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Review

Shellac-based films/coatings: Progress, applications and future trends in the field of food packaging

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ABSTRACT

As a natural biopolymer from the secretion of insect *Laccifer Lacca*, shellac shows excellent film-forming ability and safety, making it an attractive material to replace synthetic materials for food packaging. On the basis of an introduction to the structure and properties of shellac, the information on single shellac films/coatings and composite films/coatings of shellac and other bio-based materials such as proteins, polysaccharides, and lipids, including the effects of adding antimicrobial agents (i.e., natural antimicrobials, synthetic antimicrobials, and metal oxide nanoparticles) on films/coatings, was comprehensively summarized. Besides, the current application status of shellac-based films/coatings as preservation packaging for poultry products, fruits, vegetables and other food products was systematically documented. Finally, the future research directions of shellac-based films/coatings such as optimizing shellac concentrations, conducting toxicological evaluation and reducing production costs were discussed. This paper will provide guidance for a systematic understanding of the research advances on shellac-based films/coatings and possible future directions.

1. Introduction

Nowadays, food packaging has undergone unprecedented development with consumers' preference for food convenience, which not only facilitates food transportation and conveys information (production date, shelf life, precautions, etc.), but also prevents negative effects of surrounding factors on food and thus extends its shelf life (Phan The, Debeaufort, Luu & Voilley, 2008). Currently, petroleum-based plastics occupy a major position in the packaging market due to their low price and excellent barrier properties, heat sealing properties as well as mechanical properties. However, these materials are usually difficult to biodegrade and thus have a negative impact on the environment (Ribeiro et al., 2024). In recent years, as the interests of consumers in environmental protection and healthy food have increased, biodegradable packaging has been extensively studied as a promising alternative to traditional petroleum-based packaging, which not only supports food quality and safety, but also reduces the risk of irreversible environmental contamination from petroleum-based plastics (Sharma, Chaudhary & Kumar, 2019). So far, a variety of biodegradable packaging has been found to own many excellent characteristics such as reducing weight loss, preventing enzymatic/non-enzymatic browning and preventing hygroscopicity of low-moisture foods, and has been widely used for aquatic products, livestock products, nuts, fruits and vegetables (Chitravathi, Chauhan & Raju, 2016; Dong, Dai, Wang, Ma & Li, 2024; Li, Wang & Ye, 2022; Zhang et al., 2022; Zhou et al., 2021).

Depending on the differences in production methods, biodegradable packaging can be categorized into films and coatings. A thin layer formed by spraying, dipping or brushing directly onto the surface of food in liquid form is defined as coating, while film is defined as a thin material layer obtained in advance by various methods (e.g., extrusion and solvent casting) that is subsequently used to encase foodstuffs (Milani & Nemati, 2022; Ribeiro et al., 2024; Suhag, Kumar, Petkoska &

Abbreviations: Full name, Abbreviations; Generally recognized as safe, GRAS; Food and Drug Administration, FDA; European Union, EU; Polyethylene glycol, PEG; 2-hydroxyethyl methacrylate, HEMA; 2-ethylhexyl acrylate, EHA; 1,4-butanediol diacrylate, BDDA; Water vapor permeability, WVP; Elongation at break, EB; Tensile strength, TS; Soybean isolate protein, SPI; Ultraviolet, UV; Konjac glucomannan, KGM; Hydroxypropyl methylcellulose, HPMC; Cellulose acetate phthalate, CAP; Cellulose nanofibers, CNF; Chitosan porous microspheres, CSPM; Carboxymethyl cellulose, CMC; *Escherichia coli*, *E. coli*; *Staphylococcus aureus*, *S. aureus*; Tannic acid, TA; Potassium sorbate, PS; Sodium benzoate, SB; Sodium propionate, SP; Carboxymethyl chitosan, CMCS; Nanoparticles, NPs; Volatile basic nitrogen, TVB-N; Modified atmospheric packaging, MAP; Total viable count, TVC; Malonaldehyde, MDA; Thiobarbituric acid reactive substances, TBARS.

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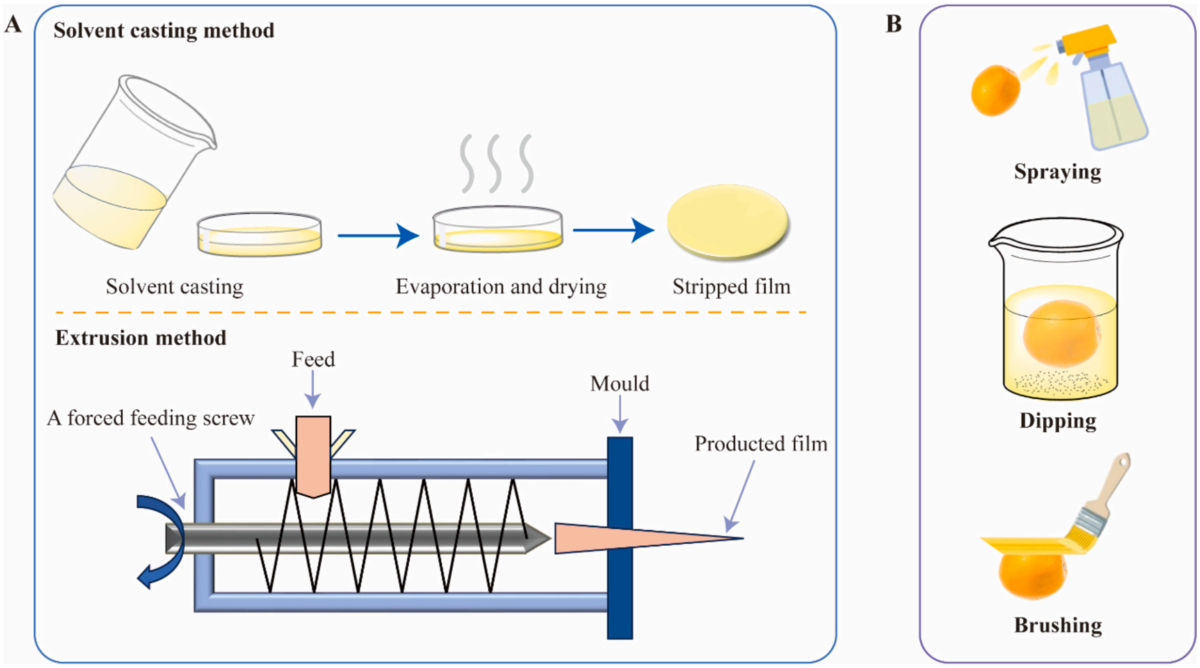

Fig. 1. Preparation methods for biodegradable (A) films and (B) coatings.

Upadhyay, 2020). The production methods of films/coatings are summarized in Fig. 1. Regardless of the production methods, films/coatings are generally in contact with food and sometimes consumed together with food (Guimarães, Abrunhosa, Pastrana & Cerqueira, 2018), which requires matrix materials used for film or coating production to comply with the generally recognized as safe (GRAS) and non-toxic criteria (Priya, Thirunavookarasu & Chidanand, 2023).

Proteins, polysaccharides, lipids and other materials from animal, plant and microorganism sources can comply with the above criteria well, and therefore have the potential to be used as substrates for food-grade films/coatings (Mohamed, Mohamed & el Mohamed, 2020). Shellac, a lipid extracted from the secretion of the insect *Laccifer Lacca*, has high hydrophobicity and glossy properties (Lu et al., 2018). Besides, shellac itself can form a film with the advantages of low permeability, barrier properties and good adhesion to various substrates, which endows it with potential to be used as a matrix material of biodegradable films or coatings for food packaging purposes (Bar & Bianco-Peled, 2021). However, it is well known that the mechanical and physicochemical properties of shellac films/coatings deteriorate over time due to the occurrence of self-polymerization induced by the highly reactive groups of shellac, limiting their application as food packaging for an extended period (Ahuja & Rastogi, 2023; Zhang et al., 2022). Therefore, in order to expand the application and precisely control the properties of shellac as a matrix material of biodegradable films/coatings, the application of some modification methods (addition of plasticizers and/or other biopolymer, electron beams, ultraviolet radiation, etc.) for shellac are necessary (Ahuja & Rastogi, 2023). Meanwhile, a number of bioactive substances with antimicrobial properties can also be added to shellac-based films/coatings, facilitating to reduce the food spoilage caused by microorganisms during the storage period (Ahuja & Rastogi, 2023; Khorram & Ramezanian, 2021).

In recent papers, the origin, structure and physicochemical properties of shellac, multiple delivery systems based on shellac and the brief overview on the industrial applications of shellac have been reviewed (Thombare et al., 2022; Yuan et al., 2021; Yuan et al., 2021). To the best of our knowledge, there is currently no detailed review on the suitability of shellac as a matrix material of films/coatings. Therefore, in this review article, after a brief presentation on the structure and properties related to film formation of shellac, various films/coatings based on single shellac or combinations of shellac and other bio-based materials and the effects of adding antimicrobial components on these films/coating are highlighted. Furthermore, the current application of shellac-based films/coatings in food preservation is summarized. Finally, the future research prospects of shellac-based films/coating are depicted. This article will provide support for a systematic understanding of shellac-based films/coatings and their innovative development in the future.

2. Chemical structure and properties of shellac

2.1. Chemical structure

Shellac, a natural resin purified from the secretion of insect *Laccifer Lacca*, is mainly produced in India, Thailand, Bangladesh and China (Thombare et al., 2022; Yuan, He, Dong, et al., 2021). After feeding on and digesting tree sap, insects parasitize certain plants and leave secretions on the branches. These secretions are then collected and processed to form shellac (Yang et al., 2022). From the perspective of structural composition, shellac is comprised of a complex mixture containing hydroxy fatty acids (aleuritic acid, threoaleuritic acid, butolic acid, etc.) and sesquiterpene acids (jalaric acid, laccijalaric acid, shellolic acid, etc.), which can be separated into 30 % monoesters (soft resin) and 70 % polyesters (hard resin) (Lu et al., 2018). Typically, a unit of shellac (Fig. 2A) should have three ester groups, a free carboxyl group, a partially free and partially bound aldehyde and five hydroxyl groups (Thombare et al., 2022). Due to the existence of carboxyl groups in the molecular structure that do not participate in the esterification reaction of cyclic terpenoic acid, the protonation of these carboxyl groups makes shellac weakly acidic and thus difficult to be dissolved in acidic solutions (Yuan, He, Xue, et al., 2021).

