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Review

Shellac-based materials: Structures, properties, and applications

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ABSTRACT

Shellac stands out among natural polymers as the sole animal-derived resin, boasting a complex polyester composition comprising polyhydroxy long-chain fatty acids and sesquiterpene acids. Its unique attributes include biocompatibility, non-toxicity, distinctive amphiphilicity, superb film-forming and adhesive properties, excellent dielectric properties, rapid drying, and solubility in alkaline solutions while resisting acidic ones. These exceptional qualities have propelled shellac beyond its traditional role as a varnish and decorative material, positioning it as a viable option for diverse applications such as food packaging, pharmaceutical formulations, electronic devices, fiber dyeing, and wood restoration. Furthermore, shellac serves as a crucial carbon source for graphene materials. This review comprehensively explores shellac's contributions to prolonging food shelf life, enhancing the carbon sourcing of graphene materials, facilitating the delivery of active substances, boosting the performance of organic field-effect transistors, enabling environmentally friendly textile dyeing, and providing protective coatings for wood. Additionally, it delves into the current limitations and future directions of shellac's applications. By disseminating this knowledge, we aim to deepen researchers' comprehension of shellac and inspire further exploration, thereby fostering sustainable advancements across various industries.

1. Introduction

In recent decades, there has been rapid progress in polymers and materials based on polymers. Conventional polymer materials often fail to meet the specific requirements in various areas, leading to the adoption of new preparation methods for special polymers. These include electrically conductive polymers [1], stimuli-responsive polymers [2], luminescent polymers [3], covalent organic backbone polymers [4], and supramolecular polymers [5].

In recent years, the environmental impact of artificially synthesized polymers has become increasingly evident. Consequently, there is a burgeoning interest in bio-based materials known for their superior biodegradability. Natural polymers derived from plants and animals, such as proteins, cellulose [6], starch [7], and non-starch polysaccharides [8,9], have often been underutilized due to their sensitivity to water [10,11], low barrier properties [12], and limited mechanical strength [13,14]. However, they present a promising alternative to synthetic materials because of their abundance, cost-effectiveness, and inherent properties that can rival or surpass those of synthetic polymers in specific applications.

In the past decade, there has been an increasing number of research publications each year alongside a steady number of patents over years (Fig. 1), indicating a robust research emphasis on shellac. Shellac is a resin secreted by lac insects, especially *Kerria lacca* [15]. These insects typically parasitize over 300 types of trees in regions such as China, Thailand, India, and Mexico [16,17]. The lac insects extract sap from tree bark and undergo chemical transformations within their bodies to secrete a hard shell, which is the raw material for shellac [18]. Since the 12th century, shellac has served as a coating agent for furniture and public buildings and as an adhesive for repairing jewelry and ceramics.

Abbreviations: CA, citric acid; CMC, carboxymethyl cellulose; CuNP, copper nanoparticle; ESI, electrospray ionization; FIR, far-infrared; FTIR, Fourier-transform infrared; SCF, simulated colon fluid; SIF, simulated intestinal fluid; SGF, simulated gastric fluid; HA, hydroxyapatite; SOD, superoxide dismutase; SPI, soy protein isolate; OFETs, organic field-effect transistors; PAM, photoactive antiviral mask; PEG, polyethylene glycol; PLA, polylactic acid; T_g, glass transition temperature; TSS, total soluble solids.

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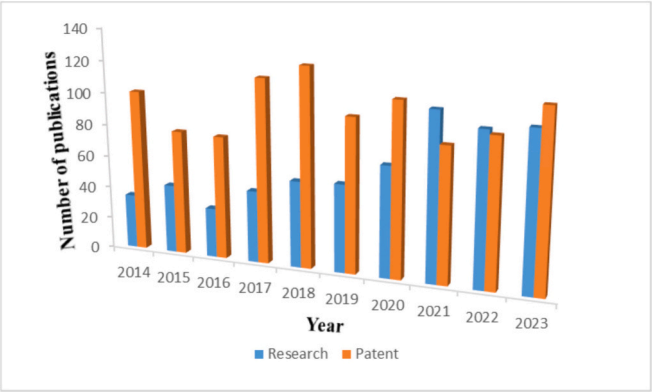

Fig. 1. Number of publications on shellac from 2014 to 2023. Data retrieved from searches on Web of Science (https://www.webofscience.com) and the World Intellectual Property Organization (https://www.wipo.int/portal/en/) using the topic "shellac".

Air-dried and oil-based shellac varnishes are prepared by dissolving shellac in a solvent and evaporating the solvent. These varnishes are smooth and glossy, and adhere well to metal or wood surfaces [19,20].

Shellac has garnered significant attention for its considerable benefits, particularly within the food industry [21]. However, there remains a dearth of comprehensive reviews that fully explore its research standing as a versatile material across multiple domains, taking into account its wide-ranging applications. This review aims to address this gap by exploring the functionality of shellac and its applications in fields such as food, medicine, electronics, and woodworking. This article begins by discussing the chemical composition, structure, identification, and fundament properties of shellac. Subsequent sections delve into its diverse functional characteristics and applications across different fields. Furthermore, the review considers the future application prospects and other potential avenues for shellac. This review aims to consolidate recent advancements, establishing a theoretical framework and outlining future directions for the exploration of shellac-based materials. It endeavors to provide insights into the functionality and diverse applications of shellac, while also highlighting current research constraints.

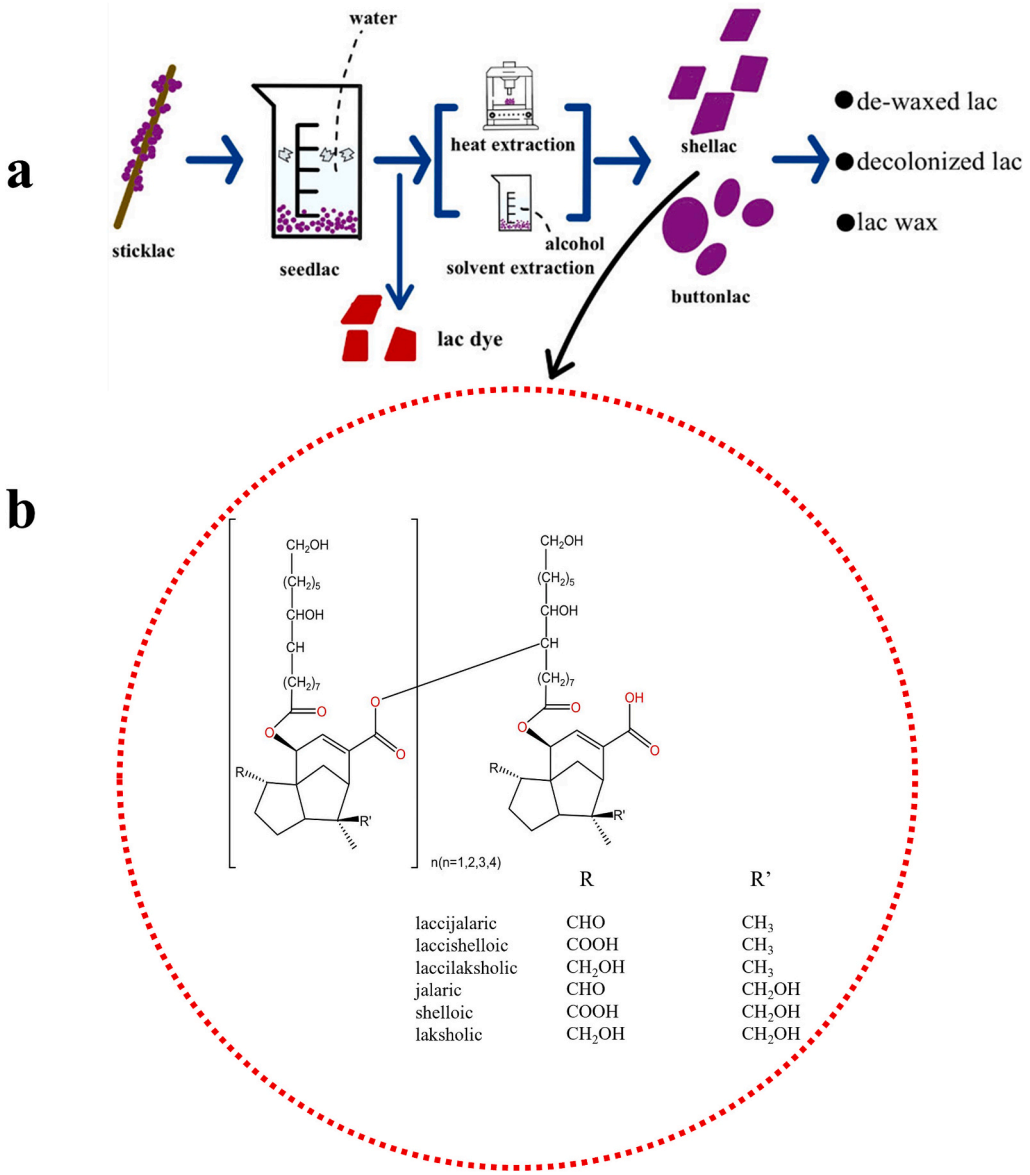

Fig. 2. (a) Schematic illustration of the processing of lac into shellac and other byproducts. (b) Chemical structure of shellac.

2. Structure and properties of shellac

2.1. Chemical structure and composition

2.1.1. Composition

Shellac is the sole animal resin secreted from the insect's body. Fig. 2a illustrates that sticklac, collected from tree branches, contains numerous impurities. Therefore, it typically undergoes primary decontamination and either melt filtration or solvent extraction to yield seedlac and button lac before use. The refined gum is further processed into dewaxed gum and bleached gum, as required. Valuable by-products like shellac dyes and waxes are obtained during these processes [22].

Natural shellac exhibits a sophisticated chemical structure, characterized by a complex, long-chain polyester resin consisting predominantly of monoesters and lactones of polyhydroxy carboxylic acids, with shellac resin comprising 70–90 % of its composition [23]. Additionally, it contains minor quantities of shellac waxes, shellac pigments, and other impurities such as salts, proteins, and insect remnants.

Shellac resin primarily consists of long-chain aliphatic hydroxy acids and cyclic terpene acids in a 1:1 ratio [24]. The various aliphatic hydroxy acids determine the hydrophobic nature of shellac, while the carboxyl groups on the cyclic terpene acids contribute to its hydrophilicity (see Fig. 2b). When shellac resin is dissolved in ether, it divided into two distinct fractions: the soft resin, which dissolves in ether and consists of long-chain hydroxy fatty acids and cyclic terpene acids, and the hard resin (or pure shellac resin), which is insoluble in ether. This pure shellac resin, the main constituent of shellac [25], is a mixture of dimers, trimers, and tetramers formed through the polymerization of hydroxyl groups in the soft resin, with tetramers being the predominant form [24]. The molecular weights reported are about 550 for the soft resin and 2000 for the hard resin [26], contributing to an average molecular weight of around 1000 for shellac [25].

Each shellac unit contains 4–5 hydroxyl groups, 2–3 ester groups, 1 aldehyde group, a free carboxyl group, and an unsaturated double bond [25,27]. Aleuritic acid and jalaric acid are representative fractions of aliphatic hydroxy acids and cyclic terpenoids, respectively [27,28].

Shellac wax comprises a lengthy chain of monohydric alcohols and acids, with approximately 30 % free wax alcohols, 1 % lactic acid, and a minor hydrocarbon component [29,30]. Indian shellac gum dyes consist of a blend of at least five anthraquinone derivatives, known as laccases. The structures of four known shellac gum dyes can be discerned using a combination of analytical techniques such as infrared (IR) spectroscopy, high-resolution electrospray ionization mass spectrometry (HR-ESI-MS), and 1D and 2D nuclear magnetic resonance (NMR) [31].

Its two oxyacids grant it superior amphiphilic properties compared to other natural polymers [32]. Despite its acidity, shellac exhibits tolerance in gastric fluids with lower pH and good solubility in higher-pH intestinal solutions, making it a favored material for enteric coatings [33–35].

