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Review Article

Interaction mechanisms of edible film ingredients and their effects on food quality

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ABSTRACT

Traditional food packaging has problems such as nondegradable and poor food safety. Edible films play an important role in food packaging, transportation and storage, having become a focus of research due to their low cost, renewable, degradable, safe and non-toxic characteristics. According to the different materials of edible films substrate, edible films are usually categorized into proteins, polysaccharides and composite edible films. Functional properties of edible films prepared from different substrate materials also vary, single substrate edible films are defective in some aspects. Functional ingredients such as proteins, polysaccharides, essential oils, natural products, nanomaterials, emulsifiers, and so on are commonly added to edible films to improve their functional properties, extend the shelf life of foods, improve the preservation of sensory properties of foods, and make them widely used in the field of food preservation. This paper introduced the classification, characteristics, and modification methods of common edible films, discussed the interactions among the substrate ingredients of composite edible films, the influence of functional ingredients on the properties of edible films, and the effects of modified edible films on the quality of food, aiming to provide new research ideas for the wide application and further study of edible films.

1. Introduction

Edible films are safe, environmentally friendly and biodegradable packaging materials with vast potential for application in the bioactive packaging community. According to the source of substrates, Edible films are mainly classified into proteins, polysaccharides and composite. With edible, gas barrier, water vapor barrier and mechanical characteristics, which can inhibit the growth of microorganisms in the food, to extend the shelf life of food (Emragi et al., 2022). Proteins-based edible films materials have good film-forming ability and emulsification tendency, the common substrate materials include gelatin (Liu et al., 2021), whey protein (García et al., 2020), and soybean isolate protein (Alves et al., 2017). Polysaccharides-based edible films materials with good biodegradability, abundant sources, inexpensive and non-toxic and non-hazardous characteristics, the common materials are starch (Menzel, 2020), chitosan (van den Broek et al., 2015), cellulose (Lim and Gong, 2018), etc. In addition, the performance of edible with a single may be defective, and composite edible films have emerged. Gelatin-chitosan composite film showed significant antibacterial properties (Peng et al., 2021); egg white protein films supplemented with tea polyphenols showed excellent antibacterial activity against *Escherichia coli and Staphylococcus aureus* on fresh pork (Liu et al., 2023). This paper described the interaction mechanism of edible film substrate ingredients, the interaction mechanism between functional ingredients added to edible films and substrate ingredients, and the influence mechanism of edible film ingredients on food quality, so as to generate

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new research ideas for the advanced study of edible films.

2. Interactions of edible film substrate ingredients

Interactions of edible film substrate ingredients determine the functional properties of edible films. As shown in Fig. 1, the edible film substrate materials are broadly classified into proteins, polysaccharides and composite. Due to its unique structure of carboxyl and amino groups, protein based edible films have a good emulsifying tendency and better mechanical properties than polysaccharide based edible films. However, compared with common polymers, protein based films have lower mechanical strength and higher water vapor permeability. As the content of gelatin increases, the thickness and mechanical properties of the gelatin film increase, but the water resistance decreases (Li, Sha, Yang, Ren and Tu, 2023). Compared with films formed by proteins from other plant sources, edible soy protein isolate films are smoother, more flexible, and transparent (Huang et al., 2019). Edible whey and egg films have good flexibility, are colorless and odorless, and can also be used as antibacterial agents The carrier of food additives such as antioxidants (Chollakup et al., 2020). Polysaccharide based edible film is non-toxic, harmless, sustainable, and selectively permeable to carbon dioxide and oxygen. Chitosan based edible films have significant antioxidant activity (Chungsiriporn et al., 2022). Carboxymethyl cellulose films have excellent film-forming properties and thermal stability, but due to the presence of a large number of hydrophilic groups, their water vapor barrier performance is poor (Li et al., 2023). Pectin based edible films have excellent mechanical properties and good barrier properties to oil and oxygen, but they have poor moisture resistance and low elongation (Gao et al., 2019). In comparison to single substrate films, composite edible films frequently perform better. Among these, starch-gelatin composite films exhibit superior mechanical qualities and stability (Karakoyun and Keskin, 2023). The gelatin chitosan composite film exhibits excellent antibacterial properties (Bonilla et al., 2018). The gelatin carboxymethyl cellulose composite film has significant antioxidant and UV blocking abilities (Vargas-Torrico et al., 2024).

2.1. Characteristics and modifications of edible films

2.1.1. Protein based edible films

Protein-based edible films have excellent oxygen barrier properties and inhibit the penetration of organic volatiles and oils, but their ductility and resistance to water permeation were poor, and can be modified chemically or physically. The ductility of a film determines its structural integrity. Protein based edible films are brittle and hard, and films with poor ductility are prone to breakage after coating. Adding hydrophobic components can enhance the ductility of edible films, which greatly limits industrial production and widespread application (Ahammed et al., 2020). Generally speaking, the hardness and ductility of a film are opposite indicators that are related to the thickness of the film. The range of hardness and ductility should be determined based on specific applications. Li believes that when the film thickness is 44 × 10^{-3} mm, the tensile strength of the film is 55.39 MPa, and the elongation at break is 333.26% (Li, Sha, Yang, Ren and Tu, 2023). Gelatin hydrolysate can be used as a plasticizer for fish myofibrillar fibrillar protein films, and its plasticizing effect and properties depended on the degree of hydrolysis and the gelatin hydrolysate added (Nuanmano

