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Review

Polysaccharides from Food-Medicine Homology Sources in the Control of Advanced Glycation End Products During Food Processing

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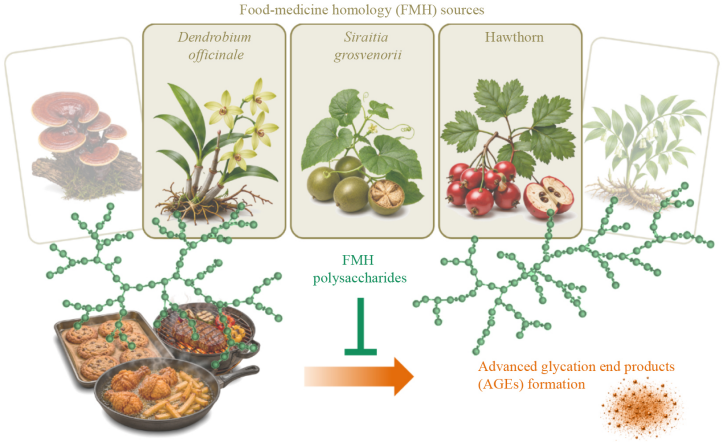
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Food-medicine homology polysaccharides may limit advanced glycation end products.
- Mechanisms span trapping, shielding, chelation, antioxidant and protein protection.
- Direct evidence centers on *G. lucidum*, *D. officinale*, *S. grosvenorii*, and hawthorn.
- Glycation inhibition must balance texture, color, flavor, and acceptability.
- Standardized measurements and process–structure–activity studies are needed.

ABSTRACT Advanced glycation end products (AGEs) generated during thermal processing have raised food-safety concerns because of their potential links to oxidative stress, inflammation, and chronic disease risk. Natural inhibitors have attracted substantial attention, but current evidence remains centered largely on polyphenols, whereas the role of polysaccharides from food-medicine homology (FMH) sources in food AGE control has not been reviewed systematically. This review outlines the formation pathways, representative markers, and dietary relevance of AGEs in food systems and integrates current evidence on FMH-derived polysaccharides with respect to antiglycation mechanisms, structure–activity relationships, source-specific findings, and food-system applications. Available studies indicate that polysaccharide preparations may reduce AGE formation through reactive dicarbonyl trapping, competition for glycation sites, metal-ion chelation, antioxidative protection, and regulation of protein conformation. Among FMH sources, *Ganoderma lucidum*, *Dendrobium officinale*, *Siraitia grosvenorii*, and hawthorn provide relatively direct antiglycation evidence, whereas *Angelica sinensis*, *Polygonatum* spp., chrysanthemum, and several other catalog-listed materials are supported mainly by preliminary, indirect, or putative evidence. Limited food-

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system studies suggest that some FMH-derived polysaccharides can reduce AGE accumulation while also affecting texture, stability, or sensory quality. FMH-derived polysaccharides may therefore serve as multifunctional ingredients for low-AGE food design, but practical application requires more standardized evaluation, stronger process-structure-activity evidence, and models that better approximate real dietary exposure.

KEYWORDS Advanced glycation end products; Food-medicine homology; Polysaccharides; Food processing; Antiglycation; Maillard reaction; Food engineering

1 Introduction

Advanced glycation end products (AGEs) comprise a structurally diverse group of stable products formed through non-enzymatic reactions between reducing sugars or reactive carbonyl compounds and amino groups in proteins, lipids, or nucleic acids [1]. These reactions form the late stage of the Maillard reaction and ultimately generate irreversible modifications through reactive carbonyl intermediates [2]. AGEs arise endogenously and are also generated during food processing, particularly under dry-heat conditions such as frying, baking, and grilling. These treatments can increase AGE levels by more than 10- to 100-fold relative to the unprocessed state [3]. As thermally processed foods account for an increasing share of modern diets, dietary AGE exposure has become an issue of growing concern in food safety and public health [4,5].

Epidemiological studies and animal experiments suggest that excessive dietary AGE intake is associated with chronic pathological processes, including type 2 diabetes, cardiovascular disease, neurodegenerative disorders, and accelerated aging [6,7]. AGEs can trigger oxidative stress and inflammatory signaling through binding to the receptor for advanced glycation end products (RAGE), representing the receptor-dependent pathway. They can also directly impair tissue function through covalent protein modification, representing the receptor-independent pathway [8]. Although more rigorous long-term human intervention studies are still needed [9–11], limiting excessive AGE formation during food processing remains a reasonable preventive strategy [12].