Shellac resins possess a unique nanostructure (bicontinuous

Fig. 3. Applications of shellac in different fields.

structure) featuring hydrophilic and lipophilic phases with an amphiphile at the interface, explaining their excellent adhesion and low permeability [36]. Additionally, shellac boasts dielectric and antimicrobial properties, along with rapid drying at room temperature. These attributes position it as a potential replacement for synthetic materials, opening up a broader array of applications in modern fields, as depicted in Fig. 3. The emergence of novel applications has recently garnered significant attention.

2.1.2. Structure characterization

Various spectroscopic techniques, such as UV, fluorescence, Fourier-transform infrared (FTIR), far-infrared (FIR), and Raman spectroscopies, are commonly employed for characterizing the molecular structures of shellac. In FTIR spectra, the vibration of the acidic and hydroxyl functional groups of shellac produces a distinct broad peak within the range of 3700–3200 cm^{-1}. Additionally, strong absorption bands at 2928–2920 cm^{-1} and 2852 cm^{-1} correspond to C—H stretching vibrations, while peaks at 1710 cm^{-1} (from acid carbonyl) and a slight shoulder band at 1636 cm^{-1} (from ester C═O) are also observed. Undewaxed shellac exhibits a weak peak at 720 cm^{-1} due to CH_2 rocking effects [37,38]. UV spectra of different shellac types display nearly identical absorption patterns [38,39], with a broad peak typically appearing around 215–230 nm [39–41].

ATR-FIR spectroscopy enables the differentiation of sesquiterpenes, diterpenes, polymeric communication acids, and triterpenoid resins, facilitating the identification of shellac resins composed of sesquiterpenoid acids [38,42]. Fourier-transform Raman spectroscopy allows for the observation of C═C in shellac resin [43]. Fluorescence excitation and emission spectra reveal that un-decolorized cherry shellac exhibits more fluorescent bands than colorless platina shellac, with variations in the emitted peaks between the short-lived and long-lived components of the two types of shellac [44]. By delving deeper into the components of shellac resin, researchers have identified three long-chain fatty acids: aleuritic acid, kerrolic acid, and butolic acid; additionally, they have discovered eight cyclic oenoterpenes, namely shellolic acid, jalaric acid, laksholic acid, laccishellolic acid, epijalaric acid, laccilaksholic acid, laccijalaric acid, and epilaccishelbolic acid [45,46]. Six unknown sesquiterpenes were isolated from shellac and their molecular formulas were determined by NMR and HR-ESI-MS to be $C_{15}H_{22}O_3$, $C_{15}H_{20}O_5$, $C_{17}H_{26}O_5$, $C_{15}H_{22}O_3$, $C_{15}H_{20}O_3$, and $C_{15}H_{18}O_4$ [31].

Modern techniques, such as flow injection analysis coupled with high-performance liquid chromatography (HPLC), negative-mode electrospray ionization (ESI), and quadrupole time-of-flight (Q-ToF), have been utilized to characterize the structures of resin molecules. This approach has detected various compounds resulting from the hydroxyl oxidation of aleuritic, butolic, jalaric, laccijalaric, and shellacolic acids, along with previously undetected compounds and free acids, esters, and polyesters consisting of up to eight units [47]. While there is a common chemical structure among different types of shellac [37], slight variations in chemical composition often occur due to differences in geography, host plants, environmental conditions, insect species, and processing treatments. Reactive pyrolysis-gas chromatography (Py-GC) with tetramethylammonium hydroxide can be employed to determine the molar ratios of the constituent acids, allowing differentiation between shellac samples from different locations such as India and Thailand [48]. Additionally, gas chromatography–mass spectrometry (GC–MS) analysis can distinguish between fresh and aged shellac by detecting the key molecular structures, including butolic and aleuric acids and their derived acids, and typical sesquiterpenes [49].

2.2. Modification

2.2.1. Chemical modification

To broaden the applications of shellac, it is often chemically modified. The molecular structure of shellac contains hydroxyl, carboxyl, ester, and aldehyde groups as the main active functional groups, which can be readily chemically modified. The formation of ether bonds through the reaction between acrylic acid groups and hydroxyl groups represent a significant enhancement in mechanical properties [50,51]. Achieving this often necessitates a synergistic approach involving UV exposure, γ-radiation, and grafting. For instance, grafting 2-hydroxyethyl methacrylate (HEM) onto shellac under UV light notably boosted tensile strength by 36.8 % and elongation at break by 17.64 % [50]. Furthermore, esterification reactions can yield comparable benefits [52]. For instance, grafting succinic anhydride onto shellac increased puncture strength by 6 MPa and elongation at break by 88 %. However, it is worth noting that, in shellac succinate, the introduction of free carboxylic acid from succinic anhydride elevated water vapor permeability by 16.18 % [52].

The quantity of carboxyl groups is a key factor affecting the solubility of shellac. The use of 2 % sodium hydroxide and ammonium hydroxide to promote ester bond cleavage on shellac increased the carboxyl content and enhanced the solubility of shellac under acidic conditions [53]. This carboxyl salt shellac resin can prevent self-polymerization of shellac and improve the mechanical properties of shellac film during storage. Jeffamine® is an excellent modifier containing amino groups. When the amine functional group on it reacts with the carboxyl group of shellac, an amide bond can be formed. This leads to a decrease in free carboxyl groups, thereby delaying aging [54].

Another important structure in shellac molecules is the upper α,β-unsaturated double bond. When sodium hypochlorite is used to bleach natural shellac, it also adds and destroys the α,β-unsaturated double bonds, adding chlorine radicals to the carbon-carbon double bonds [55,56]. This will accelerate the polymerization of shellac resin and affect its service life [57]. To solve the problem, Ni—Fe was used as a catalyst to add hydrogen gas to bleached purple gum resin to combine with the chlorine on the resin, reducing the chlorine content to 1/5 of its original level [58]. Preparation of Pd-Ni@SiO bimetallic nanoparticles can reduce the chlorine content of shellac to 0.38 wt% by a ultrasound-enhanced chemical precipitation method [59]. In order to achieve sustainable green bleaching, hydrogen peroxide is gradually gaining popularity. However, hydrogen peroxide can hydrolyze the ester chains of shellac and oxidize the hydroxyl groups into aldehydes or ketones, resulting in decreased softening point and increased acid value [56]. Anyway, in the process of bleaching, shellac not only decreases in molecular weight, but also deteriorates its mechanical properties, which is mainly due to the hydrolysis of the backbone [55,60]. The decrease in polarity also leads to an increase in its hydrophilicity, which is most intuitively reflected in the increase in water vapor transmission rate [60].

2.2.2. Physical modification

Compared to chemical modification, mixing shellac with plasticizers or other safe organic materials is a safer and more economical method. In the past, when several short-chain and linear chain additives were used for shellac, the flexibility of shellac films was improved, and the aging (self-polymerization) of the films over time was also delayed [61–63]. When citric acid (CA) was added to shellac films based on weight, triacetin effectively plasticized the films with a maximum strain of 60 %, while triethyl citrate (TEC) had a minimal effect, resulting in only a maximum strain of 3.1 % [62,63]. Polyethylene glycol (PEG) 400, due to its larger molecules, interfered with the interactions between carboxyl and hydroxyl groups in shellac, making it a more prominent plasticizer for extending the stability of shellac film [63]. In a recent study, oleic acid also showed a similar effect. The long-chain fatty chains of oleic acid are integrated into the molecular chains of shellac, causing damage to the matrix and increasing the elongation at break of the shellac film by nearly 35 times [64].

Non-covalent bonds such as hydrogen bonds, electrostatic attractions, and hydrophobic interactions are the main ways in which shellac interacts with other polymers. The hydrogen bonding and hydrophobic interactions between shellac and active substances are beneficial for

forming a stable core-shell structure [65–69]. Integrating positively charged molecular materials such as chitosan [70,71], gelatin [72], and telechelic α,ω-diamino functionalized polydimethylsiloxane (NH_2-PDMS-NH_2) [73] into shellac, driven by hydrogen bonding and electrostatic interactions, can form highly dispersed, stable, and mechanically excellent composites. This section will be discussed in detail in Sections 2.3.4 and 3.1.3.

2.3. Physicochemical properties

2.3.1. Solubility

Shellac, insoluble in water, possesses acidic properties attributed to its free carboxyl and hydroxyl groups, rendering it soluble in alkaline solutions (Table 1). Additionally, the dissolution rate and quantity of shellac are directly proportional to pH [39]. Protonation under acidic conditions impedes shellac solubilization [71,74]. Furthermore, organic acids and ketones serve as effective solvents. Shellac demonstrates partial solubility or insolubility in organic solvents such as glycerol, esters, benzene, and ether [27,75,76].

Research by Banerjee et al. explored solubility parameters, demonstrating that shellac remains insoluble in weakly hydrogen-bonded solvents like hydrocarbons and chlorinated hydrocarbons but exhibits solubility in medium to strong hydrogen-bonded solvents [131]. Aging diminishes shellac's solubility in organic solvents and enteric solutions [39]. Moreover, wax-containing shellac exhibits reduced solubility rates at the same pH due to the hydrophobicity of the waxes [39]. Despite its solubility in various solvents, the selection of solvent should be tailored to specific requirements. For instance, ketone solvents, known for their strong odor and corrosive nature, are typically avoided or used sparingly. Moreover, when employed as a lacquer material, the solvent choice influences drying time and adhesion properties.

2.3.2. Thermal properties

As a polymer resin, shellac exhibits a modest disparity between its softening and melting temperatures. The softening temperature spans from 65 to 70 °C, while the melting temperature falls between 75 and 80 °C [25]. Unlike beeswax and insect white waxes, insect waxes, including shellac, lack a specific relationship between the enthalpy change (ΔH) of melting and crystallization and the melting point [132]. Over time, the polymerization reaction leads to the formation of a denser shellac structure, resulting in an increase in the transition temperature [39]. Shellac demonstrates typical shear-thinning behavior, with the viscosity of both waxed and dewaxed shellac decreasing as shear rate increases. Notably, wax-containing shellac exhibits higher melt viscosity and a lower glass transition temperature (T_g) than dewaxed shellac [38]. Murthy et al. also reported that the thermal transition range and latent heat of shellac waxes remained consistent even after 300 thermal cycles, indicating good thermal stability [133].

While shellac is polycrystalline, its crystallinity is relatively low. X-ray diffraction (XRD) studies have confirmed the amorphous structure of shellac, displaying two distinct crystalline regions and a broad peak [134]. Furthermore, observations from the cooling of molten shellac using differential scanning analysis have revealed the formation of spherical crystals at various temperatures, providing further evidence of shellac's crystallization behavior [134,135].

2.3.3. Aging or polymerization

The aging process of shellac is essentially a polymerization process. Over time, the aldehyde groups on the molecular structure of shellac undergo oxidation, converting into carboxylic acid groups, and the ester bonds also undergo modifications, as evidenced by FTIR analysis. Investigation into the polymerization process of shellac involved spectroscopic measurements of different types of shellac, revealing an increase in the intensity of ester peaks and a decrease in the intensity of —OH peaks [37]. The polymerization reaction resulting from esterification leads to a reduction in the acid value and T_g of shellac, impacting various properties of shellac [39].

To investigate the aging process of shellac, melt rheology was employed alongside liquid and gas chromatography to monitor molecular changes [136]. Natural and artificial aging conditions led to the formation of a three-dimensional network within shellac, increasing its relative molecular weight and viscosity through polyester matrix cross-linking [136,137]. Additionally, photoaging induced the appearance of fragments resembling hydroxyl fatty acid molecules similar to aleuritic acid, which were absent in the initial shellac [138]. Laser-induced fluorescence intensity and shifts in infrared spectra increased,

Table 1
Selection of solvents for shellac in different fields.