2.2. Properties related to formation of films/coatings

As a natural material of animal origin, the safety of shellac is guaranteed. In addition, the unique structure endows shellac with attractive properties including solubility in alcohol or alkaline solutions, amphiphilicity and easily modified characteristic (Fig. 2B), establishing the basis for its application as food packaging.

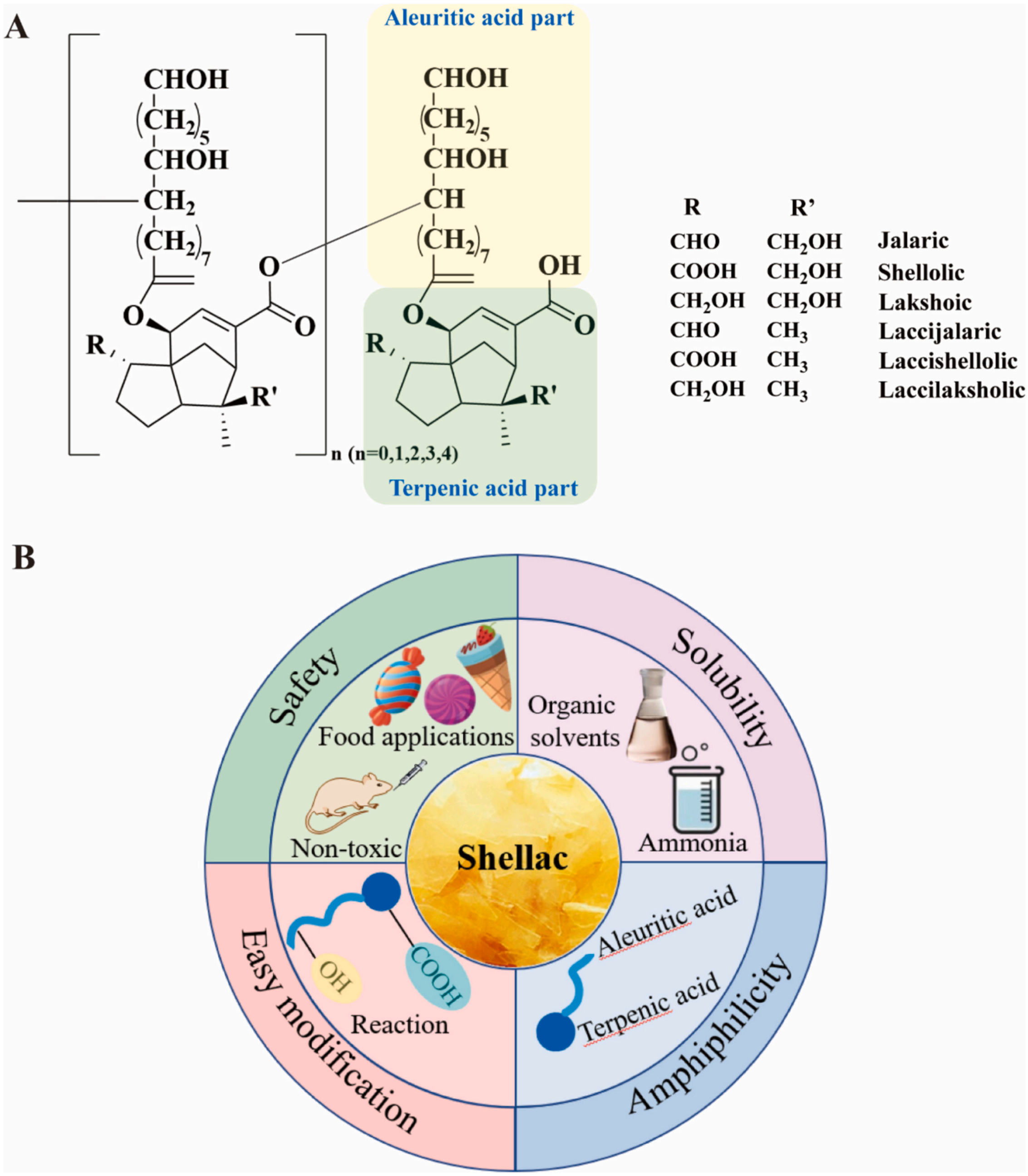

Fig. 2. (A)The structure unit of shellac; (B) the properties of shellac related to formation of films/coatings.

2.2.1. *Safety*

Shellac has been generally recognized as safe (GRAS) polymer by the Food and Drug Administration (FDA) and has also been permitted by the European Union (EU) as a food additive (E409) (Coelho, Nanabala, Ménager, Commereuc & Verney, 2012). In the food industry, shellac has been used as a coating to maintain the glossy appearance of candies and as a vapor barrier inside ice cream cones (Musa, Ulaiwi & Al-Hajo, 2011). Besides, in a chronic toxicity test of 180 days for Wistar rats that were orally fed feedstuff mixed with 5000 ppm of shellac, the rats did not show significant toxic reactions, which demonstrated the non-toxicity of shellac (Srivastava & Thombare, 2017). The researchers conducted cytotoxicity experiments on seven sesquiterpenes and six sesquiterpenoid esters derived from the hydrolysis of shellac, and found that none of the compounds exhibited any inhibitory effects on cell growth, thereby confirming the non-toxic and non-hazardous nature of shellac hydrolysates (Lu et al., 2014; Lu et al., 2018). As a result, it is reasonable to believe that shellac is an excellent alternative to potentially harmful materials and thus has the potential to become a safe matrix material for films/coatings.

2.2.2. *Solubility*

Similar to most natural resins, shellac is insoluble in water and only soluble in organic solvents such as methanol as well as ethanol, and alkaline solutions (Ahuja & Rastogi, 2023). Therefore, alcohol or alkaline solutions are often used as solvents to prepare precursor solution of shellac films/coatings. Although highly hydrophobic shellac films/coatings can be easily prepared by continuously adding an alcohol solution to water and then evaporating in a vacuum condition, the shellac exhibits significant hardening due to continuous polymerization. In contrast, shellac-based films/coatings obtained from an alkaline medium such as ammonia solutions show no or less hardening during subsequent storage (Farag & Leopold, 2009). This is because the carboxyl groups of shellac react with ammonia when dissolved in ammonia water and form dense contacts between the ions during drying, which contributes to the formation of smooth and tough shellac films/coatings and ensures their stability during long-term storage (Strich et al., 2023). However, this process is accompanied by a decrease in hydrophobicity of shellac. Therefore, it is obvious that the solvent is a crucial factor affecting the production and performance of shellac-based films/coatings, and it is possible to fabricate suitable shellac-based films/coatings by tuning the solvents based on the anticipated characteristics of the final product as well as the actual results observed in experiments.

2.2.3. Amphiphilicity

Shellac is a biopolymer consisting of hydroxy fatty acids and cyclic terpenes (Strich et al., 2023). Aleuritic acids are long-chain hydroxy fatty acids in the shellac skeleton that impart hydrophobic properties to shellac. Additionally, cyclic terpene acids contribute to the hydrophilicity of shellac (Ahuja & Rastogi, 2023). Therefore, in terms of structural composition, shellac is considered to be amphiphilic. However, it is worth noting that despite the presence of hydrophilic groups, previous study has also suggested that shellac is significantly more soluble in medium and strong hydrogen-bonded solvents than weak hydrogen-bonded solvents (insoluble), which indicates that shellac is more hydrophobic than hydrophilic (Banerjee, Srivastava & Kumar, 1982). The affinity of the matrix material for water usually affects the physicochemical properties of the final films/coatings. While both hydrophilic and hydrophobic materials can be used to prepare films and coatings, the removal of solvents from the hydrophobic component is more rapid (Ahmad, Leo, Ahmad & Ramli, 2015). Besides, films/coatings are expected to have good barrier properties against water vapor. Hence, the more hydrophobic shellac can exhibit better results in preventing water transfer than more hydrophilic materials such as polysaccharides and proteins.

2.2.4. Easy modification

There are many highly reactive groups in the structure of shellac, which can react with each other through hydrogen bonding or electrostatic interactions, leading to undesirable consequences. These unavoidable phenomena are known as self-esterification or self-polymerization and have become the unignorable problem limiting the application of shellac in different scenes (Ahuja & Rastogi, 2023). Accordingly, many studies have been conducted to modify shellac by increasing the consumption of free reactive groups in order to prevent its aging and thus make it more durable and stable, thereby giving it greater potential as a film/coating-forming material.

Presently, protecting carboxyl groups to inhibit the self-polymerization of shellac is a common method used to prevent its aging. Polyethylene glycol (PEG) as a plasticizer was found to delay the self-polymerization of shellac (Luangtana-Anan et al., 2007). The reason was that the carboxyl groups of shellac and the hydroxyl groups of PEG could form hydrogen bonds, and the consumption of free carboxyl groups contributed to inhibiting the self-polymerization of shellac. Moreover, the molecular weight (or chain length) of the plasticizers was the key factors affecting the ability to protect the active sites and thus the stability of shellac (Luangtana-Anan, Nunthanid & Limmatvapirat, 2010). Compared with the longer chain length of PEG 4000 and the insufficient chain length of PEG 200, PEG 400 with a suitable chain length could destroy the self-polymerization of shellac and did not penetrate into the shellac network at the same time, thus delaying the aging of shellac more effectively (Khairuddin Pramono, Utomo, Wulandari, Zahrotul & Clegg, 2016a). Heating time was also an important factor affecting the stability of shellac for shellac plasticized by the plasticizers with moderate molecular weight. After being heated at 125 °C for 30 min, the PEG 400 plasticized shellac system exhibited less insoluble solids compared to the PEG 600–shellac system, representing a better plasticizing effect that was beneficial for the stability of shellac. However, prolonged heating for more than 90 min resulted in superior plasticization of shellac by PEG 600 (Khairuddin Pramono, Utomo, Wulandari, Zahrotul & Clegg, 2016b). Furthermore, hydrolysis of shellac through alkali treatment, such as calcium phosphate, before the formation of films and coatings, also could enhance the stability of shellac by combining the carboxyl groups with the amine groups, which was also proved to be safe for clinical studies through cytotoxicity experiment (Lim, 2020).

