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DEVELOPMENT OF CHITOSAN-ZNO NANOCOMPOSITE FILMS BASED ON BIOPOLYMERS FOR FOOD PACKAGING APPLICATION: A REVIEW OF SYNTHESIS, CHARACTERIZATION, AND APPLICATIONS

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ABSTRACT

The development of environmentally friendly food packaging has driven the use of biopolymers as alternatives to non-degradable petroleum-based plastics. Among them, chitosan–ZnO nanocomposite films have gained significant attention due to their combined biodegradability, biocompatibility, and antimicrobial properties. This review aims to analyze recent advances in the synthesis, characterization, and application of chitosan–ZnO composite films for food packaging. The findings reveal that ZnO synthesis methods have evolved from conventional techniques such as sol–gel to more advanced approaches including green synthesis, surface functionalization, and doping, leading to improved material performance. Solution casting is identified as the most widely used method for film fabrication due to its simplicity and ability to produce homogeneous nanoparticle dispersion. The incorporation of ZnO significantly enhances mechanical strength, thermal stability, barrier properties, and antibacterial activity of the films. Furthermore, blending chitosan with other polymers such as polyvinyl alcohol, gelatin, starch, and polyurethane plays a crucial role in tailoring film properties for specific applications. These nanocomposite films have been successfully applied to various food systems, including fresh fruits, animal-based products, and bakery items, demonstrating their effectiveness in extending shelf life and inhibiting microbial growth. Overall, chitosan–ZnO nanocomposites show strong potential as sustainable active food packaging materials, although further research is required to address challenges related to synthesis standardization, safety, and large-scale application.

Keywords: *Chitosan–ZnO nanocomposite; Active food packaging; Biodegradable films; Zinc oxide nanoparticles; Solution casting; Antimicrobial activity; Polymer blending; Food preservation; Barrier properties; Green synthesis.*

INTRODUCTION

Plastic has become an indispensable part of modern life due to its versatility and cost-effectiveness. However, more than 40% of plastic waste originates from single-use packaging derived from petrochemical sources, which are difficult to degrade and tend to accumulate over time, leading to serious environmental impacts, particularly on soil ecosystems (Hidayat et al., 2025; Kamanna et al., 2023; Mathew et al., 2025). Therefore, there is a pressing need to develop alternative materials that are more biodegradable and safe for food applications while maintaining their protective function as packaging materials (Anugrahwidya et al., 2022; Armynah et al., 2022).

The concept of active packaging has emerged as an innovative solution to address this issue. Unlike conventional packaging, which acts as a passive barrier, active packaging is environmentally friendly and sustainable, capable of slowing down spoilage processes and effectively extending the shelf life of food products (Jovanović et al., 2021; Mathew et al., 2025). In recent years, numerous studies have focused on the development of active packaging based on biopolymers with the incorporation of organic and inorganic fillers to enhance material performance (Alqarni et al., 2024; Saeed et al., 2024).

Chitosan is one of the most widely used biopolymers as a matrix in active packaging composites. It exhibits excellent biodegradability, biocompatibility, and inherent antimicrobial activity, as well as the ability to form transparent thin films, making it highly suitable for food packaging applications (Hidayat et al., 2025; Wrońska et al., 2021). However, pure chitosan films have limitations, including poor mechanical properties and high water vapor permeability, which restrict their application under high humidity conditions (Mathew et al., 2025; Saeed et al., 2024).

The incorporation of nanofillers into the chitosan matrix has been proven to overcome these limitations. The high surface area of nanofillers enhances the mechanical and chemical properties of chitosan-based films (Hezma et al., 2019; Rodrigues et al., 2020). Among various nanofillers, zinc oxide (ZnO) is one of the most commonly used materials in active food packaging. ZnO is classified as Generally Recognized As Safe (GRAS) by food regulatory authorities and exhibits strong antibacterial and antifungal activity through the release of Zn^{2+} ions and the generation of reactive oxygen species (ROS) (Kalia et al., 2021; Saeed et al., 2024). Furthermore, the incorporation of ZnO nanoparticles has been reported to improve mechanical strength, thermal stability, and UV barrier properties of composite films (Hezma et al., 2019; Zhang & Yu, 2024).

The integration of ZnO nanoparticles into the chitosan matrix results in chitosan–ZnO composite films that combine the biodegradability of chitosan with the superior functional properties of ZnO, making them promising candidates for active food packaging applications (Kalia et al., 2021; Motelica et al., 2020). In addition, the blending of chitosan with other polymers such as polyvinyl alcohol (PVA), gelatin, starch, polyurethane, and alginate has been widely reported to enhance the mechanical strength and barrier properties of composite films (Arroyo et al., 2020; Choubaki et al., 2025; Mathew et al., 2025; Zhang & Yu, 2024).

Given the rapid development of research on the synthesis and modification of chitosan–ZnO composite films, this literature review aims to provide a comprehensive analysis of recent advancements in this field. The focus includes ZnO nanoparticle synthesis, composite film fabrication methods, material characterization, mechanical and barrier properties, biological activity, and the application of these films in food packaging. This review is expected to provide insights into the optimal composition and synthesis methods for developing chitosan–ZnO composite films as sustainable alternatives to conventional plastic packaging.

RESEARCH METHODS

The literature search was conducted using the “Publish or Perish 8” application with the Scopus database. The keywords used were film AND biopolymer AND chitosan AND ZnO. The collected articles were then screened based on inclusion and exclusion criteria. The inclusion criteria were as follows: (1) articles related to chitosan–ZnO biopolymer films; (2) publications between 2016 and 2026; (3) full-text, open-access journal articles; (4) articles categorized as research articles; and (5) studies that addressed packaging and/or applications, considering the strong relevance of chitosan–ZnO composite films to active packaging applications. The article selection process is illustrated in Figure 1.

