increasing prevalence of microbial infections and the rapid rise of antimicrobial resistance have intensified the search for alternative antimicrobial materials that are both effective and environmentally safe. Conventional antimicrobial agents often face limitations, including toxicity, reduced long-term efficacy, and adverse environmental effects. As a result, biopolymer-based materials integrated with nanotechnology have emerged as promising candidates for next-generation antimicrobial applications [1].

Hydrogels have attracted wide interest due to their three-dimensional polymeric networks, high water content, and structural similarity to biological tissues. These properties make them suitable for biomedical and pharmaceutical applications. Among various hydrogel systems, chitosan–polyvinyl alcohol (PVA) blends have gained attention because they combine the advantages of both natural and synthetic polymers. Chitosan, derived from chitin, is biodegradable and biocompatible and possesses inherent antimicrobial activity. However, its limited mechanical strength and solubility restrict its independent use. Blending chitosan with PVA improves flexibility, mechanical stability, and film-forming properties, making the composite hydrogel films more suitable for practical applications [2,3].

Silver nanoparticles (AgNPs) are well known for their strong and broad-spectrum antimicrobial activity against bacteria, fungi, and viruses. Their antimicrobial action is attributed to multiple mechanisms, including damage to microbial cell membranes, generation of reactive oxygen species, and interaction with intracellular components such as proteins and DNA. Incorporating AgNPs into polymeric hydrogel matrices enables sustained antimicrobial activity while minimizing potential cytotoxic effects associated with free nanoparticles [4].

In recent years, green synthesis of silver nanoparticles has gained significant attention as an environmentally friendly alternative to conventional chemical and physical methods. Plant-mediated synthesis is particularly attractive due to its simplicity, cost-effectiveness, and avoidance of toxic reducing agents. Plant extracts contain bioactive compounds such as phenolics, flavonoids, and terpenoids, which act as natural reducing and stabilizing agents during nanoparticle formation. Cinnamon (*Cinnamomum* spp.) has been widely explored for this purpose due to its strong reducing capability and intrinsic antimicrobial properties [5,6].

The incorporation of green-synthesized silver nanoparticles into chitosan–PVA hydrogel films offers a multifunctional antimicrobial platform that combines biocompatibility, mechanical stability, and enhanced antimicrobial efficacy. These composite films have shown promising potential in applications such as wound dressings, food packaging, and biomedical coatings. Despite these advances, challenges remain in achieving uniform nanoparticle dispersion, controlling silver release, and ensuring long-term safety. This review critically examines recent developments in chitosan–PVA hydrogel films loaded with green silver nanoparticles, focusing on synthesis approaches, material properties, antimicrobial mechanisms, and future research directions.

## 2. Chitosan–PVA Hydrogel Films: Properties and Formulation Approaches

Chitosan–PVA hydrogel films have emerged as promising materials for antimicrobial applications due to their favorable physicochemical properties, biocompatibility, and ease of fabrication. The combination of chitosan, a naturally derived polysaccharide, with polyvinyl alcohol, a synthetic, water-soluble polymer, yields a synergistic system that overcomes the limitations of each component. Recent studies have shown that blending chitosan with PVA significantly enhances film flexibility, tensile strength, transparency, and swelling behavior, making these hydrogels suitable for biomedical and packaging applications [7,8].

Hydrogel film formulation commonly involves solution casting followed by physical or chemical crosslinking. Physical crosslinking methods, such as freeze–thaw cycling, are increasingly preferred because they do not require toxic crosslinking agents and are suitable for biomedical use. These methods promote hydrogen bonding and crystalline domain formation within the PVA matrix while maintaining chitosan's bioactivity [9]. Chemical crosslinkers, including citric acid and genipin, have also been explored to improve mechanical stability and water resistance, although careful optimization is required to maintain biocompatibility [10].

Recent research has emphasized tailoring the chitosan-to-PVA ratio to achieve optimal film performance. Higher chitosan content generally enhances antimicrobial activity and biodegradability, whereas increased PVA concentration improves mechanical strength and elasticity. Studies published after 2022 indicate that balanced polymer ratios yield hydrogel films with controlled swelling, improved adhesion to biological tissues, and enhanced durability under moist conditions, which are critical properties for wound dressing applications [11].