Among the available strategies for controlling AGEs, synthetic inhibitors initially attracted substantial attention. Aminoguanidine can effectively inhibit AGE formation by trapping α-dicarbonyl intermediates, but serious adverse effects observed in clinical trials, including pernicious anemia, gastrointestinal symptoms, vasculitis, and pro-oxidant effects, have largely halted its clinical development [2]. Process optimization is another important approach. Low-temperature processing, moist heating, short treatment times, and acidic conditions can all reduce AGE formation to some extent, but these measures are often constrained by their effects on sensory quality, texture, and processing efficiency and therefore cannot serve as universal solutions. Emerging non-thermal processing technologies have also shown promise, but direct quantitative evidence for AGE control remains limited [13].

Natural bioactive compounds have emerged as one of the most active areas of research on food AGE inhibition because of their broad availability and multi-target modes of action [2,14]. However, existing reviews and experimental studies in this field have focused predominantly on polyphenols [14,15]. Although some reviews have considered polysaccharides, terpenoids, alkaloids, and vitamins within a broader framework of natural inhibitors [2], polysaccharides, as an important class of natural bioactive macromolecules, still lack a dedicated and systematic overview in the context of food AGE inhibition. Among the many natural sources of polysaccharides, materials that serve as both food and medicine warrant particular attention because they have a long history of dietary use.

The concept of food-medicine homology (FMH) is rooted in traditional Chinese dietary therapy and medical practice and refers to natural materials with both food and medicinal attributes [16]. The FMH catalog, maintained and periodically updated by the National Health Commission of China, currently includes 106 materials, including *Dendrobium officinale*, *Lycium barbarum*, *Ganoderma lucidum*, *Siraitia grosvenorii*, and *Polygonatum* spp. These materials are widely incorporated into daily diets [17]. Polysaccharides are among the most intensively studied active constituents of FMH materials, and substantial knowledge has accumulated regarding their extraction and purification, structural characterization, and bioactivities such as antioxidant, immunomodulatory, and hypoglycemic effects [17,18]. However, existing reviews on FMH polysaccharides have focused on their broad biological functions rather than on AGE regulation in food processing systems.

Against this background, the present review provides a systematic overview of evidence on the regulation of AGE formation during food processing by polysaccharides from FMH sources. Unlike existing reviews that emphasize polyphenolic natural products or natural inhibitors in general, and unlike reviews on FMH

polysaccharides that emphasize broad bioactivities, this review aims to integrate polysaccharide structural characteristics, antiglycation activity, mechanisms of action, and food-system applications into a single framework.

2 Formation and Toxicity of AGEs in Food Systems

2.1 Formation pathways of AGEs

AGEs in food systems are not a single compound but a structurally heterogeneous group of reaction products that are continuously generated during thermal processing and storage. Their formation largely follows the late stage of the Maillard reaction (Fig. 1). The carbonyl groups of reducing sugars first react with amino compounds to form Schiff bases, which then undergo Amadori rearrangement to generate early glycation products. These products are further degraded, oxidized, and dehydrated to yield highly reactive α-dicarbonyl intermediates such as methylglyoxal (MGO), glyoxal (GO), and 3-deoxyglucosone (3-DG), which then react irreversibly with amino acid residues in proteins to form AGEs [1,6,8,19,20]. In addition to this classical sugar-amino pathway, other routes may also contribute to the generation of reactive dicarbonyl intermediates, including ascorbic acid oxidation, sorbitol-related polyol metabolism pathways, and lipid oxidation of polyunsaturated fatty acids (PUFAs) [8,19,20]. Therefore, AGE formation in real foods does not arise from a single pathway but reflects the convergence of multiple reaction networks.

