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Abstract: The preservation of meat via sustainable methods and packaging is an area of continued interest driven by the need to address food security. The use of biomaterial films and coatings has gained significant attention due to their non-toxicity and biodegradability compared with conventional synthetic films. Starch and chitosan are sustainable sources for the preparation of films/coatings owing to their relatively low cost, natural abundance derived from numerous sources, biocompatibility, biodegradability, and antimicrobial, antioxidant, and film-forming attributes. These remarkable features have notably increased the shelf life of meat by inhibiting lipid oxidation and microbial activity in food products. Furthermore, recent studies have successfully incorporated binary biopolymer (starch and chitosan) systems to combine their beneficial properties upon composite formation. This literature review from 2020 to the present reveals that chitosan- and starch-based films and coatings have potential to contribute to enhanced food security and safety measures whilst reducing environmental issues and improving sustainability, compared with conventional synthetic materials.

Keywords: chitosan; starch; binary composites; films and coatings; meat preservation

1. Introduction

In recent years, the global demand for meat has persistently increased owing to rising consumption, which has inspired the invention of better methods of packing and preservation [1]. Meat and its products are important components of human nutrition because they offer key nutrients that are difficult to obtain from plant-based sources [2]. The global consumption of meat proteins is expected to rise by 11% by 2031 compared with the base time average of 2019–2021, with income and population growth playing a major role [3]. However, the microbial degradation of meat is a challenging problem to address owing to its limited shelf life, stability-based nutrition content, and high water activity. Other elements, such as oxygen and light, may also contribute to the loss of value by lipid oxidation, which reduces the shelf life and changes the physical aesthetics of meat products. Consequently, several techniques have been used to preserve meat products, such as coatings made of biodegradable biopolymers and edible films [4]. Generally, films are independent structures, prepared in their solid form (e.g., as sheets, molded, or cast and dried), that are employed as a wrapping or packaging material for the preservation and protection of food. By comparison, coatings can serve as a defense barrier applied onto food surfaces through dipping or spraying, along with the potential drying of the coating. A key difference between films and coatings is that coatings are applied as thin liquid layers, whereas films are fabricated as solid sheets with a greater thickness as food wrap or packaging materials.
Biodegradable films/coatings sourced from starch [5], chitosan [6], gelatin [7], cellulose [8], etc., are preferred over petrochemical-based plastics due to their sustainability, bioactivity, biodegradability, abundance, non-toxicity, and food safety [9–11]. Moreover, the utilization of these biodegradable biopolymers helps to mitigate the environmental pollution and serious health effects that may occur due to the breakdown byproducts of conventional plastic films when discarded [12,13]. Therefore, researchers have sought to produce durable and biodegradable starch and chitosan coatings/films with strong antibacterial and antioxidant properties that can effectively retard spoilage and prolong the lifespan of meat.

Chitosan (Cht) is a unique alkaline polysaccharide found in nature, produced via the deacetylation of chitin (poly β-(1-4)-N-acetyl-D-glucosamine) [14,15]. Chitosan is a biopolymer comprising β-(1-4)-2-amino-D-glucose and β-(1-4)-2-acetamido-D-glucose units, which endow it with intrinsic antibacterial qualities [16]. Chitosan exhibits excellent film-forming properties, degradability, safety, and non-toxicity [6,17]. Its synthetic versatility and numerous qualities make it a prime choice for use in advanced food packaging films with unique features [18]. Nevertheless, it is crucial to recognize that films may often utilize chitosan as a primary material, despite some apparent disadvantages (e.g., inferior mechanical strength, resulting in poor water resistance and insufficient barrier resistance) [19]. Moreover, chitosan has inferior antioxidant and bacteriostatic properties due to its chemical inertness and comparatively poor H-atom donor capacity in relation to strong intramolecular and intermolecular hydrogen bonding networks [20]. Thus, these constraints have slowed down the advancement of chitosan-based food packaging films.

On the other hand, starch (St) is a naturally available biopolymer that is used as a substitute for conventional synthetic biopolymers. Starch is edible, readily available, reasonably priced, biodegradable, and has favorable film-forming capacity. The major attributes of starch-based edible films include various merits: they are colorless, odorless, tasteless, transparent/translucent, and have low O₂ permeability in low-to-moderate relative humidity environments [21]. Hence, starch-based edible coatings and films can be eaten with the food they are coated onto. This implies that starch is generally recognized as food-safe (GRAFS) and presents an attractive option as a suitable biomaterial. Starch coatings can also serve as carriers for food additives, such as antimicrobials and antioxidants [22]. In addition, these materials can increase the shelf life of products, and thus have drawn increasing attention in the food-preservation industry. However, there are certain drawbacks to starch-based films, such as their inferior mechanical properties and high water permeability [23]. To improve the properties of starch-based films, researchers have sought to combine them with other biopolymers and additives to yield biocomposites, which display unique properties relative to singular-component systems. Biopolymers such as chitosan, in various structural forms and size ranges (e.g., micro- to nanoparticles), can be incorporated into composite starch–film materials. In turn, chitosan biopolymer additives can enhance the biodegradability, barrier, and thermal and mechanical properties of the films, along with promoting antioxidant and antibacterial properties [24–26].

The dual blending of biopolymers such as starch and chitosan is an effective means of improving the properties of films/coatings. Several research studies have documented the production of higher-quality films due to the synergistic effects of these two additive biopolymers [27–29]. Lipatova et al. reported that the tensile strength, vapor, and elongation permeability of films increase with greater chitosan content. As well, the viscosity of the casting solution increases with greater chitosan content for corn starch/highly deacetylated chitosan and corn starch/low-deacetylated chitosan blends [30]. Deng et al. found that mechanical properties increased as the amount of 2-hydroxypropyl-trimethylammonium chloride chitosan (HTCCht) increased in HTCCht–amylose starch coatings. The optimal chitosan–amylose starch films showed an increase of 207% in tensile strength and an increase of 54% in elongation at break (EB), compared with the pure amylose starch film [31]. Moreover, Hasan et al. [32] established that the introduction of chitosan to brown rice starch samples caused the film’s water absorption capacity to decrease. The film showed outstanding...
ing water resistance when the amounts of chitosan and brown rice starch were varied [32]. Furthermore, when compared to chitosan coatings, a chitosan–starch aldehyde–catechin conjugate composite coating improved the preservation of pork meat [33].

Notwithstanding, the effectiveness of chitosan–starch coatings/films depends on the nature and types of chitosan and starch employed. Chitosan has a variable degree of deacetylation (DDAc) that depends on the source and extraction process, which could result in the production of chitosan with different molecular weights, influencing the properties of the resulting film. The molecular weight of chitosan is also known to influence the water vapor permeability of the film [30]. Moreover, in the production of chitosan–starch biofilm, the intrinsic properties of starch would determine the fundamental characteristics of the film produced. Different starch varieties can yield films with variable thickness, which can impact the barrier and mechanical qualities of films. In addition, there are two structural variants of starch (amylose and amylopectin) that could influence the nature of the film produced. A binary amylose-rich starch system may result in improved mechanical performance. However, a rigid structure may lead to low flexibility and challenges to film formation and effects due to gelatinization [34]. Therefore, recent studies have sought to optimize the concentration and types of chitosan and starch employed for film preparation.

Furthermore, natural active ingredients from various sources (such as *Thymus kotschyanus* essential oil [35]; *Artemisia annua* essential oil [36]; clove essential oil (CLO) [37]; *Zanthoxylum Bungeanum* essential oil [38]; *Zanthoxylum limonella* oil [39]; natural blueberry anthocyanin [17]; *Cyclocarya paliurus* flavonoids [40]; rosemary essential oils [41]; clitoria ternatea flower extract [42]; papain [43]; apple polyphenol extract [44]; *Lycium barbarum* leaf flavonoids [45]; pomegranate peel extract [35]; polyphenolic extract of waste petioles of betel leaf [46]; and red dragon fruit peel anthocyanin extract [47]) were introduced into chitosan–starch composites to act as reinforcing agents in packaging films. The introduction of these additives serves to address challenges related to the barrier and antibacterial properties that are commonly observed in chitosan–starch biofilms, although there may be issues related to the widespread application of these additives in food packaging. Essential oils have helped to inhibit microbial spoilage and to improve food quality and shelf life [48,49]. Notable studies have introduced terpenoids in essential oils, which act as hydrogen donors, singlet oxygen quenchers, transition metal chelators, and/or free-radical scavengers [49,50].

In addition, additives such as polyvinyl alcohol (PVA) have been included to improve the tensile strength of chitosan–starch blends [51]. Similarly, researchers have recently investigated an array of methods, such as the addition of different polymers (like cellulose, pectin, gelatin, etc.) and/or doping nanomaterials (like carbon nanotubes, ZnO, TiO$_2$, etc.) to improve their characteristics and produce food-safe packaging for the preservation of meat products [17,36,52,53].

A body of research has been reported on the production, modification, and application of chitosan, starch, and chitosan–starch films and coatings in meat preservation. The continued interest in this area is demonstrated by active ongoing research [35,36,53,54]. Compared to existing reviews on food coatings and films, the present mini review focuses on the recent progress in the application of composite materials that contain chitosan and starch coatings as protective barriers for meat products, including the incorporation of innovative additives to improve film properties. Moreover, this overview highlights existing studies of composites that contain chitosan and starch that are under active research and development. In comparison with other categories of biopolymer films and coatings, the coverage of chitosan–starch systems has been sparsely reported, especially for the preservation of meat products. This contribution offers a detailed insight into the recent publications specifically related to films/coatings containing chitosan, starch, or chitosan–starch systems to address the food safety of meat products. This work emphasizes film packaging over conventional liquid coatings, as outlined in the studies presented. The coverage of this research spans the last four years (2020–2024), with a greater emphasis on studies from 2022 to the present. Antibacterial, antifungal, and antioxidant activities are highlighted for chitosan, starch, and chitosan–starch films/coatings, including the preparation of liquid
formulations for applications involving dip coating and/or the spraying of meat products. The literature was sourced from the Scopus and Web of Science databases, and describes the preparation of chitosan, starch, and chitosan–starch systems and the usage of chitosan, starch, and chitosan–starch films/coatings for intelligent and sustainable food packaging systems. These composites have unique functional properties for maintaining meat quality, and have practical applications related to food safety and food security.

2. Chitosan-Based Coatings/Films for Meat Preservation

2.1. Brief Description of Chitosan

As indicated in § 1, chitosan can exist as a cationic polysaccharide in acidic media (various organic or inorganic acids) due to the presence of ionizable amine groups in the biopolymer. Chitosan is a derivative of chitin that can be generated via deacetylation under alkaline hydrolysis (Figure 1). Chitin is derived from various sources, including insect cuticles, fungi, and exoskeletons of crustaceans and mollusks [55–57]. In contrast to chitin, chitosan readily dissolves in aqueous acidic media (such as acetic and lactic acid) at pH conditions below its pKₐ (ca. 6.5) to afford the protonation of its amino groups, which are relevant to food preservation. Chitosan becomes insoluble at higher pH values above its pKₐ (ca. pH > 6.5), where deprotonation and a loss of charge occur. Studies have shown that the molecular weight and the degree of deacetylation (DDAc) of chitosan significantly impact its biopolymer structure, contributing to its biological (e.g., antioxidant and antibacterial) and physicochemical properties (e.g., crystallinity and viscosity) [13,55,58]. The degree of deacetylation determines the proportion of D-glucosamine units of the chitosan chain to the total amount of D-glucosamine and N-acetyl glucosamine units. Previous work indicates that chitosan with a greater DDAc offers enhanced antibacterial activity [59]. On the other hand, the molecular weight of chitosan influences its water-uptake capacity, biodegradability, viscosity, and hydrophilicity [60,61]. Chitosan with a greater molecular weight exhibits greater stability under thermal changes in the environment, where slower degradation occurs over time at ambient conditions during storage owing to its reduced porous structure and decreased water-uptake capacity [13,61].