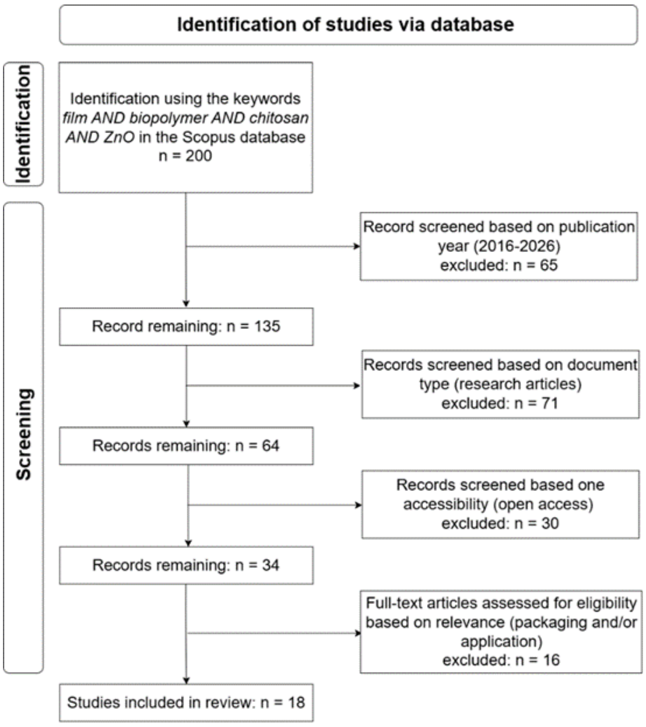

Figure 1. Information source identification scheme from database

The selected articles were then grouped and classified into a synthesis matrix. This matrix was developed to compare different perspectives from various studies and to integrate multiple elements in order to derive general conclusions from the overall literature.

RESULT AND DISCUSSION

Chitosan as a Biopolymer Film Matrix

Chitosan is a natural polysaccharide obtained through the deacetylation of chitin, a biopolymer commonly found in the exoskeletons of animals, particularly crustaceans such as shrimp, crabs, and lobsters. Chitosan consists of linear polysaccharide chains composed of repeating units of β-(1→4)-D-glucosamine and N-acetyl-D-glucosamine. These structures contain key functional groups, namely amino ($–NH_2$) and hydroxyl (–OH) groups, which play a crucial role in determining the chemical properties and interactions of chitosan with other materials, such as metal oxide nanoparticles or additional polymers. These functional groups enable hydrogen bonding, electrostatic interactions, and the formation of polymer networks within composite film systems (Hezma et al., 2019; Rodrigues et al., 2020; Saeed et al., 2024).

Chitosan is widely utilized in various applications, including biomaterials, pharmaceuticals, and food packaging, due to its biodegradability, biocompatibility, non-toxicity, and inherent antibacterial activity (Kalia et al., 2021; Kamanna et al., 2023; Wrońska et al., 2021). It also exhibits excellent film-forming ability when dissolved in weak acidic solutions, allowing it to form thin layers (Jovanović et al., 2021; Mathew et al., 2025; Sani et al., 2019).

Chitosan possesses natural antibacterial activity that can inhibit the growth of microorganisms. This activity is associated with interactions between positively charged amino groups and negatively charged microbial cell membranes, leading to disruption of the bacterial cell structure (Arroyo et al., 2020; Motelica et al., 2020). This property makes chitosan a commonly used base material in active food packaging systems, as it can inhibit microorganisms responsible for food spoilage.

Due to its rich functional group structure, chitosan is highly suitable as a polymer matrix in nanocomposite systems. Several studies have reported that chitosan is frequently used as a matrix for dispersing nanoparticles such as ZnO, resulting in improved mechanical properties, barrier performance, and antibacterial activity of composite films (Alqarni et al., 2024; Taktak & Kaya, 2025; Zhang & Yu, 2024). In addition, chitosan can be combined with various other polymers such as polyvinyl alcohol (PVA), gelatin, and starch to enhance the stability and flexibility of composite films (Anugrahwidya et al., 2022; Armynah et al., 2022; Choubaki et al., 2025). This is because pure chitosan films exhibit limitations such as relatively low mechanical strength and high water vapor permeability, which often necessitate modification to improve overall material performance (Hidayat et al., 2025).

ZnO Nanoparticles as Functional Fillers and Their Synthesis Development

ZnO nanoparticles are semiconductor materials widely utilized in the development of composite materials due to their excellent optical and antibacterial properties. ZnO possesses a relatively wide bandgap, enabling it to absorb ultraviolet (UV) radiation and protect polymer materials from degradation caused by UV exposure (Alqarni et al., 2024). In that study, it was reported that the use of Co-doped ZnO reduced the bandgap value from 5.22 eV to 4.92 eV, indicating enhanced energy absorption capability and the potential for improved antibacterial activity. These characteristics make ZnO not only a structural filler but also a functional agent capable of enhancing the stability and performance of composite materials.