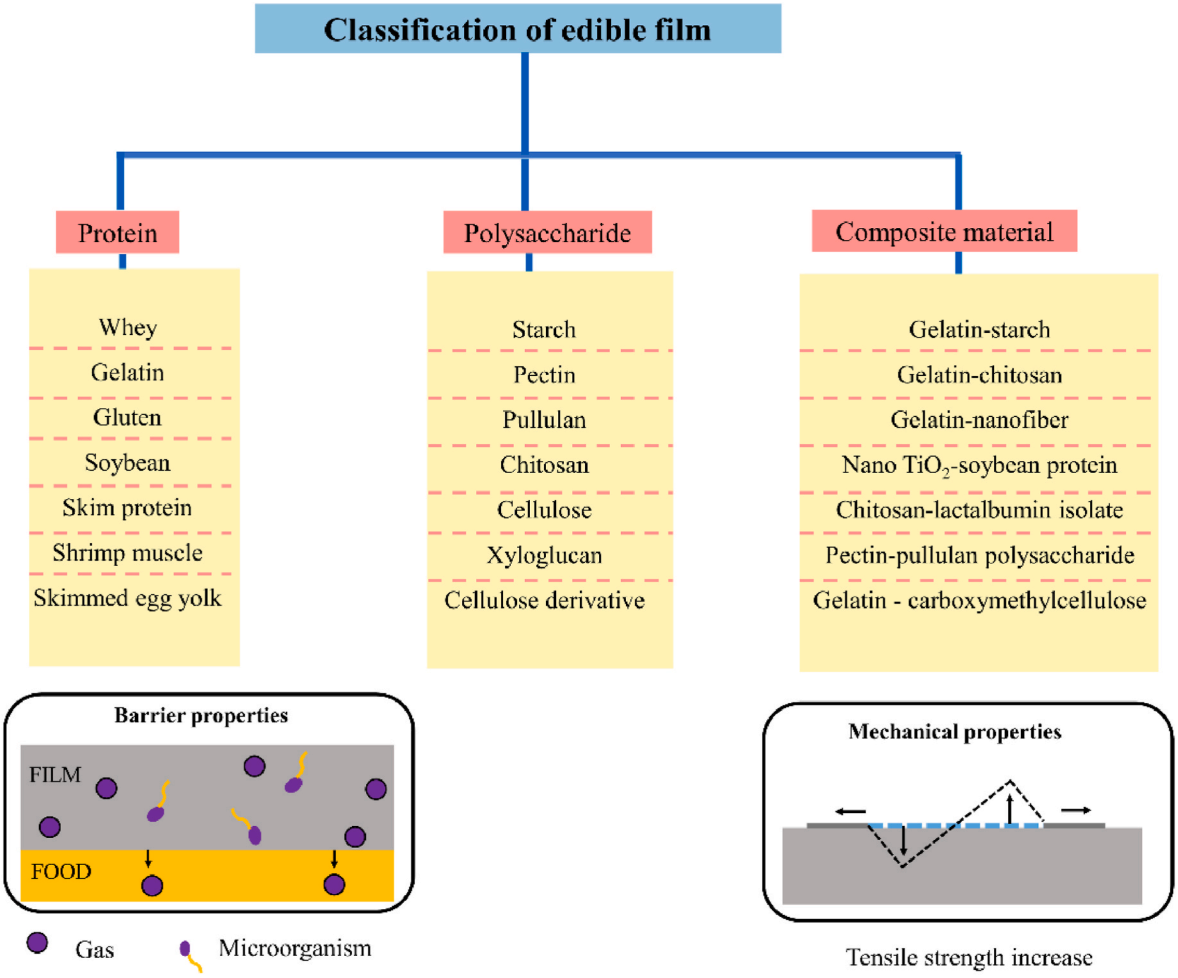

Fig. 1. Schematic diagram of edible film substrate ingredients and their functional properties.

et al., 2015). The use of dimethyl sulfoxide as a solvent for gelatin films prevented gelatin hydrolysate from partially restoring the triple helical structure of collagen during the gelling process, resulting in films with significant ductility (Rubini et al., 2020). The addition of polyphenols to corn alcohol soluble protein-gelatin films significantly enhanced the antioxidant, hydrophobic and freshness retention properties of the composite films Zhao et al. (2023); Liu et al., 2023 Utilization of physical modification to obtain high-quality gelatin films, at 12 min of ultrasonication at 400 W, the water vapor permeability of the gelatin film was reduced and the ductility and thermal stability were significantly increased. Wu et al. (2021) demonstrated that antimicrobial soy isolate protein films containing diatomaceous earth and thymol complexes had modifiable physical properties and antibacterial activity. The addition of pomegranate peel to the mung bean protein films effectively increased the thickness, moisture permeability, tensile strength and flexibility of the composite films, and make the mung bean protein films have higher total phenol content, antioxidant activity and antibacterial ability, but reduced solubility and moisture content. It has been shown that ultrasound-assisted succinic anhydride modification resulted in enhanced protein gel network, particle size reduction, and increased water holding capacity (Wu et al., 2022a). Ball milling pretreatment dramatically improved the gel properties of whey proteins (Wu et al., 2022b).

2.1.2. *Polysaccharide based edible films*

Polysaccharide-based edible films can successfully reduce the migration of water, carbon dioxide, oxygen, aromatic compounds, lipids, and others in food products and lengthen the shelf-life of food products (Liu et al., 2019), however, their strength is low and their resistance to water is poor. They are mainly modified chemically. Chitosan is a biodegradable biopolymer with excellent antibacterial activity and structural properties, yet with worse mechanical and water resistance, which can be improved through chemical modification (Sanchez-Salvador et al., 2021). Compared with pure chitosan-based films, chitosan-based antibacterial and antioxidant films incorporating carvacrol-loaded modified halloysite nanotube due to electrostatic and hydrogen bonding interactions improved the mechanical properties and barrier properties (water vapor, oxygen, and light) of the composite films (Zhang et al., 2023). Graphene oxide was modified with carboxymethyl cellulose for the preparation of starch-chitosan films, when the content of modified graphene oxide is 0.01 wt%, the tensile strength, water resistance, and UV barrier properties of the composite films are obviously enhanced, meanwhile, the composite film changes from overflow antibacterial modes to contact antibacterial modes (Wu et al., 2023). Cellulose is often used as an edible film substrate material due to its hard molecular structure, biocompatibility, biodegradability, low toxicity and abundance, but cellulose films have poor flexibility and elongation. The mechanical properties of cellulose films can be substantially improved by adding plasticizers (Paudel et al., 2023). After the corn starch-based films were composited with alkyl ketene dimer, the low surface energy inherent in alkyl ketene dimer and the increase in surface roughness due to recrystallization led to a significant enhancement of the hydrophobicity of the composite films; moreover, owing to chemical cross-linking and intermolecular hydrogen bonding between them, the ductility of the composite films was improved as well (Duan et al., 2023).

2.2. *Interactions of substrate ingredients*

Pure protein based films have good mechanical strength, but poor water resistance and ductility; Pure polysaccharide based films have good barrier properties for oxygen, but have extremely strong water solubility; Usually, two or more substrate are used to improve the quality of the films through the interaction of substrate components. For example, chitosan is added to gelatin films, through hydrogen bonding, ion bonding, and other interactions, molecular crosslinking is strengthened to enhance its water resistance. At the same time, it can also be used as a plasticizer to increase its flexibility.