Forms	Solvent	Methods	References
Gel	Dimethyl sulfoxide (DMSO), *N*-methyl-pyrrolidone (NMP), 2-pyrrolidone	In-situ formation	[77–81]
	Ammonium	Chemically crosslinked	[82]
	Ammonium hydroxide	γ-irradiation	[83]
	Alkaline solution	Co-folding by pH-shifting	[84]
Films/coatings	Ammonium	Solvent evaporation	[85]
	Alcohol	Solvent evaporation	[71,86,87]
	Alcohol	Spin coating	[40,88,89]
	$NH_3{\cdot}H_2O$	Solvent evaporation	[90–92]
	Alcohol	Spray coating	[29]
	Propylene Glycol-water	Paste coating	[93]
	Ammonium hydroxide	Dip coating	[94,95]
	Ammonia	Dip coating	[96]
	$NH_3{\cdot}H_2O$	Dip coating	[97]
	Alcohol	Dip coating	[95,98–102]
	Methanol	Dip coating	[103]
Microcapsule/ microparticle	–	pH-driven	[104],
	Ethanol	Anti-solvent precipitation	[105]
	Alkaline solution at pH 8	pH-driven	[106]
	NaOH	pH-driven	[69,107]
	Water	Emulsion and cold-gelation	[108]
	Ethanol	Coaxial electrospray	[109]
	Ethanol	Triaxial electrospinning	[110]
	Sodium carbonate	Anti-solvent precipitation	[111]
	Ammonium bicarbonate	Spray-dried	[112]
	Ethanol	pH-driven	[113–115]
	Ammonia	pH-driven	[116]
	Ammonia	External gelation	[116]
	DMSO, NMP, 2-pyrrolidone	In-situ formation	[77,78,117]
Nanofiber	Ethanol	Electrospinning	[117–121]
Nanoparticle/ nanocapsule	Sodium carbonate	Ionic cross-linking	[122]
	Ethanol	Antisolvent precipitation	[123]
	Ethanol	Coaxial electrospray	[124]
	Ethanol	Microfluidics	[66]
	Water (pH 12.0)	pH-driven	[65]
	Ammonia	pH-driven	[125]
	Methanol, ethanol, or butanol	Electrospraying	[126]
Matrix tablets	–	Fusion and molding	[127,128]
	–	Direct compression	[129]
	–	Wet granulation	[130]

Abbreviations: DMSO, dimethyl sulfoxide; NMP, *N*-methyl-pyrrolidone.

indicating oxidation and cross-linking products during shellac polymerization [139]. These changes were corroborated by reductions in flat areas in multiphoton excitation fluorescence curves [139]. Furthermore, GC–MS and pyrolysis gas chromatography–mass spectrometry (Py-GC–MS) using quaternary ammonium reagents (tetramethylammonium hydroxide and trimethyl[α,α,α-trifluoro-*m*-tolyl]ammonium hydroxide) revealed increased terpenes abundance in aged resins due to oxidation of jalaric and laccijalaric acids [140].

2.3.4. Miscibility

Shellac, featuring functional groups like hydroxyl, carboxyl, and aldehyde, can create composite coatings with diverse biomolecules such as starch, proteins, and hydrophilic colloids via noncovalent interactions such as hydrogen bonding, hydrophobic interactions, and electrostatic attractions. Unlike rice and corn starch, glutinous rice and tapioca starch with lower amylose content can tightly bind with shellac [85]. Hydrogen bonding and hydrophobic interaction between shellac and substances like curcumin and fucoxanthin resulted in stable composite materials with a core-shell structure, facilitating the delivery of hydrophobic active substances [65,66]. However, shellac nanoparticles tended to aggregate under acidic conditions, potentially reducing the utilization of encapsulated active substances in the intestine [141].

To address this issue, a 2 % w/v shellac solution was added to a quaternized chitosan (QCS) solution, forming a double-layer nanoshell (Sh-QCS) via electrostatic interactions. When the QCS concentration exceeded 0.05 %, this approach effectively solved the aforementioned problem, increasing the encapsulation efficiency of quercetin from 37.92 % to 65.48 % [70]. Using microfluidics, water-in-oil-in-water double emulsions were formed, incorporating 1.7 mg/L of negatively charged shellac nanoparticles dispersed in water and 1 wt% positively charged NH_2-PDMS-NH_2, resulting in the creation of porous ultra-shell microcapsules [73]. The cross-linked structure of shellac enabled selective permeation, enabling the encapsulation of large molecules within the core while facilitating the transport of small molecules across the shells [73].

Moreover, electrostatic interactions facilitated the successful integration of shellac nanocapsules containing cinnamaldehyde into chitosan membranes, creating a versatile packaging film exhibiting controlled-release properties activated by pH variations [142]. Through the joint driving force of disulfide bonds and hydrophobic interactions, shellac and protein can exhibit good compatibility [84,143]. Guo et al. demonstrated the fabrication of soy protein isolate/shellac hydrogels with dense structures through pH transformation by mixing 10 w/w shellac dispersed in an alkaline solution of pH 8 with a 12 % w/w soy protein isolate (SPI) suspension, overcoming the challenge of forming hydrogels with SPI alone through pH adjustment [84].

3. Development of shellac as a functional material in multiple fields

3.1. Leveraging film-forming characteristics

3.1.1. Influence of solvents

Shellac, a natural acidic polysaccharide with a specific structure, exhibits unique properties. While insoluble in water, it demonstrates film-forming ability in alcohol and alkaline solutions [27,144]. In alcoholic solutions, esterification occurs between the carboxylic acid group of shellac and the hydroxyl group of the alcohol, leading to the formation of a homogeneous shellac solution; under alkaline conditions, the polyester chain in shellac is susceptible to hydrolysis, breaking down the ester bond into free carboxyl groups [53,63]. The increased carboxyl groups react with salts to form stable carboxylate solutions. Previous studies have indicated that shellac exhibits better stability in alkali metal solutions compared to ethanol solutions [145,146]. Polyethylene glycol can shape the thermoplastic properties of shellac, making it a good candidate material for 3D printing [147].

Traditionally, shellac coatings have been utilized as varnish materials for wood products [148], metals [149], or artifacts such as paintings and sculptures [19], ensuring surface smoothness and wear resistance while serving as a protective function. In recent years, numerous studies have focused on employing shellac in food packaging to extend the shelf life of packaged products (Table 2). Smooth muscle cells and endothelial cells coated on alkali-treated shellac demonstrated excellent adhesion and blood compatibility with the substrate, highlighting shellac's significance as a material for intravascular device coatings [150,151].

3.1.2. Impact of additives

Shellac films alone often exhibit brittleness. However, the addition of plasticizers can mitigate this brittleness by disrupting the hydrogen bonding between lipid and hydrocolloid molecules [157,158]. Consequently, incorporating plasticizers significantly enhances the mechanical properties of shellac films. Compared to the commonly used plasticizer TEC, organic acids proved more effective in enhancing the flexibility of shellac films, leading to a significantly reduced T_g in the modified films [33].

To enhance the stability of shellac, carboxylic acid groups are typically protected using alkali metal salt solutions [94,96,155]. Furthermore, it has been observed that the interaction between 2-amino-2-methyl-1-propanol (AMP) and carboxylate ion binding sites is stronger compared to ammonium ions. Therefore, when AMP and ammonium hydroxide (AMN) were used as salt-forming agents in different ratios, shellac films exhibited improved solubility and flexibility with increasing AMP content, as depicted in Fig. 4(a, b) [146]. A similar phenomenon was noted in enteric-coated films: ammoniated enteric-coated films displayed greater brittleness than acid-formed films prepared from organic solvents [159]. Additionally, the mechanical properties of the films were enhanced by grafting different concentrations of 2-methacrylic acid-hydroxyethyl monomer under UV irradiation [50].

Emulsifiers play a crucial role in overcoming phase separation during the preparation of composites [157]. While shellac and hydroxypropyl methylcellulose are not inherently compatible, the addition of two emulsifiers, stearic acid, and lauric acid, enabled the formation of films with favorable properties such as hydrophobicity, mechanical robustness, and thermal stability [160].

3.1.3. Mixed with other polymers

Combining individual biomolecules is a common practice to enhance structural integrity and functionality, as individual biomolecules lack these attributes [161]. The approach is particularly effective in mitigating the aging of wormwood. Fig. 4(c, d) illustrates how the active sites of shellac were protected by gelatin. Enhancing the stability of the laminated film occurred notably when higher concentrations of gelatin (30–50 %) were added to a 6 % (w/w) shellac solution, owing to electrostatic interactions between them [72].

The addition of juglone from walnut green husk extract (WGHE) to shellac, soy protein, instant starch coatings, and their equal-part mixtures including 5 g of decolorized shellac, respectively, resulted in composite coatings with superior efficacy in inhibiting the rate of fat content decline in walnuts during storage [93]. Hydrogen bonding facilitated the connection between shellac and konjac glucomannan (KGM) [162]. Incorporating 10 mL of a 10 % shellac solution into the KGM film not only improved the film's hydrophobicity but also enhanced its heat resistance and mechanical properties [162].

Optimizing films by adding cellulose nanocrystals, glycerin, sodium alginate, and carrageenan, followed by the addition of 0.6 % (w/w) shellac, results in a film with lower tensile strength and higher elongation at break [86]. Electrostatic interactions facilitated the formation of a homogeneous solution between shellac and chitosan (Fig. 4e). Films composed of shellac nanoparticles and chitosan with higher shellac content (25 mg/mL) exhibited superior physical properties and thermal performance compared with those with lower shellac content (15–20

Table 2
Shellac-based coatings for food preservation.