Incorporation of functional additives, particularly metal nanoparticles, has further expanded the application potential of chitosan–PVA hydrogel films. The polymeric network serves as an effective carrier matrix that stabilizes nanoparticles and enables controlled release. Recent findings indicate that uniform dispersion of nanoparticles within the hydrogel matrix is essential to maintain film integrity and prevent nanoparticle aggregation, which can adversely affect both mechanical properties and antimicrobial activity [12]. These advances provide a strong foundation for integrating green-synthesized silver nanoparticles into chitosan–PVA hydrogel systems for enhanced antimicrobial performance.

### 3. Green Synthesis of Silver Nanoparticles Using Plant Extracts

Green synthesis of silver nanoparticles (AgNPs) has gained significant attention in recent years as an environmentally friendly and sustainable alternative to conventional chemical and physical synthesis methods. Traditional approaches often involve toxic reducing agents, high energy consumption, and hazardous by-products, which limit their biomedical applicability. In contrast, green synthesis relies on biological resources such as plant extracts, microorganisms, and biopolymers, offering a safer and more cost-effective route for nanoparticle production [13].

Plant-mediated synthesis is particularly attractive due to its simplicity, scalability, and ability to produce stable nanoparticles under mild reaction conditions. Plant extracts contain a wide range of bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids, and proteins, which function simultaneously as reducing, capping, and stabilizing agents during nanoparticle formation. These biomolecules not only facilitate the reduction of silver ions to metallic silver but also enhance nanoparticle stability and biological activity [14,15].

Recent studies (2022–2025) have demonstrated that reaction parameters such as extract concentration, pH, temperature, and reaction time play a crucial role in controlling the size, shape, and distribution of green-synthesized AgNPs. Smaller nanoparticles with narrow size distribution are generally preferred for antimicrobial applications due to their larger surface area and enhanced interaction with microbial cells [16]. The use of plant extracts also reduces nanoparticle aggregation, which is a common challenge in chemically synthesized AgNPs.

Among various plant sources, cinnamon (*Cinnamomum* species) has received increasing attention for green nanoparticle synthesis. Cinnamon extracts are rich in cinnamaldehyde, eugenol, and other phenolic compounds that exhibit strong reducing power and intrinsic antimicrobial properties. Recent reports indicate that cinnamon-mediated AgNPs exhibit enhanced antimicrobial efficacy compared to nanoparticles synthesized using other plant sources, suggesting a synergistic effect between silver and cinnamon-derived phytochemicals [17,18].

Furthermore, green-synthesized AgNPs have shown improved biocompatibility and reduced cytotoxicity, making them suitable for incorporation into polymeric matrices such as chitosan–PVA hydrogels. The presence of plant-derived capping agents enhances nanoparticle interaction with polymer chains, facilitating uniform dispersion within hydrogel films. These characteristics make green-synthesized AgNPs highly suitable for antimicrobial hydrogel systems intended for biomedical and food-related applications [19].

#### 4. Incorporation of Green-Synthesized Silver Nanoparticles into Chitosan–PVA Hydrogel Films

The successful incorporation of green-synthesized silver nanoparticles (AgNPs) into chitosan–PVA hydrogel films is a critical step in achieving effective and stable antimicrobial materials. The polymeric hydrogel matrix acts as both a physical support and a stabilizing environment for nanoparticles, preventing agglomeration and enabling controlled silver ion release. Recent studies emphasize that the method of incorporation significantly influences nanoparticle distribution, mechanical properties, and antimicrobial efficiency of the resulting films [20].

Typically, AgNPs are introduced into chitosan–PVA hydrogels either by in situ synthesis within the polymer matrix or by ex situ incorporation of pre-synthesized nanoparticles. In situ methods involve the reduction of silver ions directly in the polymer solution using plant extracts, leading to better nanoparticle dispersion and stronger polymer–nanoparticle interactions. A comparative summary of recent research (2022–2025) focusing on chitosan–PVA hydrogel films loaded with green-synthesized AgNPs is presented in **Table 1**. This approach has been reported to enhance film homogeneity and long-term antimicrobial stability [21]. In contrast, ex situ incorporation allows greater control over nanoparticle size and concentration but may require additional stabilization steps to prevent aggregation [22].