Although relatively few studies have been conducted on the modification of shellac utilizing the method of binding hydroxyl groups, previous studies have shown that the emergence of self-polymerization of shellac can also be reduced by consumption of free hydroxyl groups. Higher concentrations of gelatin (≥30 %) and succinic anhydride enabled shellac to exhibit good stability by consuming free hydroxyl groups, which delayed the self-polymerization of shellac (Limmatvapirat et al., 2008; Soradech, Nunthanid, Limmatvapirat & Luangtana-anan, 2017). Various acrylic monomers with different functional groups, such as 2-hydroxyethyl methacrylate (HEMA), 2-ethylhexyl acrylate (EHA) and 1,4-butanediol diacrylate (BDDA), could be used to react with the free hydroxyl groups of shellac by grafting, reducing the occurrence of self-polymerization (Ghoshal, Khan, Khan, Gul-E-Noor & Chowdhury, 2010). Besides, *t*-butylacetoacetate had also been shown to reduce the degree of polymerization of shellac by cross-linking with the hydroxyl groups of shellac, and the solubility of the modified shellac in some solvents ($CHCl_3$, glycol monomethyl ether, methyl amyl ketone, etc.) was improved (Otto & Trumbo, 2010), showing an increased range of available solvents for modified shellac.

In addition, a new modifier, Jeffamine®, was found to improve the stability of shellac through the formation of amide bonds and acid-base interactions, and the results showed that the use of the new modifier maintained the solubility, mechanical properties and thermal stability of shellac in ethanol during storage periods of 18 months (Bar & Bianco-Peled, 2020).

3. Shellac-based films/coatings

3.1. Single shellac films/coatings

Due to excellent film-forming properties, environmental friendliness and biodegradability of shellac, great efforts have been devoted to the development of shellac films/coatings for a wide variety of applications. However, mechanical brittleness caused by the weak interaction forces between natural polymer molecules limits the ultimate application of shellac films/coatings (Soradech, Limatvapirat & Luangtana-anan, 2013). Therefore, it is crucial to overcome brittleness and to maximize the mechanical performance of shellac films/coatings by suitable approaches during the film-forming process.

The addition of salts was shown to improve the mechanical performance of the shellac film. The addition of calcium phosphate (10 %) increased the bending stress of the film by 20 % and the surface hardness efficiency from 5B to 6B compared to the pure shellac film. This was attributed to the increased hydrogen-bonding interactions between shellac and calcium phosphate (Lim, 2020). Adding plasticizers of a suitable concentration to the shellac film could also improve its mechanical properties. Compared to the un-plasticized shellac film, the shellac film with PEG 400 showed a slight decrease in stress and an increase in strain. This was attributed to the fact that the addition of PEG 400 reduced the intermolecular interactions and increased the mobility of polymer chains. Additionally, there was a higher water vapor permeability (WVP) coefficient after plasticizing (Luangtana-Anan et al., 2010). Altogether, these changes provided a good basis for the subsequent storage process. The addition of a new modifier, Jeffamine®, which combined the effects of salts and plasticizers, significantly improved the puncture strength and elongation at break (EB) of the shellac films. When the addition of the modifier was at 20 %, the shellac film exhibited maximum EB while keeping the relatively high puncture

Fig. 3. Films/coatings formed by compounding shellac with other bio-based materials.

Table 1
Overview of the properties of shellac-based composite films.

Composite film solution formulation	Other additives	Water vapor permeability (g•m)/(m^2•h•Pa) × 10^{-8}	Mechanical properties		Water contact angle (°)	References
			Tensile strength (MPa)	Elongation at break (%)		
Shellac (2 %, w/v) and zein (2 %, *w/v*), 1:1 (*v/v*)	Tributyl citrate and oleic acid	40.5 ± 1.5	0.725 ± 0.021	0.642 ± 0.013	33.92 ± 1.55 (0 s) 19.19 ± 0.93 (60 s)	Han et al. (2023)
Shellac (6 %, *w/w*) and gelatin (6 %, w/w), 1:1 (*w/w*)		9.46 ± 0.46			68.55 ± 0.57	Soradech et al. (2012)
Shellac (6 %, w/w) and gelatin (6 %, w/w), 3:2 (w/w)	Polyethylene glycol 400	6.55 ± 1.54				Soradech et al. (2013)
Shellac and casein, 1:10 (w/w)		About 4.8	About 2.8			Wang, Sun, et al. (2022)
Shellac (3.33 %) and soybean protein isolate (3.33 %), 4.8:1 (w/w)	Glycerol	3.2319	5.75 ± 0.23	85.69 ± 7.35	About 76	Zhang et al. (2020)
Shellac and pullulan, 2:3 (w/w)	Glycerol	149 ± 2	About 8	50.92	48.23 ± 2.7	Tang et al. (2025)
Shellac (4 %, w/w) and pectin (4 %, w/w), 1:1 (w/w)	Polyethylene glycol 400	22.1 ± 6.8 (0 d) 17.5 ± 3.3 (90 d)	About 27.5 (0 d) About 21.5 (90 d)	About 7.5 (0 d) About 7 (90 d)		Luangtana-anan et al. (2017)
Shellac (40 %db), pea starch and guar gum	stearic acid and Tween-20	44.89 ± 5.99	16.166 ± 2.158	25.953 ± 2.071		Saberi et al. (2017)
Shellac (0.6 %, w/w), cellulose nanocrystals (3.52 %, w/w), sodium alginate (1.44 %, w/w) and carrageenan (1.56 %, w/w)	Glycerol		18.93	15.7		Zhang et al. (2022)
Shellac and hydroxypropyl methylcellulose (1:100, w/w)	Lauric acid	About 3.24	About 62	About 4		Byun, Ward, and Whiteside (2012)
Shellac (5 %, w/w) and hydroxypropyl methylcellulose (95 %, w/w)	Glycerol, graphene oxide and titanium dioxide nanoparticles, 1:1 (w/w)		50.16 ± 1.68		74	Tohamy et al. (2024)
Shellac (3 %, w/w), carvacrol (6 %, w/w) and cellulose acetate phthalate		About 1.36	37.9	3.1		Dong et al. (2024)

strength (Pekerman, Yom-Tov, Bar & Bianco-Peled, 2024).

In addition to the physical addition of the above-mentioned modifiers (calcium phosphate, PEG 400 and Jeffamine®), the chemical grafting of acrylic monomers has been demonstrated to enhance the mechanical properties of shellac films. After gamma ray-assisted grafting, the tensile strength (TS) and EB of the shellac films treated with three acrylic monomers of different functionalities (i.e., EHA, BDDA and HEMA) were improved. This might be attributed to the denser network structure of the shellac due to the synergistic effect of gamma radiation and grafting of acrylic monomers. Besides, it was attractive that the HEMA-treated films showed better biodegradability among the films grafted with the above three components (Ghoshal et al., 2010).

3.2. Shellac-based composite films/coatings

The performance of films/coatings always depends on the physicochemical properties of matrix materials (Guimarães et al., 2018). In order to meet the demands for biodegradability and environmental protection, proteins, lipids, and polysaccharides derived from natural sources such as animals, plants, and algae have garnered significant attention, which have been demonstrated to be effective in film and coating formation applications (Ribeiro et al., 2024). Polysaccharides and proteins provide structure stability to films/coatings, while lipids contribute to the water vapor barrier of films/coatings. Considering that composite films/coatings fabricated from different materials can usually overcome the shortcomings of the single material-based films/coatings and endow them with improved properties (Soradech, Nunthanid, Limmatvapirat & Luangtana-anan, 2012), various films/coatings based on combinations of other bio-based materials and shellac have been developed (Fig. 3), and their properties have been summarized in Table 1.

3.2.1. Composite films/coatings based on shellac and proteins

Some common proteins used in the food industry, such as gelatin, casein, soybean isolate protein (SPI) and zein, have been extensively studied for blending with shellac to prepare films/coatings. Gelatin is a natural polymer with excellent film-forming properties and good mechanical properties that can be used to enhance the flexibility of shellac films (Vanin, Sobral, Menegalli, Carvalho & Habitante, 2005). With different concentrations of gelatin and shellac mixed to form films, the researchers found that the strength and flexibility of the composite films increased as the gelatin content increased, which could be attributed to the fact that the amino and carboxyl groups of gelatin were connected to the highly reactive groups of shellac through hydrogen bonding (Soradech et al., 2012). Notably, the puncture strength of shellac-based film containing 50 % (*w*/w) gelatin increased from 3.61 MPa to 15.58 MPa, and the EB increased by 8.5 times, compared to single shellac films. Meanwhile, the higher content of gelatin produced more highly polar groups, which contributed to forming stronger hydrogen bonds with the shellac molecules to enhance the mechanical strength and hydrophilicity of the films (Soradech et al., 2012). However, due to the loss of free water and aging of the shellac, the gelatin–shellac films were not able to completely overcome the problem of enhanced brittleness after a long storage period. Therefore, the researchers added plasticizers to the composite films to solve this problem, and found that the PEG 400 of 10 % added could ensure that the films still had adequate mechanical properties at the end of the 180-day storage period (Soradech et al., 2013).