Table 1. Comparison of ZnO Synthesis Method Development in Chitosan-ZnO Composites

Referensi	**Synthesis Method Category**	**ZnO Synthesis Approach**	**Main Reported Characteristics**
Hezma et al. (2019)	Sol–gel synthesis	ZnO synthesized via sol–gel method	Crystallite size of approximately 24.5 nm
Saeed et al. (2024)		Sol–gel method used to produce ZnO nanorods	Diameter of approximately 35 nm; film conductivity of 3.39×10^{-9} S/cm
Zhang & Yu (2024)	Green synthesis	ZnO synthesized using *Mentha pulegium* leaf extract	Crystallite size of approximately 28 nm
Kalia et al. (2021)		ZnO synthesized using *Urtica dioica* leaf extract	ZnO exhibited strong antibacterial activity
Kamanna et al. (2023)	Green synthesis + functionalization	Biogenic ZnO synthesized from WEMPA followed by functionalization with L-glutamic acid	High photocatalytic activity; methylene blue degradation of 98% within 120 minutes
Alqarni et al. (2023)	Doping	Synthesis of Co-doped ZnO	Bandgap reduced from 5.22 to 4.92 eV; ionic conductivity of 1.089×10^{-7} S/cm

In addition to its role as a UV-protective agent, ZnO is also known to exhibit strong antibacterial activity against various pathogenic microorganisms. The antibacterial activity of ZnO occurs through multiple complementary mechanisms. One of the primary mechanisms is the generation of reactive oxygen species (ROS), such as hydroxyl radicals and superoxide ions, which can damage microbial cellular components. Furthermore, the release of Zn^{2+} ions from the nanoparticle surface can disrupt bacterial metabolic processes and induce damage to proteins and DNA. Direct interaction between ZnO nanoparticles and the cell membrane can also increase membrane permeability and lead to structural damage of bacterial cells (Saeed et al., 2024). In that study, the incorporation of ZnO nanorods into chitosan–PVA composite films increased electrical conductivity up to 3.39×10^{-9} S/cm at 373 K, indicating strong interactions between the nanoparticles and the polymer matrix. These combined mechanisms demonstrate that ZnO exhibits a multi-target antibacterial mode of action, making it more effective than several conventional antimicrobial agents. Therefore, the incorporation of ZnO into polymer matrices not only enhances mechanical properties but also provides essential antimicrobial functionality for the development of active food packaging.

The effectiveness of ZnO in polymer composites is not solely determined by its presence as a filler but is also strongly influenced by nanoparticle size, morphology, and dispersion within the polymer matrix. As shown in Table 1, various studies indicate that variations in particle size can affect the specific surface area and the intensity of interactions between nanoparticles and the polymer matrix. Hezma et al. (2019) reported that ZnO synthesized via the sol–gel method exhibited a crystallite size of approximately 24.5 nm and was relatively homogeneously dispersed within the chitosan–PVA matrix. Meanwhile, Saeed et al. (2024) reported ZnO nanorods with an average diameter of approximately 35 nm. These differences in size and morphology influence nanoparticle dispersion within the polymer matrix, which ultimately affects the mechanical properties, thermal stability, and antibacterial activity of the composite films.

The development of ZnO synthesis methods in the analyzed literature demonstrates a shift from approaches focused primarily on nanoparticle formation toward strategies emphasizing morphological control, process sustainability, surface modification, and the engineering of intrinsic material properties. In the early stage, the sol–gel method was the most commonly employed approach to produce ZnO with relatively small and homogeneous particle sizes. Hezma et al. (2019) reported that sol–gel synthesized ZnO exhibited a crystallite size of approximately 24.5 nm, while Saeed et al. damage to proteins and DNA. Direct interaction between ZnO nanoparticles and the cell membrane can also increase membrane permeability and lead to structural damage of bacterial cells (Saeed et al., 2024). In that study, the incorporation of ZnO nanorods into chitosan–PVA composite films increased electrical conductivity up to 3.39×10^{-9} S/cm at 373 K, indicating strong interactions between the nanoparticles and the polymer matrix. These combined mechanisms demonstrate that ZnO exhibits a multi-target antibacterial mode of action, making it more effective than several conventional antimicrobial agents. Therefore, the incorporation of ZnO into polymer matrices not only enhances mechanical properties but also provides essential antimicrobial functionality for the development of active food packaging.

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Fabrication Methods of Chitosan-ZnO Composite Films

The fabrication methods of chitosan–ZnO composite films in the reviewed literature are predominantly based on solution casting or solvent casting techniques. This method is widely used due to the ability of chitosan to form film-forming solutions in acidic media, particularly acetic acid, allowing easy processing with ZnO and other supporting components. Although the fundamental technique is similar, variations exist in solution preparation, mixing sequence, homogenization strategy, and final application form, either as standalone films or coatings (Zhang & Yu, 2024; Hezma et al., 2019; Saeed et al., 2024).

The initial step typically involves dissolving chitosan in acetic acid to form the base matrix. In simpler systems, such as chitosan–ZnO or chitosan–ZnO combined with essential oils, ZnO is directly incorporated into the chitosan solution, followed by stirring, casting, and drying. This approach is applied in systems such as CS/ZnO/Melissa essential oil films and chitosan films with green-synthesized nanoparticles (Sani et al., 2019; Kalia et al., 2021). In contrast, for polymer blend systems, each polymer is usually prepared separately before mixing, as observed in PU/CS, CS/PVA, and CS/gelatin systems (Zhang & Yu, 2024; Mathew et al., 2025; Choubaki et al., 2025). In blended systems, the fabrication process emphasizes achieving a homogeneous and stable mixture. For example, Zhang and Yu (2024) prepared polyurethane and chitosan solutions separately before mixing, followed by ZnO incorporation using ultrasonication and high-speed homogenization. A similar approach is applied in CS/PVA systems, where ZnO is introduced into the polymer blend before casting to ensure uniform distribution (Hezma et al., 2019; Saeed et al., 2024). Therefore, homogenization is a critical step in determining the stability of the film-forming solution prior to drying.