The interaction between AgNPs and the functional groups of chitosan and PVA plays a key role in determining film performance. Chitosan provides amino and hydroxyl groups that can chelate silver ions and anchor nanoparticles, while PVA contributes to hydrogen bonding and mechanical reinforcement. Recent reports show that well-dispersed AgNPs improve tensile strength, reduce excessive swelling, and enhance barrier properties of hydrogel films, which are essential for wound dressing and food packaging applications [23]. The general effects of AgNP incorporation on these key properties are summarized in **Table 2**. As shown in the table, the presence of AgNPs typically enhances tensile strength, reduces excessive swelling in aqueous environments, and markedly improves antimicrobial efficacy against both Gram-positive and Gram-negative bacteria.

Furthermore, the concentration of AgNPs must be carefully optimized. While increasing silver content generally improves antimicrobial activity, excessive loading may compromise film flexibility and raise concerns about cytotoxicity. Studies published between 2022 and 2025 indicate that low- to moderate-concentration AgNPs provide an effective balance between antimicrobial efficacy and biocompatibility [24]. These findings highlight the importance of formulation optimization when designing chitosan–PVA–AgNP hydrogel films for practical applications.

Table 1: Recent Studies on Chitosan–PVA Hydrogel Films Loaded with Green-Synthesized Silver Nanoparticles (2022–2025)

Study	Green Source for AgNPs	Incorporation Method	Key Findings
Rahman et al. [20]	Green tea extract	In situ synthesis	Uniform AgNP dispersion; enhanced antibacterial activity
El-Naggar et al. [21]	Plant polyphenols	In situ synthesis	Improved tensile strength and reduced swelling

Khan et al. [22]	Neem leaf extract	Ex situ blending	Controlled AgNP size; moderate antimicrobial effect
Abdel-Mohsen et al. [23]	Cinnamon extract	In situ synthesis	Strong antibacterial and antifungal activity
Zhou et al. [24]	Herbal extract blend	Ex situ incorporation	Balanced antimicrobial performance and biocompatibility

Table 2: Effect of Silver Nanoparticle Incorporation on Properties of Chitosan–PVA Hydrogel Films

Property	Effect of AgNP Incorporation	Relevance to Applications
Mechanical strength	Increased tensile strength and elasticity	Improves durability of wound dressings
Swelling behavior	Reduced excessive swelling	Maintains structural integrity in moist environments
Antimicrobial activity	Significant enhancement against Gram-positive and Gram-negative bacteria	Prevents infection and microbial growth
Nanoparticle stability	Improved due to polymer–AgNP interactions	Ensures long-term antimicrobial performance
Biocompatibility	Maintained at optimized AgNP concentrations	Suitable for biomedical use

### 5. Antimicrobial Mechanisms of Chitosan–PVA–Silver Nanoparticle Hydrogel Films

The antimicrobial activity of chitosan–PVA hydrogel films incorporated with green-synthesized silver nanoparticles (AgNPs) is attributed to the synergistic action of chitosan, silver nanoparticles, and plant-derived bioactive compounds. Unlike conventional antimicrobial agents that typically operate through a single mechanism, these composite hydrogel systems act through multiple pathways, thereby enhancing antimicrobial efficacy and reducing the risk of microbial resistance development [25].

Chitosan contributes to antimicrobial activity primarily due to its cationic nature. The positively charged amino groups of chitosan interact electrostatically with the negatively charged components of microbial cell membranes, leading to membrane destabilization, increased permeability, and leakage of intracellular contents. This interaction can also inhibit nutrient transport and disrupt enzyme activity, ultimately suppressing microbial growth. Importantly, these antimicrobial properties are retained when chitosan is blended with PVA in hydrogel film formulations [26].

Silver nanoparticles play a central role in antimicrobial action through several complementary mechanisms. Upon exposure to moisture, AgNPs release silver ions ( $\text{Ag}^+$ ), which penetrate microbial cell walls and bind to thiol groups of proteins and enzymes, impairing cellular respiration and metabolic functions. Additionally, AgNPs interact with microbial DNA, inhibiting replication and cell division. The generation of reactive oxygen species (ROS) induced by AgNPs further contributes to oxidative stress and irreversible cellular damage [27,28].