The film-forming properties of casein have been well demonstrated in both self-assembly and co-assembly with other proteins. However, single casein films are known to be highly brittle, limiting their application. Although shellac films also have high brittleness, the smaller molecular size of shellac enables itself to act as a structural binder for casein and to overcome the inherent brittleness of individual materials by interacting with casein molecules and to achieve more elastic composite films (Wang, An, Feng, Zhang & Wang, 2022). Interestingly, as the proportion of shellac increased, the fracture strain of composite film increased, indicating greater resistance to fracture, but the TS decreased, indicating poorer deformability. Calcium played an important role in stabilizing the casein network, while shellac crosslinked with Ca^{2+} and blocked the casein–calcium binding. Therefore, reduced TS seemed to be an inevitable result of the high addition levels of shellac. It was worth pointing out that a low proportion of shellac facilitated to promote the elongation of the composite films. Thus, a suitable mass ratio (10:1) of casein/shellac was considered to be beneficial for both TS and fracture strain in this study.

SPI, a grain and oil by-product, has received considerable attention due to its low price and excellent film-forming properties. However, the poor water resistance of SPI film is a concern in the application. In order to overcome the problem, the researchers prepared the composite film by adding an appropriate amount of shellac with good hydrophobicity to SPI solution. Attractively, it was found that with the increase of shellac content, the contact angle increased, and the WVP, water content and water absorption of the films decreased, which indicated increased ability to resist water. This was probably due to that the hydrophobic effect of the lipids in shellac limited the strong combination between water and SPI and improved the densification of films. Additionally, as the content of added shellac increased, both the TS and EB of the films improved in comparison to pure SPI films. This improvement could be attributed to an increase in the crystallinity of the shellac itself or of the shellac and SPI (Zhang et al., 2020).

In addition, as a more hydrophobic alcohol-soluble protein, zein has a wide range of sources and excellent moisture barrier properties, which has been used to prepare composite films with shellac as a matrix material. Han et al. (2023) prepared a composite film by mixing zein with shellac at a mass ratio of 1:1, which had a TS of 0.725 MPa and an EB of 0.642 %. Moreover, the researchers found that adding curcumin to the composite film could increase TS and EB of the film, which was due to the formation of hydrogen bonds among curcumin, zein and shellac in the system. Besides, the hydrophobicity of the composite film was enhanced due to the presence of curcumin. More attractively, the addition of curcumin resulted in a good pH responsiveness of the composite film.

3.2.2. Composite films/coatings based on shellac and polysaccharides

In general, most of single polysaccharide films/coatings exhibit poor water resistance due to hydrophilic nature of polysaccharides, and the mechanical performance of single polysaccharide films/coatings is not as good as that of composite films. In contrast, the addition of shellac into polysaccharide-containing solutions effectively improves the water resistance of films/coatings containing polysaccharides and may improve other properties such as mechanical properties.

As a hydrophilic polysaccharide, pullulan is highly affected by environmental humidity. The brittleness of pure pullulan film increases due to water loss under low humidity conditions, while the viscosity increases due to water absorption under high humidity conditions. Attractively, the addition of shellac was found to effectively enhance the water resistance of pullulan films, which could be reflected by the increased water contact angle and lower moisture content, swelling ratio in deionized water and water solubility of the composite film. The results could be related to the inherent hydrophobicity of shellac and the hydrogen-bonding interactions between shellac and pullulan that reduced the affinity of hydrophilic groups in pullulan for water (Tang et al., 2025). Notably, the addition of shellac endowed composite films with improved EB and ultraviolet (UV) shielding performance. Similarly, in another study, researchers found that compared with pure konjac glucomannan (KGM) films, the composite films with hydrophobic shellac exhibited improved water contact angle and reduced WVP, indicating their stronger water resistance (Du et al., 2019). Furthermore, the KGM–shellac composite films exhibited enhanced flexibility due to the low molecular weight of shellac filling the macromolecular space and reducing intermolecular forces. Similar to pullulan and KGM-based films containing shellac, the stronger water resistance of pectin–shellac composite films had also been observed. With the increase in the content of shellac, it was found that all water parameters such as water content, water solubility and WVP showed a decreasing trend, and 50 % of shellac provided the best moisture barrier and lowest WVP coefficients of composite films for long-term storage (Luangtana-anan, Soradech, Saengsod, Nunthanid & Limmatvapirat, 2017). However, it was regretful that the mechanical properties of composite films with high content of shellac were poor. Therefore, the researchers used PEG 400 to plasticize the composite film to enhance its mechanical properties while maintaining high moisture resistance during storage.

Different from the hydrophilic polysaccharides mentioned above, cellulose is insoluble in water and general organic solvents. Therefore, a variety of cellulose derivatives obtained through modification, including hydroxypropyl methylcellulose (HPMC) and cellulose acetate phthalate (CAP), were used for film preparation instead of cellulose itself. Interestingly, shellac also contributed to improving the performance of cellulose derivative-based films. Compared with pure HPMC films, the incorporation of shellac of 5 % increased the TS and elastic modulus by 96 % and 121 %, respectively (Tohamy, Mohamed, El-

Sakhawy, Elsayed & Kamel, 2024). For CAP-based films, the addition of shellac significantly increased the oxygen permeability of the composite films, and this might be associated with the fact that shellac was embedded in the CAP matrix as a dispersed phase, resulting in a less compact and homogeneous film structure (Dong et al., 2024). However, the CAP–shellac composite films exhibited slightly lower TS and EB, probably due to insufficient compatibility between shellac and CAP. Different from HPMC and CAP, cellulose nanofibers (CNF) are nanomaterials made from cellulose fibers (Zhang et al., 2024), and thus they have poor film-forming properties on their own. However, CNF can be added as a nanosized polysaccharide to shellac film solutions to improve the properties of the final shellac-based films. The incorporation of CNF significantly improved the thermal stability of the shellac-based film, which was related to the high crystallinity of CNF and network-like structure produced by hydrogen bonds between CNF and shellac. Besides, the maximum tensile stress of shellac-based film increased with the increase of CNF content, indicating the beneficial effect of CNF on mechanical performance of shellac-based films. This was attributed to the high aspect ratio as well as specific surface area and nano size of CNFs that allowed the contact area between CNF and shellac to be increased thereby creating strong hydrogen bonding interactions.

Although films based on two polysaccharides can have somewhat better performance than single polysaccharide-based films, the addition of shellac still contributes to improving the properties of films based on two polysaccharides. The incorporation of shellac led to the alginate–carrageenan composite film lower water absorption, solubility and water vapor transmission rate, which were beneficial for its application as moisture-proof food packaging (Zhang et al., 2022). Additionally, shellac significantly increased the EB of the alginate–carrageenan composite film by almost 2 time and reduce its TS by 34.7 %. This indicated excellent flexibility of the composite film containing shellac, and such a phenomenon could be attributed to the shorter chain length of shellac. Saberi, Chockchaisawasdee, Golding, Scarlett & Stathopoulos (2017) concluded from the response surface design that the incorporation of shellac of 40 % (*w*/w) could achieve the minimum thickness and lowest WVP of the guar gum–pea starch composite films, which could be related to the enhanced water resistance of films. Besides, it was found that guar gum–pea starch coating containing shellac exhibited good gas barrier properties, reducing the respiration rate of postharvest oranges and maintaining nutrient levels and antioxidant capacity during storage (Saberi, Golding, Chockchaisawasdee, Scarlett & Stathopoulos, 2018).

Despite the fact that most composite films of polysaccharides and shellac demonstrate good performance, they still fail to fully meet the preservation requirements for perishable fruits and vegetables. As a result, researchers innovatively developed a tunable breathable film by combining shellac with chitosan porous microspheres (CSPM) (Zhou et al., 2021). The film has a similar function to the plant leaf epidermis, allowing for highly controllable gas permeability and selectivity. Due to the porous structure of CSPM, the oxygen permeability and carbon dioxide permeability of the composite films were increased by 91.3 % and 178.6 %, respectively, compared to the pure shellac films. Although the high content of CSPM resulted in lower intra-interfacial adhesion and reduced the mechanical properties of the composite films, the results proved that the worst mechanical properties of the composite films were still acceptable, which were similar to those of edible films prepared from most natural polysaccharides. More attractively, shellac–CSPM film was effective in extending the shelf life of five fruits (i.e., strawberries, cherries, mangoes, oranges and wax berries).

Shellac was also added to the polysaccharide-based coating formulation, which could maximize its water resistance. In the study of Chauhan et al. (2015), the addition of shellac enabled the *Aloe vera* gel coating to have better moisture resistance, which contributed to reducing the weight loss of the coated food during storage. In addition, the unique color of shellac also facilitated to provide excellent gloss to the composite coatings. Past research demonstrated that both locust bean gum composite coatings and HPMC composite coatings with high shellac content in the formulation showed a tendency to contribute to the maintenance of excellent gloss. Inevitably, excessively high levels of shellac brought about a strong barrier effect for gases, leading to increased ethanol levels. (Contreras-Oliva, Rojas-Argudo & Pérez-Gago, 2011; Rojas-Argudo, del Río & Pérez-Gago, 2009). Appealingly, this issue could be resolved by adding plasticizers. Furthermore, Rojas-Argudo et al. (2009) found that higher storage humidity (90 % – 95 %) was more conducive to plasticizers reducing ethanol accumulation.

3.2.3. Composite films/coatings based on shellac and other lipids

Lipids are commonly used as coating materials to enhance the gloss of postharvest fruits, reduce water loss and extend shelf life. The coatings composed of shellac and other lipids have been fabricated considering the possibly better results of lipid complexes. In a previous study, researchers prepared coatings for apples by mixing different ratios of candelilla wax and shellac. It was demonstrated that the gloss of the coated apples improved with an increasing concentration of shellac, and the composite coating effectively inhibited the respiration of coated apples due to the good water vapor and gas barrier properties of both components. Moreover, it was noteworthy that when the mass ratio of candelilla wax to shellac was 2:1, the coated apples exhibited consistent gloss characteristics similar to commercial carnauba-coated apples (Alleyne & Hagenmaier, 2000).