![Figure 1. Molecular structure of chitin and chitosan. The circles denote the amino groups of chitosan.](image)

2.2. Application of Chitosan in Food Packaging

Chitosan’s non-toxicity, biodegradability, and compatibility, along with its antibacterial and antioxidant qualities, make it a potentially useful addition to a variety of food applications [62]. Specifically, the ability of chitosan to form films and to serve as a gas
and moisture barrier favors its potential application as an edible food coating and packaging material [63]. Consequently, researchers have sought to apply chitosan directly, as a coating or as a film, as a means of extending the shelf life and quality of meat and meat products. Hence, Abdel-Naeem and colleagues investigated the effectiveness of chitosan as a coating material to enhance its antioxidant activity, microbial purity, and sensory characteristics. In particular, chitosan was investigated as a means to prolong the shelf life of smoked herring fish during a three-month period of frozen storage at \(-18^\circ C\) [64]. By the conclusion of the first month of testing, the authors discovered that the aerobic plate count of the exposed (control) samples and the samples infused with 0.5% lactic acid were beyond the permissible limit (5 Log10 CFU/g) set by ES-288 (2005) [65] for smoked herring fish. Furthermore, the mold and yeast counts in these samples were higher than the recommended limit (should be pathogen-free) according to ES-288 (2005) [65]. On the other hand, samples coated with chitosan at varying concentrations (2%, 3%, and 4%) showed aerobic plate count levels within the allowable limit and the samples were devoid of mold and yeast up until the conclusion of the third month of refrigerated storage. These findings unequivocally revealed that the chitosan coatings, particularly at 3 wt.% and 4 wt.% concentrations, significantly inhibited the microbiological development of smoked herring and increased its shelf life [64].

2.3. Antibacterial and Antifungal Mechanism of Chitosan in Food Preservation

The most widely recognized antibacterial mechanism relies on the reaction between the microbial cell membrane (which has a negative surface charge) and chitosan (with a positive surface charge). This interaction occurs along with the chelation of specific ions from the lipopolysaccharide layer of the bacterial cell membrane, altering the permeability of the membrane and enabling the seepage of intracellular components. Arshad and Batool [66] demonstrate that chitosan coatings function as an oxygen barrier that impedes the proliferation of aerobic bacteria. This might be responsible for the notable decrease in aerobic plate count in chitosan-coated samples [64]. The ability of chitosan to inhibit sporulation and spore germination, as well as its polycationic nature, have helped to clarify its antifungal mechanism. Additionally, chitosan oligomers disperse inside hyphae and obstruct enzyme activities. This causes fungus to proliferate. In addition, chitosan effectively serves as an antioxidant by impeding oxidation reactions by supplying free radicals with an electron or a hydrogen atom, which transforms them into stable radical intermediates and stops additional free-radical reactions [67,68]. Moreover, chitosan-coated products might exhibit low pH when compared to uncoated systems, and this can be attributed to the inhibitive effect of chitosan coatings against the liberation of lactic acid from chitosan biopolymers, in addition to the inhibitive effect against microbial growth, and the intrinsic actions of enzymes. On the other hand, a higher pH in uncoated samples could occur owing to the proliferation of bacteria that cause spoilage [69]. Thus, the antibacterial activity of chitosan is contingent upon several variables (e.g., temperature, pH, water solubility, concentration, deacetylation degree, and biopolymer molecular weight).

Other studies have sought to improve the antibacterial and antifungal properties of chitosan by blending it with other components such as gelatin, pectin, and essential oils, among others. A summary of the key findings related to various recent studies on the modification and application of chitosan-based films in meat preservation is listed in Table 1. An inspection of the various studies reveals that chitosan has intrinsic antimicrobial properties, which can be enhanced with the presence of additives (e.g., essential oils, antimicrobials, peptides, preservatives, and biopolymers) for various categories of meat (beef, pork, chicken, fish, and seafood). The film-forming properties of chitosan and its colloidal properties enable the formation of composite films and coatings, as evidenced by the various additives in the various systems outlined in Table 1. In addition to the antimicrobial properties of the various composites, variable resistance to yeast and fungi are reported, along with increased shelf life, resistance to moisture loss or water vapor permeability (WVP), and resistance to oxidation and UV due to the barrier properties of
the films/coatings. The composite materials display variable properties due to the content and composition of the composites, including variations in thermal stability, wettability, flexibility, and mechanical properties (tensile strength (TS) and elongation at break (EB)). Table 1 provides an overview of various studies on chitosan-based composites that further elaborate on key findings regarding the properties of these materials.

Table 1. Recent studies on the modification and application of chitosan-based films in meat preservation.