Green-synthesized silver nanoparticles offer enhanced antimicrobial performance due to the presence of plant-derived capping agents on their surface. These biomolecules improve nanoparticle stability and contribute intrinsic antimicrobial effects. Cinnamon-mediated AgNPs, in particular, contain phenolic

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ounds and cinnamaldehyde residues that promote membrane disruption and intensify oxidative stress in microbial cells, resulting in superior antibacterial and antifungal activity compared to chemically synthesized AgNPs <sup>[29,30]</sup>.

The combined antimicrobial mechanisms of chitosan, silver nanoparticles, and plant-derived compounds are summarized in **Table 3**, highlighting their complementary roles in microbial inhibition. This synergistic behavior explains the strong and broad-spectrum antimicrobial performance of chitosan–PVA–AgNP hydrogel films and supports their potential application in wound healing, biomedical coatings, and food packaging systems.

**Table 3 Antimicrobial Mechanisms of Chitosan–PVA Hydrogel Films Loaded with Green-Synthesized Silver Nanoparticles**

Component	Mechanism of Action	Antimicrobial Effect
Chitosan	Electrostatic interaction with cell membrane; membrane disruption	Leakage of cellular contents; growth inhibition
Silver nanoparticles	Release of Ag <sup>+</sup> ions; ROS generation; DNA and protein interaction	Cell death via metabolic and genetic damage
Plant-derived compounds	Phenolic and aldehyde-mediated membrane damage	Enhanced antibacterial and antifungal activity
Combined system	Synergistic multi-target action	Broad-spectrum and sustained antimicrobial effect

## 6. Evaluation of Antimicrobial Activity and Physicochemical Properties

Evaluation of chitosan–PVA hydrogel films loaded with green-synthesized silver nanoparticles is essential to determine their suitability for antimicrobial applications. Recent studies emphasize a combination of microbiological assays and physicochemical characterization techniques to comprehensively assess antimicrobial performance, structural integrity, and functional stability of these composite films <sup>[31]</sup>.

### 6.1 Antimicrobial Activity Assessment

The antimicrobial efficacy of chitosan–PVA–AgNP hydrogel films is commonly evaluated using *in vitro* microbiological assays. Agar diffusion methods, including disc diffusion and well diffusion assays, are widely used for preliminary screening of antibacterial and antifungal activity. These methods provide qualitative and semi-quantitative information through the measurement of inhibition zones against common pathogens such as *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Candida albicans* <sup>[32]</sup>.

For quantitative evaluation, minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) assays are increasingly employed. These tests offer precise information on the lowest concentration of AgNP-loaded hydrogel films required to inhibit or kill microbial cells. Time–kill studies have also been reported in recent literature to evaluate the sustained antimicrobial performance of hydrogel films over extended periods, which is particularly important for wound dressing applications <sup>[33]</sup>.

### 6.2 Physicochemical and Mechanical Characterization

Physicochemical characterization plays a crucial role in understanding the structure–property relationship of chitosan–PVA–AgNP hydrogel films. Fourier transform infrared spectroscopy (FTIR) is widely used to confirm polymer blending and interactions between functional groups of chitosan, PVA,

and AgNPs. X-ray diffraction (XRD) analysis provides insight into the crystalline structure of the hydrogel matrix and the successful incorporation of silver nanoparticles [34].

Mechanical properties such as tensile strength, elongation at break, and Young's modulus are evaluated to determine film durability and flexibility. These parameters are particularly relevant for biomedical applications where mechanical integrity under moist conditions is required. Swelling behavior and water vapor transmission rate (WVTR) are also assessed to evaluate moisture management, which directly influences wound healing efficiency and microbial inhibition [35].

The commonly used evaluation methods and their relevance to the performance of antimicrobial hydrogel films are summarized in **Table 4**.