In addition to being used as a coating for fruits, composite solutions of shellac and other lipids can also be used to coat the films for food packaging purposes to enhanced their moisture barrier properties. Shellac was shown to achieve an improvement in the moisture resistance of KGM films when co-coated with stearic acid (Wei et al., 2015). Compared to the KGM films, the shellac–stearic acid coatings effectively reduced the WVP and water uptake of the KGM films over various temperature gradients and humidity ranges due to moisture-resistant buffering effect of the stearic acid and shellac. Additionally, the coating layer of shellac and stearic acid enhanced the mechanical properties and light transmittance of the KGM films. However, it was worth noting that the WVP of the coated KGM films at 38 °C was higher than that at 23 °C, which could be attributed to the thermal instability of the shellac with a softening temperature of 53.9 °C.

3.2.4. Composite films/coatings based on shellac and two components among proteins, polysaccharides and lipids

In addition to being mixed with the single components described above, shellac is also added to composite coating solutions of binary matrix materials in order to enhance their functionality. In the study of Mohamed, El-Sakhawy, Nashy & Othman (2019), the breaking length of the gelatin–carboxymethyl cellulose (CMC) composite films containing shellac increased, compared to films with similar proportions of gelatin to CMC, which was attributed to the fact that when shellac was added to the gelatin–CMC system, hydrogen bonds were produced between the carboxyl groups of shellac and the hydroxyl groups of CMC as well as the amino groups of gelatin, and between the hydroxyl groups of shellac and the carboxyl groups of gelatin. More than that, it was proven that the composite film prepared with 14 % shellac, 80 % carboxymethyl cellulose, and 6 % gelatin showed good antimicrobial activity, which inhibited *Bacillus mycoides*, *Escherichia coli* (*E. coli*), and *Candida albican* in areas with diameters of 10 mm, 17 mm, and 10 mm, respectively. In the study of Rojas-Argudo et al. (2009), compared to locust bean gum–beeswax coatings containing low concentrations of shellac, the composite coating containing high concentration of shellac was a better choice for improving gloss. However, coatings with high shellac contents were often combined with hydrophilic plasticizers to reduce the undesirable effects of excessive gas barrier.

4. Antimicrobial substances to enhance preservation effect of shellac-based films/coatings

In recent years, in order to further enhance functional properties of

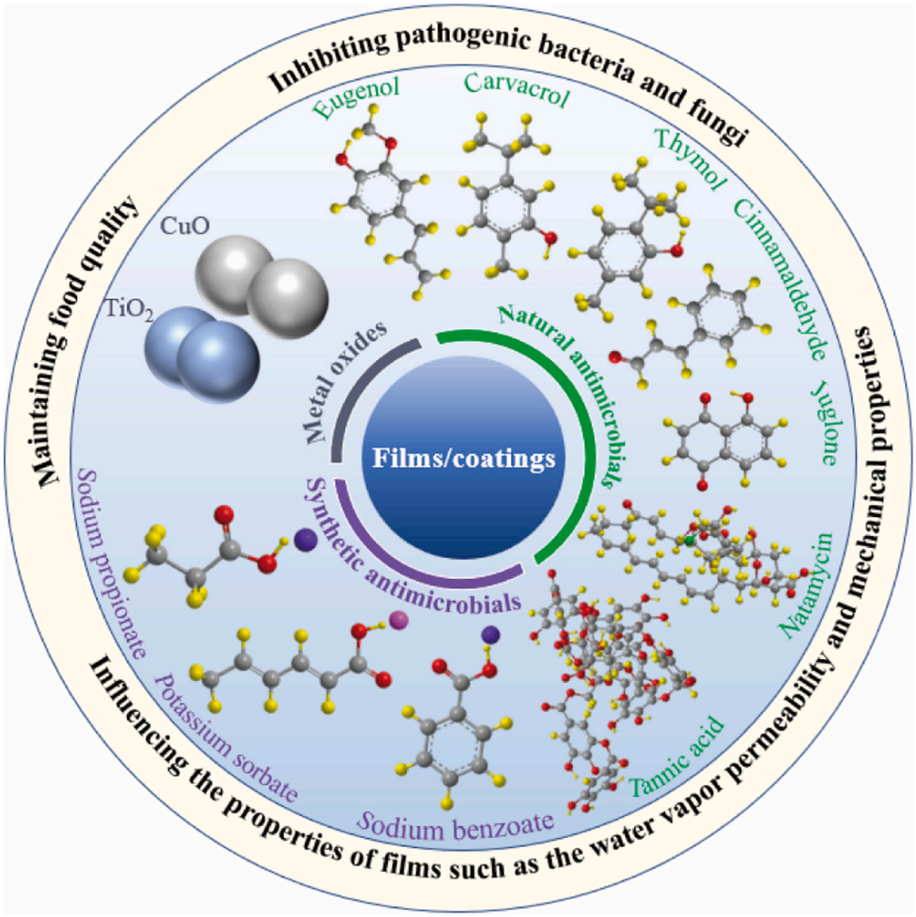

Fig. 4. Types and effects of antimicrobial agents used in combination with shellac-based films/coatings.

shellac-based films/coatings and endow them with bioactivity in addition to barrier properties, a variety of substances with antimicrobial activity including natural antimicrobials, synthetic antimicrobials and nano-metal oxides have been incorporated into films/coatings. These films/coatings containing bioactive substances are known as active packaging that can facilitate better preservation effect for food products. Herein, antimicrobial substances added to shellac-based films/coatings and their effects on films/coatings are reviewed (Fig. 4).

4.1. Natural antimicrobials

Natural antimicrobials can be obtained from plants, animals and microorganisms, which typically have low toxicity, biocompatibility and biodegradability, and exhibit broad-spectrum antimicrobial activity (Kumar, Mukherjee & Dutta, 2020). Moreover, they can effectively maintain the appearance and nutritional quality of food products.

Essential oils are a common type of commercially available natural antimicrobials, which are extracted from plants, contain a wide range of components with strong antifungal activity and are considered to be safe for human health and environment (Yan, Zhang, Hu, Deng & Ritenour, 2020). At present, essential oils and their volatile compounds are used in the formulation of shellac-based films/coatings to impart additional antimicrobial activity to the shellac-based films/coatings. In the study of Wang, An, et al. (2022), casein–shellac composite films incorporating eugenol exhibited excellent antioxidant properties and inhibitory effects against *Bacillus mycoides*, *E. coli* and *Staphylococcus aureus* (*S. aureus*) that were similar to those of free eugenol. Moreover, eugenol also possessed a plasticizing effect. The results showed that 1 % (*w*/*v*) of eugenol resulted in good TS of the composite films while achieving the highest toughness. Furthermore, the WVP of the composite films was reduced because the phenyl groups in the structure of eugenol enhanced the hydrophobicity of the composite films. Carvacrol has been approved by the FDA as a food additive. It was shown that CAP–shellac composite films containing carvacrol significantly inhibited the growth of *S. aureus* and *E. coli*, and the antimicrobial activity gradually increased as more carvacrol was added to CAP–shellac composite films (Dong et al., 2024).

In addition to being used in shellac-based films, essential oils are also used in shellac-based coatings. Carvacrol and thymol are the main compounds found in thyme oil, with strong inhibition effect against *Lasiodiplodia theobromae*. Researchers incorporated carvacrol or thymol into shellac coatings and found that the shellac coatings containing carvacrol or thymol significantly decreased the disease severity of postharvest 'Ruby Red' grapefruit related to *Lasiodiplodia theobromae*. (Yan et al., 2020). In the study of Khorram & Ramezanian (2021), the shellac coatings containing cinnamon essential oil could effectively inhibit fruit decay after inoculation with *Penicillium digitatum* spores, and adding cinnamon essential oil of 0.5 % could reduce the decay rates of fruits by nearly 90 % while maintaining an acceptable appearance and overall appearance for consumers. This result was consistent with the findings of Kouassi, Bajji & Jijakli (2012) that the shellac coating achieved excellent postharvest disease inhibition for *Penicillium digitatum* and *Penicillium italicum* after adding cinnamon essential oil.

Tannic acid (TA) is a water-soluble polyphenol derived from plants, which has been demonstrated to possess antimicrobial activity and applied as an antimicrobial component of shellac-based films and coatings. It was found that the incorporation of TA enabled the TA–CSPMs–shellac composite films to exert a more pronounced inhibition effect on the growth of *Bacillus cereus* and *S. aureus* (Zhou et al., 2021). Moreover, the results of in vivo toxicology experiments in mice showed that the TA–CSPMs–shellac composite films had good biosafety,

Table 2
Application of shellac-based films/coatings on various foods.