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<thead>
<tr>
<th>Chitosan-Based Coating/Film</th>
<th>Coated Meat Sample</th>
<th>Key Findings</th>
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<tr>
<td>Chitosan (Cht) films incorporated with Zanthoxylum limonella (Zl) oil</td>
<td>Fresh pork</td>
<td>The incorporation of Zanthoxylum limonella (Zl) oil into chitosan film efficiently preserves pork, prolonging its shelf life and sustaining its physical attributes. Moreover, the inclusion of the essential oil resulted in a significant antibacterial effect against E. coli and S. aureus, in contrast to the chitosan film without essential oil, owing to the synergistic effects on antibacterial activity. The chitosan films without Zl oil had a tensile strength (TS) of 10.21 MPa, while the chitosan films that contained 2 and 4% of Zl essential oil had tensile strength values of 12.54 and 13.64 MPa, respectively. Furthermore, % elongation at break (EB) values for chitosan films integrated with 0%, 2%, and 4% Zl essential oil were determined to be 72.14%, 81.24%, and 84.23%, respectively. The water vapor permeability (WVP) of chitosan-free films was $1.50 \times 10^{-9} \pm 1.80 \times 10^{-10}$ g/s·m·Pa, whereas films containing 2% and 4% Zl essential oil showed similar values of WVP $1.51 \times 10^{-9} \pm 1.30 \times 10^{-10}$ g/s·m·Pa and $1.53 \times 10^{-9} \pm 1.78 \times 10^{-10}$ g/s·m·Pa. The incorporation of essential oil improved flexibility and mechanical strength, and no significant effects occurred in relation to thermal stability, WVP, or water solubility.</td>
<td>[39]</td>
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<td>Chitosan–furcellaran–hydrolysate gelatin edible coatings enriched with bioactive peptides</td>
<td>Pork loin</td>
<td>Microbiological tests demonstrated the resistance of the coatings against yeasts, microscopic fungi, and aerobic bacteria, especially in the early stages of storage when coated samples showed microbial reductions of 0.5–2 log CFU/g versus the controls. When stored in a freezer or refrigerator, the coatings did not seem to affect water activity. Applying edible coatings refined with bioactive peptides extended the pork loin’s acceptability by up to seven days.</td>
<td>[70]</td>
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<td>Edible chitosan (Cht) films containing a combination of carvacrol and rosemary nanoemulsion (NE)</td>
<td>Ground meat</td>
<td>The chitosan-free films’ water vapor permeability (WVP) was estimated at 3102 g/m²/day. However, when the carvacrol nanoemulsion (NE) (1.56%) was added to the chitosan films, the WVP significantly reduced (2648 g/m²/day). Moreover, compared to the control films, the chitosan films with carvacrol NE (1.56%) showed higher tensile strength (61.42 ± 0.06 MPa) and elongation (30.56 ± 0.07%). Furthermore, chitosan-based films containing essential oil NEs, such as carvacrol (0.78%) and rosemary (1.56%), effectively reduced pathogenic contamination and improved the quality of the meat. The constant 1.56% carvacrol NE release into the chitosan layer guaranteed continued antibacterial activity.</td>
<td>[41]</td>
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<td>Garlic essential oil nanoemulsions (GEO-NEs) fabricated by mixing carboxymethyl chitosan (CMCh), Tween 80 (TW 80), and the oil phase of garlic essential oil (GEO).</td>
<td>Fresh pork (hind-leg muscle)</td>
<td>Garlic essential oil nanoemulsions (GEO-NEs) displayed enhanced antioxidant capacity in scavenging free radicals of 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), diammonium salt, and 1,1-diphenyl-2-picrylhydrazyl (DPPH), and had greater antibacterial activity against S. aureus and E. coli than free GEO. Moreover, the loading of GEO-NEs with 3% GEO significantly increased the chilled pork’s shelf life by ca. 1 week.</td>
<td>[71]</td>
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<td>Poly(lactic acid)/chitosan/graphene oxide (PLA/Cht/GO) flexible films. GO was deposited layer-by-layer (LbL) on PLA-poly (butylene itaconate) (PBI) copolymers with chitosan (Cht) as the bonding layer</td>
<td>Pork loin meat</td>
<td>The addition of PBI (poly (butylene itaconate)) prevents PLA (poly(l-lactic acid)) from physically aging and crystallizing while increasing its hydrophilicity and flexibility. The oxygen transmission rate (OTR) of the films showed a decreasing trend with the LBL (layer-by-layer) deposition of GO (graphene oxide). The OTR of the PLBI/Cht/(GO-Ch)10 film decreased to 1.6 cm³/m²·d and the oxygen transmission coefficient (OTC) decreased to 0.4 × 10⁻⁸ cm³/m²·h·Pa. The water vapor permeability (WVP) of the PLBI/Cht/(GO-Ch)10 films decreased to 4.48 × 10⁻⁸ cm³/m²·h·Pa, a 55.0% reduction compared to the PLBI film. The utility of chitosan as the outermost component resulted in anti-microbial properties of the generated LBL films. Based on the results, PLBI/Cht/(GO-Ch)x with a higher number of GO layers considerably reduced the oxidation and microbiological development of chilled meat, while preserving its superior texture and color. Most significantly, owing to the incredibly low OTR, the PLBI/Cht/(GO-Ch)10 film outperformed a commercially available polyacrylate/polyethylene film for the preservation of chilled meat.</td>
<td>[72]</td>
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<td>Chitosan–alginate–pectin (Cht/Alg/Pct) biopolymer-based NEs</td>
<td>Chicken breast</td>
<td>The most effective coating to reduce cooking loss was an essential oil (EO)–nanoemulsion (EO-NE)–chitosan (Cht) coating; the synthesized coatings, such as EO–NE–chitosan, EO–NE–alginate, and EO–NE–pectin, showed promising results in maintaining color stability. Microbiological analysis showed that the EO–NE–chitosan coating significantly inhibited the growth of mesophilic and psychrophilic bacteria, as well as yeasts, extending the shelf life of chicken breasts.</td>
<td>[73]</td>
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<td>Chitosan/oxidized konjac glucomannan (KGM) films incorporated with Zanthoxylum Bungeanum (ZB) essential oil</td>
<td>Pork</td>
<td>Treatment with Zanthoxylum Bungeanum essential oil (ZB-EO) increases water vapor permeability (WVP) and reduces mechanical properties. The addition of 1% ZB-EO increased tensile strength (TS) by 18.92% and decreased water solubility by 10.05%, WVP by 6.60%, and moisture content by 1.03%. The TS levels of film were increased as the ZB-EO concentration increased, and the highest value (36.52 MPa) was observed in sliced meat wrapped in chitosan/oxidized KGM (OKGM with ozone) film with 1% ZB-EO. As the ZB-EO concentration exceeded 1.5%, a decrease in TS occurred. In addition, the elongation at break (EB) was at maximum with the addition of 1% ZB-EO (35.8%), whereas the EB decreased above 1.5%. Increasing the ZB-EO content improved the properties of the composite films (antibacterial, antioxidant, and UV barrier). The inclusion of ZB-EO dramatically reduced the thiobarbituric acid, total volatile basic nitrogen, redness, total viable count, and pH value. This formulation increased pork meat hardness after 10 days of preservation.</td>
<td>[38]</td>
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<td>Chitosan/zein nanoparticle (NP) Pickering emulsion incorporating chitosan (Cht) coatings in the presence of cinnamaldehyde and tea polyphenol</td>
<td>Pork loin meat</td>
<td>Tea polyphenols greatly increased the antioxidant potential of chitosan coatings from 2.09% to 57.61% in terms of DPPH (1,1-diphenyl-2-picrylhydrazyl) value and from 2.63% to 38.85% in terms of ABTS (2,2’-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt) value. Cinnamaldehyde greatly enhanced the antibacterial efficacy of chitosan coatings against E. coli and S. aureus. The inhibition zones rose from 3.03 ± 0.23 mm to 18.39 ± 1.22 mm and from 7.66 ± 1.61 mm to 15.70 ± 1.75 mm, respectively, under 20% oil content. Pickering emulsions with micro-scale particle size and the addition of cinnamaldehyde and tea polyphenol may alter droplet dispersion. The shelf life of fresh pork may increase by more than 4 days, further confirming the preservation effect of chitosan coatings.</td>
<td>[74]</td>
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<td>Chitosan (Cht)-based nano-TiO$_2$-nisin composite packaging film</td>
<td>Chilled pork</td>
<td>Nisin encouraged nano-TiO$_2$ dispersion within chitosan, and the components of the film (nisin, nano-TiO$_2$, and chitosan) were linked together by hydrogen bonding. The film tensile strength (TS) was evaluated for chitosan (31.63 ± 0.90 MPa) and nisin–chitosan (34.35 ± 1.01 MPa) versus films for nano-TiO$_2$–chitosan (48.19 ± 1.13 MPa) and nano-TiO$_2$–nisin–chitosan (49.38 ± 0.63 MPa). As a result, the nano-TiO$_2$–chitosan film had a greater TS at break than the chitosan film. The mechanical strength of the composite film grew dramatically as the nano-TiO$_2$ content in the film matrix increased, but the rate of water vapor permeability and light transmittance reduced, while the antibacterial activity steadily increased. According to the bacterial phase results, the active composite film considerably slowed down the growth of <em>Acinetobacter</em> in chilled pork. Furthermore, transcriptome analysis revealed that photo-catalytic nano-TiO$_2$ can work in concert to enhance preservation by reducing spoilage-related gene expression, upregulating secondary metabolite synthesis in <em>A. johnnii</em> X881, and dramatically blocking cell autoregulation and membrane wall system repair.</td>
<td>[75]</td>
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<td>Chitosan–gelatin (Cht/Gel)-based active packaging films containing S-chitin (Cht/Gel@S-chitin)</td>
<td>Chicken meat</td>
<td>The introduction of S-chitin improved the chitosan–gelatin film’s tensile strength (by 18.4%) and elongation at break (by 42.2%), while somewhat reducing the film’s transparency and boosting UV blocking with 98.7% UV-A and 100% UV-B light screening. The composite films demonstrated significant antioxidant activity. The films demonstrated efficacious antibacterial action, effectively impeding the development of <em>L. monocytogenes</em> and <em>E. coli</em> after 3 and 12 h of incubation, respectively. The chicken packaged with Cht/Gel@S-chitin films maintained its appearance, total viable colony count, thiobarbituric acid (TBA) reactive substance, and pH after 20 days of storage at 4 °C.</td>
<td>[76]</td>
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<td>Pectin film incorporated with gallic acid (GA)-loaded ovalbumin (OVA)/chitosan NPs</td>
<td>Salmon fillets</td>
<td>The pectin film integrated with gallic acid (GA)-loaded OVA/chitosan NPs demonstrated good mechanical and light-barrier properties. The film’s tensile strength (TS) and elongation at break (EB) were 15.97 ± 1.55 MPa and 7.29 ± 0.42%, respectively, and its opacity value was 1.65 ± 0.06 UA/mm. The TVB-N (total volatile base nitrogen), pH, and microbial growth analysis results showed that the nanocomposite (NC) films effectively delayed the spoiling of salmon fillets over their 12-day refrigerated storage period. Salmon fillets treated with pectin film infused with GA-loaded OVA/chitosan NPs had a 3-day longer shelf life than the control group, and their sensory quality also improved. Additionally, the growth of amine-producing bacteria (<em>E. coli</em> and <em>Morganella morganii</em>) and the formation of biogenic amines (particularly histamine) in salmon fillets were postponed by the NC films.</td>
<td>[77]</td>
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<td>Active films (CPB) were developed based on chitosan/polyvinyl alcohol (PVA) integrated with ginger essential oil (GEO) loaded with bacterial cellulose</td>
<td>Sea bass fillets</td>
<td>Following 12 days of storage, the sample enveloped in CPB0.8 film exhibited a reduced microbial load in contrast to the active film sample where ginger essential oil (GEO) was absent. In particular, CPB0.8 film demonstrated potent antioxidant and antibacterial properties that could hinder the spread of microorganisms and absorb exudates, preventing the oxidation of lipids and protein while being stored in the refrigerator. Thus, the depreciation of sea bass fillets during storage could be effectively delayed by CPB0.8 film.</td>
<td>[78]</td>
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<td>Chitosan/polyvinyl alcohol (Cht/PVA) composite film integrated with sulfur-modified montmorillonite (S-MMT)</td>
<td>Chicken fillets</td>
<td>In comparison to chitosan/polyvinyl alcohol (Cht/PVA) films, Cht/PVA/S-MMT composite films revealed enhanced hydrophobicity, strength, and flexibility with better moisture barrier qualities. The Cht/PVA/S-MMT4% composite film exhibited a notable improvement over the neat Cht/PVA film in terms of tensile strength (~25.1%), elongation at break (~94.1%), and UV-blocking performance (98.2% UV-A and 100% UV-B). In addition, the Cht/PVA/S-MMT composite films revealed strong bactericidal and antioxidant properties (100% ABTS and 65.4% DPPH scavenging activity) against <em>E. Coli</em> and <em>L. monocytogenes</em>. For a 20-day storage period, the chicken in the composite film exhibited a notable decrease in total viable colonies, TBA reactive substances, pH, and physical appearance.</td>
<td>[79]</td>
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<tr>
<td>Coating with whey protein isolate (WPI), nano-chitosan, bacterial nanocellulose, and cinnamon essential oil</td>
<td>Chicken meat fillets</td>
<td>The antibacterial activity of the WPI-NCh (whey protein isolate, nano-chitosan, and bacterial nanocellulose) coating was greatly enhanced by the addition of CEO (cinnamon essential oil), which effectively inhibited the growth of yeast, mold, S. aureus, lactic acid bacteria, Enterobacteriaceae, Pseudomonas spp., psychrotrophic bacteria, and mesophilic bacteria. Additionally, the coating decreased the rate of decomposition by inhibiting the rise in thiobarbituric acid (TBA) level, peroxide value, and total volatile base nitrogen level. Sensory tests showed that coated fillets retained their outstanding flavor, color, and odor versus the control group. Relative to the uncoated (control) group, the chicken breast fillets’ shelf life was prolonged beyond 5 days via the application of WPI-NC+ 1.5% cinnamon EO coating.</td>
<td>[80]</td>
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<tr>
<td>Gelatin–chitosan–<em>Cyclocarya paliurus</em> flavonoid edible coating film (Gel–Cht–CPF)</td>
<td>Fresh beef</td>
<td>During storage, gelatin–chitosan–<em>Cyclocarya paliurus</em> (Gel–Cht–CPF) films effectively maintained the freshness of chilled beef, and the preservation impact grew as the CPF (<em>C. paliurus</em> flavonoid) concentration increased. Compared to the gelatin–chitosan (Gel–Cht) film treatment group, the addition of CPF slowed the rate at which the pH and weight of the beef increased, and to some extent also conserved the meat’s color. In addition, CPF-added films, versus the Gel–Cht film, suppressed the growth of microorganisms and subsequent increases in TBB (2-thiobarbitone) and TVB-N (total volatile base nitrogen) in beef samples, and also impeded the oxidation of proteins and lipids in beef. On day 14, the TVB-N was 15.517 mg/100 g, which was 36.75 mg/100 g less than the control group. In summary, the Gel-Cht-CPF film successfully increased the life span of beef, with an excellent preservation effect on chilled meat.</td>
<td>[40]</td>
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<td>Ethyl cellulose–Gel–CM–Cht bilayer films doped with <em>Euryale ferox</em> (EF) seed shell polyphenol</td>
<td>Cooked beef and chicken</td>
<td><em>L. monocytogenes</em> was effectively inhibited by <em>Euryale ferox</em> (EF) polyphenol, resulting in superior antibacterial and antioxidant properties. The presence of EP improved the barrier and mechanical properties of the bilayer film. Furthermore, the active bilayer film preparation demonstrated good protection against <em>L. monocytogenes</em> and delayed lipid oxidation in ready-for-consumption meat products with considerably delayed changes in color, moisture loss, pH, and texture in cooked beef/chicken, according to preservation tests.</td>
<td>[81]</td>
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<td>Chitosan (Cht)/anthocyanin intelligent packaging film fortified by cellulose nanocrystal</td>
<td>Shrimp</td>
<td>Cellulose nanocrystals (CNCs) and natural blueberry anthocyanin (AN) were added to the film as property enhancers and color indicators, respectively. The film’s constituent parts were intricately connected by a profusion of ionic and hydrogen bonds. By varying the quantity of added CNCs, Cht-AN-CNCs 9% film was obtained, demonstrating exceptional antibacterial, antioxidant, barrier, and mechanical capabilities. The tensile strength of the Cht-AN-CNCs 9% film was significantly increased from 15 MPa to 35 MPa; whereas the water vapor permeability, oxygen permeability, and swelling properties decreased from $31.6 \times 10^{-12}$ g/(m·s·Pa) to $1.6 \times 10^{-12}$ g/(m·s·Pa), from 51.7 g/(m²·d) to 12.2 g/(m²·d), and from 159.2% to 92.0%, respectively. In addition, the intelligent film demonstrated good biodegradability in a natural setting. The composite film caused a discernible color change when it was used to preserve fresh shrimp, which closely matched changes in the TVB-N (total volatile base nitrogen) levels and pH levels of the shrimp meat. The findings demonstrate that the ecologically friendly intelligent packaging film can be used to visually monitor food freshness via color changes to enable the detection of deterioration by consumers.</td>
<td>[17]</td>
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Table 1. Cont.