2.2.1. *Interactions between gelatin and chitosan*

In protein-polysaccharide composite films the most important parameters affecting the stability of the emulsion are the type and concentration of the polysaccharide and the pH of the composite (Liu et al., 2023), the main interaction between proteins and polysaccharides being Intermolecular and intramolecular hydrogen bonding interactions (Liu et al., 2023). Gelatin films have high tensile strength, but pure gelatin films have poor ductility and water resistance. Chitosan films are viscous solutions created by intermolecular and intramolecular hydrogen bonding in chitosan that are dried to produce films with superior gas barrier, broad-spectrum bacterial suppression, and good antioxidant properties. However, the shortage of water resistance, mechanical capabilities, and freshness retention properties in single chitosan films has hampered their widespread applicability. Therefore, the current research mainly focused on the preparation of composite films and property improvement. The interactions between gelatin and chitosan are electrostatic and intermolecular hydrogen bonding. This electrostatic interaction occurred mainly between the carboxyl group of gelatin and the amino group of chitosan, while hydrogen bonds were formed within and between the polymer chains of its carbonyl, hydroxyl and amino groups. The interactions between gelatin and chitosan have good compatibility, but which inhibits the physical gelation of gelatin (Qiao et al., 2017). The interactions between gelatin and chitosan can be affected by factors such as gelatin source, pH, concentration and temperature. The composition and intrinsic properties of gelatin will vary depending on the source of gelatin, and the interactions with chitosan will be different. When the emulsion pH is 4.5–6.5, it is beneficial to the electrostatic interaction and can promote the hydrogen bonding between gelatin and chitosan. The concentration of gelatin and chitosan determined the number of their reactive groups, functional groups and special structures, which affected their electrostatic interactions and hydrogen bonding, resulting in different substrate structures of gelatin-chitosan composite (Wang et al., 2021). Gelatin is a triple helix structure formed by the entanglement of three polypeptide chains after partial hydrolysis of collagen, with a large number of carboxyl and amino groups in the molecules (Yunoki et al., 2024); Chitosan is a natural cationic polysaccharide composed of a series of glucose molecules connected by 1.4 glycosidic bonds. Amino, hydroxyl, N-acetylamino groups on the molecular chain participate in the formation of intramolecular and intermolecular hydrogen bonds. Gelatin can interact with chitosan to form a large number of intermolecular hydrogen and ionic bonds (Acevedo et al., 2015). After electron beam irradiation of gelatin-chitosan composite films, there are interactions between them that change the chemical bonding in gelatin and the interactions between the polymer chains, such as hydrogen bonding and amide groups (BenBettaïeb et al., 2015). The spectra of gelatin-chitosan composite films showed bands corresponding to the different amide types in gelatin, indicating the presence of interactions between groups such as N–H, C═O and C–N in gelatin and chitosan (Wang et al., 2022). The interactions between gelatin and chitosan are mainly generated by hydrogen bonding between the carboxyl, amino and hydroxyl groups of gelatin and the amino and hydroxyl groups of chitosan, the interactions are dependent on the physical and chemical properties of gelatin, Whereas the main factors determining the physical properties and quality of gelatin are amino acid composition and molecular weight distribution (Gómez-Estaca et al., 2011). In addition, gelatin-chitosan composite films showed a significant increase in elongation at break over single component edible films (Handayasari et al., 2019). As shown in Fig. 2, Between gelatin and chitosan are mainly hydrogen bonding and electrostatic interactions, the polymerization network is dense, the ductility of the composite films, antibacterial properties and gas barrier properties significantly improved.

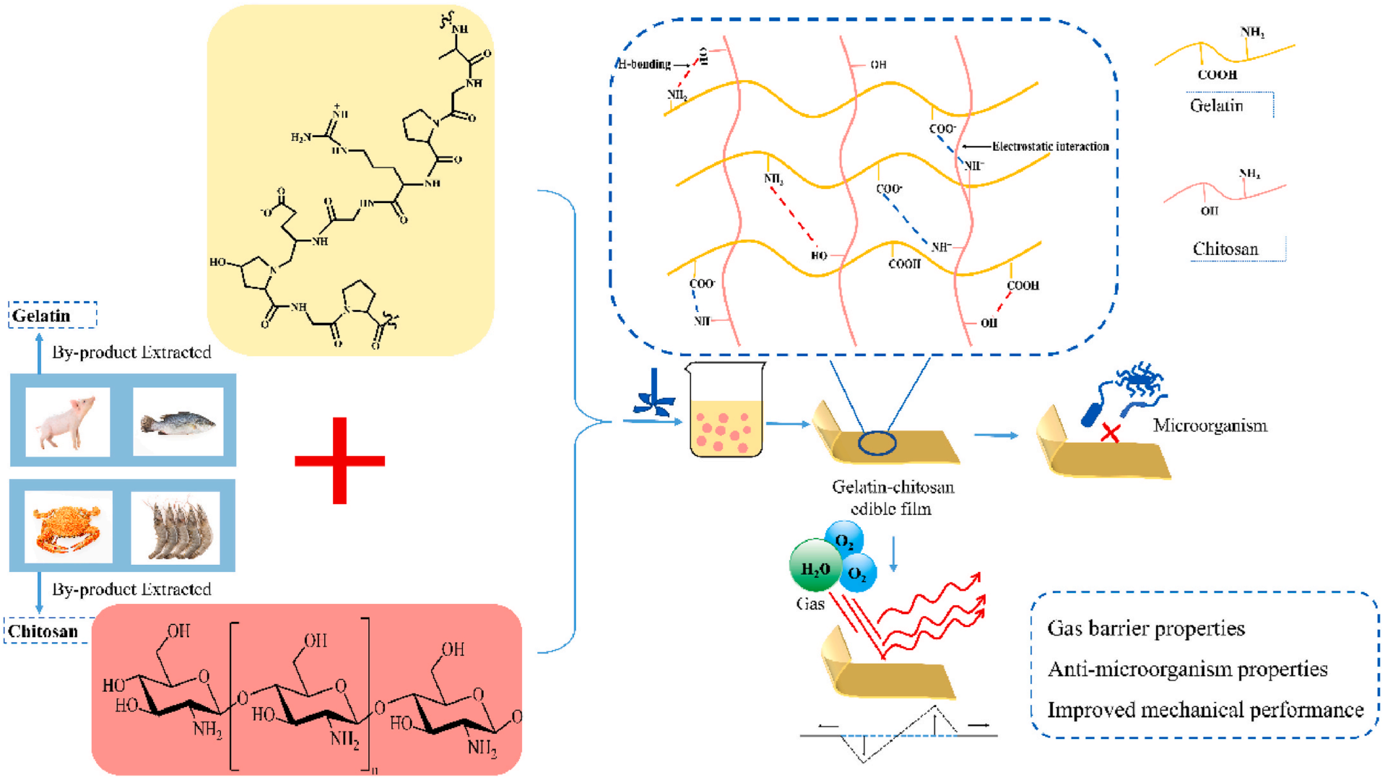

Fig. 2. Gelatin - chitosan edible films mechanism of interaction and functional properties.