2.2 Major types of AGEs in food processing

Dozens of AGE structures have been reported in food research, but only a limited number of representative markers are routinely quantified and used for cross-study comparison (Table 1). Among them, N^{ε}-carboxymethyllysine (CML) and N^{ε}-carboxyethyllysine (CEL) have become the most commonly used markers in food AGE studies because of their broad distribution and

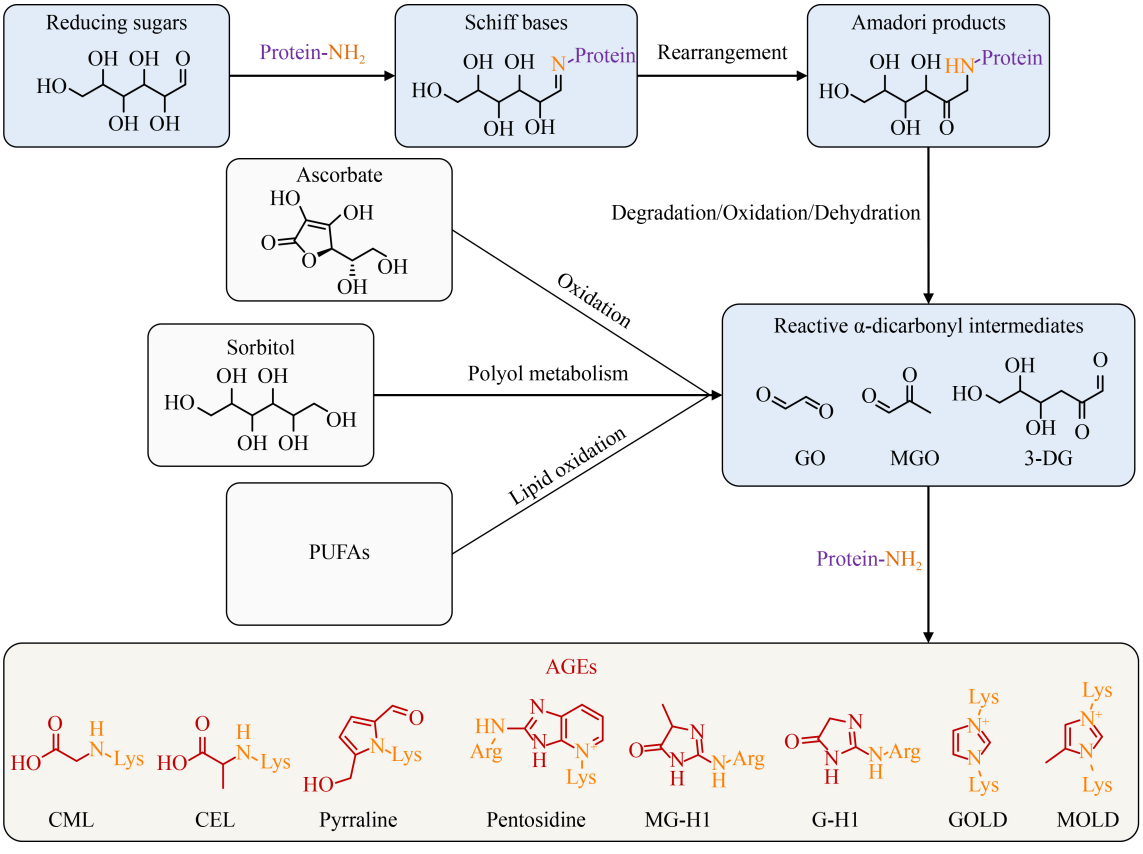

Fig. 1 Major formation pathways of AGEs in food systems. Reducing sugars react with amino groups in proteins to form Schiff bases and Amadori products, which further generate reactive α-dicarbonyl intermediates such as GO, MGO, and 3-DG, ultimately leading to AGE formation. Ascorbate oxidation, polyol metabolism, and lipid oxidation of PUFAs may also contribute to dicarbonyl generation. The structures shown at the bottom represent typical AGE species.

Table 1 Summary of representative AGEs commonly monitored in food processing.

AGE marker	Main reactive residue	Commonly associated precursor/pathway	Cross-linking status	Typical use in food studies
CML (N^{ε}-carboxymethyllysine)	Lys	GO and related oxidative pathways	Non-cross-linked	One of the most widely quantified AGE markers in foods
CEL (N^{ε}-carboxyethyllysine)	Lys	MGO pathway	Non-cross-linked	One of the most widely quantified AGE markers in foods
Pyrraline	Lys	Late Maillard pathway, commonly associated with 3-DG	Non-cross-linked	Representative marker of advanced glycation products
Pentosidine	Lys + Arg	Pentose- and oxidation-related glycation pathway	Cross-linked	Representative marker of cross-linking modification
MG-H1	Arg	MGO pathway	Non-cross-linked	Representative hydroimidazolone marker
G-H1	Arg	GO pathway	Non-cross-linked	Representative hydroimidazolone marker
GOLD	Lys + Lys	GO pathway	Cross-linked	Representative marker of more complex cross-linking products
MOLD	Lys + Lys	MGO pathway	Cross-linked	Representative marker of more complex cross-linking products