Coatings	Solvent	Application effects	References
Shellac/glutinous rice starch or shellac/tapioca starch	Ammonium solution	1. The browning of the surface of lime (*Citrus aurantiifolia*) was delayed. 2. Weight loss and hardness loss were reduced.	[85]
Alginate/carrageenan/shellac films with cellulose nanocrystals	Alcohol	1. The quality loss and bacterial attachment of chicken breast meat were reduced; The increase of TVB-N was delayed. 2. The quality loss, water vapor transmission rate, and pH change in cherry tomatoes were reduced; Antibacterial ability was increased.	[86,150]
Shellac coating	Alcohol	1. The intimal hyperplasia in rat collateral arteries was inhibited.	[40]
Shellac (bleached shellac) coating	Ammonia	1. The weight loss, hardness, loss of ascorbic acid content, respiratory rate, lipid peroxidation, and titratable acidity of mangoes were reduced; The smoothness of the fruit peel surface and TSS were increased. 2. Skin browning was suppressed; Aromatic compounds were retained; Cell permeability was reduced. 3. Excellent antifungal ability against *Colletotrichum gloeosporioides* and Mango Phoma leaf spot.	[90]
Double-layer coating of shellac/ascorbic acid, citric acid, or hydrochloric acid	Alcohol	1. The weight loss, hardness loss, and decay rate of litchi fruit were reduced; Browning and titratable acidity were delayed. 2. The contents of ascorbic acid, anthocyanins, and total phenol were decreased. 3. The activity of various enzymes was reduced.	[87]
Beeswax/shellac wax coating	Alcohol	1. The contact angle of the coated paper became larger. 2. Water absorption rate was decreased.	[29]
Decolorizing shellac coating with juglone	Propylene glycol-water	1. The quality loss of walnut kernels was reduced; The decrease in fat content, acid value, and peroxide value was suppressed. 2. The contents of soluble proteins were increased; Sensory evaluation scores were improved. 3. Bacteria, especially *Staphylococcus epidermidis*, were inhibited.	[93]
Chitosan/shellac nanoparticle film with curcumin	Alcohol	1. The color change of shrimps was delayed. 2. Bacteria were inhibited.	[71]
Shellac wax coating with carvacrol or thymol	Alcohol	1. The development of diploid stem-end rot and the impact of cold damage on 'Ruby Red' grapefruit were reduced. 2. Weight loss and spoilage rate were reduced. 3. Softening was delayed.	[152]
Shellac (dewaxing and bleaching)/aloe gel coating	Ammonium hydroxide solution	1. The respiration rate, ethylene synthesis, and color change of tomatoes were delayed. 2. Weight loss was reduced; Hardness was maintained. 3. Decay was inhibited.	[94]
Carnauba/shellac wax coatings with lemongrass oil	Alcohol	1. The growth of aerobic bacteria, yeast, and mold in 'Fuji' apples was inhibited. 2. Weight loss and the change in TSS/TA ratio were reduced. 3. Hardness and color were maintained.	[153]
Shellac/sodium alginate coating	Alkaline aqueous solution (0.6 % ammonia)	1. The respiratory rate, weight, and loss of ascorbic acid, phenolic, and flavonoid compounds in green chilies were reduced. 2. Hardness was maintained; Color change was delayed.	[96]
Shellac (dewaxing and bleaching) coating	NH_3 (0.8 g/100 mL water)	1. The weight loss rate and respiration rate of Chinese water chestnut (*Eleocharis tuberosa*) were reduced. 2. Hardness and brittleness were maintained; Electrolyte leakage and fruit decay were inhibited. 3. The decline in peroxidase (POD) was delayed.	[97]
Shellac (dewaxing, bleaching) coating	Alcohol	1. The softening, enzyme activity, and weight loss rate of Hami melon (*Cucumis melo* var. *saccharinus*) were reduced. 2. Degradation of cellulose and hemicellulose was delayed.	[98]
Shellac coating	Alcohol	1. The color change of lime fruit was delayed; Respiration rate and water loss were reduced. 2. Total chlorophyll content was maintained; Enzyme activity was inhibited. 3. Titratable acidity was reduced; the accumulation of total ascorbic acid and hydrogen peroxide content was increased.	[154]
Shellac coating	Alcohol	1. The weight loss rate, TSS, and protein viscosity of eggs were reduced. 2. High Haval units (HU), and yolk index (YI) were maintained.	[99]
Shellac coating	Alcohol	1. The mechanical strength of eggshells was improved. 2. The bacteria of eggs was reduced (*Enterobacteriaceae*, coagulase-positive staphylococci, total viable mesophilic bacterial counts, yeast, and mold).	[100]
Shellac/gelatin coating	Alcohol	1. The color of bananas changed slowly. 2. The decrease in TA and the increase in soluble sugars TSS were delayed. 3. Weight loss and hardness were decreased; yeast and mold were inhibited.	[91]
Shellac coating	Alcohol	1. The weight loss, respiratory rate, and TA of 'Valencia' oranges were decreased. 2. The decrease in hardness was delayed. 3. TSS, pH, ascorbic acid content, total phenolic content (TPC), and total antioxidant capacity (TAC) were increased.	[101]
Shellac coating with cinnamon essential oil (CEO)	Alcohol	1. The weight loss, firmness loss, and ascorbic acid content loss of 'Thomson navel' oranges were reduced. 2. The decay rate was decreased.	[95]
Shellac coating	0.5 % NH_4OH solution	1. The weight loss of apples (Royal Delicious) was reduced; Hardness and maturity index were maintained. 2. Decay rate was reduced. 3. Aroma volatile loss and respiratory rate were reduced.	[155]

(*continued on next page*)

Table 2 (*continued*)

Coatings	Solvent	Application effects	References
Shellac coating with 1-methylcyclopropene (1-MCP) encapsulated into α-cyclodextrin (α-CD)	Alcohol	1. The production rate of ethylene in apples was reduced. 2. Hardness and titratable acidity were increased.	[156]
Pullulan-shellac film	Ammonia	1. The color of cherries changed slowly 2. The increases in weight loss rate, hardness, TSS, and TA was delayed 3. The storage period was extended to 7 days.	[92]

Abbreviations: TA, titratable acid; TSS, total soluble solids.

mg/mL) [71]. Incorporating inhibitors into shellac coatings effectively inhibited spot development and fruit rot caused by natural infections and cold damage without fruit quality compared to shellac coatings alone [90,121].

3.1.4. Conjunction with modern processing technologies

Shellac coatings, when combined with modern technologies, offer an enhanced advantage in preserving the freshness of fruits. Electron beam irradiation applied to fresh fruits inhibited physiological growth and extended shelf-life through its sterilization function [163]. However, irradiation at 3 kGy in cauliflower delayed chlorophyll degradation but compromised quality [164]. This drawback of electron beam irradiation was also reported by Ramakrishnan et al. [165]. Combining shellac coating with electron beam irradiation maintained the quality of lime fruits by delaying the color change of lime peel, reducing respiration rate and water loss, and delaying chlorophyll degradation [154].

Electrospinning technology plays a vital role in producing nanofibrous films characterized by a large specific surface area, smooth surface, and uniform fiber distribution [119]. Utilizing electrospinning, the ethanol solution of shellac could be directed to form a continuous jet through the tip of a needle, leading to the creation of fibrous structures on the collector [120]. Compared to polyvinyl pyrrolidone (PVP) fiber, a shellac/PVP fiber membrane containing 50 % (w/v) shellac maintained a homogeneous structure. These membranes, when loaded with eugenol, demonstrated the ability to inhibit strawberry respiration rate and preserve the quality of strawberries for up to six days post-harvesting, attributed to excellent moisture resistance and thermal stability (Fig. 5A) [121].

The utilization of shellac, particularly in the form of nanoparticles, in fabricating functional packaging films has garnered significant attention [124,142]. Incorporating shellac nanoparticles into a chitosan film solution enabled real-time monitoring of pork spoilage and deterioration (Fig. 5B) [142]. Moreover, when thymol/zein/shellac particles, produced using coaxial electrostatic technology, were applied as coatings on cantaloupe, the shelf life of the fruit was extended to 16 days [124]. As illustrated in Fig. 5C, a packaging film exhibiting selectivity for carbon dioxide and oxygen was achieved by adding chitosan porous microspheres (CSPM) and poly(L-lactic acid) porous microspheres (PPM) to a shellac coating [167]. Conversely, shellac nanoparticles offered advantages in improving the film-forming properties of chitosan [71].

3.2. Leveraging electrical properties

As shown in Fig. 6a, the performance of organic field-effect transistors (OFETs) is significantly influenced by carrier migration efficiency and the quality of the interface contact, which is closely tied to the gate dielectric. High dielectric materials can decrease operating voltage, enhance electron injection efficiency, and facilitate smoother planes with lower contact resistance [168]. Previous assessments have highlighted the insulation properties of shellac [169].

When shellac was employed in OFETs, with fullerene C60 and pentacene serving as organic semiconductors, electron mobility values of 0.4 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and 0.2 $cm^2 \cdot V^{-1} \cdot s^{-1}$ were achieved, respectively [170]. When utilized as an insulating dielectric on silicon, shellac could produce a smooth and flat plane, exhibiting good charge mobility and low leakage current when combined with both P (DPP-T) and P (DPP-TVT) semiconductor materials, respectively [88]. In the bottom-gate top-contact structure utilizing gold electrodes, the absorption of active materials in a paper substrate was reduced, as the semiconducting material was directly deposited on shellac instead of the paper, resulting in improved output and transmission characteristics of the overall construction [88].

Furthermore, a bipolar organic thin-film transistor (OTFT) was developed by using shellac as a green dielectric material, exhibiting hole and electron carrier mobility values as high as 0.042 and 0.14 $cm^2 \cdot V^{-1} \cdot s^{-1}$, respectively [89]. All combinations demonstrated low hysteresis due to the low trap density and defects between the semiconductor material/shellac interface. The low hysteresis of field-effect transistors suggested a potential comparable to commercial dielectric materials such as polyvinyl alcohol and poly(methyl methacrylate) [103,170].

As a dielectric material, the dielectric constant of shellac may be affected by ambient temperature and humidity [171]. This may affect the stability of the whole device. Moreover, the bulk size of shellac changes with temperature, which is also detrimental to the performance of the device.

3.3. Leveraging encapsulating capabilities and pH-responsiveness

Bioactive substances like probiotics [172,173], enzymes, [174], and polyphenols are often encapsulated to enhance their stability, improve viability, and regulate their release behavior in the gastrointestinal environment. This encapsulation is crucial due to their responsiveness to various factors such as temperature, humidity, and pH during processing and application. As depicted in Fig. 7, shellac demonstrates unique solubility characteristics in the gastrointestinal environment owing to carboxyl ionization, being insoluble in the highly acidic gastric environment and soluble in the pH-neutral intestinal tract [175]. In addition, shellac shows promising potential for encapsulating hydrophobic active substances through hydrophobic interactions [65–69]. This noncovalent bonding minimizes the impact on the activity of these active substances to the greatest extent. This pH-dependent solubility of shellac makes shellac an excellent enteric coating (Table 3). Composite enteric coatings of modified rice protein (MRP)/ammonium shellac (NH_4SL) were fabricated by mixing NH_4SL (obtained by adding a 2.0 M aqueous $(NH_4)_2CO_3$ solution to a 20 % (w/v) shellac ethanol solution) at pH = 8.2 with MRP solutions ranging from pH 7.0 to 13.0. These coatings maintained integrity in 0.1 M HCl without affecting their disintegration at neutral pH [102]. In shellac microcapsules, sodium alginate in the internal aqueous phase and soybean oil or coconut oil in the intermediate phase could provide additional barrier layers, greatly increasing the survival rate and stability of plant *Lactobacilli* under various conditions [104].

The insolubility of shellac in acids and the dense structure formed between shellac and buckwheat protein in microcapsules increased the viability of *Lactobacillus plantarum* in SGF and SIF from 2.85 log CFU/mL to over 8 log CFU/mL, showing the improved viability of the probiotic in the gastrointestinal tract [106]. Beads are favored as another form of encapsulation and delivery of orally administered drugs due to their good bioavailability [116,178,179]. In contrast to natural rubber/sodium bicarbonate beads, natural rubber/shellac beads controlled the