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<tr>
<td>Gelatin–chitosan-lactate–curcuma hydroethanolic extract-based antimicrobial films</td>
<td>Chicken meat</td>
<td>In comparison to gelatin film alone, its combination with chitosan–lactate produces an intricate network structure and improves hydrogen bonding in the film structure. This enhanced the optical, physicochemical, rheological, and active properties of the gelatin–chitosan–lactate (Gel/ChtL) films, but the chitosan–lactate-added films did not exhibit any antimicrobial activity. Moreover, the incorporation of curcuma hydroethanolic extract (CEE) into the Gel/ChtL-based film signified connections that occurred between the phenolic chemicals found in CEE and the biopolymer matrix. These interactions had a major impact on the antimicrobial, antioxidant, physical, optical, barrier, mechanical, and morphological properties of the gelatin–chitosan–lactate–CEE-based film. The water vapor transfer rate (WVTR) of the Gel\textsubscript{1.5}–chitosan–lactate (ChtL\textsubscript{1})-based film reduced significantly ($p &lt; 0.05$) from 7.95 ± 0.06 (Gel\textsubscript{1.5}/ChtL\textsubscript{1}) to 6.58 ± 0.13 g/h·m(^2) (Gel\textsubscript{1.5}/ChtL\textsubscript{1}/CEE\textsubscript{200}) with the incorporation of CEE. The tensile strength of the Gel/ChtL/CEE films increased from 20.60 ± 0.58 MPa (for Gel\textsubscript{1.5}/ChtL\textsubscript{1} to 33.89 ± 3.29 MPa (for Gel\textsubscript{1.5}/ChtL\textsubscript{1}/CEE\textsubscript{200}). Also, the elastic modulus (EM) increased from 13.15 ± 1.75 MPa (for Gel\textsubscript{1.5}/ChtL\textsubscript{1}) to 17.87 ± 1.14 MPa (for Gel\textsubscript{1.5}/ChtL\textsubscript{1}/CEE\textsubscript{200}), while the flexibility simultaneously reduced from 42.64 ± 2.28% to 21.85 ± 2.04%. Simultaneously, minor modifications were noted in thermal and rheological characteristics. Furthermore, when compared to an unwrapped chicken kept at 4°C for 10 days, the films successfully maintained the freshness of the chicken meat.</td>
<td>[82]</td>
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<td>Polysaccharide film containing cinnamaldehyde–chitosan nanoparticles (NPs)</td>
<td>Burgers prepared with minced meat</td>
<td>A variety of film characteristics were assessed, including transmittance in the 200–800 nm range and water in the chitosan film. Moreover, the findings showed that the development of Listeria had a significant impact on hamburgers without film. However, the CFU/g level was lower in burgers with the film. The entirety of cinnamaldehyde was released in vitro during the first 5 days, which was crucial for safeguarding the meat against potential bacterial growth. When the films’ antibacterial qualities were examined, the results showed that, over 20 days, L. monocitogenes’ total aerobic value (4.85 log CFU/g) decreased, the total coliform value of 1.26 log CFU/g decreased, and the potential growth value was less than 0.5 log10.</td>
<td>[83]</td>
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<tr>
<td>Chitosan–furcellaran–gelatin hydrolysate (GelH) coatings enhanced with bioactive peptides</td>
<td>Smoked pork ham and fresh pork loin</td>
<td>The incorporation of GelH into the biopolymer structure resulted in coatings containing peptides that had strong antibacterial and antioxidant capabilities, as demonstrated by tests conducted on two distinct preserved meat products: fresh pork loin and smoked pork ham. All studied food pathogens were suppressed in growth by the peptide coatings, except for A. flavus. A reduction in total viable counts by more than 3.5 log CFU/g occurred, effectively inhibiting their proliferation. The most promising coatings, containing RW4 and LL37 (1.25–2.5 µg/mL), were efficient in suppressing the total viable counts for fresh pork loin.</td>
<td>[84]</td>
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<tr>
<td>Chitosan coating combined with thermal treatment</td>
<td>Duck-leg meat</td>
<td>The findings demonstrated that the application of chitosan coating in conjunction with thermal treatment significantly enhanced the quality and extended the shelf life of braised duck meat by lowering carbonyl concentrations and restricting Enterobacteriaceae counts, total viable counts, and the occurrence of 4 primary spoilage organisms (Pseudomonas, Acinetobacter, Weissella, and Brochothrix). Furthermore, an examination of the volatile taste compound composition showed that the mixed treatment greatly increased the primary contributors to the main aroma.</td>
<td>[85]</td>
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<td>Carboxymethyl (CM) chitosan/zinc alginate (CMCht/Zn-Alg) composite film</td>
<td>Pork</td>
<td>The incorporation of Zn ions into the composite structure conferred exceptional antibacterial and water resistance properties to the film, as evidenced by the water vapor permeability (WVP) and antibacterial tests conducted on <em>E. coli</em> and <em>S. aureus</em>. In addition, the freshly prepared composite film displayed an improved mechanical property owing to chelation bond formation between the carboxyl groups and Zn ions. The solubility of the composite film CMCht/SA (Na-Alg) was almost 100%, and its thickness was roughly 58 μm. Following Zn-ion post-treatment, the thickness of the CMCht/SA-Zn1, CMCht/SA-Zn2, and CMCht/SA-Zn3 composite films increased to 112 μm, 118 μm, and 121 μm, respectively. Furthermore, the CMCht/SA WVTR was very high, ca. 1.91 × 10⁻¹¹ g s⁻¹ m⁻¹ Pa⁻¹. After Zn-ion post-treatment, the WVP of the composite films CMCht/SA-Zn1, CMCht/SA-Zn2, and CMCht/SA-Zn3 was reduced to 1.27 × 10⁻¹¹ g s⁻¹ m⁻¹ Pa⁻¹, 1.19 × 10⁻¹¹ g s⁻¹ m⁻¹ Pa⁻¹, and 1.17 × 10⁻¹¹ g s⁻¹ m⁻¹ Pa⁻¹, respectively. Additionally, the chilled meat preservation test showed that the composite film may considerably increase the lifespan of pork by 5 days, demonstrating its exceptional ability for effective preservation.</td>
<td>[86]</td>
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Note: Refer to the Glossary of Terms (after § 6) for a complete list of the acronyms used in Table 1.

3. Starch-Based Coatings/Films for Meat Preservation

3.1. Brief Description of Starch

Starch is a low-cost, readily available, and biodegradable food ingredient with good film-forming properties. Starch molecules exist in two different forms: amylopectin, which has a more intricately branched structure, and amylose, a linear biopolymer. Amylopectin contains both α-1,4 and α-1,6 glycosidic links, whereas amylose has α-1,4 glycosidic bonds. Amylose has a molecular weight that ranges from 10⁴ to 10⁶ kDa, comprises ca. 20–30% starch, and is insoluble in water. Due to its linear character, amylose content is instrumental in the development of films [87]. On the other hand, amylopectin assists starch granules in maintaining their peripheral crystalline structure (Figure 2). The concentrations of amylose and amylopectin in food are the main factors that determine its quality. This is due to the key role played by amylopectin and amylose in the functional properties, gelatinization, and retrogradation of starch [88,89].

![Figure 2. Molecular structure of starch, which exists as amylopectin and amylose.](image)

3.2. Amylose–Amylopectin Ratios Influence the Structure and Properties of Starch-Based Films

Starch-based composites derived from various sources have different concentrations and ratios of amylose–amylopectin, along with different branch chain lengths, sizes, shapes,
and chemical and physical properties. For instance, rice starch contains 28.58% amylase [90], 2.20% fat, 4.90% ash, 0.01% lipid, and 0.71% protein [91]. Potato starch granules comprise around 26.90% amylase [92], 75–80% amylopectin [93], and 1% additional minor components such as phosphate and lipids [93]. Cassava starch is typically reported to have an amylase content of 22.50% [94]. Corn starch contains about 25% linear amylase and 75% amylopectin [95]. Hence, Colussi et al. [96] noted that using different varieties of starch at the same concentration produced variations in film thickness with different film-forming solutions. In essence, the starch-based film made of wheat starch (0.189 mm) was the thinnest, followed by corn starch (0.196 mm) and potato starch (0.227 mm) as the thickest. The variations in film thickness resulted from differences in the composition of amylase for specific types of starch. The starch composition varied between 26.90% [92], 25% [95], and 20.90% [92] for the potato, corn, and wheat starches, respectively. Thus, it was determined that high amylase levels induce stronger hydrogen bond formation by increasing the degree of interaction among amylase molecules; this raises the film’s heterogeneity and the thickness of the film matrix [89,97].

In addition, starch with low amylopectin or high amylase content results in high tensile strength (TS) in starch-based films [98]. Compared to amorphous short-branched amylopectin, starch with high amylase content will form crystals with superior mechanical properties [99]. Chandla et al. [100] reported that films made from corn starch had the highest tensile strength (TS = 2.97 MPa), followed by films made from buckwheat starch (2.92 MPa), and films made from amaranth starch, with the lowest tensile strength (2.61 MPa). The amaranth starch film yielded the lowest tensile strength (TS) due to its extremely low amylase concentration (3.47%) in comparison to buckwheat starch (18.20%) and corn starch (25%). Moreover, comparing mung bean starch-based film to the films generated from cassava, sweet potato, and chestnut starch, Suh et al. [101] found that the mung bean film had the lowest elongation value and highest TS value. This was due to the higher amylase content exhibited by the mung bean starch (30.87%) compared to cassava starch (15.20%), sweet potato starch (21.70%), and chestnut starch (22.10%).

3.3. Application of Starch-Based Films in Meat Preservation

In contrast to chitosan, which has favorable coating/film formation properties and antimicrobial activity, starch films do not display intrinsic antimicrobial properties. In the absence of additives, starch films tend to be more brittle than chitosan-based systems, where the presence of additives results in improved mechanical properties. Table 2 provides a summary of the modification and application of starch-based films in the context of meat preservation. As noted in the various composite systems, starch is either combined with low-molecular-weight additives or an additional biopolymer with additives. As described above, starch can exist in two structural forms (amylose versus amylopectin), and certain plant sources contain a fractional variation in these two polysaccharides (e.g., corn starch versus potato starch). Furthermore, a high degree of amylase raises the moisture content (%) in films, and an elevated amount of moisture would accelerate the film’s microbial deterioration [89,98]. Consequently, edible films with a lower water content are favored since they can offer better protection and prolong the shelf life of meats. We conclude that the relative ratio of amylase and amylopectin in starch has a significant impact on the characteristics of starch-based films. Therefore, to circumvent the drawbacks of starch-based films, a large amount of research (cf. Table 2) has been reported on the use of additives (such as natural extracts, essential oils, metal oxides, carbon dots, phenolics, polyvinyl alcohol, or other biopolymers like alginate, gelatin, modified cellulose, etc.) to improve the properties of starch-based films in meat packaging applications. Similarly to the observations made for chitosan-based composites, starch-based composites also display variable physicochemical and antimicrobial properties according to the nature and composition of the mixed systems.
Table 2. Recent studies on the modification and application of starch-based films in meat preservation.