the relative maturity of current analytical methods. In addition, pyrraline, pentosidine, methylglyoxal-derived hydroimidazolone 1 (MG-H1), and glyoxal-derived hydroimidazolone 1 (G-H1) are also commonly used to characterize products associated with different reaction pathways [1,19–21]. From a structural perspective, AGEs can be broadly divided into non-cross-linked and cross-linked types. CML, CEL, pyrraline, and MG-H1 usually belong to the former group, whereas pentosidine, glyoxal-lysine dimer (GOLD), and methylglyoxal-lysine dimer (MOLD) represent more complex cross-linking modifications [19,20]. Although CML and CEL are the most commonly measured markers, the dominant AGE species differ among food categories and study outcomes are also constrained by the choice of analytical targets [1,8,20], indicating that the AGE profile associated with real dietary exposure is more complex than the traditional CML and CEL-centered view suggests [22].

2.3 Key factors affecting AGE formation in foods

Processing conditions strongly shape AGE formation in foods. Higher temperatures, longer heating, and lower moisture usually promote AGE accumulation, and dry-heat methods generally generate more AGEs than boiling or steaming in foods such as meat products, baked goods, and nuts. This trend has been consistently noted across multiple reviews [1,8,19,23]. But heating intensity alone does not determine the outcome, because AGE formation also depends on substrate composition and the reaction environment. Proteins, especially lysine and arginine residues, provide the major reaction sites. The type and amount of reducing sugars determine carbonyl availability. Lipid oxidation can provide additional dicarbonyl intermediates. pH, water activity, metal ions, and antioxidant components further alter reaction rates and dominant pathways [1,5,8,20]. As a result, food systems rich in protein and fat, low in moisture, and exposed to more severe heating generally accumulate higher AGE levels, whereas fruits, vegetables, and most high-moisture plant-based foods usually remain relatively low [22,23].

These combined effects are ultimately reflected in dietary exposure patterns. Current studies generally suggest that meat products, baked foods, nuts, and some processed cereal products are important dietary sources of AGEs, whereas fruits, vegetables, and most beverages usually contain relatively low levels [1,22,23]. Exposure therefore depends not only on individual high-AGE foods but also on the relative contribution of different food categories within the overall diet [22]. At the same time, many current databases still cover only a limited set of markers and often do not distinguish clearly between free and bound AGEs. Reported total AGE values therefore cannot be pooled or compared directly [21,24].

2.4 Health implications and *in vivo* fate of dietary AGEs

The health significance of dietary AGEs is better understood from their gastrointestinal fate after ingestion (Fig. 2) than from disease endpoints alone. Existing studies show that dietary AGEs are not digested and absorbed uniformly, and that free AGEs behave differently from peptide- or protein-bound AGEs during this process [19,21,24,25]. Free AGEs may be present directly in foods, but their transepithelial transport efficiency is usually limited. By contrast, bound AGEs often need to be partially released during gastrointestinal digestion before they can participate in subsequent transport. Some AGE-containing dipeptides may undergo peptide transporter 1 (PepT1)-mediated transport, whereas longer peptide chains usually require further hydrolysis [21,25]. Glycation may also reduce protein digestibility, allowing some AGEs or glycated peptides to reach the distal intestine in incompletely degraded forms [24,26]. Actual bioavailability therefore depends not only on molecular size and structure but also on food matrix, digestive behavior, and renal clearance. A simple linear