Applied foods	Matrix materials for films/ coatings	Bioactive components	Application ways	Beneficial effects	References
Shellac-based coatings					
Green chili	Shellac and sodium alginate		Immersion in coating solution	Extending the shelf life of coated green chilies stored at room temperature (26 ± 2 °C) to 12 d	Chitravathi, Chauhan, and Raju (2014)
Tomato	Shellac and *Aloe vera* gel		Immersion in coating solution	Tomatoes kept at room temperature (28 °C) for 12 d	Chauhan et al. (2015)
Orange	Shellac		Immersion in coating solution	Improving post-harvest quality and appearance characteristics of oranges	Khorram et al. (2017)
Apple	Shellac		Immersion in coating solution	Delaying the quality deterioration of apples after 60 d of storage at 65 % and 85 % humidity conditions	Ali et al. (2019)
Grape	Shellac		Immersion in coating solution	Maintaining the overall acceptability of the grapes during the storage period, whether refrigerated or at 30 °C	Guru Jambheshwar et al. (2019)
Grapefruit	Shellac	Carvacrol/ thymol	Spray coating solution	Reducing the degree of disease development and cold damage of fruit; extending the shelf life	Yan et al. (2020)
Egg	Shellac		Immersion in coating solution	The shellac coating maintaining the stability and functionality of eggs during the 6-week storage period	Yüceer and Caner (2021)
Mango	Shellac		Immersion in coating solution	Coating controlling the development of mango anthracnose and extending the storage life	Vivas Zárate et al. (2022)
Mango	Shellac and nanocellulose fiber		Spraying coating solution	Delaying the ripening and rotting of the mango while maintaining good sensory properties	Zhang et al. (2024)
Egg	Shellac	Nano-montmorillonite	Immersion in coating solution	Extending shelf life of coated eggs to 30 d without refrigeration	Şahansoy et al. (2024)
Egg	Shellac	Pine needle essential oil	Spraying coating solution	Delaying hydrolysis of proteins in coated eggs; extending the storage period	Song et al. (2022)
Mango	Shellac	Tannic acid		Composite coating reducing the disease incidence rate of mango and improving its postharvest quality	Ma et al. (2021)
Orange	Shellac	Cinnamon essential oil	Immersion in coating solution	Significantly reducing the disease incidence of fruit; fruit stored at 5 °C for 28 d	Khorram and Ramezanian (2021)
Litchi	Shellac and hydrochloric acid		Smearing coating solution	Maintaining acceptable quality of litchi for 2 weeks at 2–3 °C and 90 % – 95 % humidity	Nanglia et al. (2022)
Pecan	Shellac	Juglone	Smearing coating solution	Composite coating maintaining the nutritional level and high quality of pecans for 180 d	Li et al. (2022)
Shellac-based films					
Wheat flour	Shellac and konjac glucomannan		Films for sealing containers	No microbiological contamination in the wheat flour during the 28 d of storage	Wei et al. (2015)
Banana	Shellac and gelatin		Directly sealing foodstuffs	Delaying ripening of bananas to maintain their edibility for at least 30 d	Soradech et al. (2017)
Fresh mackerel fillet	Shellac and cellulose acetate phthalate	Carvacrol	Films for sealing containers	Composite film delaying microbiological spoilage of mackerel fillets and extending their shelf life	Dong et al. (2024)
Fresh chicken breast	Shellac, cellulose nanocrystals, sodium alginate and carrageenan		Films for sealing containers	Composite film maintaining overall acceptance and freshness of chicken breasts	Zhang et al. (2022)
Cherry	Shellac and pullulan		Films for sealing containers	Extending shelf life of cherries at room temperature to 7 d	Tang et al. (2025)
Cherry tomato	Shellac, cellulose nanocrystals, sodium alginate and carrageenan		Directly sealing foodstuffs	Composite film maintaining the sensory properties and freshness of cherry tomatoes	Zhang et al. (2022)

indicating their attractive application prospect as food packaging. In another study, TA was added into shellac coatings. Attractively, the TA–shellac coatings were found to have a dense structure that reduced the WVP of the coatings and exhibited high antioxidant and antifungal activities against *Colletotrichum gloeosporioides* and *Phomopsis mangiferae* (Ma et al., 2021).

Although not as common as essential oils and polyphenols, naphthoquinones are widely available in plants, one of which is juglone, which has been shown to have many biological activities such as antifungal and anti-inflammatory activities. Additionally, juglone has been applied to enhance preservation effect of shellac-based coatings. The research results of Li et al. (2022) showed that the incorporation of juglone into shellac coating formulations facilitated to slow down the rise of the acid and peroxide values within the hickory nuts. Natamycin is an unstable natural antimicrobial that is easily inactivated, but adding it to film packaging formulations can enhance its stability and prolong its antifungal efficacy. Song (2016) found that shellac was an effective substrate coating material that avoided the problem of instability of natamycin and achieved prolongation of its antifungal activity. Moreover, the shellac coating containing 400 μg/mL of natamycin was effective in preventing the contamination of *Cladosporium romotenellum*, *Mucor hiemalis*, and *Penicillium commune* during the storage of commercially washed eggs.

4.2. Synthetic antimicrobials

Despite the fact that synthetic antimicrobial components are not as well accepted by consumers as natural antimicrobial components, synthetic antimicrobials such as potassium sorbate (PS), sodium benzoate (SB), and sodium propionate (SP) are still widely used in food industry due to their low price. In previous studies, researchers added PS, SB or SP to composite coating solutions containing HPMC, shellac and beeswax, either alone or in combination to enhance the antimicrobial activity of coating solutions. The results showed that all composite coatings containing preservatives resulted in a reduction in the incidence and development of green mold and blue mold. It was noteworthy that composite coatings containing SB and SB + SP consistently showed an inhibitory effect on disease development after a long period of cold storage (Valencia-Chamorro, Pérez-Gago, del Río & Palou, 2010). Based on this, subsequent study showed that the composite coatings containing

SB and SB + PS had the best inhibition of *Penicillium digitatum and Penicillium italicum*. In addition to inhibitory effect on fungi, it was found that the composite coatings containing SB + PS and SB + SP had the strongest oxygen shielding properties, and these two coatings were the most effective in maintaining weight after being stored for up to 30 days at a temperature environment of 5 °C, in relation to their low WVP (Valencia-Chamorro, Palou, del Río & Pérez-Gago, 2011).

4.3. Metal oxide nanoparticles

Currently, metal oxide nanoparticles are receiving a lot of attention due to their antimicrobial properties and their ability to optimize film properties. There have been significant advances in research, leading to a range of various nanomaterials available on the market (El-Seedi et al., 2019; Wang et al., 2023). On this basis, the combination of polymers and metal nanoparticles gives better properties to the composites, and new antimicrobial shellac-based films caused by the addition of metal oxide nanoparticles have been successfully developed. In the study of Wang et al. (2023), polyvinyl alcohol and shellac were used as raw materials for a bilayer film, and carboxymethyl chitosan (CMCS)–CuO nanoparticles (NPs) were incorporated into the system. When the addition of CMCS–CuO NPs was 2.5 %, the composite film had the best mechanical properties and exhibited an inhibition rate of more than 90 % against *E. coli* and *S. aureus*. In addition, the composite film allowed less than 10 % of UV light to pass through, in comparison to the polyvinyl alcohol–shellac film (about 20 %), which was attributed to the additional enhancement of refractive index due to the incorporation of CMCS–CuO NPs. Appealingly, the WVP of the composite films decreased with the increase of the addition ratio of CMCS–CuO NPs, which was attributed to the fact that the uniformly dispersed nanoparticles lengthened the effective path of water molecules diffusion. In addition to CuO NPs, another metal oxide nanoparticle with high stability and antimicrobial properties, which is also harmless, TiO_2 NPs, were also used in shellac-based films (Umair et al., 2023). Tohamy et al. (2024) incorporated TiO_2 NPs into HPMC–shellac–graphene oxide composite films. They observed that when the addition of TiO_2 NPs was increased to 0.125 %, the composite film showed the strongest inhibitory effect on *Candida albicans* with a 24 mm diameter of the inhibition circle and also showed a good inhibitory effect on *E. coli* (17 mm) and *Bacillus mycoides* (21 mm). Meanwhile, TiO_2 NPs were also beneficial for hydrophobic properties of HPMC–shellac–graphene oxide composite films. The incorporation of TiO_2 NPs of 0.08 % resulted in an increase of 54.17 % in the contact angle of the composite film.

5. Shellac-based films/coatings for food preservation applications

Based on the fact that shellac-based films/coatings exhibit attractive mechanical properties, barrier effects as well as appearances and the addition of various antimicrobial components endowed the shellac-based films/coatings with additional antimicrobial activity and thus better preservation effect, researchers have applied shellac-based films or coatings as packaging for food products to maintain their quality as well as sensory properties and retard microbiological spoilage. In this section, the application of shellac-based films/coatings for various foods such as poultry products, fruits and vegetables were reviewed (Table 2).

5.1. Poultry products

Chicken breast was favored by most consumers due to high nutritional value and relatively low price. However, like other meat products, fresh chicken breast is susceptible to spoilage during storage due to the hydrolysis of lipids as well as proteins and microbial infection (Wang et al., 2022). Therefore, in order to ensure the acceptability and safety of fresh chicken breast, Zhang et al. (2022) produced preservation films through the incorporation of shellac into sodium alginate–carrageenan composite. The results showed that the shellac-optimized films resulted in chicken breast with higher-rated color and flavors and less weight loss compared to the unoptimized film. Besides, the shellac-optimized films effectively maintained the freshness of the chicken breast, as evidenced by the relatively low pH and total volatile basic nitrogen (TVB-N), and this could be attributed to the immobilizing effect of the shellac on the bacteria and the better bacteriostatic effect of the optimized film.

Eggs are not only one of the cheapest sources of nutrients, but they are also widely used in the food industry as foaming agents and emulsifiers. However, due to the surface of the shell being covered with tiny pores that allow gas exchange, eggs are susceptible to deterioration, which can affect their physicochemical properties and functionality (Şahansoy, Caner & Yüceer, 2024; Yüceer & Caner, 2021). Therefore, with its superior gas barrier properties, shellac has been successfully developed as a good coating material to effectively extend the shelf life of eggs. By measuring the weight loss, pH, yolk index, haugh unit, and foam stability of eggs treated with the shellac coating, Şahansoy et al. (2024) found that during storage, indicators (e.g. yolk index, haugh units) reflecting the freshness of the egg were well retained by the shellac coatings. Particularly, the shellac coating of 8 % not only contributed to the best storage stability but also effectively improved eggshell strength. This was attributed to the sealing effect of the shell surface pores by the shellac coating, thus reducing the exchange of gases in the environment. Similar results were observed in the study of Yüceer and Caner (2021), where a shellac coating of 10 % showed the best result in maintaining the surface color and foaming ability of the eggs. In addition to the single shellac coatings, the preservation effect of shellac coatings containing antimicrobials on eggs has also been confirmed. It was found that the shellac coating with 400 μg/mL natamycin prevented mold contamination of eggs after commercial washing and pasteurization, extending the shelf life up to two times compared to uncoated eggs, minimizing economic and quality losses caused by mold contamination (Song, 2016). In summary, shellac films and coatings are a relatively effective packaging material that can reduce economic losses due to spoilage and deterioration of poultry products.