The fabrication process becomes more complex in films containing active or multifunctional components. In systems such as PVA/CS/GT/ZnO/safflower oil, CS/PVA/ZnO + garlic extract, and CS/ZnO/Ag/CEO, the mixing process must not only produce uniform films but also maintain the stability of active components within the polymer matrix (Taktak & Kaya, 2025; Mathew et al., 2025; Motelica et al., 2020). Similarly, in smart films based on CS/gelatin/ZnO combined with anthocyanin-based indicators, compatibility among all components must be maintained during mixing and drying (Choubaki et al., 2025). This indicates that in active systems, the fabrication method functions as a formulation strategy rather than merely a casting technique.

Table 2. Comparison of Fabrication Methods for Chitosan–ZnO Composite Films

Reference	Fabrication Method	Composite System	Final Form
Zhang & Yu (2024)	Solution casting	PU/CS/ZnO	Film
Wrońska et al. (2021)		CS–metal oxide films	Film
Taktak & Kaya (2025)		PVA/CS/GT/ZnO/SFO	Film
Sani et al. (2019)		CS/ZnO/Melissa essential oil	Film
Saeed et al. (2024)		CS/PVA/ZnO nanorods	Film
Motelica et al. (2020)		CS/ZnO/Ag/CEO	Film/Coating
Mathew et al. (2025)		CS/PVA/ZnO + garlic extract	Film
Kamanna et al. (2023)		CS/PVA/ZnO-L-Glu	Film
Kalia et al. (2021)		CS/ZnO or CS/CuO	Film/Coating
Hidayat et al.		CS/ZnO/MoS_2	Film

Reference	Fabrication Method	Composite System	Final Form
(2025)			
Hezma et al. (2019)		CS/PVA/ZnO	Film
Choubaki et al. (2025)		CS/gelatin/ZnO + PFEN	Film
Alqarni et al. (2023)		CS/gelatin/Co-doped ZnO	Film
Rodrigues et al. (2020)	Intercalation in solution + solution casting	CS/ZnO/clay	Film
Armynah et al. (2022)	Bioplastic casting	Starch/CS/PALF/ZnO	Bioplastic/Film
Anugrahwidya et al. (2022)		Starch/ZnO and Starch/CS/ZnO	Bioplastic
Jovanović et al. (2021)	Solution casting + coating application	CS/gelatin + ZnO/Zn-acetate + lemongrass essential oil	Film and coating
Arroyo et al. (2019)	Coating solution preparation	Alginate/CS/nanoZnO coating	Coating

In addition to standalone films, several studies apply similar principles to coating systems. Arroyo et al. (2019) prepared alginate and chitosan solutions separately, mixed them with glycerol and nano-ZnO, and applied the coating through fruit dipping. A similar approach was reported by Jovanović et al. (2021), where the formulation was used both as a cast film and as a coating for raspberries. In coating applications, the focus shifts from film sheet formation to the stability of the film-forming solution and its ability to form a thin protective layer on food surfaces.

In starch-based and bioplastic systems, fabrication methods involve additional steps such as gelatinization, plasticization, and incorporation of natural reinforcing materials. This is observed in studies by Armynah et al. (2022) and Anugrahwidya et al. (2022), where starch/CS/ZnO systems are designed to produce biodegradable bioplastics. Compared to pure chitosan or synthetic blends, this approach emphasizes environmental friendliness while maintaining a balance between mechanical strength and biodegradability.

Overall, the fabrication methods of chitosan–ZnO composite films can be categorized into three main approaches: polymer blend casting, active/multifunctional film casting, and coating or bioplastic formulation. The differences among these approaches lie in matrix preparation, mixing strategy, and final application form. Therefore, fabrication methods should be viewed as process design strategies that determine film performance and its relevance to food packaging applications. pangan (Zhang & Yu, 2024; Mathew et al., 2025; Arroyo et al., 2019; Armynah et al., 2022).

Combination of Chitosan with Other Polymers

In the analyzed literature, chitosan is generally not used as a single matrix when the film is intended to achieve improved mechanical properties, barrier performance, and active functionality. This is due to the inherent characteristics of chitosan, which is relatively hydrophilic and brittle, thus requiring combination with other polymers to enhance structural stability, flexibility, and film-forming ability. In general, these combinations include hydrophilic synthetic polymers such as polyvinyl alcohol (PVA), engineering polymers such as polyurethane, proteins or other polysaccharides such as gelatin, alginate, and gum tragacanth, as well as starch-based systems and natural fibers for the development of biodegradable bioplastics (Hezma et al., 2019; Zhang & Yu, 2024; Choubaki et al., 2025; Armynah et al., 2022).

The chitosan/PVA combination represents the most dominant approach in the compared studies, as reported by Hezma et al. (2019), Saeed et al. (2024), Mathew et al. (2025), and Kamanna et al. (2023). PVA plays a role in enhancing flexibility, film-forming ability, and matrix stability, thereby enabling better dispersion of ZnO within the blend system. In this system, improvements are observed not only in mechanical and barrier properties but also in more specific functional aspects. Hezma et al. (2019) reported enhancements in thermal stability, mechanical strength, and antibacterial activity in CS/PVA/ZnO films, while Saeed et al. (2024) demonstrated that CS/PVA/ZnO nanorod films achieved electrical conductivity of 3.39×10^{-9} S/cm at 12 wt.% ZnO and 373 K. The most comprehensive results were reported by Mathew et al. (2025), with tensile strength of 30.1 MPa, elongation at break of 203%, water vapor permeability (WVP) of 4.73×10^{-11} g/m²/s, and oxygen permeability of 4.76×10^{-13} g/m²/s in CS/PVA/ZnO films loaded with garlic extract. Therefore, the chitosan–PVA combination can be considered the most balanced system for achieving overall film performance.