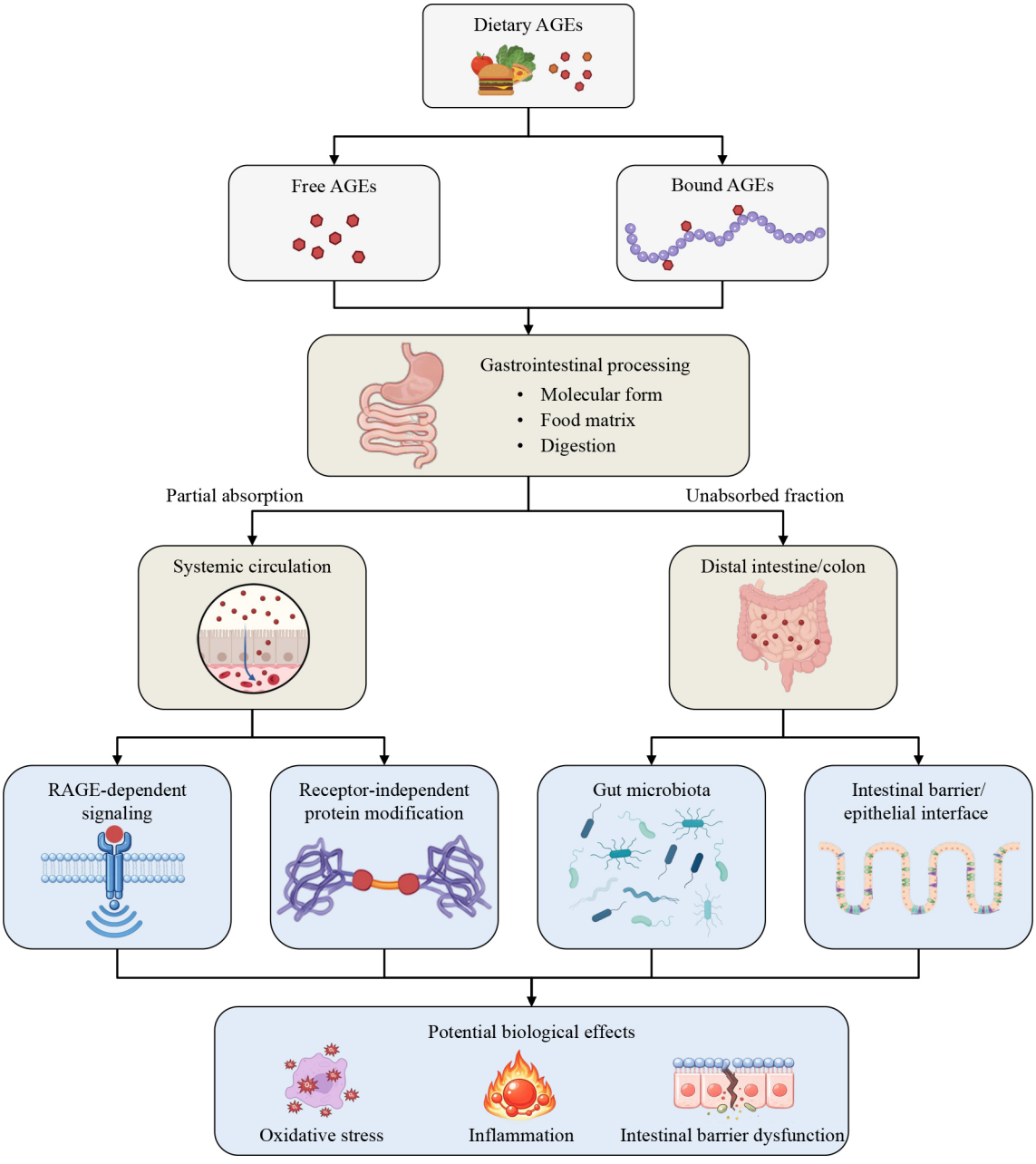

Fig. 2 Post-ingestion fate and potential biological effects of dietary AGEs. Dietary AGEs occur in free and bound forms and undergo gastrointestinal processing after ingestion. A fraction may enter systemic circulation, whereas the unabsorbed fraction may reach the distal intestine and colon. Through these routes, dietary AGEs may be linked to RAGE-dependent signaling, receptor-independent protein modification, interactions with the gut microbiota and intestinal barrier, and potential biological effects such as oxidative stress, inflammation, and intestinal barrier dysfunction.

assumption that a given dietary AGE intake directly translates into an equivalent internal burden is therefore not appropriate.

Unabsorbed AGEs and related Maillard reaction products are not biologically irrelevant. Instead, the intestinal interface may be one of the key sites at which exogenous AGEs exert their effects. Increasing attention has been paid to the relationships between dietary AGEs, the gut microbiota, intestinal barrier function, and local inflammation, but the findings remain inconsistent. Some studies suggest that certain glycated products may alter microbial composition and metabolic profiles and may even exhibit prebiotic-like effects. Other studies indicate that high-AGE diets are associated with dysbiosis, a pro-inflammatory milieu, and increased risk of intestinal injury [24–27]. Taken together, the gut interface is likely