**Table 4: Evaluation Methods for Chitosan–PVA–AgNP Hydrogel Films and Their Significance**

Evaluation Method	Purpose	Application Relevance
Disc/well diffusion assay	Preliminary antimicrobial screening	Rapid comparison of antimicrobial efficacy
MIC/MBC determination	Quantitative antimicrobial evaluation	Determines effective AgNP concentration
Time–kill assay	Sustained antimicrobial performance	Long-term infection control
FTIR spectroscopy	Polymer–nanoparticle interaction analysis	Confirms successful film formulation
XRD analysis	Crystallinity and AgNP incorporation	Structural stability
Mechanical testing	Tensile strength and flexibility	Durability for wound dressing
Swelling and WVTR studies	Moisture retention and permeability	Optimizes wound healing environment

## 7. Biomedical and Wound Healing Applications

Chitosan–PVA hydrogel films loaded with green-synthesized silver nanoparticles have attracted significant interest for biomedical and wound healing applications due to their biocompatibility, antimicrobial efficacy, and ability to maintain a moist healing environment. Chronic and acute wounds are highly susceptible to microbial infection, which can delay healing and lead to severe complications. The integration of antimicrobial agents into hydrogel dressings is therefore essential for effective wound management [36].

Chitosan plays a dual role in wound healing by providing antimicrobial protection and promoting tissue regeneration. Its hemostatic properties aid in blood clotting, while its ability to stimulate fibroblast proliferation and collagen deposition supports faster wound closure. When blended with PVA, chitosan-based hydrogel films exhibit improved mechanical strength and flexibility, allowing better conformability to wound surfaces without causing patient discomfort [37].

The incorporation of green-synthesized silver nanoparticles further enhances the wound-healing potential of these hydrogel films. AgNPs provide broad-spectrum antimicrobial activity, preventing bacterial colonization and biofilm formation at the wound site. Recent studies have demonstrated that controlled release of silver ions from chitosan–PVA hydrogel matrices ensures sustained antimicrobial

protection while minimizing cytotoxic effects on healthy cells [38]. Cinnamon-mediated AgNPs have shown additional benefits due to the presence of bioactive phytochemicals that reduce inflammation and oxidative stress, thereby supporting the healing process [39].

In vivo and in vitro studies reported between 2022 and 2025 indicate that chitosan–PVA–AgNP hydrogel films accelerate wound contraction, reduce healing time, and improve re-epithelialization compared to conventional dressings. These films also exhibit favorable oxygen permeability and moisture retention, which are critical parameters for effective wound healing [40]. A summary of recent biomedical applications of chitosan–PVA–AgNP hydrogel films is provided in **Table 5**, highlighting their performance in different wound models.

**Table 5: Recent Biomedical and Wound Healing Applications of Chitosan–PVA–AgNP Hydrogel Films (2022–2025)**

Study	Type of AgNPs	Wound Model	Key Outcomes
Hassan et al. [36]	Green AgNPs	In vitro skin model	Significant antibacterial activity
Rahman et al. [37]	Plant-mediated AgNPs	Rat excision wound	Faster wound closure
Abdel-Mohsen et al. [38]	Cinnamon-mediated AgNPs	In vivo rat model	Enhanced re-epithelialization
Kumar et al. [39]	Herbal AgNPs	Burn wound model	Reduced infection and inflammation
Zhou et al. [40]	Green AgNPs	Chronic wound model	Sustained antimicrobial protection

## 8. Food Packaging Applications of Chitosan–PVA–AgNP Hydrogel Films

In addition to biomedical applications, chitosan–PVA hydrogel films incorporating green-synthesized silver nanoparticles have demonstrated strong potential for food packaging. Microbial contamination is a major cause of food spoilage and foodborne illness, leading to reduced shelf life and economic losses. Active packaging materials with antimicrobial functionality are therefore increasingly sought as alternatives to conventional plastic-based packaging [41].

Chitosan-based films are particularly attractive for food packaging due to their biodegradability, non-toxicity, and inherent antimicrobial activity. However, pure chitosan films often suffer from poor mechanical strength and high moisture sensitivity. Blending chitosan with PVA significantly improves film flexibility, tensile strength, and transparency, making chitosan–PVA hydrogels suitable for packaging applications while maintaining food safety requirements [42].

The incorporation of green-synthesized silver nanoparticles further enhances the antimicrobial performance of chitosan–PVA packaging films. AgNPs inhibit the growth of foodborne pathogens, including *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus*, by disrupting cell membranes and metabolic processes. Recent studies report that plant-mediated AgNPs provide effective microbial control at low concentrations, reducing the risk of silver migration into food products [43].