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<tr>
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<tr>
<td>Carbon dots (CDs), prepared with carrot as a precursor, were introduced into corn starch (CS) to construct a bio-based CS-CD composite film</td>
<td>Deep-fried meatballs</td>
<td>The thermal stability and elasticity of the composite film were enhanced by the high carbon content and dense surface produced by the uniform doping of carbon dots (CDs). The films with a low concentration of CDs exhibited superior solubility, water vapor permeability (WVP), tensile strength (TS), elongation at break (EB), and heat resistance in comparison to the corn starch (CS) films. Furthermore, the CS-CD composite films exhibited strong techno-functional characteristics like antibacterial and antioxidant activities. These films successfully prevented the growth of microbes when used to store and preserve fried meatballs, preserving the meatballs’ flavor, texture, and appearance.</td>
<td>[102]</td>
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<td>Porous starch embedded with anthocyanins–carboxymethyl cellulose (PS-ACMC) coating</td>
<td>Shrimp</td>
<td>The porous citrate–starch displayed improved mechanical and water properties with an esterification degree of 32.0% ± 0.8% and substitution degree of 0.44% ± 0.0%. The composite was stabilized and given structural support by the porous starch matrix, which also gave it exceptional mechanical resistance—up to 5-fold that of typical expanded polystyrene foam. Carboxymethyl cellulose (CMC) functioned as a host complex, providing efficient colorimetric pH-sensing characteristics and guaranteeing a sustained reaction by successfully anchoring the active natural anthocyanins. These biopolymers exhibit perfect synergy, with no gaps or cavitation between the two phases, which would have compromised some of the biocomposite’s functional characteristics. When shrimp were utilized as test items, PS-ACMC composites showed a rapid and efficient color reaction, changing from violet to greenish blue, enabling a visual and instantaneous freshness evaluation.</td>
<td>[103]</td>
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<td>Phloroglucinol (Phg)-loaded pea starch coating</td>
<td>Atlantic salmon (Salmo salar)</td>
<td>The properties of the control (without phloroglucinol—Phg) and Phg-loaded films varied with different Phg levels (2%, 4%, and 8%), denoted as Phg2%, Phg4%, and Phg8%, respectively. For instance, the water vapor permeability (WVP) of the control films was found to be 6.58 ± 1.49 × 10^{-10} \text{g·m}^{-2}·\text{s}^{-1}·\text{Pa}, compared to 7.04 × 10^{-10} \text{g·m}^{-2}·\text{s}^{-1}·\text{Pa}, 6.23 × 10^{-10} \text{g·m}^{-2}·\text{s}^{-1}·\text{Pa}, and 6.30 × 10^{-10} \text{g·m}^{-2}·\text{s}^{-1}·\text{Pa} reported for Phg2%, Phg4%, and Phg8%, respectively. The Young’s modulus was found to decrease from 474.53 MPa (control) to 326.47 MPa (Phg2%), 189.343 MPa (Phg4%), and 103.92 MPa (Phg8%). The tensile strength also decreased from 12.63 MPa (control) to 9.67 MPa (Phg2%), 8.64 MPa (Phg4%), and 7.62 MPa (Phg8%). Phg caused a notable, dose-dependent delay in the proteolysis of meat. The slower rise in pH, trimethylamine, and flesh softening during storage (4°C for up to 17 days) served as supporting evidence. Furthermore, the development of oxidation indicators, such as sulfur-derived volatiles and methyl and ethyl ester volatiles, was also suppressed or delayed (in a dose-dependent manner) by Phg (solid-phase microextraction—SPME; gas chromatography/mass spectrometry—GC/MS). On the other hand, these molecules were marginally more abundant at the maximum Phg concentration (Phg 8%).</td>
<td>[104]</td>
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<td>Sodium alginate, taro starch and lactic acid-based biodegradable films</td>
<td>Spanish chorizo-type meat product</td>
<td>As the concentration of lactic acid (LA) increased, water vapor permeability (WVP), solubility, humidity, and thickness increased, whereas mechanical properties reduced. The optimal composition was determined as 1.25% v/v LA, 0.75% w/v glycerol, and 1.04% w/v SA, with a WVP of 1.05 g·mm·kPa·h·m² and a thickness of 0.14 mm. The optimized biodegradable film (OBF) evidenced in vitro antibacterial performance against L. monocytogenes, Salmonella, and E. coli. Spanish chorizo-type meat samples packaged with OBF (T3), control biodegradable film, CBF (T2), and samples without biodegradable film (T1) showed significant physicochemical changes (humidity, weight loss, pH, acidity, and hardness) during the first 9 days.</td>
<td>[105]</td>
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<td>Starch-based functional film embedded with polyphenolic extract of waste petioles of betel leaf (BLP).</td>
<td>Chicken meat</td>
<td>Loading the extract increased the intermolecular interactions between potato St, guar gum, and the extract, which in turn improved flexibility, thickness, water solubility, DPPH radical-scavenging activity, and UV light protection ability. The integration of betel leaf petiole (BLPE) extract increased the water vapor permeability of the films from 1.89 ± 0.16 to 2.84 ± 0.18 (×10^{-7} g mm/m^2 Pa s). With the incorporation of 8% betel leaf petiole extract, the tensile strength and elastic modulus of the potato starch–guar gum–BLPE (PSGG-BLPE) composite films decreased from 8.29 ± 0.17 MPa to 1.02 ± 0.04 MPa and 2.11 ± 0.06 GPa to 0.48 ± 0.09 GPa, respectively. The produced film exhibited optimum water and mechanical barrier qualities. The extract-embedded film preserved the quality of chicken flesh ca. 4 °C for up to 12 days throughout the shelf-life investigation. The extract-blended films’ biodegradation time was significantly shortened from 28 days for the original film to 14 days for the blended film. This suggests that these films are a good substitute for non-biodegradable film when it comes to preserving raw meat.</td>
<td>[46]</td>
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<td>Pullulan (P)/tapioca starch (TSt)-based antibacterial films incorporated with Litsea cubeba essential oil</td>
<td>Beef meat</td>
<td>The film showed important barrier qualities by decreasing water vapor and oxygen permeability (OP; by 38.19% and 32.14%, respectively) and increasing antioxidant activity (by 21.19%). The main characteristic of this packaging material is the controlled and gradual release of <em>L. cubeba</em> essential oil (LC-EO), which prolongs shelf life and helps maintain the quality of food products. On the other hand, the tensile strength and elongation at break decreased (from 28.94 MPa to 11.29 MPa, and from 15.36% to 12.19%, respectively) when LC-EO was used. Most remarkably, the film showed a strong antibacterial effect (with substantial inhibition diameters of 17.32 mm and 18.59 mm, respectively) against foodborne pathogens, namely <em>E. coli</em> and <em>S. aureus</em>. Bacterial growth, pH, texture, color, and TBARS (thiobarbituric acid-reactive substances) values all showed that the film successfully maintained the quality of beef meat at 4 °C, inhibiting deterioration and prolonging the term of storage.</td>
<td>[106]</td>
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<td>Double-layer (FeO and ZnO) nano-particle-infused starch-based thermoplastic food packaging system</td>
<td>Mutton and chicken meat</td>
<td>FeO and ZnO NP-infused bio-thermoplastic films demonstrated strong oxygen-scavenging and antibacterial activity, respectively. Consequently, a double-layer nano-biothermoplastic (NBP) packaging technique for food preservation was created by combining the two films. Thus, the tensile strength, Young’s modulus, swelling index, and water vapor permeability of the tamarind seed St films were found to be 10.22 MPa, 16.43 MPa, 62.41%, and 0.61 g s^{-1} m^{-1} Pa^{-1}, respectively. The amorphous nature of starch (St) and the film’s swelling index were found to have an impact on the distribution and diffusion of NPs in the St-based films, respectively. In the NBP films, the crystalline features of the NPs were obscured by the amorphous nature of St. Hence, it was discovered that the color, chemical, and microbial properties of mutton and chicken meat kept at 4 °C were influenced by the dissemination of NPs from the NBP packaging system.</td>
<td>[107]</td>
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<td>Potato starch (PS)/watermelon peel pectin (Wpp) composite film with <em>Lycium barbarum</em> microencapsulated leaf flavonoids (MLFs) and nano-TiO$_2$ (Pst/Wpp/MLF/TiO$_2$)</td>
<td>Tan mutton</td>
<td>The concentration of nano-TiO$_2$ influenced the composite film’s water vapor permeability. When 0.03% TiO$_2$ was employed, the water vapor permeability was the lowest, at roughly $2.06 \times 10^{-9}$ (g·m$^{-2}$·Pa·s). In addition, the combined effects of MLFs and nano-TiO$_2$ enhanced the composite film’s thermal stability, UV-blocking capabilities, and mechanical strength whilst enhancing its antioxidant and antibacterial properties. Additionally, there was a regulated and continuous release of flavonoids from the composite film onto the meat surface when tan mutton was coated with the composite film containing MLFs and nano-TiO$_2$. The results showed that all wrapped treatments, particularly Pst/Wpp/MLF/TiO$_2$, significantly reduced the increments of TVC (total viable count), TBARS (thiobarbituric acid-reactive substances), and pH values in tan mutton. The color and texture were preserved throughout the entire storage period at 4°C.</td>
<td>[45]</td>
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<td>Antimicrobial film based on potato starch (PS) and polyvinyl alcohol (PVA) incorporated with clove essential oil (CLO) Pickering emulsion</td>
<td>Pork meat</td>
<td>The films’ crystallinity was established based on hydrogen bonding and electrostatic interactions reducing the elongation (37.53–91.6%) and tensile strength (22.4–6.80 MPa). The color difference, opacity, water vapor permeability, water absorption, and moisture content of the antimicrobial films were 5.06–7.15, 3.32–8.95 A/mm, 1.70–2.20 $\times 10^{-12}$ g cm/cm$^2$·s·Pa, 38.6–65.9%, and 8.80–10.5%, respectively. Moreover, the antimicrobial film exhibited strong antibacterial qualities, preventing the development and reproduction of <em>S. aureus</em> and <em>E. coli</em>, which have consistent and stable structures. The film was very transparent with minimal permeability, and barely any color difference. Raising the PECEO (Pickering emulsion based on clove essential oil) concentration further enhanced the antibacterial and antioxidant qualities of the composite film. Fresh pork was kept for an additional 6–10 days by the application of the antimicrobial film, indicating the film’s potential for pork preservation.</td>
<td>[37]</td>
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<td>Acylated pectin–gelatin-based films incorporated with alkylated starch crystals (AP/G-ASC)</td>
<td>Golden pomfret (<em>Trachinotus blochii</em>) fillets</td>
<td>It was shown that the AP/G-ASC-3% composite film had significantly better mechanical qualities, with a surface that was compact, dense, and uncrackable. The evaluated composite films showed a noticeable improvement in barrier efficiency, and the AP/G-ASC-10% composite film showed a considerable increase in contact angle to 94.02°. In addition, the composite film solutions demonstrated potent antibacterial and antioxidation properties against <em>S. aureus</em> and <em>E. coli</em>. Furthermore, the results from the preservation experiments showed that the composite coatings—particularly AP/G-ASC-3%—could successfully extend the lifespan of golden pomfret (<em>T. blochii</em>) fillets during storage at 4°C, giving the fish better texture and better antioxidant qualities.</td>
<td>[108]</td>
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<tr>
<td>Ginger starch-based edible films incorporated with coconut shell liquid smoke (CSLS) by ultrasound treatment</td>
<td>Ground beef</td>
<td>The samples coated with ginger starch films with the incorporation of 0, 5, 10, or 15% CSLS (CF, LSF1, LSF2, or LSF3, respectively) demonstrated varying tensile strength (14.28 MPa, 15.35 MPa, 15.81 MPa, and 15.74 MPa, respectively), elongation at break (27.35%, 33.34%, 35.92%, and 38.95%, respectively), and water vapor permeability (1.54, 1.38, 1.35, 1.33 (g mm/m$^2$·kPa), respectively). Antibacterial, thermal, mechanical, and barrier properties were all improved in the CSLS–ginger starch films treated with ultrasound. Upon ultrasonic treatment, the antibacterial efficacy of CSLS against <em>B. cereus</em>, <em>S. Enteritidis</em>, <em>L. monocytogenes</em>, <em>E. coli</em> O157:H7, <em>S. aureus</em>, and <em>E. coli</em> rose dramatically. Over the course of a 12-day storage period, the <em>E. Coli</em> O157:H7 populations in ground beef were lowered by 1.33 log CFU/g in the films comprising 15% CSLS. During the period of refrigeration, the ground beef samples’ lipid oxidation was successfully suppressed by the CSLS–starch films. These findings suggest that CSLS–ginger St film treated with ultrasound has potential use as a novel antimicrobial active food packaging material.</td>
<td>[23]</td>
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<tr>
<td>Cassava starch/sodium carboxymethyl cellulose (CMC) edible film with apple polyphenols</td>
<td>Chicken breast</td>
<td>Adding apple polyphenol enhances the film’s flexibility initially, then causes it to decline, while the barrier ability increases dramatically, and the tensile strength marginally drops. When the concentration of AP was 70 mg/mL, the film’s tensile strength (TS) reduced from 5.61 ± 0.45 to 3.36 ± 0.19, its water vapor transmittance dropped from 7.17 ± 0.17 to 4.97 ± 0.07, and its peroxide value dropped from 1.896 ± 0.04 to 0.53 ± 0.04. It was discovered that hydrogen bonds developed between apple polyphenol, cassava starch, and carboxymethyl cellulose (CMC), and these interactions displayed high compatibility, improving the crystallinity of the cassava starch/CMC/AP-4 film microstructure, with the film becoming more compact with less roughness. The rise in blocking ability is exactly proportional to the increase in compactness. Simultaneously, the rise in crystallinity is credited with improving thermal stability.</td>
<td>[44]</td>
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<tr>
<td>Starch–polyester (PLA:PHBV blend) bilayer films incorporating phenolic acids (ferulic, p-coumaric, and protocatechuic acid) into the polyester layer</td>
<td>Pork meat</td>
<td>The tensile strength (TS), elongation at break (EB), oxygen transmission rate (OTR), oxygen permeability (OP), water vapor permeability (WVP) values of the bilayer films coated with ferulic acid were 9.0 MPa, 2.0%, 0.347 cm³/dm², 0.76 cm³·m⁻¹·s⁻¹·Pa⁻¹, 70 g/d·m², and 0.4 g·mm·kPa⁻¹·h⁻¹·m⁻²; with p-coumaric acid were 8.0 MPa, 3.0%, 0.325 cm³/dm², 0.73 cm³·m⁻¹·s⁻¹·Pa⁻¹, 58 g/d·m², and 0.41 g·mm·kPa⁻¹·h⁻¹·m⁻²; and with protocatechuic acid were 8.0 MPa, 2.0%, 0.280 cm³/dm², 0.62 cm³·m⁻¹·s⁻¹·Pa⁻¹, 86 g/d·m², and 0.54 g·mm·kPa⁻¹·h⁻¹·m⁻², respectively. Incorporating phenolic acids decreased the stiffness and break-resistant properties of the bilayers while increasing their capacity to withstand water vapor and oxygen, primarily in the case of proto-catechuic acid. The bilayer films’ antioxidant capacity was greatly increased by phenolic acids, which also decreased the amount of packaged meat that oxidized during storage. The meat microbial counts were similarly decreased by phenolic acid-loaded bilayers, primarily in terms of lactic acid bacteria. Throughout storage, these impacts were favorable for the sample pH and for color parameter development. Active starch–polyester bilayer films show tremendous promise for enhancing the quality preservation and shelf life of pork meat.</td>
<td>[109]</td>
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<tr>
<td>Pregelatinized high-dissolution (HD) and low-dissolution (LD) cassava starch with different water solubilities were incorporated with papain</td>
<td>Chilled Australian grass-fed lean beef (Bos taurus) sirloin steaks</td>
<td>The incorporation of papain altered the shape, permeability, mechanical properties, and physical characteristics of starch sheets. Papain-containing edible films, especially LD films, showed decreased water dissolution and disintegration in the water. The mechanical properties of the HD and LD films varied depending on the increase in papain concentration. In addition to producing rougher surface microstructures from enhanced starch crystallization in HD films, papain significantly decreased oxygen and water vapor permeability through polymer matrices by limiting diffusivity. Consequently, the addition of 5–15% papain to edible starch-based films resulted in functional packaging that altered the texture of the meat.</td>
<td>[43]</td>
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</table>
Table 2. Cont.