5.2. Fruits and vegetables

After the harvest, fruits and vegetables undergo a respiratory process that involves the continuous utilization of oxygen and release of carbon dioxide. This inherent feature causes the basic metabolic depletion of internal nutrients, ultimately leading to a deterioration in quality and a shortened shelf life. Additionally, post-harvest decay resulting from microbiological contamination is an inevitable issue that further impacts the overall quality of fresh products (Ghosh & Singh, 2022). As a result, researchers have devoted their efforts to studying methods that can inhibit the ripening process of fruits and vegetables and delay their decay, and some research groups have identified the beneficial effects of shellac-based films/coatings in extending the shelf life of fruits and vegetables in recent years.

In previous studies, single shellac coatings have been shown to be effective in delaying the quality deterioration of fruits and vegetables during storage. The study of Khorram, Ramezanian & Hosseini (2017) showed that the shellac coatings formed uniform films on the surface of oranges, allowing for gas exchange. This coating not only improved the glossiness of the oranges during storage but also reduced weight, hardness and ascorbic acid loss. Importantly, due to the uniformity and good gas barrier properties of the shellac coatings, the postharvest respiration rate of the fruits was reduced without causing the oranges to under-respire and develop an odor because of anaerobic respiration. In another study, both at 30 ± 3 °C and 4 ± 1 °C, it was found that the shellac-coated grapes showed the highest overall grades due to the temperature-independent inhibitory effect of the coatings on the respiratory and metabolic activities of the grapes, indicating their overall acceptability (Guru Jambheshwar, Sharma, Sharma, Nema & Gajera, 2019). Interestingly, the preservation effect of single shellac coatings was similar for different varieties of the same type of fruits, which could be proven by the studies of Ali, Kanwar, Yadav, Basu & Mazumder (2019) and Ali, Basu & Mazumder (2020). The results of coating treatments on both *Royal Delicious* and *Rich Red* apples showed that the shellac coatings reduced the respiration rate and the outward migration of water from the apples, which helped to maintain weight and color, and inhibit softening and ripening. Although shellac coatings exhibit good preservation effects on various fruits such as oranges, apples and grapes, in practical applications, shellac concentration is a factor that must be considered, which can affect the final preservation effect of the film. The 30 % shellac coating was considered to be the optimum concentration to reduce the incidence of mango anthracnose and the extent of disease development, which had been proven by Vivas Zárate et al. (2022). This was because a low concentration of shellac was not able to form a uniform protective film on the surface of the mango, while a high concentration of shellac made the coating sticky due to its high hygroscopicity.

In addition to single shellac coatings, the preservation effects of shellac–polysaccharide composite coatings/films in fruits and vegetables have been explored, and it was found that some shellac–polysaccharide composite films/coatings have the similar preservation effects. Tang et al. (2025) demonstrated that pullulan–-shellac composite films could inhibit the growth and multiplication of microorganisms on the surface of cherries, while reducing their weight loss and firmness loss. Additionally, it was interesting that the composite films possessed excellent UV-blocking properties and acted as a barrier to oxygen and microorganisms, facilitating to inhibit the respiration rate and nutrient degradation of cherries, and extending their shelf life to 7 days at 25 °C. Zhang et al. (2022) found that compared to cherry tomatoes packed in alginate–carrageenan films, cherry tomatoes packed in shellac-optimized composite films had lower weight loss and maintained better organoleptic properties. Moreover, the pH change of cherry tomatoes was minimal due to the immobilizing effect of bacteria by the shellac, which suggested that shellac-optimized composite films facilitated to retard decay of cherry tomatoes. In another study on tomatoes coated with shellac–polysaccharide composite, similar results were also obtained. Chauhan et al. (2015) found that composite coatings of shellac–*Aloe vera* gel also showed inhibitory effects on respiratory and metabolic activities of tomatoes, thus helping to maintain the weight, firmness and color of the fruits. Moreover, they concluded that the composite coating treatment extended the shelf life of tomatoes stored at 26–32 °C to 12 days compared to untreated tomatoes that could only be stored for 6 days.

Although the single shellac coatings/films and shellac–polysaccharide composite coatings/films provide effectiveness in delaying post-harvest quality deterioration of fruits during storage, research on shellac-based coatings/films containing bioactive substances in the field of fruit and vegetable preservation has also begun to emerge in recent years. Inhibiting the development of mango diseases could be easily achieved by adding 0.5 % TA to 9 % shellac coatings (Ma et al., 2021). The optimized film-treated group of mangoes had higher antioxidant and antifungal activity while maintaining higher acceptable quality compared to untreated mangoes. The addition of TA to shellac composite films had been applied to preserve the freshness of cherries (Zhou et al., 2021), and the results showed that cherries containing 0.1 % TA packed in CSPM–shellac films maintained the best level of edibility and good sensory properties. Similar to TA, plant essential oils with antimicrobial properties were also added to shellac coatings and applied to preserve grapefruit and citrus. In the study of Yan et al. (2020), composite coatings incorporating carvacrol or thymol significantly reduced the disease incidence and development and helped to maintain fruit weight compared to grapefruit coated with shellac alone. Notably, after 8 weeks of storage at 10 °C and then transferred to 25 °C for 1 week, the composite coatings of shellac with the addition of carvacrol and thymol reduced the development of cold damage of fruit by 62 % and 59 %, respectively, compared to untreated grapefruit. This was attributed to the oily property of the essential oils that enhanced the protective effect of the coatings, limiting the water diffusion and gas exchange of the fruits with the external environment, thus reducing the susceptibility to cold damage. Khorram & Ramezanian (2021) added 0.5 % cinnamon essential oil to the 10 % shellac to obtain an antimicrobial coating for citrus. After 28 days of storage at 5 °C, the severity of green mold in the coated citrus was reduced by almost 90 % compared to the control. In addition, the shellac coatings containing a mixture of two essential oils were found to exhibit better preservation effect than those containing a single essential oil. In the study of Rashmi Tandon, Kalia, Bhardwaj & Mahajan (2024), after 75 days of storage, the decay rate of citrus after being treated by the shellac coating containing citral and thymol (1 %, 1:1, *w*/w) was recorded at 2.77 %, which represented a reduction of 40 % and 66.6 % compared to the shellac–citral coating and the shellac–thymol coating, respectively. It was found that hydrogen bonds were formed between the aldehyde group of citral and the hydroxyl group of thymol with the surface cuticle of the fruit, and that the two bioactive components acted cooperatively, which might be a reason for improved antifungal ability of the coating.

In addition to incorporating bioactive ingredients, some other preservation methods are also used in combination with shellac-based films/coatings to achieve the preservation of fruits and vegetables. Physical preservation methods are widely used due to their minimal effect on the flavor of the food itself, and some physical preservation methods such as modified atmospheric packaging (MAP) and irradiation have been demonstrated to be effective in preserving fruits and vegetables when used in combination with shellac-based coatings. MAP has been proven to regulate the internal atmosphere of the fruit by accumulating CO_2 and consuming O_2. When MAP was used to combined with shellac coatings, the respiration of green chilies was inhibited, and the combination treatment of MAP–shellac coating contributed to maintaining the weight, firmness, and levels of nutrients such as capsaicin. Besides, at the end of the 48-day storage period, untreated green chilies showed only 50 % marketability, but co-treated green chilies showed 94 % acceptability (Chitravathi et al., 2016). Irradiation has been used to preserve fruits and vegetables by generating ionizing energy, such as electron beams and UV-C, and the combination of irradiation and shellac-based coatings has been demonstrated to exhibit better preservation effects. Although the shellac coating of 10 % was shown to reduce the respiration rate of lime and decrease weight loss, based on that, the combined treatment of electron beam and shellac coating further slowed down the color change of lime and maintained its good appearance. This was attributed to the inhibition of chlorophyll degrading enzymes by the combined treatment, which allowed lime to retain the highest chlorophyll level during storage (Pongsri, Aiamla-or, Srilaong, Uthairatanakij & Jitareerat, 2021). Besides, the combined treatment of shellac coating and UV-C was found to reduce microbial-induced deterioration of potatoes throughout the storage period, which could not be achieved only by relying on shellac coating although the shellac coating maintained the good quality of potatoes by avoiding light-induced sprouting and greening as well as rotting due to anaerobic respiration (Lee, Ahn & Han, 2024).