2.2.2. *Interactions between gelatin and starch*

Starch-based edible films have the poor tensile strength, elongation at break and flexibility, so that they make it difficult to be applied in industrial production. Many studies have prepared gelatin-starch edible films and characterized their interaction mechanisms, physical and mechanical properties. Gelatin molecules contain hydroxyl, amino and carboxyl with high reactivity, which was added to starch-based films, and can change the starch molecule size and starch granule properties, thus improving the ductility and tensile strength of starch films. The interactions between gelatin and starch are mainly hydrogen bonding. The interaction between gelatin and starch particles is reflected in two aspects. On the one hand, cracks and wrinkles appear on the surface of starch particles, which increase with the proportion of gelatin in the substrates. This is due to the shrinkage of gelatin during the drying and film-forming process, as well as the incompatibility between gelatin and starch; on the other hand, as the proportion of gelatin increases, starch particles will aggregate together, affecting the relative interfacial tension between phases, leading to droplet conjugation (Zhang et al., 2024). In addition, the recrystallization of starch in oil in water lotion is mononuclear, gelatin can completely coat starch, and protein has surface activity, tends to migrate and coat the surface of starch microspheres, forming a gelatin shell (Yang et al., 2020). Higher concentrations of gelatin increase the water vapor permeability, water solubility, thickness and mechanical strength of gelatin-starch composite films, the higher the starch concentration, the greater the thickness and the better the mechanical properties of the composite films (Rosseto et al., 2019). Wang et al. (2021) analyzed that the dialdehyde starch crystals can be reacted with the amine groups of gelatin molecules and covalently crosslinked via C═N chemical bonds. In the starch gelatin mixture, gelatin forms a continuous triple helix network in which starch inclusions are dispersed, and the intermediate phase consists of straight-chain starch interacting with gelatin. The addition of starch improves the water resistance, transparency and thermal stability of the films (Wang et al., 2021).

2.2.3. *Interactions between starch with chitosan*

Owing to the inferior tensile strength, elongation at break and moisture resistance of starch-based films, it is common to add chitosan to them, which forms a complex vibration of hydrogen bonding between the –NH_2 of chitosan and the –OH of starch, thereby forming a molecular network that enhances the tensile strength and elongation at break of the starch-based films, aiming to achieve the purpose of the modification of the starch-based films (Alimi et al., 2023). The reactive functional groups on starch molecules can be combined with functional groups such as –NH_2, –OH, and N-acetyl groups on chitosan molecules in different ways to improve the mechanical and barrier properties of the composite films. The starch-starch interaction was caused by the formation of intramolecular and intermolecular networks in the film substrate by the generation of covalent bonds. This interaction was the main interaction mode of most hydrophilic polymer (Zheng et al., 2022). The interactions between starch and chitosan mainly occurred between the hydroxyl groups of starch and the amino groups of chitosan, and when chitosan was added, the hydrogen bonding between starch molecules becomes weaker as some of them form intermolecular hydrogen bonding with chitosan (Dang and Yoksan, 2015). In starch-chitosan solutions, hydrogen bonding interactions occur between the molecules, adding chitosan to starch films results in a decrease in starch films thickness, moisture permeability and solubility (BenBettaïeb et al., 2015). Adding chitosan to starch affects the mechanical properties and hydrophilicity of the composite films, and the chitosan-starch interaction depends on the functional groups of the used starch (Escamilla-García et al., 2017). Pasting and oxidizing starch can promote the interaction between starch and chitosan, in which pasting promotes the decomposition of starch intermolecular bonds and increases the hydrogen bonding interactions between starch hydroxyl groups and chitosan amino groups; starch oxidized forms a double aldehyde group, which interacts with the amino groups of chitosan (Horn et al., 2011). The water absorption of starch-chitosan composite films can be decreased by mixing chitosan with brown rice starch, and the higher the chitosan content, the stronger the tensile strength of the composite film.

The hydrogen bonding interaction between chitosan and starch enhances the thermal stability of the composite film (Hasan et al., 2020). As shown in Fig. 3, the interactions between starch and chitosan were mainly hydrogen and ionic bonding, forming intramolecular and intermolecular network structure. The starch-chitosan composite films can be used as an antioxidant and antibacterial barrier for food products to maintain the appearance, flavor and nutrition of food products, and effectively extend the shelf life of food products.

2.2.4. Interactions between other substrate ingredients

Several studies have also outlined the interactions between other substrate ingredients in edible films and characterized these films properties. There are hydrophobic interactions and hydrogen bonding between starch-protein-polyphenols, where starch-protein interactions may alter the surface properties of the film and enhance the hydrophobicity of its surface; protein-polyphenol interactions reduce free polyphenols, leading to a decrease in the release of phenolic compounds into water (Chollakup et al., 2020). Ternary complex emulsions were prepared from gelatin, high-methoxyl pectin and epigallocatechin gallate (EGCG), FTIR analysis showed that hydrogen bonding was the main non-covalent interaction between EGCG and gelatin-high-methoxyl pectin binary complexes (Huang et al., 2023). The egg white protein-κ-carrageenan composite films have strong film-forming ability and excellent mechanical properties in alkaline environment (Liu et al., 2022).

3. Mechanisms of interactions between edible film functional ingredients and edible film substrate ingredients

Edible films are green, non-toxic, biodegradable and have good packaging performance, but the edible films prepared from different substrates have deficiencies in the barrier, mechanical, and stability properties. For example, polysaccharide films have good gas barrier properties, but their water vapor permeability is high (Mouzakitis et al., 2022); protein films have good mechanical and gas barrier properties, but their moisture resistance is poor (Galus, 2018). In order to compensate for the deficiencies of the films in the above mentioned functions, they can be improved by adding modifiers. As shown in Table 1, hydrophobic modifiers, bioactive modifiers, nano-component modifiers and emulsifiers were used to be incorporated into edible films to interact with the edible film substrates significantly improve the functional properties of edible films.