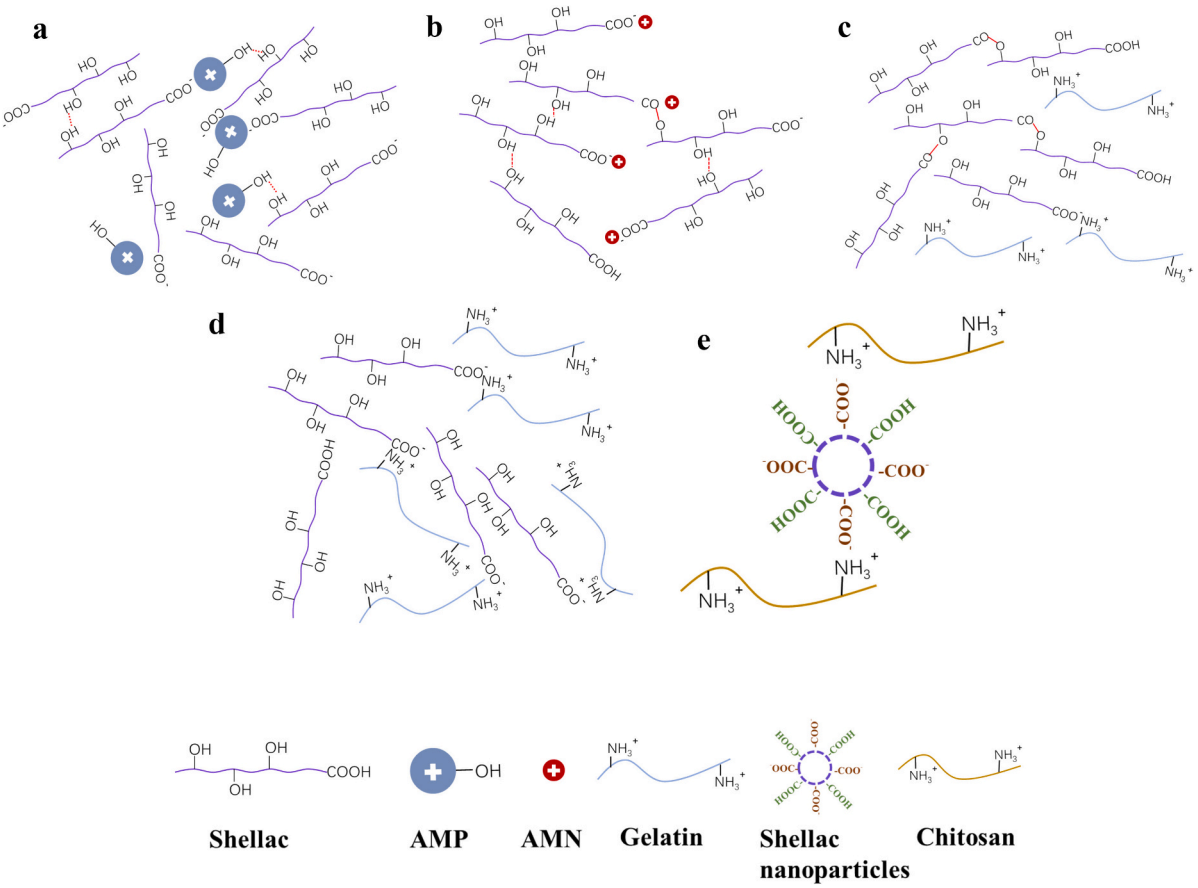

Fig. 4. Proposed diagram illustrating the formation of 2-amino-2-methyl-1-propanol (AMP) (a) and ammonium hydroxide (AMN) (b) salts of different shellac forms. Redrawn from [146] with permission from Elsevier, Copyright 2007. Proposed diagrams depicting the polymerization process of composite films after 180 days of storage at 40 °C and 75 % RH: composite films with low (c) and high (d) concentrations of gelatin. Redrawn from [72] with permission from Elsevier, Copyright 2013. (e) Schematic representation of the interaction between shellac nanoparticles and chitosan. Redrawn from [71] with permission from Elsevier, Copyright 2021.

release of theophylline in a phosphate buffer (pH 6.8), while there was almost no release in a HCl buffer (pH 1.2). It is worth noting that in the concentration range of 25–40 % (w/v), the higher the shellac content, the more considerable the drug release [116]. Similarly, effervescent floating matrix tablets obtained by annealing shellac and sodium bicarbonate reduced the rate of drug release in 0.1 N HCl [180]. Alginate/shellac beads involving 1.5 % (w/v) alginate and 6.5 % (w/v) shellac encapsulating R-phycoerythrin effectively prevented premature leakage before reaching the colon. Furthermore, inclusion of $CaCl_2$ at 5 $g{\cdot}L^{-1}$ loading increased the encapsulation efficiency of the alginate/shellac material to 97.5 % [68].

The main factors affecting the drug release of shellac-based matrix tablets are the annealing process and shellac concentration [129,130,180]. With increasing shellac content, the inhibitory effect of the shellac network on drugs became more obvious [130,180]. Tablets containing 40–50 % shellac released metronidazole (MZ) over a period of 6–8 h in 0.1 N HCl (pH 1.2) solution. The release rate of MZ in matrix tablets containing 5 % w/w shellac was similar to that of regular tablets [130]. As the annealing temperature increased from 40 °C to 80 °C, the tablets became stronger due to the in-situ polymerization of shellac, and its disintegration rate was further delayed [129]. Shellac wax, as a lipid matrix, led to excessively slow drug release, and this issue can be addressed by modifying the drug release profile of the wax backbone using hydrophilic polymers [127,128]. The addition of 7:3 lutein/shellac instead of lutein as an inner layer promoted the release rate of propranolol hydrochloride and hydrochlorothiazide. This is because the lower hydrophilic lutein content promotes the dissolution of shellac matrix pieces by increasing water absorption, while the gel network with higher lutein content exerts a slow-release effect [128].

Chitosan films embedded with shellac/cinnamaldehyde nanocapsules (CSNCs) were employed for assessing pork freshness. Notably, there was a considerable decrease in cinnamaldehyde release in an acidic environment at pH = 5 (15.52 ± 0.92 mg/g) compared to an alkaline condition at pH = 9 (34.09 ± 2.35 mg/g) [142].

Shellac/SPI hydrogels exhibited low protein hydrolysis in the gastrointestinal tract, possibly attributed to shellac's insolubility at acidic pH or the inaccessibility of the binding sites of shellac and SPI by digestive enzymes, which enhanced digestive stability [84]. Shellac effectively transported therapeutic enzymes and antibacterial substances to the colon, thereby preventing colon cancer [107,122]. In the fabrication of chitosan/sodium alginate gel particles (CS/SA) loaded with superoxide dismutase (SOD), incorporating 15 % shellac improved acid resistance, preventing premature SOD release in intestinal fluids [122]. Shellac nanoparticles encapsulating curcumin and quercetin demonstrated 48 % bioavailability, with a significant portion delivered to the colon [107]. Unmodified shellac underwent irreversible aggregation under acidic conditions [181], often necessitating modification with polysaccharides with improved stability [141]. Shellac/sodium caseinate nanoparticles loaded with quercetin, optimized at 2 % (w/v) shellac and 0.3 wt% sodium caseinate, addressed these challenges, achieving a 72.39 % release rate of quercetin within 4 h [123]. Nanoparticles made from shellac and locust bean gum was successfully used for the sustained delivery of curcumin and epigallocatechin gallate. This approach offers a viable strategy for managing diabetes and nephropathy [125]. Snowman-like nanoparticles, comprising polylactic acid (PLA) and shellac spheres loaded with the hydrophobic fluorescent dye

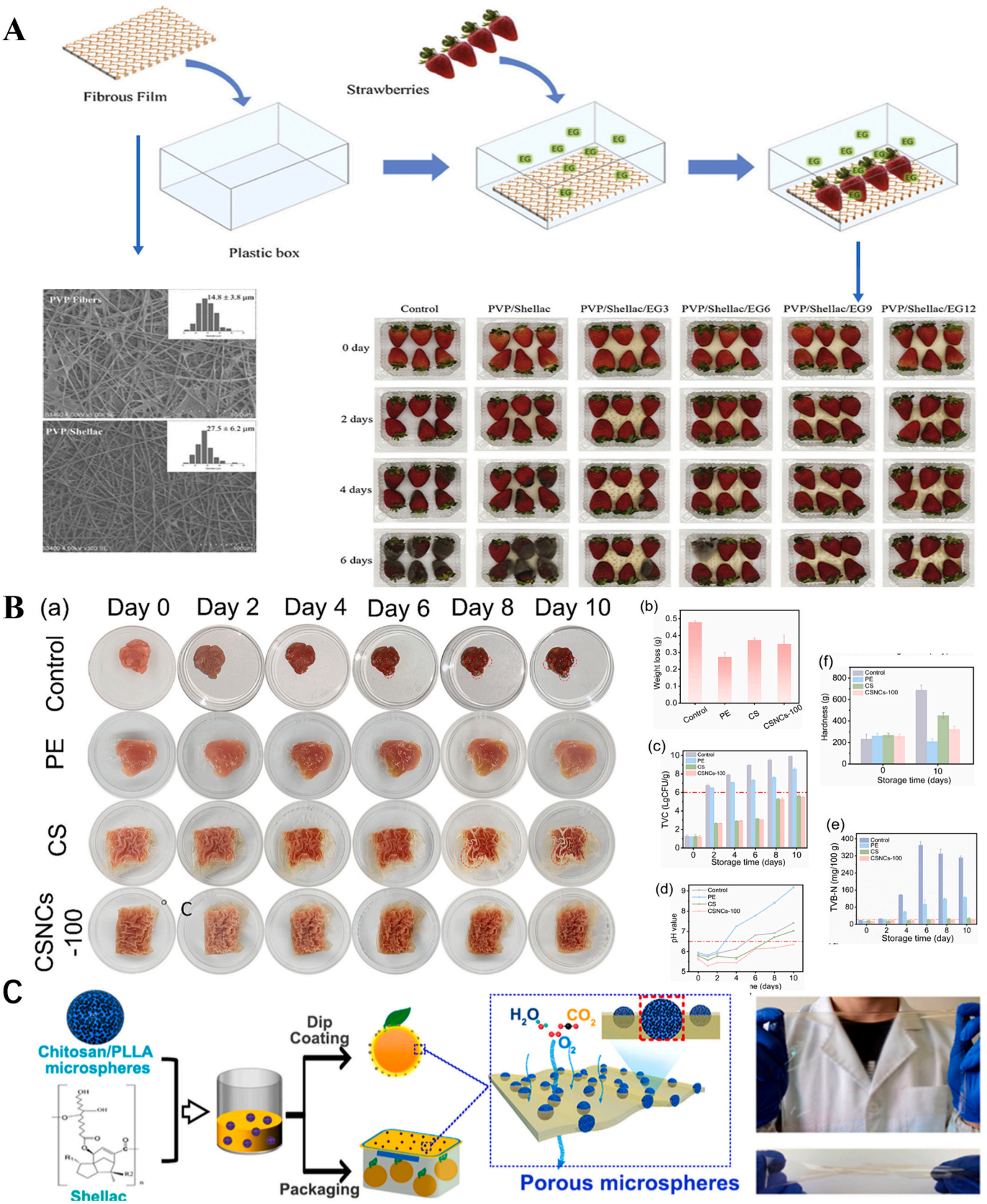

Fig. 5. (A) Diagram depicting strawberry fresh packaging. Adapted from [121] with permission from Elsevier, Copyright 2020. (B) Changes of pork in different films (chitosan film without or with shellac nanoparticles) during storage. Reprinted from [142] with permission from Elsevier, Copyright 2024. (C) Schematic representation of the preparation of the chitosan/PLLA/shellac hybrid membrane and the dip-coating or packaging processes for using the membrane on fruits. Reprinted from [166] with permission from the American Chemical Society, Copyright 2021.

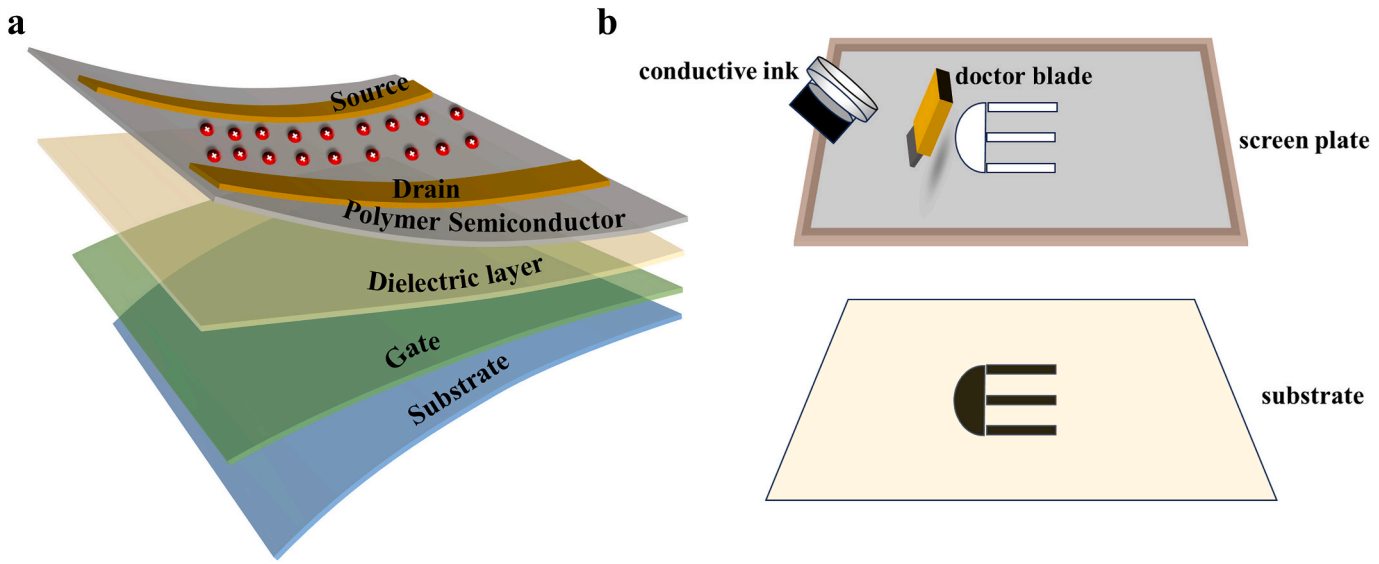

Fig. 6. (a) Architecture of organic field-effect transistors (OFETs) employing shellac as a dielectric layer. (b) Application of shellac conductive ink in 3D printing.