Furthermore, chemical preservation methods in combination with shellac coatings have been shown to be effective in preserving fruits. In the study of Nanglia et al. (2022), the effects of different types of acids (e.g. citric acid, ascorbic acid, and hydrochloric acid) in combination with shellac coatings on the freshness of post-harvest litchi fruits were investigated. The results indicated that the incorporation of hydrochloric acid into the shellac coating formulation served to inhibit the activity of oxidative enzymes. This not only reduced the degree of browning in coated fruits, but also helped maintain their overall quality. Moreover, the hydrochloric acid–shellac combined treatment was found to effectively preserve the weight and hardness of litchi fruits by creating a semi-permeable barrier that minimized water loss and lowered respiratory and metabolic activity. As a result, the decay rate of litchi fruits treated by hydrochloric acid–shellac coating at 2–3 °C and

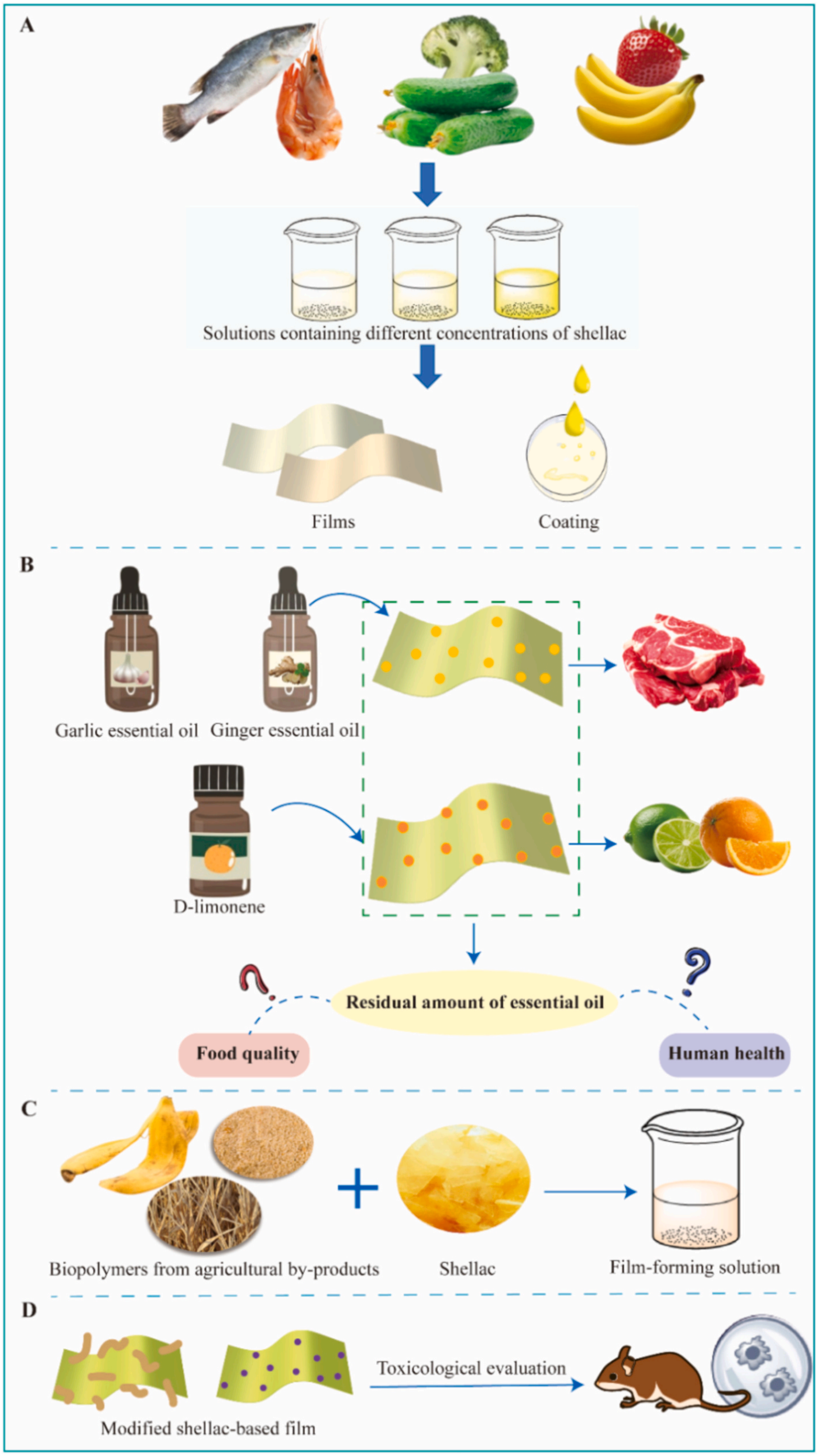

Fig. 5. Schematic illustration for future prospects of shellac. (A) Investigating the appropriate concentration of shellac for packaged foods; (B) the rational selection of essential oils to be added to the shellac-based films and the effects of their residue amounts on food quality and human health; (C) reducing the production cost of shellac-based materials through compounding with cheaper biopolymers; (D) toxicological evaluation of modified shellac-based films.

90 % – 95 % humidity was only 40 % compared to untreated fruits, allowing them to remain edible and acceptable for up to 2 weeks.

5.3. Other food products

The shellac-based films/coatings were also found to have good preservation effects for other food products such as raw mackerel fillet, wheat flour, rice cake and pecan. Raw mackerel fillet as a kind of seafood products, being rich in unsaturated fatty acids, are susceptible to lipid oxidation, protein hydrolysis and microbial contamination, and thus inevitable deteriorate (Dehghani, Hosseini & Regenstein, 2018). A suitable packaging based on shellac can effectively inhibit the spoilage of raw mackerel fillet and extend its shelf life. In a recent study, Dong et al. (2024) assessed the effect of carvacrol loaded CAP–shellac composite films on the quality changes of raw mackerel fillet, and concluded that the composite film treatment achieved an extension of the shelf life by 2 days. Specifically, after 6 days of storage, compared to the CAP film and CAP–shellac film without carvacrol, the composite film treatment significantly reduced the total viable count (TVC) and TVB-N value of mackerel fillet, indicating more acceptable freshness of mackerel fillet treated by the composite film. Besides, in the group treated by composite film, the value of thiobarbituric acid reactive substances (TBARS) remained at 1.5 mg malonaldehyde (MDA)/kg even after 10 days, which did not exceed upper acceptability limit (2 mg MDA/kg). In the study of Wei et al. (2015), KGM–shellac composite films were found to maintain the dryness of wheat flour similar to that of polyethylene film during 28 days of storage and protect it from mold contamination, indicating that KGM–shellac composite films had the potential to become an alternative to commercial polythene films. Rice cakes may become inedible due to mold contamination during storage. Wang, An, et al. (2022) found that after the rice cakes were dipped in the shellac–casein composite solutions, mold growth on the surface of the rice cakes was effectively inhibited. The composite coating not only extended the storage time of the rice cakes to 7 days but also improved their texture while maintaining their visual appeal. Nutrient levels and quality of pecans decline rapidly during storage. Attractively, shellac-based coating containing juglone significantly inhibited oxidation and hydrolysis of internal fats and delayed nutrient depletion in pecans (Li et al., 2022), indicating its beneficial effects for the quality and economic value of pecans.

6. Future prospects

There is no doubt that the concentration of shellac is a crucial factor affecting the final properties of films/coatings. A general result in the production of shellac-based films/coatings is that lower concentrations of shellac are not sufficient to provide a protective barrier for coated foods, while higher concentrations often lead to insufficient respiration of the coated fruits and vegetables due to excessive gas barrier properties. In future studies, it is necessary to optimize the concentration of shellac for the type (seafood products, fruits, vegetables, etc.) of food being packaged in order to obtain more general results to guide production (Fig. 5A), which contributes to avoiding the development of undesirable sensory characteristics of the coated foodstuffs and greatly reducing the waste of coating materials caused by excessive shellac concentration.

While essential oils have shown good antimicrobial activity and delayed effect on quality deterioration of food products after being added to shellac films/coatings, the impact of their own smell on the food flavor cannot be neglected, which affects consumer acceptance for packaged foods. To reduce this adverse effect, it is promising to design the type of essential oil to be added to the shellac-based packaging according to the characteristics of the different food products (Fig. 5B). For example, garlic essential oil or ginger essential oil can be added to shellac-based films/coatings to preserve meat products. For lemons and oranges, plant essential oils with lemon flavor such as D-limonene can be used. Such a shellac-based packaging is expected to not only achieve antimicrobial effect but also improve the flavor of the food, making it more acceptable to the consumers. At the same time, the release of essential oils in the shellac-based films/coatings is noteworthy, as the residues caused by their release may not only have adverse effects on the nutritional quality of coated food but also cause undesirable effects on human health, such as allergies and gastrointestinal disorders. Therefore, subsequent studies should determine the release modes of essential oils during storage and the relationship between residual amounts caused by their release and food quality as well as human health through a large number of experiments (Fig. 5B).

For the industrialized production of shellac-based films/coatings, despite the availability of shellac and other biodegradable biopolymers, the production costs of biodegradable films/coatings based on shellac and/or other biomacromolecules are still much higher than that of plastic packaging. Therefore, to further reduce industrialized production costs, biopolymers derived from agricultural by-products such as fruit peels, rice bran and straws can be developed and utilized as matrix materials to produce films/coatings by complexing them with shellac (Fig. 5C). In addition to concern about production costs, currently, many chemical reagents and nanomaterials have been used to modify the shellac-based films/coatings, and yet the safety of many modified films/coatings has not been demonstrated. Therefore, in subsequent studies, the toxicological evaluation of modified shellac films/coatings should be conducted (Fig. 5D), as non-toxicity is the basis for their industrialization.

7. Conclusions

In order to achieve the targets of sustainability and maintaining food quality, the research focus of food packaging is shifting towards finding alternatives to petroleum-based plastic packaging. As a biodegradable and non-toxic biopolymer of insect origin, shellac has excellent film-forming ability that makes it a promising material for food packaging. However, single shellac films typically have poor mechanical properties. Therefore, researchers have successfully developed a variety of shellac-based composite films with improved mechanical properties by adding other bio-based materials to the shellac solutions. Furthermore, it has been demonstrated that incorporating antimicrobial agents in the formulation of the shellac-based films/coatings helps to endow them with extra antimicrobial activity and possibly improves their other properties. Additionally, in recent years, shellac-based films/coatings, whether used alone or in combination with antimicrobial agents, exhibit a certain degree of preservation effect on food products, indicating that they have great application prospects. Despite certain achievements from laboratory-scale studies and applications of shellac-based films/coatings, it is important to recognize that there is still much effort needed for industrial production. Many theoretical studies need to be carried out further, such as conducting toxicity assessment, understanding the relationship between added antimicrobials and human health, reducing production costs and optimizing shellac concentrations for industrial applications.

CRediT authorship contribution statement

Jiayi Wang: Writing – original draft, Investigation, Conceptualization. **Xin Wang:** Investigation. **Bingjie Liu:** Visualization. **Jianbo Xiao:** Visualization. **Zhang Fang:** Writing – review & editing, Supervision, Project administration.

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.

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Data availability

The authors do not have permission to share data.

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