<table>
<thead>
<tr>
<th>Starch-Based Coating/Film</th>
<th>Coated Meat Sample</th>
<th>Key Findings</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>Starch-based film was developed by incorporating carbon dots (CDs) from soy protein isolate (SPI) and anthocyanin extracted from clitoria ternatea flower extract (CTE)</td>
<td>Pork</td>
<td>For starch/carbon dot/clitoria ternatea (CT) flower extract (SED), SED&lt;sub&gt;1&lt;/sub&gt; and SED&lt;sub&gt;2&lt;/sub&gt; were synthesized with carbon dot concentrations of 9% (w/v) and 17% (w/v), and it was revealed that the moisture content, swelling degree, and solubility were 17.30%, 73.20, and 28.21% for SED&lt;sub&gt;1&lt;/sub&gt; and 12.40%, 62.60, and 27.15%, for SED&lt;sub&gt;2&lt;/sub&gt;, respectively. This contrasted films without carbon dots (20.20%, 76.69, and 29.12%) and films without carbon dots and CT flower extract (18.45%, 51.75, and 30.78%). The starch/carbon dot/CT flower extract films (SED) demonstrated the best mechanical, barrier, thermal, and antioxidant qualities, owing to the complementary effects of carbon dots and CTE. In addition, the SED films showed color changes at varying pH levels because CTE contains anthocyanin. Therefore, the SED film can be employed as a low-cost visual indicator to check the freshness of packed pork samples. The study demonstrated how the color changed from purple to green as the amount of storage time grew. The films might be used to keep an eye on the freshness of food products, such as pork.</td>
<td>[42]</td>
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<tr>
<td>Corn starch coatings incorporated with Zataria multiflora essential oil (ZEO) and cinnamaldehyde (CIN) in conventional nanoemulsion (NZEO) and fortified nanoemulsion (NZEOC) forms</td>
<td>Chicken meat</td>
<td>Over 20 days of storage at 4 ± 1 °C, starch coatings containing Zataria multiflora essential oil (ZEO) nanoemulsions showed stronger antibacterial effects on certain spoilage microorganisms and pathogenic bacteria of chicken flesh compared to coatings containing traditional forms of ZEO. In addition, the best antibacterial properties were found in chicken meat coated with a starch solution containing a nanoemulsion of ZEO fortified with cinnamon (NZEOC). At the end of storage, NZEOC treatment exhibited elevated antibacterial qualities, according to the following outcomes: 7.96 log&lt;sub&gt;10&lt;/sub&gt; CFU/g for total viable count, 7.29 log&lt;sub&gt;10&lt;/sub&gt; CFU/g for psychrotrophic count, 6.51 log&lt;sub&gt;10&lt;/sub&gt; CFU/g for lactic acid bacteria, 6.98 log&lt;sub&gt;10&lt;/sub&gt; CFU/g for Enterobacteriaceae count, 5.16 log&lt;sub&gt;10&lt;/sub&gt; CFU/g for mold and yeast count, and 6.51 log&lt;sub&gt;10&lt;/sub&gt; CFU/g for inoculated L. monocytogenes. However, when cinnamaldehyde (CIN) was introduced to ZEO during the nanoemulsion production process (NZEOC), the antimicrobial effects of coating solutions were enhanced in comparison to when NZEO and CIN were added separately to the St solution (NZEO + CIN).</td>
<td>[110]</td>
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<tr>
<td>Starch, red cabbage extract (RCE), glycerol, sweet whey (SW), and water.</td>
<td>Ground beef</td>
<td>Two independent variables, red cabbage extract (RCE) and sweet whey (SW), were optimized, and it was observed that T2, T7, and T10 films composed of (64.18% RCE and 4.36% SW), (50% RCE and 0.0% SW), and (50% RCE and 15% SW), respectively, presented good mechanical properties, high antioxidant capacity (due to the presence of phenolic compounds and anthocyanins), low solubility, and low water vapor permeability. The moisture content, water vapor permeability, solubility, tensile strength, elongation at break, and Young’s modulus of the T2, T7, and T10 films were (22.95%, 0.34 g·mm·h&lt;sup&gt;-1&lt;/sup&gt;·m&lt;sup&gt;-2&lt;/sup&gt;·kPa&lt;sup&gt;-1&lt;/sup&gt;, 28.23%, 3.14 MPa, 28.73%, 10.87 MPa), (14.20%, 0.41 g·mm·h&lt;sup&gt;-1&lt;/sup&gt;·m&lt;sup&gt;-2&lt;/sup&gt;·kPa&lt;sup&gt;-1&lt;/sup&gt;, 26.14%, 6.28 MPa, 54.44%, 12.15 MPa), and (17.35%, 0.35 g·mm·h&lt;sup&gt;-1&lt;/sup&gt;·m&lt;sup&gt;-2&lt;/sup&gt;·kPa&lt;sup&gt;-1&lt;/sup&gt;, 25.43%, 4.88 MPa, 22.06%, 22.42 MPa), respectively. Ground beef packaged with the T2 film showed the least change in quality parameters.</td>
<td>[111]</td>
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Note: Refer to the Glossary of Terms (after § 6) for a complete list of the acronyms used in Table 2.

In addition, variable resistance to yeast and fungi are reported, along with increased shelf life and reductions in water vapor permeability (WVP), UV, and oxidative resistance due to the barrier properties of the films/coatings. The composite materials display variable properties due to their nature and composition, including variability in thermal stability, wettability, flexibility, and mechanical properties. Table 2 provides an overview of some selected studies that cover a range of starch-based composites. An inspection of the results provides further elaboration on the key findings for the composites reported.
4. Chitosan- and Starch-Based Biocomposite Coatings/Films for Meat Preservation

4.1. Brief Discussion on Chitosan–Starch-Based Composites

Antibacterial films derived from amalgamations of starch and chitosan have garnered significant interest in recent years. The functional qualities of starch–chitosan films are enhanced owing to the blending of starch and chitosan as biocomposites (Figure 3). Chitosan is a functional supplement that imparts biomedical and nutritional qualities to food owing to its heavy-metal-binding capabilities, as well as hypcholesterolemic and antimicrobial properties [30]. Hence, studies have observed an increase in the antibacterial, film-forming, and mechanical properties of starch films incorporated with chitosan [29,112]. Biocomposite antibacterial films demonstrate outstanding mechanical behaviors and improved microstructural features, which are controlled by the interfacial bonding mechanism between chitosan and starch [27,28].

Figure 3. A schematic illustration of a biocomposite film containing starch and chitosan that shows interchain hydrogen bonding interactions.

Unfortunately, the utility of chitosan for the preparation of starch–chitosan antibacterial films in aqueous media at a neutral pH has been constrained owing to its relative insolubility in alkaline solutions [113,114]. This challenge can be addressed by employing functionalized quaternary chitosan derivatives that possess greater solubility when immersed in aqueous media at a neutral pH [115]. The superb quaternized 2-hydroxypropyltrimethylammonium chloride chitosan (HTCCht) has been effectively utilized as an antibacterial agent due to its enhanced water solubility over a broad range of pHs and notable broad spectrum of antibacterial action [116,117].

4.2. Antibacterial and Mechanical Attributes of Starch–Chitosan-Based Films

A study on the antibacterial activity of composites films containing HTCCht and amylose starch film was reported by Deng et al. [31]. In that study, glutaraldehyde (GA) was used as the cross-linker, amylose served as the matrix, and HTCCht served as the antibacterial additive in the biocomposite. The macromolecular chains of amylose starch and HTCCht were reported to become intertwined due to their intermolecular H bonds, which subsequently underwent cross-linking with glutaraldehyde (GA) through the Schiff base reaction. The mechanical attributes of the amylose films were enhanced by the com-
posite formation between amylose starch and HTCCht. For the best HTCCht/amylose films, the elongation at break (EB) and tensile strength (TS) were increased by 109% and 207%, respectively, compared with single-component amylose films. Moreover, HTCCht/amylose films had a clear bacteriostatic activity, comparatively low cytotoxicity, and reduced transmittance in the UV spectral region, showing their potential to improve fresh meat preservation.