In contrast to PVA, the chitosan/polyurethane combination is more specifically directed toward enhancing structural strength. Zhang and Yu (2024) reported that the PU/CS/ZnO system with an optimal ratio of 60:40 resulted in a 51% increase in tensile strength, a 68% increase in Young's modulus, and a UV protection factor (UPF) of 42.7. These findings indicate that polyurethane acts as a reinforcing component that improves the rigidity of the chitosan matrix, making the film more suitable for applications requiring higher mechanical stability.

Table 3. Classification of Chitosan–Polymer Combinations in Chitosan–ZnO Composites

Reference	Fabrication Method	Composite System	Final Form
Zhang & Yu (2024)	Solution casting	PU/CS/ZnO	Film
Wrońska et al. (2021)		CS–metal oxide films	Film
Taktak & Kaya (2025)		PVA/CS/GT/ZnO/SFO	Film
Sani et al. (2019)		CS/ZnO/Melissa essential oil	Film
Saeed et al. (2024)		CS/PVA/ZnO nanorods	Film
Motelica et al. (2020)		CS/ZnO/Ag/CEO	Film/Coating
Mathew et al. (2025)		CS/PVA/ZnO + garlic extract	Film
Kamanna et al. (2023)		CS/PVA/ZnO-L-Glu	Film
Kalia et al. (2021)		CS/ZnO or CS/CuO	Film/Coating
Hidayat et al. (2025)		CS/ZnO/MoS_2	Film
Hezma et al. (2019)		CS/PVA/ZnO	Film
Choubaki et al. (2025)		CS/gelatin/ZnO + PFEN	Film
Alqarni et al. (2023)		CS/gelatin/Co-doped ZnO	Film
Rodrigues et al. (2020)	Intercalation in solution + solution casting	CS/ZnO/clay	Film

Reference	Fabrication Method	Composite System	Final Form
Armynah et al. (2022)	Bioplastic casting	Starch/CS/PALF/ZnO	Bioplastic/Film
Anugrahwidya et al. (2022)		Starch/ZnO and Starch/CS/ZnO	Bioplastic
Jovanović et al. (2021)	Solution casting + coating application	CS/gelatin + ZnO/Zn-acetate + lemongrass essential oil	Film and coating
Arroyo et al. (2019)	Coating solution preparation	Alginate/CS/nanoZnO coating	Coating

The chitosan/gelatin combination is particularly prominent in active and smart film systems. Choubaki et al. (2025), Jovanović et al. (2021), and Alqarni et al. (2023) demonstrated that gelatin not only facilitates film formation but also supports the incorporation of active components such as ZnO, anthocyanin indicators, essential oils, and doped ZnO. Choubaki et al. (2025) reported that the CS/gelatin/ZnO + PFEN system reduced WVP from 6.37 to 2.94 × 10^{-11}, increased tensile strength by approximately 20%, and achieved antioxidant activity of 78.9%. Jovanović et al. (2021) showed that CS/gelatin films combined with ZnO or zinc acetate and lemongrass essential oil extended the shelf life of raspberries from 4 to 8 days. Meanwhile, Alqarni et al. (2023) reported that the CS/gelatin matrix supported optical and electrical functions in Co-doped ZnO systems, as evidenced by a reduction in bandgap from 5.22 to 4.92 eV and an increase in ionic conductivity up to 1.089 × 10^{-7} S/cm. Therefore, CS/gelatin systems are more appropriately positioned as matrices for multifunctional films rather than merely reinforcing films.

Another approach involves combining chitosan with additional polysaccharides such as gum tragacanth and alginate. Taktak and Kaya (2025) reported that the PVA/CS/GT/ZnO/SFO system exhibited strong antibacterial activity, with inhibition zones of 20 mm against S. aureus and 13.5 mm against E. coli, as well as antioxidant activity of 49.21%. In this system, gum tragacanth appears to function as a stabilizer of the polymer network, particularly in films containing oil phases. Meanwhile, Arroyo et al. (2019) utilized alginate/chitosan combinations primarily in coating systems rather than standalone films, where alginate plays a role in forming protective layers on fruit surfaces rather than reinforcing structural films.

The combination of chitosan with starch represents a different development pathway. In studies by Armynah et al. (2022) and Anugrahwidya et al. (2022), starch/CS/ZnO or starch/CS/PALF/ZnO systems were designed to produce biodegradable bioplastics. In these systems, chitosan contributes biological activity and reinforces the starch matrix, while ZnO provides antimicrobial functionality and additional reinforcement. Armynah et al. (2022) reported complete degradation within approximately 21 days in soil and 18 days in seawater, while Anugrahwidya et al. (2022) demonstrated optimal tensile strength at 13% ZnO and an increase in bread shelf life from 10 to 30 days. These findings indicate that chitosan–starch combinations are more suitable for biodegradable packaging applications rather than for films requiring high mechanical performance.

Overall, the selection of companion polymers determines the functional direction of chitosan–ZnO composites. CS/PVA systems are the most effective in enhancing flexibility, homogeneity, and overall film performance; PU/CS systems are more suitable for mechanical reinforcement; CS/gelatin systems support the development of active, smart, and optoelectronic films; CS/GT systems play a role in stabilizing multicomponent systems; and starch/CS systems are more appropriate for biodegradable bioplastics. Therefore, combining chitosan with other polymers is not only a matrix modification strategy but also an approach to defining the functional identity of chitosan–ZnO composite materials.