3.1. Hydrophobic modifiers

Some researchers have added hydrophobic modifiers to edible films to analyze substrate ingredients and functional ingredients interactions, physical and mechanical properties, with simultaneous characterization for the preservation of the films in food products. Hydrophobic modification of edible films can effectively block the transfer of water in food products, and common hydrophobic modifying materials such as essential oils, palm oils, and natural waxes can effectively reduce their hydrophilicity when were added to bio-based edible films. The

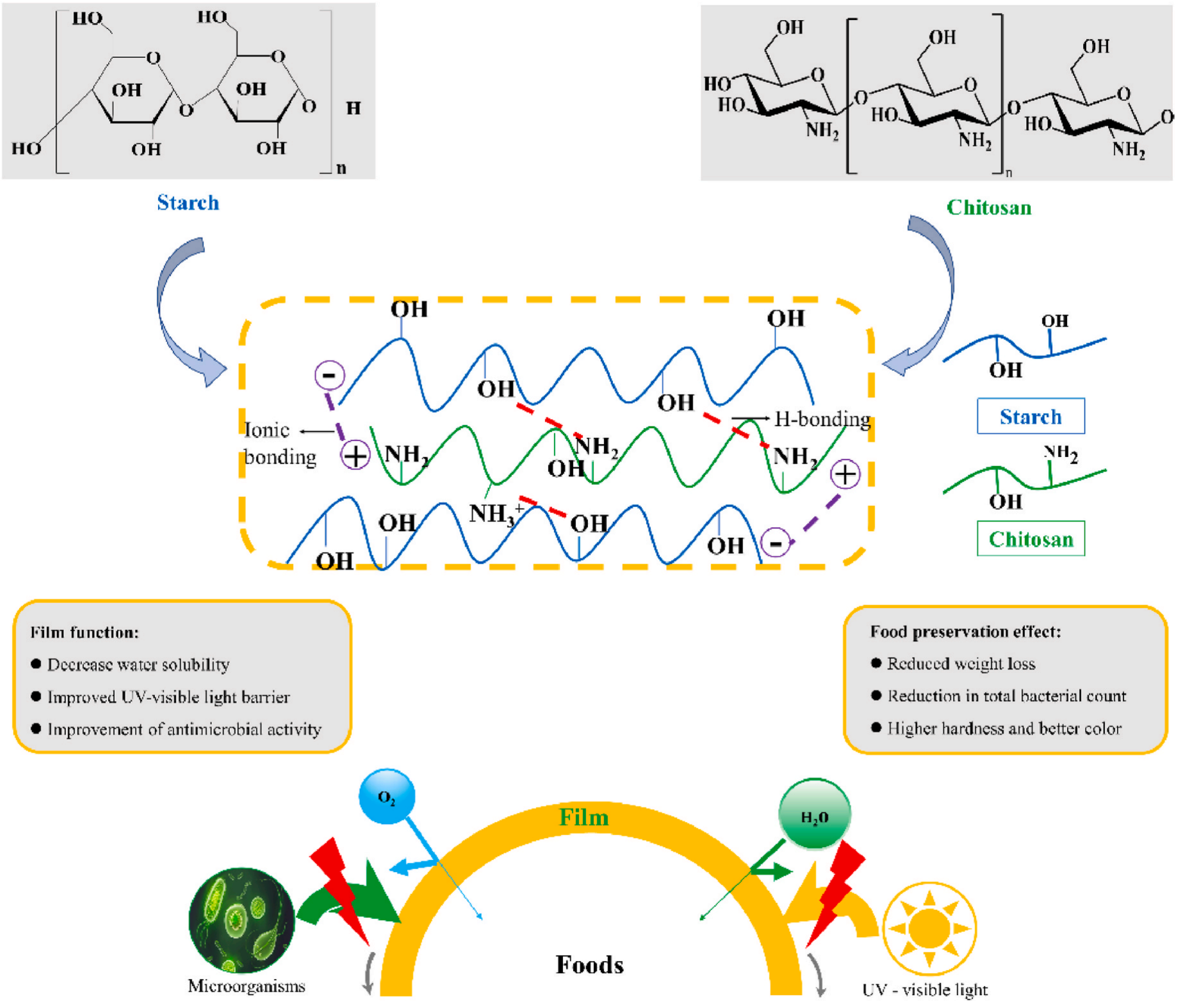

Fig. 3. Starch-chitosan edible films mechanism of interaction and functional properties.

Table 1
Improvement of films properties by different functional ingredients.

Substrate ingredients	Source category	Functional ingredients	Primary Findings
Polysaccharide	Polysaccharide	Essential oil	● Improved hydrophobicity (Vieira et al., 2019)
oxidized hydroxypropyl cassava starch	Polysaccharide	cinnamon essential oil	●Lower tensile strength ●Higher elongation at break (Zhou et al., 2021)
Gelatin-chitosan	Composite substrates	Garlic essential oil	●Form hydrophobic interactions (Wang et al., 2021)
Pullulan polysaccharide	Polysaccharide	Essential oil	●Hydrogen bonding interactions (Hassan, 2018)
Starch	Polysaccharide	Palm oil fatty acids	●Improved the water resistance (Homsaard et al., 2021)
Chitosan	Polysaccharide	Beeswax、Basil essential oil	●Resulted in low water vapor permeability ●Improved contact angle and stability (Sun et al., 2021)
Methylcellulose	Polysaccharide	Beeswax	●Improved moisture resistance (Navarro-Tarazaga et al., 2011)
Chitosan	Polysaccharide	Fruit extracts	●Enhanced its antioxidant properties (Dordevic et al., 2021)
Starch	Polysaccharide	Phenolic compounds	●Changed in mechanical properties of antioxidant starch films (Menzel et al., 2019)
Polysaccharide	Polysaccharide	Cellulose nanofibers	●Improved film tensile strength and elongation (Pritchard et al., 2022)
Gelatin	Protein	Cinnamon essential oil nanoliposomes	●Decreased tensile strength, water solubility, water content, and water vapor permeability (Wu et al., 2015)
Pregelatinized glutinous rice starch	Polysaccharide	Starch	●Its efficacy as an emulsifier is dependent on the pasting temperature and concentration (Yulianingsih and Gohtani, 2019)
Legume protein	Protein	Polysaccharide	●Protein emulsification properties are associated with protein composition, structure, molecular size, surface hydrophobicity, solubility, flexibility, and environmental variables (Sharif et al., 2018)

distribution of hydrophobic components in the substrate can take the form of micrometer, nanometer, and picking particles. Factors such as the type and content of hydrophobic modifier and the substrate composition of the edible films affect the hydrophobic modification.