Furthermore, several investigations have evaluated the impact of the starch–chitosan ratio on the barrier and mechanical characteristics of biodegradable composite films [30,118]. A significant number of articles claim that when chitosan loading increases, the water vapor permeability of the films becomes reduced [119,120]. Moreover, it was found that using chitosan with an exceptionally high molecular weight caused films’ water vapor permeability to decrease [121,122]. In addition, contradictory information has been reported by different authors on the impact of chitosan loading on the tensile characteristics of composite films. According to several sources, the tensile strength of films either rises [119,120], reaches a maximum [123], or decreases [122] as the chitosan content increases. A possible explanation for this data disparity may be variations in the techniques used to prepare the film-forming mixtures, such as the sequence of addition of biopolymer additives.

In various studies, chitosan was found to be more successful in impeding the growth of Gram-positive bacteria than Gram-negative bacteria [124–127]. Gram-positive bacteria’s thick cell walls are often surrounded by protonated amino groups (−NH₃⁺) of chitosan, which can create a barrier that blocks the flow of nutrients and oxygen necessary for metabolic processes [127]. Moreover, chitosan NPs in the smaller size range can immediately bind to the permeable outer cell wall of Gram-positive bacteria, which allows for rapid diffusion into the cells and disruption of the cell membrane, which causes intracellular content to leach out, causing cell death [26,124]. On the other hand, Gram-negative bacteria require chitosan to adhere to their outer membrane, which is composed of lipopolysaccharides, lipoproteins, and phospholipids. This process reduces the ability of chitosan to adhere to the cell wall domain. Nevertheless, the strong cell wall structure and hydrogen bonding between starch and chitosan contribute to delayed diffusion, which restricts chitosan’s ability to repel Gram-negative bacteria [124,127]. Furthermore, the non-volatile nature of chitosan diminishes the effectiveness of antibacterial agents against Gram-negative bacteria [26,124].

Hence, recent investigations (cf. Table 3) focus on the addition of other components, such as ZnO [126], thymol [25], and curcumin [128], among other additives, to starch–chitosan films to strengthen the films and their antibacterial properties. These additives possess antibacterial properties, either encapsulated by chitosan or directly incorporated into the films. This leads to a synergistic antibacterial action, as opposed to the inclusion of chitosan alone, thereby resulting in improved film properties such as antifungal and/or antibacterial properties. A remarkable example of a chitosan–starch-based film incorporated with Lonicera caerulea L. anthocyanins (LCA) was made by Li et al. [129], who prepared a pH- and NH₃-responsive colorimetric film (PS-CH-LCA) based on potato starch (PS), chitosan, and LCA by adjusting the pH of the film-forming solution. This film was used to assess the freshness of shrimp in real time (Figure 4).

In contrast to starch-based films (cf. § 3), chitosan–starch systems offer certain advantages, including favorable coating/film formation, along with stable composites due to the favorable electrostatic interactions within chitosan–starch composites. Their mechanical, physicochemical, and antimicrobial properties bear parallel trends, as noted for the chitosan-based systems with various additives described in § 2. In many cases, synergism resulting from the biopolymer content and additives results in a maximum response, according to the properties of interest. Table 3 provides an overview of some selected studies that cover a diverse range of starch-based composites. The inspection of the tabular results provides further elaboration on the key findings of the systems reported.
Recent studies on the modification and application of chitosan–starch-based films in meat preservation.

Table 3.

<table>
<thead>
<tr>
<th>Chitosan–Starch Coating/Films</th>
<th>Coated Meat Sample</th>
<th>Key Findings</th>
<th>Ref.</th>
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<tr>
<td>Antibacterial packing film based on amylose starch and 2-hydroxypropyl-trimethylammonium chloride chitosan (HTCCht)</td>
<td>Meat</td>
<td>The mechanical characteristics of the amylose films were enhanced by a composite of HTCCht (2-hydroxypropyl-trimethylammonium chloride chitosan) and amylose starch. The antibacterial efficacy of the HTCCht/amylose films was HTCCht dose-dependent and showed good antibacterial activity against both S. aureus and E. coli. The ideal mass ratio of HTCCht to amylose was found to be 1:4, based on the antibacterial and mechanical properties and quantity of HTCCht required. In contrast to amylose films, the ideal HTCCht/amylose films exhibited an elongation at break and tensile strength of 53.86% (a 109.59% increase) and 16.13 MPa (a 266.65% increase), respectively. It was found that the HTCCht/amylose films displayed bacteriostatic activity, comparatively low cytotoxicity, reduced UV transmittance, and the capacity to improve the durability of fresh meat.</td>
<td>[31]</td>
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<td>Nitrogen, phosphorus-doped green-tea-derived carbon nanodots (CNDs) incorporated with chitosan–starch (Ch/St)</td>
<td>Pork meat</td>
<td>With varying concentrations of carbon nanodots (CNDs), various chitosan–starch–CND films were produced at 0%, 1%, 2%, and 3% to yield water vapor permeability values of 1.15, 1.28, 1.31, and 1.35 (×10⁻³ g·m⁻²·Pa⁻¹·s⁻¹), respectively. The addition of CNDs (nitrogen, phosphorus-doped, green-tea-derived carbon dots) increased the blockage of UV light (93.1% of UV-A and approximately 99.7% of UV-B) without considerably altering the water vapor permeability (WVP) or transparency of the films. Moreover, the addition of CNDs to the chitosan–starch films increased the antioxidant activity (71.4% for DPPH and 98.0% for ABTS) and demonstrated high antibacterial activity against S. aureus, E. coli, and L. monocytogenes. It was established that wrapping the meat in the resulting film at 20 °C reduces bacterial growth (below 2.5 Log CFU/g after 48 h) with no appreciable distortion in the color of the wrapped meat.</td>
<td>[52]</td>
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<td>Chitosan–starch-based colorimetric film synthesized based on potato starch (PS), chitosan (Ch), and Lonicera caerulea L. anthocyanins (LCA)</td>
<td>Fresh shrimp</td>
<td>The colorimetric film exhibiting the lowest water solubility (33.11%) and the highest tensile strength (6.43 MPa) showed a sub-freshness indication effect when the pH of the film-forming solution was set to 2.5. Hydrogen bonds favored the binding of chitosan to the surface of the PS in the film matrix, where LCA was firmly embedded. The shrimp freshness evaluations showed that when the storage time was extended to 4 °C, the PS-CH-LCA pH 2.5 film showed noticeable color changes (red → grey-pink/grey → grey-green). This film was highly correlated with shrimp degeneration indices (pH, TVC, TBARS, and TVB-N), enabling the authors to determine if the shrimp were fresh, sub-fresh, or spoiled.</td>
<td>[129]</td>
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<tr>
<td>Chitosan–coix seed starch films incorporated with nano zinc oxide and Artemisia annua essential oil (AAEO)</td>
<td>Pork</td>
<td>The addition of ZnO significantly improved the films’ antibacterial, barrier, hydrophobic, and mechanical activity, but did not affect their antioxidant capacity. Increasing ZnO from 0% to 5% resulted in a significant drop in water vapor permeability (WVP) and oxygen permeability (OP), which rapidly reduced from 385 g·m⁻²·day and 1950 cm⁻²·m⁻²·day to 218 g·m⁻²·day and 1624 cm⁻²·m⁻²·day, respectively. A further increase in the ZnO content from 5% to 7% also reduced the WVP and OP of the film by 4.58% and 2.77%, respectively. The incorporation of AAEO (A. annua essential oil) enhanced the films’ flexibility, hydrophobicity, barrier qualities, antibacterial activity, and antioxidant activity. When Artemisia annua essential oil was increased from 0 to 8%, the OP and WVP of the films significantly reduced from 1624 cm⁻²·m⁻²·day and 218 g·m⁻²·day to 1388 cm⁻²·m⁻²·day and 125 g·m⁻²·day, respectively. The structural analysis revealed that ZnO and AAEO were evenly distributed and well incorporated into the film matrix with good inter-compatibility among all the constituents. When the ZnO and AAEO contents were 5% and 8%, respectively, the film’s physio-chemical and biological qualities attained an optimum state. The results of the pork preservation tests indicated that the pork samples coated with the 5% ZnO-8% AAEO film were able to effectively suppress (p &lt; 0.05) the growth of microorganisms and lipid oxidation, hence extending the pork’s shelf life.</td>
<td>[36]</td>
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</table>
The chitosan and starch aldehyde–catechin conjugate (SACC) exhibited synergistic antimicrobial and antioxidant properties. On day 14, the chitosan–SACC-coated pork loins displayed lower shear force (27.40 N), protein oxidation level (0.047 mmol free thiol group g⁻¹), lipid oxidation level (0.47 mg malondialdehyde kg⁻¹), total volatile base nitrogen content (130.2 mg kg⁻¹), total viable count (7.11 log CFU g⁻¹), pH value (5.99), and weight loss (7.16%) compared to the uncoated and chitosan-coated pork loins. In the meantime, during the chilled storage period, the pork loins’ sensory, microstructure, and color properties were successfully preserved by the chitosan–SACC composite coating. The application of a chitosan–SACC composite coating increased the shelf life of pork loins from 8 days (uncoated) to 14 days.

The addition of essential oils to the films remarkably enhanced protection against oxygen, water vapor, and light; this enhancement may have been brought about by greater bonding connections with the chitosan–acetylated starch (Cht/ACS) matrix. The addition of 2.50% essential oil reduced the films’ moisture content and water solubility by 22.7% and 21.6%, respectively. The addition of 2.00% essential oil reduced the films’ elongation at break and tensile strength by 40.4% and 25.6%, respectively. The film opacity increased by 795.8% when the essential oil concentration reached 2.50%, while the peroxide value and water vapor permeability fell by 52.6%, and 35.5%, respectively. In a beef model, the films exhibited stronger antimicrobial properties against a Gram-negative bacterial pathogen (E. coli O157:H7) and spoilage bacteria when higher concentrations of essential oils were incorporated. This was because the films had higher concentrations of antimicrobial components and an enhanced oxygen barrier.

The mechanical properties of the starch–chitosan composite film were significantly enhanced by low-pressure argon and air plasma treatment. The composite film treated with plasma exhibited an increase in tensile strength from 10.59 to 22.09 MPa after 12 min, resulting in the creation of a steady cross-linked network on the biopolymer’s surface, which made argon plasma more effective. Moreover, after being exposed to air and argon plasma for 12 min each, the starch–polyester oxygen transmission rate (OTR) values for the film were found to be 0.024 ± 0.015 and 0.015 ± 0.013 cm³ mm⁻² day⁻¹, respectively, in contrast to the untreated film, which had an OTR of 0.062 ± 0.02 cm³ mm⁻² day⁻¹. The ductility of the film increased due to the functionalization and degradation of the biopolymers caused by air plasma. After plasma treatment, there was an increase in solubility and hydrophilicity but no discernible change in water vapor transmission rate (VTR). The film’s oxygen permeability increased following both plasma treatments. However, there was no discernible variation between the total viable count in the fillets packaged for treated and untreated films. Consequently, the chicken breast fillets’ shelf life was not extended by cold plasma therapy-treated films.