Based on the classification table of chitosan combined with other polymers in chitosan–ZnO composites, the CS/PVA system is the most dominant, indicating that PVA is the most compatible co-polymer for improving flexibility, processing stability, and overall composite film performance. In contrast, the CS/gelatin combination is more commonly directed toward the development of active and smart films, whereas starch/CS systems are generally utilized for biodegradable bioplastics. On the other hand, some studies still employ chitosan as the primary matrix without additional polymers, particularly when the main objective is to evaluate the direct contribution of ZnO or other active components to the antibacterial and barrier properties of the film. Therefore, the selection of a companion polymer in chitosan–ZnO systems is closely related to the intended functional application of the material.

Application of Composite Films in Food Packaging

The application of chitosan–ZnO-based composite films in food packaging, as directly validated in various studies, demonstrates that these materials function not only as physical barriers but also as active packaging, preservative coatings, antifungal bioplastics, and smart packaging systems. In this group of studies, the effectiveness of the films is evaluated based on their ability to maintain food quality during storage, such as reducing weight loss, preserving texture, lowering microbial load, inhibiting fungal growth, and monitoring quality changes. Therefore, the discussion in this section is more application-oriented compared to studies that rely solely on laboratory data.

In fresh fruit applications, the effectiveness of chitosan–ZnO composite films is clearly demonstrated by Zhang and Yu (2024) in strawberries. The PU/CS/ZnO film they developed was able to reduce weight loss to 4.2% and maintain firmness up to 78.5% after 14 days of storage. These results indicate that the composite film effectively slows down moisture loss while preserving fruit firmness, two critical parameters for high-respiration commodities such as strawberries. Compared to conventional plastics, this performance highlights that chitosan–ZnO-based films are not only environmentally friendly alternatives but also practically effective in extending postharvest quality.

Applications in fruits are also observed in guava through coating approaches. Arroyo et al. (2019) developed an alginate/CS/nanoZnO coating system, while Kalia et al. (2021) utilized chitosan-based films/coatings incorporating nanoparticles synthesized via green methods. Both studies demonstrated an extension of guava shelf life after coating treatment. In food applications, coatings offer advantages because the protective layer adheres directly to the fruit surface, allowing more effective control of moisture and microbial contamination. Thus, studies on guava confirm that chitosan–ZnO systems are not limited to standalone films but are also highly effective as postharvest active coatings.

Table 4. Application of Chitosan–ZnO Composite Films in Food Systems Based on Food Type

Reference	Food Category	Film/Coating System	Main Application Data	Application Direction
Zhang & Yu (2024)	Fresh fruits	PU/CS/ZnO	Weight loss 4.2%; firmness retention 78.5% after 14 days in strawberries	Active packaging for fresh fruits
Jovanović et al. (2021)	Fresh fruits	CS/gelatin + ZnO/Zn-acetate + lemongrass essential oil	Raspberry shelf life extended from 4 to 8 days	Active film/coating for fruits
Kalia et al. (2021)	Fresh fruits	CS/ZnO or CS/CuO	Increased guava shelf life	Active film/coating for fruits
Arroyo et al.	Fresh	Alginate/CS/nanoZnO	Increased guava shelf	Postharvest active

Reference	Food Category	Film/Coating System	Main Application Data	Application Direction
(2019)	fruits	coating	life	coating
Hidayat et al. (2025)	Fresh fruits	CS/ZnO/MoS_2	Fruit weight loss of 24% after 15 days	Active film with high barrier properties
Mathew et al. (2025)	Animal products	CS/PVA/ZnO + garlic extract	Microbial load reduced to 50 CFU/mL after 5 days in fish	Active packaging for animal products
Choubaki et al. (2025)	Animal products	CS/gelatin/ZnO + PFEN	Color change correlated with TVB-N in fish fillets	Smart packaging
Armynah et al. (2022)	Bakery products	Starch/CS/PALF/ZnO	Bread remained mold-free for up to 30 days; degraded within 21 days in soil	Biodegradable active bioplastic
Anugrahwidya et al. (2022)	Bakery products	Starch/CS/ZnO	Bread shelf life extended from 10 to 30 days	Biodegradable packaging for bakery

In soft fruits, Jovanović et al. (2021) demonstrated that a CS/gelatin + ZnO/Zn-acetate + lemongrass essential oil system is effective for raspberries. The developed active films and coatings were able to extend the shelf life of raspberries from 4 to 8 days. These results are significant because raspberries are highly sensitive to both physical and microbiological deterioration. This finding indicates that the combination of chitosan, ZnO, and other active components can provide effective protection for highly perishable commodities. In other words, the application in raspberries strengthens the evidence that chitosan–ZnO-based active film systems are highly relevant for high-value horticultural products.

In the category of animal-based products, the most robust validation was reported by Mathew et al. (2025). The CS/PVA/ZnO + garlic extract film applied to fish reduced the microbial load to 50 CFU/mL after 5 days of cold storage. This finding demonstrates that composite films not only exhibit antibacterial activity in vitro but also function effectively in real food systems that are highly susceptible to spoilage. This is particularly important for animal products, especially fish, which require packaging capable of controlling microbial growth while maintaining surface condition and sensory quality. In this study, the effectiveness of the application was supported by the good barrier properties of the film, allowing it to function both as active packaging and as a barrier against moisture and gas transfer.

Still within animal-based products, Choubaki et al. (2025) presented a different application approach, namely smart packaging for fish fillets. The developed CS/gelatin/ZnO + PFEN film not only functioned as a protective layer but also exhibited color changes correlated with increases in TVB-N, a key indicator of fish spoilage. This application is significant because it positions chitosan–ZnO films not only as preservative materials but also as visual monitoring systems for food quality. Thus, this study demonstrates that the development of chitosan–ZnO-based packaging has progressed from active packaging toward smart packaging systems.