3.1.1. *Essential oils*

Essential oils have antibacterial and antioxidant properties. Edible essential oils such as clove essential oil, lemon essential oil and oregano essential oil are non-toxic and non-hazardous to humans, it can be added to edible films to effectively improve their properties. Essential oils, as hydrophobic ingredients, do not interact intermolecularly with gelatin, but it will hinder the interaction of gelatine molecular chains. It was shown that by adding garlic essential oil to gelatin-chitosan edible films, garlic molecules interact with gelatin-chitosan molecules to form hydrophobic interactions, replacing the intermolecular hydrogen bonding between gelatin-chitosan molecules (Handayasari et al., 2019). Li et al., 2022 coated preserved fish meat with gelatin films and ginger essential oil-gelatin films respectively, the results showed that under the same conditions the ginger essential oil-gelatin coated group had significantly slower changes in fish weight loss rate, color, and other changes, the flavor was closer to that of fresh fish. The addition of essential oils to gelatin films enhanced the antibacterial and antioxidant properties of the films. Gelatin films with added ginger essential oil have more remarkable preservation of pork with lower loss of flavor (Li et al., 2022). However, essential oils were volatile compounds, which were usually highly lipophilic and volatile, and were prone to oxidative decomposition.

3.1.2. *Palm oil*

Palm oil is an inexpensive hydrophobic material that improves the water vapor barrier properties of films. High oleic palm oil is thermally and thermodynamically stable due to the use of food-grade emulsifiers such as lecithin and gelatin (Ricaurte et al., 2018). When palm oil was added to gelatin-based films, the amount of palm oil directly influenced the physical and molecular structure, as well as the thermal properties of the resulting gelatin films. The tensile strength, water vapor permeability, and moisture content of the films decreased as dosage rose, whereas the elongation at break of the films increased (Tongnuanchan et al., 2015). Composite films containing palm oil have higher sealing strength and efficiency compared to other hydrophobic ingredients (e.g. basil essential oil), Palm oil can reduce the strength and increase the flexibility of the film (Tongnuanchan et al., 2016). Palm oil is also effective for hydrophobic modification of starch-based films. Starch-based films have poor mechanical properties, gas barrier properties and high water vapor permeability. After the addition of carboxymethyl cellulose and palm oil fatty acids to starch-based films, it improved water resistance and significantly extended the shelf life of eggs (Homsaard et al., 2021).

3.1.3. *Beeswax*

Beeswax has high hydrophobicity and excellent moisture resistance and can be used to improve the water vapor barrier and tensile strength of edible films (Zheng et al., 2022). Beeswax, a natural fat secreted by beeswax glands, is a hydrophobic organic compound that is solid at room temperature and can form an emulsion with water under specific conditions. Incorporating beeswax and basil essential oil into chitosan emulsion, there was electrostatic interaction between beeswax and chitosan, resulting in a decrease in the water vapor permeability of the chitosan coating, increasing the contact angle and stability, with excellent compatibility between chitosan, beeswax, and basil essential oil (Sun et al., 2021). There was positive compatibility between beeswax and gelatin, with beeswax improved the hydrophobicity of the composite films (Cheng et al., 2021). In terms of applicability, the beeswax-containing films were useful in increasing plum shelf life and minimizing plum weight loss, with no effect on plum flavor (Navarro-Tarazaga et al., 2011).

3.2. *Bioactive modifiers*

3.2.1. *Natural extracts*

Natural extracts usually have excellent antioxidant and antibacterial properties, and the incorporation of natural extracts into edible films can enhance the antioxidant and antibacterial capacities of the films. The main natural extracts that can be used as antibacterial and antioxidant agents include tea polyphenols (Biao et al., 2019), grape pomace extract (Mugnaini et al., 2024), and honeysuckle leaf extract (Wang et al., 2023). Natural compounds derived from herbs, berries, or plant byproducts, such as rosemary, have been shown to boost the total phenolic content and anti-free radical activity of composite films, significantly delaying the oxidation of meat products. (Ganiari et al., 2017). Natural phenolic compounds can resist oxidation and inhibit microbial growth, and are widely used in protein based films. The hydroxyl groups in natural phenolic compounds interact with proteins, forming covalent cross-linking between polyphenols and protein molecules, reducing protein solubility and morphology, significantly reducing the water solubility and water vapor permeability of muscle fiber protein films (Nie et al., 2015). When polyphenols were added to edible films, they will interact with substrate ingredients in edible films, the interactions between polyphenols and substrates were oxidation reaction, hydrogen bonding, hydrophobicity, electrostatic and covalent interactions. The contact angle of the nanofibrous films increased and the hydrophobicity was significantly enhanced after the introduction of polyphenols because the strong hydrogen bonding between polyphenols and proteins can further lock the hydrophilic groups on the protein molecular chain to stabilize the substrate, which was conducive to blocking the water in the external environment and will not be damaged due to the decay and leakage of the food inside (Zhao et al., 2023).

3.3. Nanocomponent modifiers

Nanomaterials have good gas barrier, water vapor barrier and antibacterial activity and are suitable for preservation of fresh produce (Shi et al., 2018). The mechanical and physical properties of the films were affected by the addition of nanocomponent modifiers to edible films. Natural nanomaterials such as cellulose nanocrystals, cellulose nanoparticles, and corn alcohol soluble protein nanomaterials are widely used in the preparation of edible films. Cellulose nanocrystals can be used as physical cross-linking agents to bridge the gap between cellulose nanofiber-based edible films and extend the network of cellulose nanofibers; at the same time, cellulose nanofibers enhance the translational mobility of cellulose nanocrystals, which enables cellulose nanocrystals to increase the rigidity of the network without sacrificing the elongation and toughness of the films, significantly improving the tensile lightness and the elongation at break of the films (Pritchard et al., 2022). In Sargasso cellulose nanofiber-polyvinyl alcohol edible films, the chemical cross-linking between Sargasso cellulose nanofibers and polyvinyl alcohol consumes a large number of hydrophilic hydroxyl groups, which increases the water contact angle of the composite films and strengthens their water resistance, in addition, the composite films also have excellent thermal stability, light transmittance (Liu et al., 2022). Incorporation of cinnamon essential oil nanoliposomes into gelatin films decreased tensile strength, water solubility, water content and water vapor permeability, resulting in increased elongation at break, the composite films have a finer internal network and a more homogeneous surface structure in their cross-section (Wu et al., 2015). Surimi protein gels containing 1.0 g/100 g of calcium eggshell nanomaterials have a denser network structure with the best water retention capacity (Huang et al., 2021). In addition, nanomaterials with antibacterial nanomaterials have better barrier properties and structural integrity to inhibit the growth of spoilage and pathogenic microorganisms (Huang et al., 2021). Due to the hindrance of protein-protein interactions by lipid nanoparticles to the protein films, the tensile strength of the protein films is reduced. At the same time, the addition of lipid nanoparticles enhances the internal fluidity of the protein films and enhances its extensibility. Unlike ordinary lipids, lipid nanoparticles have a smaller particle size, which weakens their ability to hinder protein-protein interactions, and a larger specific surface area, which can effectively hinder the penetration of water vapor, thereby enhancing the water resistance of the films (Li et al., 2020). Cellulose nanocrystals can serve as physical crosslinking agents to bridge the gaps between cellulose nanofiber based edible films and expand the network of cellulose nanofibers; At the same time, cellulose nanofibers enhance the translational fluidity of cellulose nanocrystals, enabling them to improve the rigidity of the network without sacrificing the elongation and toughness of the film, greatly improving the tensile strength and fracture elongation of the film (Pritchard et al., 2022).