to be a key site in the biological action chain of dietary AGEs, but the direction and magnitude of these effects depend strongly on AGE type, presentation form, experimental model, and host condition [24,26]. For AGEs or reactive dicarbonyl intermediates that are absorbed and retained in the body, the potential harmful effects can be summarized as receptor-dependent and receptor-independent pathways. The former mainly involves AGE–RAGE interactions that induce oxidative stress and inflammation-related signaling, whereas the latter is associated with irreversible covalent modification and cross-linking of proteins. These mechanisms are considered likely to contribute to pathological processes such as insulin resistance, vascular dysfunction, kidney injury, and neurodegenerative changes [6,8,19,25]. Even so, multiple uncertain steps still separate dietary AGE intake from systemic disease outcomes, including absorption efficiency, food matrix effects, renal clearance, and long-term exposure patterns. Dietary AGEs are therefore better described as contributing factors than as direct determinants of these pathological outcomes.

Overall, animal studies and some short-term intervention studies support the idea that lowering dietary AGE exposure may be beneficial, but long-term human evidence remains limited and conclusions remain inconsistent across AGE species, food matrices, and exposure levels [8,19,27]. Even so, AGE formation during food processing remains a practical intervention target because it has a clear chemical basis and substantial technological flexibility. Because food components and processing conditions can influence AGE formation, presentation form, and subsequent exposure, exploring safe, edible, and multi-target natural inhibitors is of clear practical value. This motivates the following discussion of the antiglycation mechanisms of FMH polysaccharides.

3 Polysaccharides as AGE Inhibitors: Mechanistic Insights

Polysaccharides have received far less dedicated attention than polyphenols, phenolic acids, and plant extracts, despite growing primary evidence from chemical models and a limited number of food systems [14,18]. Their inhibitory effects appear to involve coordinated actions at the reaction, macromolecular, and matrix levels [2,25] (Fig. 3).

3.1 Multi-target mechanisms of AGE inhibition by polysaccharides

The reported mechanisms differ in both their site of action and the strength of supporting evidence. Direct reaction-level evidence is provided when a polysaccharide removes reactive dicarbonyls or forms detectable adducts with them. At the macromolecular level, polysaccharide-protein interactions may reduce the accessibility of lysine and arginine residues, limit protein aggregation, and preserve protein conformation. Additional effects may arise at the matrix level through changes in viscosity, molecular mobility, water distribution, and the local oxidative environment. By contrast, radical-scavenging activity, metal chelation, and metabolic improvement in animal models provide supportive or indirect evidence unless they are linked experimentally to reduced AGE formation. Some of these actions are shared with polyphenols, whereas protein shielding and matrix modification more directly reflect the macromolecular nature of polysaccharides.

Direct trapping of highly reactive α-dicarbonyl intermediates such as MGO and GO is one of the best-supported mechanisms of polysaccharide-mediated AGE inhibition. MGO and GO are generated after Amadori rearrangement through cleavage, oxidation, and dehydration reactions, and can directly react with lysine and arginine residues in proteins to form stable end products such as CML and CEL. Intercepting them at this stage can effectively interrupt downstream cross-linking reactions. FJP-1 showed time- and dose-dependent MGO trapping in the BSA-MGO model, reaching 31.65% at 10 mg/mL after 24 h, thereby reducing opportunities for cross-linking between free dicarbonyls and protein amino groups [28]. Chitosan also exhibited direct dicarbonyl-scavenging activity in BSA-MGO and BSA-GO models. Mass spectrometric evidence of adduct formation suggests that its free amino groups may undergo nucleophilic addition or covalent binding with MGO or GO [29]. In a lysine-glucose model, *κ*-carrageenan likewise scavenged GO and MGO and correspondingly decreased the levels of CML and CEL [30]. Notably, different polysaccharides may show different preferences for GO and MGO. Carboxymethyl cellulose (CMC) reduced GO by 90% but MGO by only 44%, which may reflect the higher nucleophilic reactivity of aldehydes than ketones [31]. This implies that polysaccharide performance may depend on which dicarbonyl intermediates dominate a given food system.