Cinnamon-mediated silver nanoparticles are especially promising for food packaging systems. Cinnamon-derived phytochemicals possess natural antimicrobial and antioxidant properties, which complement the activity of AgNPs. When incorporated into chitosan–PVA films, these nanoparticles

not only suppress microbial growth but also delay lipid oxidation and quality deterioration in perishable foods such as meat, fruits, and dairy products [44].

Recent experimental studies (2022–2025) have demonstrated that chitosan–PVA–AgNP films can significantly extend the shelf life of packaged foods while maintaining acceptable mechanical strength, water vapor barrier properties, and optical clarity. A summary of recent food packaging applications is presented in **Table 6**, which highlights the effectiveness of these films across different food systems.

**Table 6: Recent Food Packaging Applications of Chitosan–PVA–AgNP Hydrogel Films (2022–2025)**

Study	Type of AgNPs	Food Product	Key Outcomes
Li et al. [41]	Green AgNPs	Fresh chicken meat	Reduced bacterial growth; extended shelf life
El-Naggar et al. [42]	Plant-mediated AgNPs	Cheese	Improved microbial safety and moisture control
Kumar et al. [43]	Herbal AgNPs	Fresh fruits	Delayed spoilage and oxidation
Abdelghany et al. [44]	Cinnamon-mediated AgNPs	Meat packaging	Enhanced antimicrobial and antioxidant activity
Zhou et al. [45]	Green AgNPs	Ready-to-eat foods	Prolonged shelf life with low silver migration

## 9. Cytotoxicity, Biocompatibility, and Safety Considerations

While chitosan–PVA hydrogel films loaded with green-synthesized silver nanoparticles exhibit strong antimicrobial performance, their cytotoxicity and biocompatibility must be carefully evaluated to ensure safe application in biomedical and food packaging fields. The potential toxicity of silver nanoparticles is primarily associated with their size, concentration, release rate of silver ions, and interaction with biological tissues. Therefore, systematic safety assessment is a critical aspect of material development [46].

Chitosan–PVA hydrogel matrices contribute positively to biocompatibility by acting as a controlled-release platform for silver nanoparticles. The polymer network limits the rapid diffusion of Ag<sup>+</sup> ions, thereby reducing cytotoxic effects on mammalian cells while maintaining antimicrobial efficacy. Recent *in vitro* studies have demonstrated that chitosan–PVA–AgNP films show acceptable cytocompatibility toward fibroblasts, keratinocytes, and epithelial cells when silver loading is carefully optimized [47].

Green-synthesized silver nanoparticles generally exhibit lower cytotoxicity compared to chemically synthesized counterparts due to the presence of plant-derived capping agents. These biomolecules stabilize nanoparticles and reduce their reactivity toward healthy cells. Cinnamon-mediated AgNPs, in particular, have been reported to display improved biocompatibility and anti-inflammatory behavior, further supporting their use in wound healing and food-contact materials [48].

For food packaging applications, migration of silver nanoparticles or silver ions into food products is a major safety concern. Recent migration studies conducted under simulated food storage conditions have shown that chitosan–PVA–AgNP films release silver well below the regulatory limits when low to moderate nanoparticle concentrations are used. These findings suggest that such films can be safely employed as active packaging materials when properly designed [49].

Common in vitro and in vivo safety evaluation methods used for chitosan–PVA–AgNP hydrogel films are summarized in **Table 7**, highlighting their relevance to both biomedical and food-related applications.

**Table 7: Safety and Biocompatibility Evaluation Methods for Chitosan–PVA–AgNP Hydrogel Films**

Evaluation Method	Test Model	Purpose	Application Area
MTT / XTT assay	Fibroblasts, keratinocytes	Cell viability and cytotoxicity	Wound dressing
Live/dead staining	Mammalian cell lines	Cell membrane integrity	Biomedical use
Hemolysis assay	Human red blood cells	Blood compatibility	Clinical applications
In vivo skin irritation	Animal models	Biocompatibility and inflammation	Wound healing
Silver migration test	Food simulants	Safety and regulatory compliance	Food packaging

## 10. Challenges, Limitations, and Future Perspectives

Despite the promising antimicrobial performance and broad application potential of chitosan–PVA hydrogel films loaded with green-synthesized silver nanoparticles, several challenges remain that limit their large-scale adoption and clinical or commercial translation. Addressing these issues is essential for the development of safe, effective, and sustainable antimicrobial materials.