Relative to the curcumin-loaded chitosan nanoparticle (CCN)-free film, the water vapor permeability (WVP) and oxygen permeability (OP) reduced with higher CCN volume. The zein/CCN film (with 5/5 mass ratio) had the lowest WVP (1.39 ± 0.03 10⁻⁴ g mm⁻² h⁻¹ m⁻⁷ kPa), while the zein/CCN film (with 3/7 mass ratio) had the lowest OP (2.10 ± 0.15 10⁻¹⁴ cm³ m⁻² s⁻¹ Pa). Meanwhile, the composite films (CCN/zein/PS films) revealed high oxidation resistance, barrier performance, mechanical properties, and broad relative release efficiency, especially for the effective relative release of curcumin (CUR). As an indication of CCN’s antioxidant and antimicrobial properties, the CCN/zein/potato starch composite films were able to preserve the treated fish muscle’s sensorial, chemical, and microbial quality. The shelf life of Schizothorax prenati fillets was extended by up to 15 days by the CCN/zein/PS composite film, which also held off physicochemical changes in the meat.
In comparison to chitosan–starch (Cht-St) films, films containing *Thymus kotschyanus* essential oil (TKEO) and pomegranate peel extract (PPE) had lower elongation values and tensile strength. The chitosan–starch films had a water vapor permeability (WVP) of 15.01 g/m²·h. The water solubility for chitosan–starch film was 12.54% compared to 23.77% and 23.29 for the Cht-St-PPE (1%) and TKEO (2%) films, respectively. The average elongation value of 16.06% for the chitosan–starch group decreased to 10.33% and 11.18% in the Cht-St-PPE (1%) and Cht-St-PPE (1%) groups with TKEO (2%), respectively. The results showed that composite films comprising TKEO and PPE have anti-listeria effects. [35]

The utilization of TKEO and PPE effectively minimizes lipid oxidation and bacterial counts. The amounts of TKEO or PPE additives directly influenced the impact of chitosan–starch films on chilled meat. All additives showed promising outcomes in terms of antibacterial and antioxidant activity, including sensory characteristics (e.g., color, odor, and broad acceptability). Nevertheless, the Cht-St-PPE groups (1%) with TKEO (2%) produced the most favorable outcomes overall, indicating that a mixture of with TKEO and PPE can be used to extend the shelf life of meat.

**Table 3. Cont.**

<table>
<thead>
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<tr>
<td>Chitosan–starch film containing pomegranate peel extract and <em>Thymus kotschyanus</em> essential oil</td>
<td>Fresh beef (<em>Quadriceps femoris</em> muscle)</td>
<td>In comparison to chitosan–starch (Cht-St) films, films containing <em>Thymus kotschyanus</em> essential oil (TKEO) and pomegranate peel extract (PPE) had lower elongation values and tensile strength. The chitosan–starch films had a water vapor permeability (WVP) of 15.01 g/m²·h. The water solubility for chitosan–starch film was 12.54% compared to 23.77% and 23.29 for the Cht-St-PPE (1%) and TKEO (2%) films, respectively. The average elongation value of 16.06% for the chitosan–starch group decreased to 10.33% and 11.18% in the Cht-St-PPE (1%) and Cht-St-PPE (1%) groups with TKEO (2%), respectively. The results showed that composite films comprising TKEO and PPE have anti-listeria effects.</td>
<td>[35]</td>
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<tr>
<td>Cassava starch–chitosan incorporated with red dragon fruit peel anthocyanin extract</td>
<td>White leg shrimp (<em>Litopenaeus vannamei</em>)</td>
<td>Antioxidant activity was boosted to 94.44% when red dragon fruit peel anthocyanin was added, according to the results. Its flexibility was also increased, as evidenced by the lowest Young’s modulus (0.14 ± 0.01 MPa), smallest tensile strength (3.89 ± 0.15 MPa), and maximum elongation at break (27.62 ± 0.57%). The indicator film’s sensitivity to pH was demonstrated by a color change from red to yellow as pH rose. The film’s color was also altered when it was employed to evaluate packaged shrimp’s freshness at room temperature and in a chiller.</td>
<td>[47]</td>
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Note: Refer to the Glossary of Terms (after § 6) for a complete list of the acronyms used in Table 3.

**Figure 4.** The synthesis and application of a pH- and NH₃-responsive colorimetric film (PS-CH-LCA) for assessing shrimp spoilage. Reproduced with permission from [129].

**5. Future Perspectives**

The emergence of unique properties (physicochemical, biological, and mechanical) in biopolymer systems undergoing composite formation provides motivation for the development of materials that are limited only by our collective imagination [15,131–134]. Given the relatively simple structural features of chitosan and starch platforms, a wide array of materials can be developed that are guided by the principles of supramolecular chemistry, such as intermolecular interactions (e.g., electrostatic interactions and hydrogen bonding) and solvation processes, such as hydrophobic effects [134–136]. Nevertheless, research
on chitosan and starch has resulted in limited development toward commercially viable systems for packaging meat products (cf. Table 9 in [137]). This may relate to the use of the solvent casting technique for the preparation of films, which is not suitable for large-scale production due to cost considerations. Further research on other techniques such as the solvent-based extrusion or solid-phase extrusion of composites could aid in the synthesis of these films on a larger scale [24,137]. Moreover, the rational design of these composite materials for specific applications is impeded to some extent by the limited development of computational methods to gain further insight into the structure–function relationships of such biopolymer systems [138,139]. In this regard, future research is necessary to gain an improved understanding of the supramolecular chemistry of multicomponent biopolymer systems (including additives). Systematic studies that explore the preparation of composites and examine the role of structural factors are required to establish improved structure–function relationships. Structural factors include the molecular weight of biopolymers, bulk versus nano-chitosan, amylose versus amyllopectin starch variants, composition, additive components, reagent addition sequences, and solvent effects [24,27].

An improved understanding of structure–function relationships can be advanced in the context of supramolecular chemistry, which will contribute to the field of biocomposites and their technological applications. To address food-security challenges, the development of coatings and films with multifunctional properties is required [129,133,134], including antimicrobial and barrier properties (oxygen, water) to enhance food safety and storage stability. In the future, it would be beneficial to use computational-based approaches to offer additional insights into the variables influencing the structure–function relationships of starch–chitosan composites. In addition, it is possible to further develop chitosan NPs [24] and nanocomposites using alternative strategies to achieve tailored physicochemical, biological, and mechanical properties [24,132,133]. As an alternative to conventional microbiols and other additives in composites, the use of (non)metal oxides and organic additives can be tailored in unique ways to generate new properties that differ from conventional bulk materials [140]. Nanocomposites can offer sustainability advantages by minimizing the content of active ingredients (e.g., chitosan, antimicrobials), which can further contribute to food-safety metrics (e.g., antimicrobial activity and the leaching of additives) [24,140]. Hence, further in vivo and in vitro cytotoxicity studies are required to evaluate any potential adverse impacts of biocomposite coatings (starch–chitosan–additive systems) on food safety and security. By bridging these gaps, a greater understanding of molecular interactions and interfacial processes can be garnered to develop more effective composite formulations. In turn, addressing such knowledge gaps will support the commercialization of chitosan–starch films and coatings and advance the emerging and exciting field of carbohydrate-based biocomposites.

6. Conclusions

The manufacture of food packaging films and coatings that are highly biodegradable is crucial in tackling the environmental and health issues related to the use of plastic packaging derived from conventional petrochemical feedstocks. Chitosan and starch have emerged as attractive biomaterials to produce sustainable and biodegradable composite films, owing to their unique intrinsic properties. This study highlights the recent progress in the application of chitosan- and starch-based films for the preservation of meat products. It was observed that the molecular weight of chitosan and its degree of deacetylation significantly impact its physicochemical, mechanical, biological (antimicrobial and antifungal), and barrier properties due to the amino-group accessibility of chitosan. In the case of starch biopolymers, the amylose–amyllopectin ratio, molecular weight, particle size, and morphology influence their chemical and physical properties. In addition to the role of additives, the intrinsic nature of starch and chitosan could impact the quality and durability of composite films derived from multi-component biopolymers. The recent studies presented have sought to incorporate various types of bioactive components that are not limited to essential oils, natural plant extracts, or nanoparticles to improve the antibacterial,
antifungal, and mechanical properties of the studied films. Specifically, the combination of two biopolymers (chitosan and starch) along with additives can yield remarkably improved properties in coatings/films. Composite properties that surpass the additivity effects of singular biopolymer systems are a hallmark feature of composite materials. Continued interdisciplinary research in this field is anticipated to result in improved materials that will improve food safety and security in the food industry.

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Abbreviations

Acylated pectin (AP); alginate (Alg); chitosan (Cht); apple polyphenol (AP); *Artemisia annua* essential oil (AAEO); 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS); betel leaf petioles (BLPE); *C. paliurus* flavonoid (CPF); carbon nanodots (CNDs); carbon dots (CDs); carboxymethyl cellulose (CM); carboxymethyl chitosan (CMCh); cellulose (CE); chitosan (Cht); chitosan/curcumin nanoparticles (CCN); cinnamaldehyde (CIN); clitoria ternatea (CT); clitoria ternatea flower extract (CTE); clove essential oil (CLO); coconut shell liquid smoke (CSLS); corn starch (CS); curcuma hydroethanolic extract (CEE); degree of deacetylation (DDAc); 1,1-Diphenyl-2-picrylhydrazyl (DPPH); *Escherichia coli* (*E. coli*); elongation at break (EB); essential oil (EO); *Euryale ferox* (EF); gallic acid (GA); garlic essential oil (GEO); gas chromatography/mass spectrometry (GC/MS); gelatin (Gel); gelatin-based alkylated starch crystals (G-ASC); gelatin hydrolysate (GelH); generally recognized as food-safe (GRAFS); glutaraldehyde (GA); graphene oxide (GO); high dissolution (HD); 2-Hydroxypropyl-trimethylammonium chloride (HTC); HTC chitosan (HTCCh); konjac glucomannan (KGM); lactic acid (LA); layer-by-layer (LbL); low dissolution (LD); microencapsulated leaf flavonoids (MLFs); nano-biothermoplastic (NBP); nanoemulsion (NE); nanoparticles (NPs); nanocomposites (NCs); ovalbumin (OVA); oxygen transmission rate (OTR); oxygen transmission coefficient (OTC); pectin (Pec); polyactic acid (PLA); phloroglucinol (Phg); Pickering emulsion clove essential oil (PECEO); polybutylene itaconate (PBI); polyvinyl alcohol (PVA); polyactic acid (PLA); potato starch (PS); potato starch–guar gum (PSGG); pomegranate peel extract (PPE); porous starch anthocyanin–carboxymethyl cellulose (PS-ACMC); pullulan (P); red cabbage extract (RCE); *Staphylococcus aureus* (*S. aureus*); starch (St); sulfur-modified montmorillonite (S-MMT); 2-Thiobarbitone (TBB); thiobarbituric acid (TBA); sodium alginate (SA); solid-phase microextraction (SPME); starch aldehyde–catechin conjugate (SACC); sweet whey (SW); tapioca starch (TSt); tensile strength (TS); thiobarbituric acid–reactive substances (TBARS); *Thymus kotschyanus* essential oil (TKEO); total viable count (TVC); total volatile base nitrogen (TVB-N); *Trachinotus blochii* (T. blochii); vapor transmission rate (VTR); watermelon peel pectin (Wpp); water vapor permeability (WVP); water vapor transmission rate (WVTR); whey protein isolate (WPI); *Zanthoxylum Bungeanum* (*ZB*); *Zanthoxylum limonella* (*Zl*); *Zataria multiflora* essential oil (ZEO); ZEO nanoemulsion (NZEO); ZEO nanoemulsion with fortification (NZEOC).
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