In bakery products, application validation is clearly demonstrated in studies by Armynah et al. (2022) and Anugrahwidya et al. (2022). Armynah et al. (2022) showed that starch/CS/PALF/ZnO bioplastics were able to maintain bread free from mold growth for up to 30 days while maintaining high biodegradability. Similarly, Anugrahwidya et al. (2022)

reported that starch/CS/ZnO systems extended bread shelf life from 10 to 30 days. In this category, the application of films is not primarily focused on controlling moisture loss, as in fruits, but rather on inhibiting fungal growth during storage. These findings indicate that chitosan–ZnO-based systems are also highly relevant for dry or semi-dry food products, particularly when the primary objective is to prevent fungal contamination while providing biodegradable packaging.

Hidayat et al. (2025) also falls within the category of direct application studies, as the CS/ZnO/MoS_2 film was tested on fruits and showed a weight loss of 24% after 15 days. Although the application data are not as comprehensive as those reported by Zhang and Yu (2024), this study still demonstrates that hybrid chitosan–ZnO-based composite films can contribute to controlling quality deterioration during fruit storage. In this case, the effectiveness of the film is largely supported by its mechanical properties, hydrophobicity, and barrier performance.

Overall, studies that have been directly validated on food systems indicate that the application of chitosan–ZnO composite films has developed in four main directions. First, active packaging for fresh fruits, focusing on reducing weight loss and maintaining texture. Second, postharvest coatings aimed at extending shelf life through direct protection on fruit surfaces. Third, active packaging for animal-based products, focusing on reducing microbial load. Fourth, antifungal bioplastics and smart packaging, applied respectively to bakery products and fish quality monitoring. This comparison indicates that the applicability of chitosan–ZnO composite films strongly depends on the formulation tailored to the characteristics of the target food.

Overall, the results validated directly on food products confirm that chitosan–ZnO composite films have practical utility in food packaging. The success of these applications is determined not only by the antibacterial properties of ZnO but also by the synergy between the chitosan matrix, companion polymers, barrier properties, and the compatibility of the system with the packaged food. Therefore, studies involving direct food applications can be considered the strongest evidence that chitosan–ZnO composite films have significant potential for modern food packaging applications.

Based on the classification presented in the table of chitosan–ZnO composite film applications in food systems, the most frequently validated applications are found in fresh fruits, particularly strawberries, raspberries, and guava. In this category, the primary function of the films or coatings is to reduce weight loss, maintain texture, and extend shelf life during storage.

In animal-based products, the reported applications are mainly focused on controlling microbiological spoilage and, in some cases, on smart packaging functions for monitoring product quality. Meanwhile, in bakery products, starch–chitosan–ZnO-based systems are primarily developed to inhibit fungal growth while simultaneously providing biodegradable packaging solutions.

Therefore, classification based on food type indicates that chitosan–ZnO composite films have been applied to food products with different spoilage characteristics, and the film formulations are generally tailored to meet the specific protection requirements of each product.

CONCLUSION

Biopolymer-based chitosan–ZnO nanocomposite films exhibit significant potential as environmentally friendly active food packaging materials. Chitosan offers advantages such as biodegradability, biocompatibility, film-forming ability, and inherent antimicrobial activity, while the incorporation of ZnO enhances mechanical properties, thermal stability, antimicrobial effectiveness, UV protection, and other functional characteristics. The advancement of ZnO synthesis methods, along with the combination of chitosan with various polymers, plays an important role in determining the final performance of the composite films. Overall, the findings indicate that chitosan–ZnO composite films have strong potential to be developed as functional and sustainable biodegradable alternatives to conventional food packaging. However, further studies are still required, particularly regarding synthesis standardization, migration safety, and validation of applications at the industrial scale.Biopolymer-based chitosan–ZnO nanocomposite films exhibit significant potential as environmentally friendly active food packaging materials. Chitosan offers advantages such as biodegradability, biocompatibility, film-forming ability, and inherent antimicrobial activity, while the incorporation of ZnO enhances mechanical properties, thermal stability, antimicrobial effectiveness, UV protection, and other functional characteristics. The advancement of ZnO synthesis methods, along with the combination of chitosan with various polymers, plays an important role in determining the final performance of the composite films. Overall, the findings indicate that chitosan–ZnO composite films have strong potential to be developed as functional and sustainable biodegradable alternatives to conventional food packaging. However, further studies are still required, particularly regarding synthesis standardization, migration safety, and validation of applications at the industrial scale.

REFFERENCES

Alqarni, L. S., Alghamdi, A. M., Elamin, N. Y., & Rajeh, A. (2024). Enhancing the optical, electrical, dielectric properties and antimicrobial activity of chitosan/gelatin incorporated with Co-doped ZnO nanoparticles: Nanocomposites for use in energy storage and food packaging. Journal of Molecular Structure, 1297. https://doi.org/10.1016/j.molstruc.2023.137011

Anugrahwidya, R., Armynah, B., & Tahir, D. (2022). Composites bioplastic film for various concentration of zinc oxide (ZnO) nanocrystals towards physical properties for high biodegradability in soil and seawater. Journal of Polymers and the Environment, 30(6), 2589–2601. https://doi.org/10.1007/s10924-021-02363-4

Armynah, B., Anugrahwidya, R., & Tahir, D. (2022). Composite cassava starch/chitosan/pineapple leaf fiber (PALF)/zinc oxide (ZnO): Bioplastics with high mechanical properties and faster degradation in soil and seawater. International Journal of Biological Macromolecules, 213, 814–823. https://doi.org/10.1016/j.ijbiomac.2022.06.038