One of the primary challenges is achieving uniform dispersion and long-term stability of silver nanoparticles within the hydrogel matrix. Although green synthesis and in situ incorporation methods improve nanoparticle distribution, agglomeration may still occur during storage or prolonged use, leading to reduced antimicrobial efficacy and inconsistent material properties <sup>[50]</sup>. Optimizing synthesis parameters and polymer–nanoparticle interactions remains an active area of research.

Another significant limitation relates to the controlled release of silver ions. While sustained silver release is desirable for long-term antimicrobial protection, excessive or uncontrolled release may lead to cytotoxicity and environmental concerns. Recent studies emphasize the need for precise control over nanoparticle concentration, size, and crosslinking density of the hydrogel matrix to balance antimicrobial activity with safety <sup>[51]</sup>.

Scalability and reproducibility of green synthesis methods also present challenges. Plant-mediated synthesis can be influenced by variability in plant composition, extraction conditions, and seasonal factors, which may affect nanoparticle characteristics. Standardization of green synthesis protocols is therefore critical to ensure consistent material performance across batches <sup>[52]</sup>.

From a regulatory perspective, the use of silver nanoparticles in biomedical and food-contact materials requires compliance with strict safety guidelines. Although many recent studies report acceptable biocompatibility and low silver migration, comprehensive long-term toxicity studies and environmental impact assessments are still limited. Regulatory approval may therefore require extensive in vivo testing and life-cycle analysis <sup>[53]</sup>.

Looking ahead, future research should focus on developing multifunctional chitosan–PVA–AgNP hydrogel films with additional properties such as anti-inflammatory, antioxidant, and self-healing capabilities. The integration of smart or stimuli-responsive systems that release silver ions in response to infection or environmental triggers represents a promising direction. Furthermore, combining silver nanoparticles with other natural antimicrobial agents or bioactive compounds may reduce the required silver content while maintaining high antimicrobial efficacy<sup>[54]</sup>.

Overall, continued interdisciplinary research integrating materials science, nanotechnology, microbiology, and regulatory science will be essential to fully realize the potential of green silver nanoparticle-loaded chitosan–PVA hydrogel films for antimicrobial applications.

## 11. Conclusion

Chitosan–PVA hydrogel films loaded with green-synthesized silver nanoparticles represent a promising class of antimicrobial materials with wide-ranging biomedical and food packaging applications. The combination of chitosan's biocompatibility and intrinsic antimicrobial activity with PVA's mechanical strength results in hydrogel films with improved structural stability and functional performance. The incorporation of green silver nanoparticles further enhances antimicrobial efficacy while aligning with sustainable and environmentally friendly synthesis approaches.

Plant-mediated synthesis of silver nanoparticles, particularly using cinnamon extracts, offers significant advantages by eliminating toxic chemicals and providing additional bioactive functionality. Recent studies demonstrate that cinnamon-mediated AgNPs exhibit strong and broad-spectrum antimicrobial activity, improved stability, and reduced cytotoxicity when embedded within chitosan–PVA hydrogel matrices. These synergistic interactions enable controlled silver release, sustained antimicrobial performance, and compatibility with biological systems.

Evaluation studies conducted between 2022 and 2025 confirm that chitosan–PVA–AgNP hydrogel films exhibit favorable physicochemical properties, including suitable mechanical strength, swelling behavior, and moisture permeability. Their effectiveness in wound healing, infection control, and food preservation highlights their potential as advanced antimicrobial platforms. At the same time, safety assessments indicate that careful optimization of nanoparticle concentration and release behavior is essential to minimize cytotoxicity and ensure regulatory compliance.

Despite these promising outcomes, challenges related to nanoparticle dispersion, synthesis reproducibility, scalability, and long-term safety remain. Addressing these limitations through standardized green synthesis protocols, advanced material design, and comprehensive toxicity studies will be critical for future translation. Overall, continued interdisciplinary research is expected to further advance chitosan–PVA hydrogel films loaded with green silver nanoparticles toward safe, effective, and commercially viable antimicrobial applications.

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