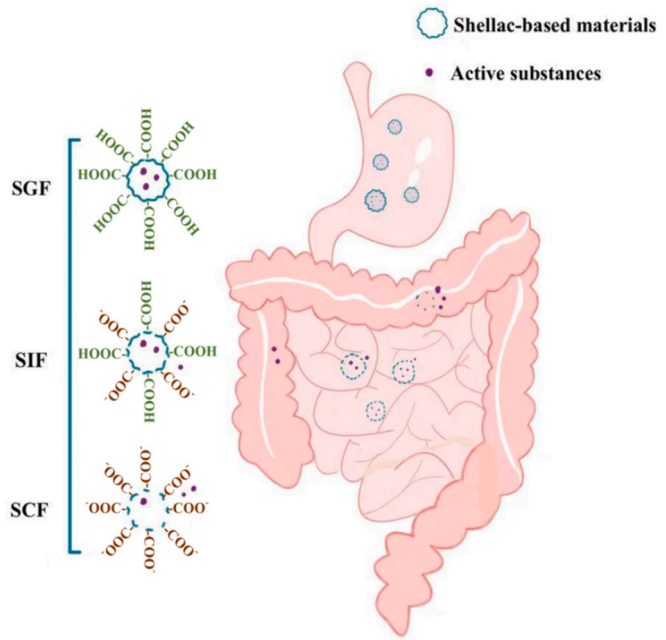

Fig. 7. Mechanism of the action of shellac-based delivery systems in the digestive tract.

Nile red, offered adjustable shape and size based on the shellac-to-PLA concentration ratio [67]. These nanoparticles, with their low surface energy, exhibited high permeability, releasing 68 % of the total drug over 10 days [182]. The concentration of shellac is a crucial factor affecting particles [126]. In the process of preparing nanoparticles by electrospray, reducing the concentration of shellac was beneficial for reducing viscosity, aiding formation of smaller droplets, and a 20 % (w/w) shellac concentration achieved the smallest nanosized particles (236.40 nm) [126].

Microwave-assisted methods further enhanced the stability of nanoparticles by reducing their size, thereby increasing surface area to volume ratio [183,184]. Employing a microwave-assisted method, celecoxib/shellac nanoparticles with a drug-to-polymer ratio of 1:3 achieved a release rate of 92.72 ± 1.7 % after 8 h at colonic pH [185].

Thin films of shellac nanofibers prepared via electrostatic spinning were utilized for targeted delivery [186]. Shellac nanofibers loaded with *Kaempferia parviflora* (KP) extracts exhibited a sustained release of KP for up to 10 h at neutral pH (pH = 7.2) [176]. After optimizing the electrospinning conditions, the shellac nanofibers containing *Senna alata* (SA) leaf extract achieved drug release for up to 12 h in a pH 7.4 phosphate buffer solution, with a release rate exceeding 90 % [118]. In ferulic acid (FA)-loaded shellac nanofibrous membranes, FA release was minimal under acidic conditions at pH 2.0. The core solution comprised 10 mL of ethanol, 7.5 g of shellac, and 1.5 g of FA, while the shell consisted of a mixture of ethanol and *N*,*N*-dimethylformamide. Upon exposure to a neutral solution, the fiber structure gradually expanded and swelled, leading to a slow release of ferulic acid [187]. Quercetin-loaded shellac nanofibers exhibited excellent anti-cancer activity against HCT-116 cells in the colon [68].

Due to the varying ionization states of its primary pigment components at different pH levels, lac dye exhibit an orange red hue in acidic conditions and shifts to purple in alkaline environments [22,188]. The color-changing property is utilized in the development of intelligent packaging indicators for real-time monitoring of food quality [188,189]. For instance, incorporating lac dye into agarose membranes enabled the monitoring of strawberry spoilage. As strawberries spoil, the indicator label changed color from purple to orange [189]. Similar applications were observed in monitoring milk quality [190].

While pH-responsive shellac-based materials are predominantly employed for drug release, their application in functional foods is limited, and research on temperature and enzyme-responsive as well as multi-responsive shellac-based materials remains scarce. The application of lac dye as a natural coloring agent in freshness indicators is still evolving, and its stability requires further exploration.

3.4. Leveraging amphipathy

3.4.1. Hydrophilicity

Hydrogels, characterized by their hydrophilic, crosslinked, three-dimensional network structure, [191] possess exceptional water absorption and swelling properties without dissolution, enabling efficient drug delivery and slow release [192]. Natural hydrogels, including shellac-based ones, loaded with anti-inflammatory drugs such as doxycycline hydrochloride, have demonstrated efficacy in periodontitis treatment [79–81,193]. In-situ forming gels, derived from bleached shellac dissolved in *N*-methylpyrrolidone (NMP), exhibited antimicrobial activity against various microorganisms such as *Staphylococcus aureus*, *Escherichia coli*, *Streptococcus mutans* and *Porphyromonas*

Table 3
Applications of shellac-based, pH-responsive encapsulating systems in delivering active substances.

Wall materials	Core materials	Solvent	Results	References
Buckwheat, shellac	*Lactiplantibacillus plantarum*	Alkaline solution at pH 8	The encapsulated probiotics improved survival rates over 6.0 log CFU/mL, compared to free *L. plantarum* (2.85 log CFU/mL).	[106]
Modified rice protein (MRP), ammonium shellac (NH_4SL)	*Lactobacillus salivarius* NRRL B-30514	Ethanol	Probiotic pellets coated with MRP-NH_4SL had significantly more viable L. *salivarius* NRRL B-30514 than uncoated pellets during simulated GI digestion.	[102]
Shellac	*Kaempferia parviflora* (KP) extract	Ethanol	Under neutral pH circumstances, the electrospun shellac fibers facilitated the release of the KP extract.	[176]
Shellac	*Senna alata* (SA) leaf extract	Ethanol	In the pH 7.4 phosphate buffer solution, SA leaf extract was released for up to 12 h, with a release rate exceeding 90 %.	[118]
Shellac, quaternized chitosan (QCS)	Quercetagetin	Ethanol	Shellac/QCS nanoparticles delayed release in the GI tract.	[70]
Chitosan-coated alginate/ shellac gel particles (CS/SA/ Lac)	Superoxide dismutase (SOD)	Sodium carbonate	In simulated intestinal fluid (SIF), CS/SA/Lac containing 15 % shellac had a slower swelling ratio (227.33 % ± 5.25 %) than CS/SA (422.15 ± 28.86 %); In SIF, SOD encapsulated in CS/SA released completely within 6 h, while CS/SA/Lac did not release SOD.	[122]
Shellac	CUR and QUE	NaOH	About 48 % of the nano-encapsulated CUR and QUE (4:1) were found bioaccessible after the simulated digestion, higher than the pristine forms.	[107]
Zein and shellac	CUR	Ethanol	The drug release from CUR/zein MPs with shellac coatings was more sustained than CUR/zein MPs in pH 6.8; CUR encapsulated in CUR/zein MPs exhibited a burst release in a pH 7.8 medium.	[109]
Shellac and sodium caseinate	QUE	Ethanol	The cumulative release of QUE embedded in shellac nanoparticles reached only 41.66 % through the GI tract passage; however, ~85 % of QUE was released in simulated gastric fluid (SGF) in the first hours and the rest of QUE continued to be released into SIF.	[123]
Shellac	CUR	Ethanol	Beads-on-the-string (BOTS) microfibers (PEO and CUR as a middle layer, ethanol as a middle layer, and shellac as a sheath layer) released a small number of CUR in SGF, and more CUR was leaked in SIF. However, in SGF, CUR without shellac as the sheath layer, a burst release occurred.	[110]
Shellac, cellulose nanocrystals, and $CaCl_2$ (ShCNCCa)	*Saccharomyces cerevisiae*	Ethanol	ShCNCCa effectively encapsulated yeast, producing lower CO_2 at pH 2, but MPs disintegrated and released yeast, producing a large amount of CO_2 at pH 7.5.	[105]
Shellac	CUR	Water (pH 12.0)	The bioaccessibility of CUR after SIF reached 75.95 %, compared to free CUR (<20 %), and it was only 5.81 % after SGF.	[65]
Shellac and zein	Thymol	Ethanol	In SGF (pH 2), thymol encapsulated showed sustainable release during the first 2 h, and thymol without encapsulation released quickly to 83.55 ± 2.58 %. The same occurred in the SIF.	[124]
Shellac	Fucoxanthin	Ethanol	The release of shellac nanoparticles loaded with fucoxanthin in SGF was <10 %, <15 % in SIF, and >80 % in SCF.	[66]
Alginate, whey protein isolate, shellac, and sucrose	*Limosilactobacillus reuteri*	Aqueous solution (pH 7.3)	The bacterial inactivation of both SGF and SIF to L. *reuteri* in alginate/sucrose MPs was greater than in alginate/whey protein isolate/shellac/sucrose MPs.	[108]
Shellac	Cinnamaldehyde	Ethanol	Shellac-encapsulated nanoparticles released cinnamaldehyde under alkaline gas conditions that volatilized during pork storage.	[142]
Shellac	CUR	NaOH	The bioaccessibility of encapsulated CUR gradually increased to 12.9 % during the 2 h SGF treatment and 41 % during the 4 h SIF treatment, indicating ~60 % of the nano-encapsulated CUR could be transported to the colon.	[69]
Shellac/locust bean gum	CUR and epigallocatechin gallate	NaOH, ammonia	Shellac-locust bean gum nanoparticles enabled sustained drug release for seven days at pH 1.2 and 7.4; The complex significantly alleviated podocyte damage in mouse nephrons and lowered serum creatinine and blood urea nitrogen levels.	[177]

Abbreviations: CUR, Curcumin; GI, gastrointestinal; MP, microparticles; QUE, quercetin; SA, *Senna alata*; SCF; simulated colon fluid; SIF; simulated intestinal fluid; SGF, simulated gastric fluid; SOD, superoxide dismutase.

gingivalis relevant to periodontitis, with higher concentrations of bleached shellac delaying drug release rate and gel degradation [193]. In-situ forming gels made by Senarat et al. also exhibited interesting results of in vitro degradation and antibacterial activity [79].

Considering the overall structure of shellac, its complex polyester nature holds the potential for constructing a three-dimensional framework. Guo et al. observed that in cold-coagulated protein hydrogel comprising shellac and soy protein isolate, higher shellac content improved swelling stability [84]. A wound dressing composed of carboxymethyl cellulose, citric acid, shellac, and self-antibacterial hydroxyapatite (CMC/CA/SHL/HA) facilitated wound healing in dogs' post-ovariohysterectomy due to strong hydrogen bonding between SHL and CMC/CA [82]. Malachite green (MG), a highly water-soluble dye, can be effectively removed by starch and chitosan-based hydrogels [194,195]. In polyacrylic acid/shellac (PAA/SH) hydrogels, an increase in shellac content (10–30 %) led to up to 95 % MG adsorption, necessitating 30 kGy gamma irradiation [83].

The hydroxyl and carboxyl groups, serving as the primary hydrophilic entities in shellac, could undergo esterification reactions with exposed hydrophobic groups to gliadin. This process enhanced the stability of gliadin nanoparticles under high-temperature conditions (Fig. 8A) [196]. Shellac nanoparticles played a crucial role in reducing the interfacial tension between oil and water, thereby facilitating the formation of Pickering lotion with a bicontinuous structure. This was achieved by controlling the oil-water transition and modifying the interfacial curvature through directional adsorption in hydrophilic and hydrophobic regions (Fig. 8B) [197].