3.4. Emulsifiers

Emulsifiers form a protective film on the surface of the dispersed phase of the emulsion and increased stability of the edible films. Emulsifiers act as surfactants to increase the polarity of the lipid phase, promoting the adsorption of water molecules and water vapor mobility thereby significantly reducing the water vapor permeability of cocoa butter films (Bravin et al., 2004). The addition of emulsifiers with lower hydrophilic-lipophilic equilibrium values resulted in a smaller size and more uniform distribution of beeswax in the agar/maltodextrin-beeswax films substrate, resulting in a significant increase in the composite films tensile strength, elongation at break and water vapor barrier properties (Zhang et al., 2022). Pickering emulsions are emulsions stabilized by surface-active colloidal particles in lieu of surfactants, with high internal phase, irreversible interfacial adsorption and anti-agglomeration. A novel emulsifier corn alcohol soluble protein/carboxymethyl dextrin nanoparticles with stabilized picoline emulsion can be used as an effective delivery system for curcumin going to improve the environmental stability and bioavailability of curcumin (Meng et al., 2020). A novel edible coating films of water-beeswax (O/W) Pickering emulsion stabilized by cellulose nanofibers/carboxymethyl chitosan inhibited the growth of typical spoilage bacteria such as *Staphylococcus aureus* or *Escherichia coli*, and the coating films have good applications in preservation and freshness of berries (Xie et al., 2020).

4. Influence of edible film functional ingredients on food quality

Edible films not only extend the shelf life of food, but more importantly, it enables the food to maintain its original quality during the shelf life. Food quality encompasses any additional attributes that impact a product’s perceived value by customers, including attributes that are detrimental like deterioration, discoloration, and odor; it also covers attributes that are beneficial like color, flavor, texture, aroma, and processing techniques (Li et al., 2021). Edible films have functions such as water vapor barrier, gas barrier, microorganic barrier, etc. The barrier effect can maintain the quality of food in many ways. As shown in Fig. 4., The application of functional edible film ingredients and their effects on food quality.

4.1. Edible films as water vapor barriers for food quality retention

Edible films act as water vapor barriers to retain water in food by inhibiting the evaporation of water vapor from the food surface, conferring better color and flavor. It has been reported that the water retention of starch-based edible films can be improved by preparing nanocomposite films by coating lipid nanolayers on starch-based films (Slavutsky and Bertuzzi, 2016). The new cellulose nanofiber-corn stover core nanocomposite films have significantly improved water vapor barrier compared to traditional plastic packaging, while the composite films also have excellent tensile strength and UV-blocking ability (Liu et al., 2023). However, some composite edible films, due to the addition of functional ingredients with irritating odor, will affect the flavor of the food, limiting its direct application in food products. The chitosan-lemon essential oil coating had good water vapor barrier and antifungal properties, the content of key aroma compounds of strawberries treated with the chitosan-lemon essential oil coating was significantly reduced during storage, which could be attributed to the masking effect of the lemon essential oil aroma compounds, but the composite edible coating films significantly reduced the flavor of the strawberries (Vargas et al., 2006).