Arroyo, B. J., Bezerra, A. C., Oliveira, L. L., Arroyo, S. J., Melo, E. A. de, & Santos, A. M. P. (2020). Antimicrobial active edible coating of alginate and chitosan add ZnO nanoparticles applied in guavas (Psidium guajava L.). Food Chemistry, 309. https://doi.org/10.1016/j.foodchem.2019.125566

Choubaki, S., Baghaei, H., & Mohammadi Nafchi, A. (2025). Smart indicator for fish freshness monitoring: A chitosan/gelatin/zinc oxide nanoparticle composite incorporating pomegranate flower anthocyanin extract nanocapsules. Food Science and Nutrition, 13(9). https://doi.org/10.1002/fsn3.70944

Hezma, A. M., Rajeh, A., & Mannaa, M. A. (2019). An insight into the effect of zinc oxide nanoparticles on the structural, thermal, mechanical properties and antimicrobial activity of Cs/PVA composite. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 581. https://doi.org/10.1016/j.colsurfa.2019.123821

Hidayat, M. I., Hardiansyah, A., Khoiriah, K., Yulianti, E., Wardhani, R. A. K., Fahrialdi, F., & Yusuf, M. R. I. (2025). Composite films based on chitosan incorporating molybdenum disulfide nanosheets and zinc oxide nanoparticles with potential antibacterial application. Food Chemistry, 477. https://doi.org/10.1016/j.foodchem.2025.143480

Jovanović, J., Ćirković, J., Radojković, A., Mutavdžić, D., Tanasijević, G., Joksimović, K., Bakić, G., Branković, G., & Branković, Z. (2021). Chitosan and pectin-based films and coatings with active components for application in antimicrobial food packaging. Progress in Organic Coatings, 158. https://doi.org/10.1016/j.porgcoat.2021.106349

Kalia, A., Kaur, M., Shami, A., Kaur Jawandha, S., Alghuthaymi, M. A., Thakur, A., & Abd-Elsalam, K. A. (2021). Nettle-leaf extract derived ZnO/CuO nanoparticle-biopolymer-based antioxidant and antimicrobial nanocomposite packaging films and their impact on extending the post-harvest shelf life of guava fruit. https://doi.org/10.3390/biom

Kamanna, K., Amaregouda, Y., & N, M. K. (2023). Chitosan/polyvinyl alcohol-based nanocomposite films incorporated with L-Glu surface functionalized ZnO NPs: Physicochemical, photocatalytic, antimicrobial and antioxidant properties evaluation. Environmental Nanotechnology, Monitoring and Management, 20. https://doi.org/10.1016/j.enmm.2023.100861

Mathew, D., Thomas, B., Sudheep, N. M., Muhammed Shamil, K. V., Anjana, R., Krishna, A., Thomas, J. B., & Krishnankutty, R. E. (2025). Development of garlic extract-loaded zinc oxide nanoparticle/chitosan/polyvinyl alcohol nanocomposite-based active eco-friendly packaging films for extending shelf-life of fish fillets. International Journal of Biological Macromolecules, 327. https://doi.org/10.1016/j.ijbiomac.2025.147273

Motelica, L., Ficai, D., Ficai, A., Truşcă, R. D., Ilie, C. I., Oprea, O. C., & Andronescu, E. (2020). Innovative antimicrobial chitosan/ZnO/Ag NPs/citronella essential oil nanocomposite—potential coating for grapes. Foods, 9(12), 1–26. https://doi.org/10.3390/foods9121801

Rodrigues, C., de Mello, J. M. M., Dalcanton, F., Macuvele, D. L. P., Padoin, N., Fiori, M. A., Soares, C., & Riella, H. G. (2020). Mechanical, thermal and antimicrobial properties of chitosan-based nanocomposite with potential applications for food packaging. Journal of Polymers and the Environment, 28(4), 1216–1236. https://doi.org/10.1007/s10924-020-01678-y

Saeed, A., Guizani, I., Hanash, F. E., Asnag, G. M., Al-Harthi, A. M., Alwafi, R., Qahtan, T. F., Morsi, M. A., & Assran, A. S. (2024). Enhancing optical, structural, thermal, electrical properties, and antibacterial activity in chitosan/polyvinyl alcohol blend with ZnO nanorods: Polymer nanocomposites for optoelectronics and food/medical packaging applications. Polymer Bulletin, 81(13), 11645–11670. https://doi.org/10.1007/s00289-024-05270-5

Sani, I. K., Pirsa, S., & Tağı, Ş. (2019). Preparation of chitosan/zinc oxide/Melissa officinalis essential oil nanocomposite film and evaluation of physical, mechanical and antimicrobial properties by response surface method. Polymer Testing, 79. https://doi.org/10.1016/j.polymertesting.2019.106004

Taktak, F. F., & Kaya, H. N. (2025). Enhanced antibacterial activity and biodegradability of PVA/chitosan/gum tragacanth films enriched with ZnO and safflower oil. Journal of Macromolecular Science, Part B: Physics. https://doi.org/10.1080/00222348.2025.2584766

Wrońska, N., Katir, N., Miłowska, K., Hammi, N., Nowak, M., Kędzierska, M., Anouar, A., Zawadzka, K., Bryszewska, M., Kadib, A. El, & Lisowska, K. (2021). Antimicrobial effect of chitosan films on food spoilage bacteria. International Journal of Molecular Sciences, 22(11). https://doi.org/10.3390/ijms22115839

Zhang, B., & Yu, L. (2024). Synthesis and characterization of nano-ZnO incorporated polyurethane-chitosan composite films. Journal of Ovonic Research, 20(6), 813–829. https://doi.org/10.15251/JOR.2024.206.813