Due to shellac's weak hydrophilicity, Sun et al. conducted carboxyl esterification reactions to graft PEG onto shellac balls. As illustrated in Fig. 8C, this process allowed for flexible adjustment of the diameter ratio between PLA balls and shellac/PEG balls by controlling shellac concentration. Consequently, it facilitated the modulation of water/oil interface curvature, enabling the formation of either an oil-in-water or water-in-oil lotion [198]. Furthermore, surface modification of shellac nanoparticles with chitosan enhanced their surface wettability and lotion stabilization capacity [167,199].

3.4.2. Hydrophobicity

As previously mentioned, despite being an amphiphilic molecule, shellac tends to exhibit more pronounced hydrophobic properties,

which can effectively block the movement of water molecules when employed as a packaging material. In pork preservation, chitosan/shellac nanoparticles acted as a protective layer, preventing water loss while maintaining low hardness (324.19 ± 28.9 g) and high elasticity index (0.228 ± 0.006) over a 10-day storage period [142].

The addition of nanocellulose to a tung oil ester material, derived from tung oil acid and shellac, enhanced the hydrophobicity and water vapor barrier properties of the composite film. Despite the water-absorbing nature of nanocellulose, the waterproofing effect of shellac ensured that it did not affect the water absorption rate of the composite film [200].

Composite films, formulated with PEG400 and diethyl phthalate as plasticizers, and shellac and pectin as film-forming substrates, addressed the shortcomings of pure pectin film in terms of water retention, moisture resistance, and mechanical properties [158]. Similarly, while pure SPI membranes exhibited poor hydrophobicity, composite membranes comprising shellac and SPI significantly improved water resistance [201].

When used as a coating on its own, shellac's hydrophobic nature led to increased moisture retention in fruits, resulting in a higher natural decay rate compared to uncoated fruits [121].

Previous studies have shown that gliadin nanoparticles, utilized as stabilizers in Pickering emulsions, are overly hydrophilic, contrasting with shellac, thus resulting in inadequate stabilization of the oil/water interface [202]. However, shellac/gliadin nanoparticles, formed through hydrophobic interactions and hydrogen bonding between shellac and gliadin, effectively adsorbed onto the oil-water interface. Incorporating 20 % shellac increased the three-phase contact angle from 52.41° to 84.85°, enhancing the emulsifying activity and stability of the emulsion [196]. Solid particles composed of a hydrophobic shellac sphere and a hydrophilic alginate sphere mimicked surfactant molecules, enhancing the stability of a Pickering lotion [111].

Moreover, porous materials fabricated from shellac nanoparticles-stabilized 50 % oil phase Pickering emulsions exhibited a high oil

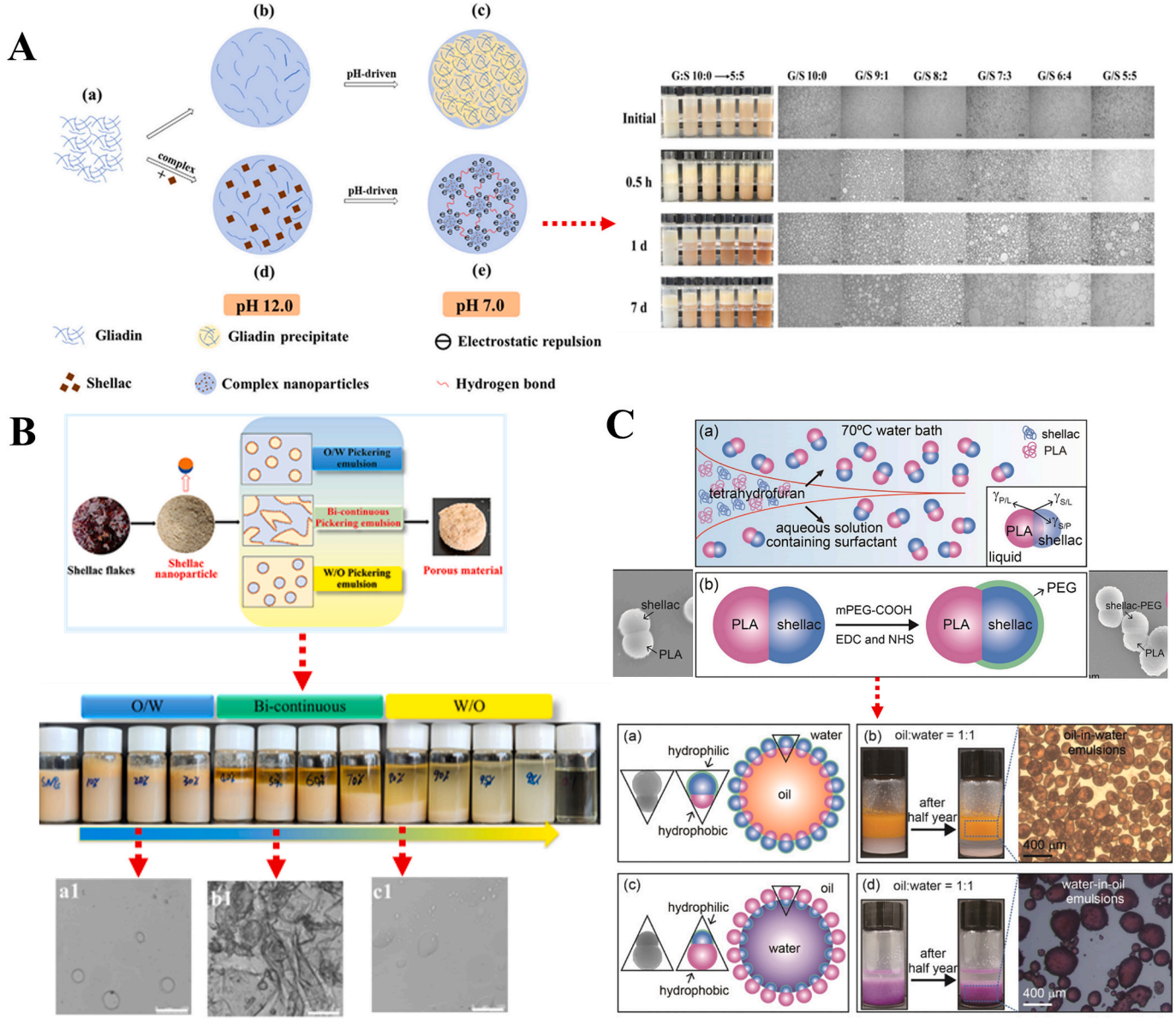

Fig. 8. (A) Schematic illustrating the potential mechanism of gliadin/shellac complex nanoparticle formation. Adapted from [196] with permission from John Wiley & Sons, Inc., Copyright 2023. (B) Pickering lotion stabilized by shellac nanoparticles. Adapted from [197] with permission from the American Chemical Society, Copyright 2022. (C) Design of biocompatible amphiphilic PLA/shellac-*g*-PEG dimer particles. Adapted from [198] with permission from John Wiley & Sons, Inc., Copyright 2020.

absorption rate (3.51 μL/s), significantly exceeding the water absorption rate (0.16 μL/s). The high hydrophobicity of shellac nanoparticles comprising the porous material framework led to oil distribution along the framework, while water filled the internal space [197].

Probiotics are vulnerable to external factors like light, oxygen, temperature, and moisture, necessitating packaging to maintain their stability. In buckwheat/shellac protein microcapsules (BS), increased shellac content enhanced the hydrophobicity of BS, ensuring good stability of embedded plant *Lactobacillus* during room-temperature storage [106]. Although the addition of shellac reduced polar sites of whey protein isolate, enhancing hydrophobicity beneficial for *Lactobacillus rhamnosus* storage, the hydrophobic nature of shellac during spray drying slowed microcapsule drying, leading to increased bacteria inactivation [112].

Paper is commonly utilized as a substrate for humidity sensors; however, the moisture absorption of cellulose in paper can impact sensor performance [203]. Aeby et al. investigated the use of shellac as a substrate for humidity sensors and found that shellac substrates exhibited significantly improved response and recovery times compared to paper [204]. Additionally, modification with a shellac/copper nanoparticle (CuNP) composite material increased the static contact angle on the photoactive antiviral mask (PAM) from 111.5° ± 3.1° to 143.4° ± 3.9°, resulting in the repulsion of aqueous droplets [205].

Oleogels have emerged as a promising alternative to fat in food applications [206]. An essential aspect of polymers as oil coagulants is their affinity for oil. The potential of shellac in preparing oleogels and oleogel-based emulsions was elucidated by Patel et al. [207]. Morales et al. developed beeswax/shellac wax flaxseed oil and beeswax/shellac wax/rapeseed oil gels, which exhibited higher oil binding capacity and lower unsaturated fatty acids compared to commercial fats. Additionally, their peroxide values were significantly below national standards [208].

Meanwhile, the inherent hydrophobic nature of shellac presents challenges in creating a moist environment conducive to wound healing and is not conducive to gas exchange. To address this issue, Liu et al. incorporated *n*-octacosanol gallate ester (GA-C28) into shellac-based dressings, resulting in the development of a novel SPG wound dressing. GA-C28 enhanced the breathability of SPG and notably improved its antibacterial and coagulation properties, thus effectively promoting wound healing in mice [209].

3.5. Leveraging room-temperature-curable ability

Shellac serves as a core material for microcapsules in wood self-repair applications due to its fast-drying rate at room temperature, ensuring coatings with excellent gloss, adhesion, hardness, and impact resistance [113,114]. For instance, a Dulux waterborne primer containing melamine/rice husk powder-coated shellac microcapsules was applied to linden wood, resulting in a reduction of coating cracks from 30.23 μm to 24.51 μm after 5 days [113]. In a subsequent study, Yan and Li incorporated 4.2 % shellac self-repairing microcapsules into a waterborne primer coating containing magnetic carbonyl iron powder, achieving a coating repair rate of 33.3 % [114]. Additionally, a novel wood-modified material with dual self-healing and thermochromic functions was developed by adding 10.0 % fluorane microcapsules to a water-based coating containing 5.0 % shellac resin microcapsules [115].

Current research does not provide conclusive evidence to support the notion that shellac microcapsules exhibit effective restorative effects on all types of wood. Wood with thicker cell walls typically possesses higher density [210], which may limit the permeability of shellac microcapsules, thus potentially impacting the repair effect.

3.6. Leveraging adhesive properties

Throughout history, shellac has served as an adhesive for a variety of laminates [148], as well as a kind of thermoplastic cement for filling gaps in materials such as walls, floors, and ceramics. Reexamined as a biomaterial, shellac is now commonly employed as a component of electrically conductive inks, exhibiting excellent stability and adhesion properties.

In 2021, electrically conductive ink incorporating shellac on a waterproof paper substrate with graphite was first developed and utilized for detecting sulfamethoxazole in water and milk [211]. Scholars have investigated the properties of electrically conductive inks comprising shellac, graphite flakes, and carbon black. Shellac, acting as a binder, facilitated the combination of graphite flakes and carbon black, resulting in enhanced conductivity and firm adhesion of the ink to the substrate, thereby exhibiting prolonged moisture stability [212]. This carbon-carrying shellac ink was utilized to produce disposable paper batteries, capable of being activated on demand for a brief period using water as an activator [213]. Furthermore, shellac has been employed in printed humidity sensors [204].

In addition to graphite, silver is also utilized in ink formulations [214]. Shellac played a crucial role in adhering silver ink with conductive properties to different substrates, including screen-printed electrodes, acetate sheets, and 3D-printed electrodes (Fig. 6b). All three pseudo-reference electrodes demonstrated relatively constant potentials throughout the evaluation tests, indicating good stability [215].