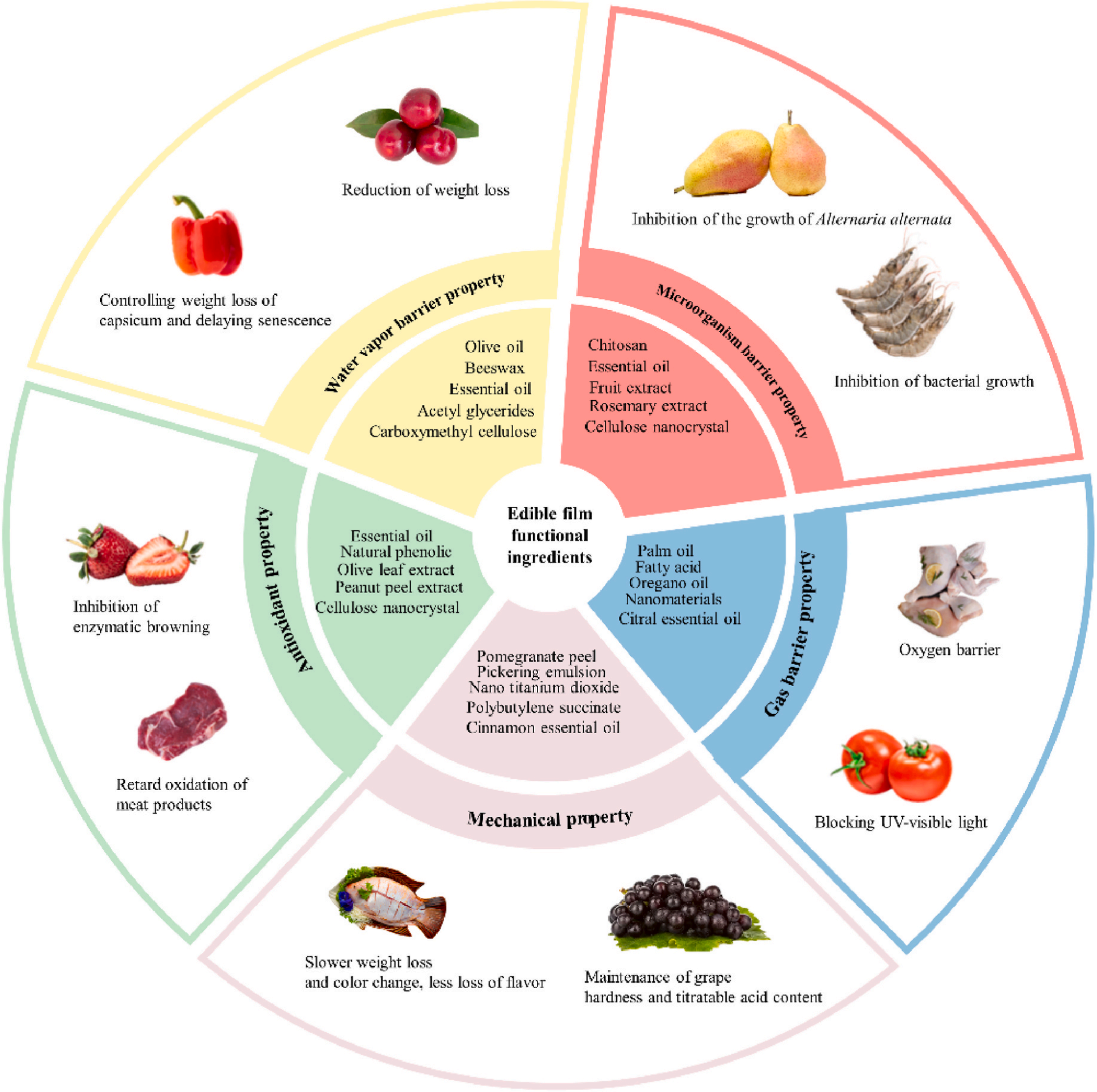

Fig. 4. Application of functional ingredients of edible film on food quality.

4.2. *Edible films as microorganisms barriers for food quality retention*

When used for food preservation, antibacterial edible films can act as a microorganic barrier to inhibit the growth of microorganisms in food and prevent it from spoilage, thus maintaining its original flavor and taste. Fruits, vegetables and meat products may be contaminated by various spoilage and pathogenic microorganisms during transport, storage and processing. Selecting modified sweet potato starch and cumin essential oil composite edible films for pear preservation can obviously reduce pear rot caused by *Alternaria*, conducive to the pear to maintain its original flavor, color and texture (Oyom et al., 2022). Oregano essential oil acted as a fungicide to inhibit the contamination of tomatoes with fungi. Addition of thyme oil and trans-cinnamaldehyde to soybean or whey isolate protein coatings at different concentrations was efficient in suppressing bacterial growth in pre-cooked shrimp, but the addition of thyme oil and trans-cinnamaldehyde affected the flavor of shrimp (Ouattara et al., 2001).

4.3. *Edible films as oxygen barriers for food quality retention*

The effectiveness of edible films on food preservation also depended on its barrier properties to oxygen, carbon dioxide. On the one hand, it can significantly inhibit the climb of respiration of fruits and vegetables to minimize the weight loss of fruits. On the other hand, the films have good stomatal density, which can effectively control the gas transfer and maintain the low-oxygen environment within the food, thus maintaining the quality and flavor of the food and prolonging its shelf-life (Wantat et al., 2022). Addition of grape juice to corn starch-based edible films effectively blocked the entry of oxygen, and packaging of chicken breasts with this composite films prolonged the shelf-life and preserved the flavor and taste of chicken breasts (Yıldırım-Yalçın et al., 2021). It was noteworthy that some of the edible films have excellent antioxidant capacity, which can effectively delay the oxidative chain reaction of food and inhibit food spoilage. Ovalbumin-inulin-pomegranate seed oil gel significantly improved the stability of pomegranate seed oil and inhibited lipid oxidation during storage (Li et al., 2021). Oxidation reaction of food will cause discoloration, rancidity and flavor change, adding thyme extract to chitosan-starch composite films makes the composite films have outstanding antioxidant activity, and thyme extract has a lower aroma intensity compared with other essential oils, which has little effect on the flavor of food (Talón et al., 2017).

4.4. Edible films as UV barriers for food quality retention

Ultraviolet radiation can have dangerous effects on food, such as producing free radicals, damaging nutrients in food, and changing color (Abdel Aziz and Salama, 2021). After adding aloe vera and zinc oxide nanoparticles to alginate based edible films, the UV barrier performance was optimized. Greatly extending the shelf life of tomato fruits, up to 16 days, without any defects (Abdel Aziz and Salama, 2022). Starch based films have received widespread attention due to their excellent biocompatibility and biodegradability; However, its UV barrier and antibacterial properties are poor. Yuan et al. prepared a hydrophobic, antibacterial, and UV resistant DS/DDA film by reacting benzoxazine with 1,12-dodecane diamine as the amine source (BOZ-DDA) with dialdehyde starch (DS) via Schiff base reaction. The Schiff base structure, amino acid residues, and Oxazine rings and benzene rings can provide antioxidant and UV blocking properties, significantly reducing the spoilage rate of mangoes and grapes and prolonging their consumption time (Yuan et al., 2024).

5. Outlook

Although edible films are highly favored in the food packaging industry, there are still many aspects that need to be modified. Firstly, adding functional ingredients can only optimize the properties of some films, not all properties, some functional ingredients can enhance the properties of some films while degrading other properties. Secondly, the inherent properties of some functional ingredients may affect food quality. In addition, another challenge for the application of edible films is how to enhance their hydrophobicity. Modifying the internal structure of edible films through physical, chemical, and biological methods to enhance the loading capacity of matrices for hydrophobic components is an important direction for future modification of edible films. Meanwhile, the current global demand for fresh food, meat, fruits and vegetables is growing, all countries are advocating a low-carbon green circular economy development system, the biological by-products of the deep processing, biodegradable materials as edible film substrates have gradually become an important development trend. Hence, it is possible in the future to integrate the advantages of edible films and smart films into one packaging system, by intensively investigating the interaction mechanisms of substrate ingredients to enhance the loading capacity of the films In order to achieve the goal of extending the shelf-life of food and monitoring its freshness without affecting the color, flavor, and other properties of the food, it is also necessary to take into account choosing suitable functional ingredients for the production of edible films. This will allow us to characterize and perfect the properties of edible films in various aspects, such as antibacterial properties, antioxidant properties, and water resistance.

CRediT authorship contribution statement

Xin Li: Conceptualization, Investigation, Writing – review & editing, Funding acquisition. **Fenghong Li:** Investigation, Resources, Writing – original draft. **Xuan Zhang:** Visualization, Investigation. **Weiyuan Tang:** Supervision. **Mingzheng Huang:** Supervision. **Qun Huang:** Supervision, Funding acquisition. **Zongcai Tu:** Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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