Shellac, as a natural adhesive, has begun to replace traditional adhesives in electrically conductive inks. However, compared to synthetic resins and other adhesives, shellac is more susceptible to moisture in humid environments, potentially affecting the durability of the ink. Additionally, shellac itself lacks electrical conductivity, necessitating the addition of a large quantity of conductive particles to achieve sufficient conductivity.

Future research efforts should focus on further optimizing the preparation process, enhancing product performance, and reducing production costs through effective composites of shellac with conductive and reinforcing materials. Moreover, the multifunctional development of conductive inks should be prioritized. By adjusting the microstructure of shellac or incorporating functional components, various functions such as self-healing and self-sensing capabilities can be achieved in the conductive ink.

Remarkably, the adhesion of a new type of wound dressing based on shellac onto pig skin surpassed that onto glass and iron, likely due to the synergy between the numerous functional groups (hydroxyl, carboxyl, and aldehyde) present in shellac and functional groups in the skin, facilitated by hydrogen bonding, non-electrostatic interactions, and other non-covalent bonds [209].

In PAM, the presence or absence of shellac influences the stability of CuNPs. When shellac was absent, over 80 % of the Cu was released from the mouthpiece [205].

3.7. Leveraging high latent heat

Shellac wax exhibited not only a favorable latent heat value and thermal conductivity but also stable thermal properties even after several thermal cycles [216], rendering it a novel bio-based phase change material suitable for a vertical shell and tube latent heat thermal energy storage (LHTES) unit [133]. Throughout the charging and discharging processes, the LHTES unit achieved maximum charging efficiency (73.4 %) and discharging efficiency (62.6 %) at a flow rate of 4 LPM and an inlet temperature of 120 °C, along with a notable 43.6 % reduction in the melting time of the shellac wax [133]. These characteristics enable its utilization for medium-temperature heating applications.

3.8. As colorant

Laccaic acid, a hydroxyanthraquinone carboxylic acid, imparts a distinctive color to lac dye [22]. Electrostatic interactions between acidic dyes and fibers drive adsorption, making lac dye popular for

dyeing textiles such as wool [217], silk [218], and cotton [219]. Similar to anthraquinone compounds, which contains phenolic hydroxyl groups, found in plants, lac dye possesses excellent antioxidant, antibacterial, and UV-barrier functions [218]. To enhance dye color intensity and durability, mordants are typically used in the dyeing process. Adding a 2 % metal ion mordant to a lac ethanol solution reduced the water solubility of the pigment and enhanced binding with fibers through coordination reactions [220]. In line with industry sustainability goals, the use of chitosan for biomordanting has emerged as a new trend [190,221,222]. Cationic chitosan enhanced dye fiber color strength significantly from 1.38 to 13.39, through hydrogen bonding and electrostatic interactions with dye functional groups [222]. Notably, both metal and chitosan mordanting slightly diminished the dye's antioxidant [218] and antibacterial [222] properties due to the complexation of phenolic hydroxyl groups [223]. When used as a food coloring agent in chicken meat at a dosage of 25 ppm, lac dye matched the color effect of 200 ppm sodium nitrite [224].

The unique combination of antioxidant and antibacterial properties in lac dye, alongside its pH sensitivity, suggests promising avenues for food intelligence research that remains largely unexplored.

3.9. As a natural carbon source for producing graphene

The long aliphatic carbon chains present in shellac, as a natural carbon source, offer an opportunity for its cyclization into graphene-like materials. Notably, compared to other synthetic polymers, shellac can undergo thermal decomposition at relatively low temperatures, facilitating more effective graphitization [225,226]. For example, Cho et al. subjected ball-milled shellac powder to thermal reduction at 900 °C in a tube vacuum furnace to obtain thermally reduced graphene oxide (TrGO) [227].

4. Toxicity, biocompatibility, and cell attachment

Shellac, as a natural polymer, exhibits good biocompatibility, biodegradability, and non-toxicity [228–230]. Shellac has been approved by the U.S. Food and Drug Administration (FDA) and the European Union (EU) for use in food coatings and formulation films [230,231]. However, as a food- and pharmaceutical-grade substance, toxicity is a key factor to consider. When conducting a 180-day chronic toxicity test on rats fed with 5000 ppm of shellac, neither the male nor female group showed any signs of toxicity [230]. The same applies to shellac concentrations up to 10,000 ppm [232]. In addition to oral toxicity assessment, various tests on the skin toxicity, reproductive toxicity, and mutagenicity of shellac have shown its safety [232]. During cytotoxicity testing of Shellac F (composed of sodium fluoride (5 %), shellac, modified epoxy resin, acetone, and silica), it was observed to be less harmful than commercial desensitizers, which highlights its potential as a desensitizer for treating dentin allergies [229]. In addition to being non-toxic itself, shellac has also been found to reduce the cytotoxicity of other toxic materials [233]. When multi-walled carbon nanotubes (MWCNTs) were functionalized with shellac, the partial leaching of various impurities such as Co, Fe, Ni, and Mo greatly reduced ROS production, thereby promoting cell viability [233].

Shellac is not only non-toxic but also demonstrates biocompatibility and promote cell adhesion, as evidenced by various studies including in vitro experiments, animal trials [82,209,234,235], and clinical investigations [235]. In anti-adhesion applications, superhydrophobic shellac films prepared by immobilizing shellac particles with dodecyl trichloride through solution casting showed significantly reduced adhesion and proliferation of NIH-3 T3 cells and platelets compared to untreated shellac films [234]. This indirectly indicates the blood and tissue compatibility of unmodified shellac. Shellac's non-covalent interactions with functional groups on the skin makes it a promising material for wound dressings [209]. Studies with CMC/CA/SHL/HA wound dressings on dogs with surgical wounds revealed no signs of infection, underscoring their efficacy. In experiments with human skin fibroblasts, shellac demonstrated over 91 % cell vitality across concentrations ranging from 0.0001 to 1 mg/mL, highlighting its biocompatibility [82]. Clinical trials involving drug-coated balloons (DCBs) coated with shellac and vitamin E successfully treated patients with in-stent restenosis without complications, demonstrating efficacy comparable to commonly used iopromide-based DCBs [235]. Furthermore, the photo lytic esters of aromatic groups enhanced shellac's cell adhesion while introducing photo-switching capabilities [236].

Enhancing the functionality and cell adhesion of biodegradable materials is an appealing area of research. Biomaterials that mimic the extracellular matrix creates a conducive environment for cell growth and vitality, attributes often influenced by surface microstructures [237] and modifications. Materials with high porosity [238,239] and roughness [240,241] promote cell adhesion. Biomaterials with rough, hydrophilic surfaces can foster an anti-inflammatory microenvironment, enhancing healing responses [242]. Shellac, with its potential for porous structure [243], holds promise in controlling cell behavior through adjustments in surface roughness and hydrophilicity/hydrophobicity. While synthetic polymer materials are widely favored for their mechanical properties that support cell adhesion, proliferation, and differentiation [244], they may lack inherent cell affinity. Coating shellac onto their surfaces could potentially improve their biocompatibility and capabilities of supporting cell growth.

5. Prospects

While shellac has garnered extensive attention as a novel biological material, emerging as a forerunner in fields like food, medicine, electrics, and furniture, its full potential remains untapped. Certain inherent characteristics also pose limitations on its widespread application, such as esterification reaction, low solubility, lack of multi-response applications, and insignificant hydrophilicity. Future endeavors in shellac development should prioritize the following areas:

(1) Modifying the hydroxyl and carboxyl groups of shellac requires several processes to address aging resulting from esterification reactions and its low solubility in the human body. For instance, employing dianhydride and succinic anhydride can enhance the number of carboxyl groups in shellac resin, thereby improving its intestinal solubility. Additionally, oxidizing aldehyde groups into carboxyl groups using oxidants, without introducing external groups, proves to be an effective method. Furthermore, incorporating certain metals into the functional groups of shellac molecules may yield antibacterial effects due to the bactericidal properties of these metals.

(2) Utilizing polysaccharides, proteins, and other natural substances to modify shellac is essential. Given its inherent hydrophobicity, enhancing its hydrophilicity with other more hydrophilic substances improves its effectiveness in stabilizing the oil-water interface in lotions as well as for tissue engineering applications. Introducing other, more hydrophobic polymers into the shellac system is necessary to expand its hydrophobic effect in certain applications.

(3) In conjunction with nanotechnology, utilizing shellac as nanoparticles or nanofibers for membrane development benefits from the high specific surface area of nanomaterials, enhancing reaction activity and efficiency in composite materials. Furthermore, including nanoparticles to shellac systems improves its mechanical properties and potentially enables the controlled release of encapsulated substances by the nanoparticles.

(4) Drawing from ongoing research on shellac's utilization as a sensor and enteric coating material, it is evident that shellac primarily responds to pH, temperature, and humidity. Expanding the application spectrum requires modifications to confer additional responsiveness, including photo-response, enzyme-response, ion-response, and the creation of multi-responsive materials capable of simultaneous reactions. Leveraging these responsive materials in the food industry holds promise for the preparation of functional food packaging, marking a

significant future development trend.

(5) Safety assessment is crucial despite shellac being considered non-toxic and harmless. Direct use in food and medicine necessitates further exploration of its fate in the human body and its effects. Therefore, future research requires more animal experiments, cell studies, and clinical trials to comprehensively understand shellac's impact.

6. Conclusion

This article provides comprehensive insights into shellac, exploring its development across diverse domains. The distinctive molecular structure of shellac underpins its outstanding attributes, including film-forming capabilities, antibacterial properties, pH-responsiveness, and amphiphilicity. These features have catalyzed significant advancements in various burgeoning sectors, including packaging, enteric coating materials, sensors, OFETs, electrically conductive inks, and microcapsules. Based on the existing research on shellac, we have gained the following insights:

(1) Caution should be exercised when selecting solvents for shellac, especially in the fields of food and medicine, as ketone solvents are known for their strong odor and corrosiveness, and should usually be avoided or used with caution.

(2) Based on the unique solubility of shellac in the human gastrointestinal tract, the focus of current research is on encapsulating active substances with shellac to achieve targeted delivery, which is widely used for oral administration. There are a few applications in the field of food packaging. Lac dye has the potential to react to certain metabolic products produced during food spoilage, offering opportunities for developing novel intelligent food packaging materials. It is anticipated to play a crucial role in future food preservation and quality monitoring.

(3) The dielectric and adhesive properties of shellac make it shine in electronic components such as OFETs and conductive inks. Shellac can not only be used as an electrical insulation material to reduce energy loss, but also to bond the substrate more firmly with other conductive materials.

(4) The multifunctionality of the amphiphilic properties of shellac makes it a valuable component in various industries. Shellac nanoparticles can be used to stabilize Pickering emulsions and promote the formation of a bicontinuous structure. It also plays an important role in creating self-assembled nanocarriers for delivering hydrophobic anticancer drugs. Of course, the ability of shellac to adsorb hydrophilic dyes in the environment cannot be ignored. Shellac is often mixed with other substances according to the actual situation to enhance its hydrophilicity or hydrophobicity.

(5) Whether it is microfluidic technology used to construct shellac particles of different sizes, electrospinning technology for producing shellac nanofibers with high aspect ratio and porosity, or irradiation grafting technology to improve the performance of shellac films, all have led to the diversification of shellac functions.

With the continuous advancement of modern technology, it is foreseeable that the role of shellac in developing environmentally friendly materials and exploring new fields will be further enhanced. Future research should prioritize breaking the solubility limitations of shellac, investigating the synergistic mechanisms between shellac and other substances, and integrating it with modern technologies, such as biotechnology, to drive forward technology innovation.

CRediT authorship contribution statement

Ying Chen: Writing – original draft, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Zhu Zhu:** Writing – original draft, Visualization. **Kunbo Shi:** Writing – original draft. **Zhiyao Jiang:** Writing – original draft. **Chengran Guan:** Writing – review & editing, Resources. **Liang Zhang:** Writing – review & editing, Visualization, Supervision, Resources. **Tao Yang:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Fengwei Xie:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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Data availability

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

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