Lysine and arginine residues on proteins are major glycation-sensitive sites. When polysaccharides bind to proteins through hydrogen bonding, hydrophobic interactions, or electrostatic attraction, they may physically shield these sites and thereby reduce AGE formation. FJP-1 caused pronounced fluorescence quenching of BSA. Stern-Volmer analysis suggested a mixed static and dynamic quenching mechanism, indicating that FJP-1 binds to BSA and alters its

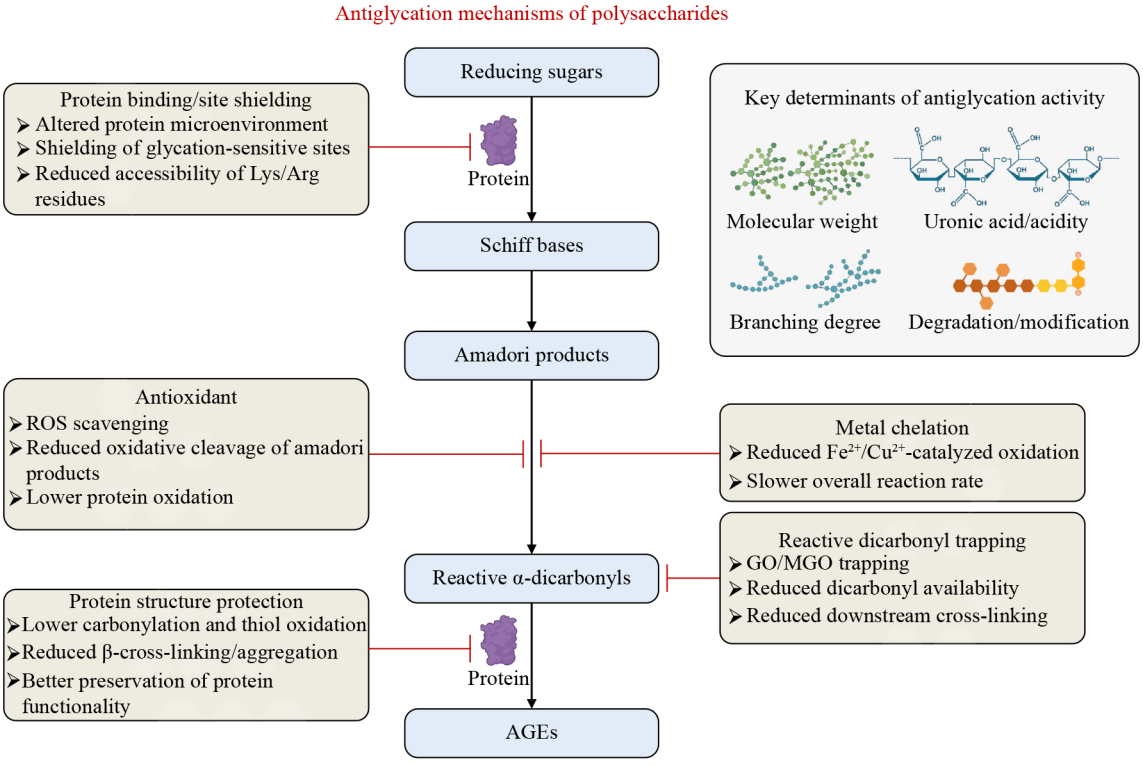

Fig. 3 Polysaccharides inhibit AGE formation through multiple mechanisms, including protein binding and site shielding, antioxidant activity, metal chelation, trapping of reactive dicarbonyl intermediates, and protection of protein structure. The inset summarizes key structural determinants that may influence antiglycation activity.

microenvironment, thereby attenuating glycation [28]. In a soy protein isolate (SPI)-glucose model, CMC significantly inhibited the formation of CML and CEL, but showed little effect in a lysine-glucose small-molecule model. This strongly suggests that its action depends more on interactions with intact proteins than on simple competition for free amino groups. More specifically, CMC appears to mask reactive sites on SPI and suppress sugar-induced protein aggregation [31]. Evidence from sodium dodecyl sulfate-polyacrylamide gel electrophoresis, Fourier transform infrared spectroscopy, and differential scanning calorimetry further indicated covalent or electrostatic interactions between CMC and SPI, improved thermal stability, and reduced exposure of reactive sites [31]. It should be noted that the effectiveness of this site-shielding mechanism depends on the protein present in the food matrix and on the charge characteristics of the polysaccharide. Its behavior in real foods will also be shaped by formulation and processing conditions.

Glycation is often accompanied by protein carbonylation, thiol oxidation, the formation of cross-β structures, and amyloid fibrillation. Limiting these structural injuries should help preserve protein functionality. AAP-2S reduced protein carbonyl content, protected free thiol groups against oxidation, and inhibited the formation of cross-β structures [28,32]. Chitosan lowered oxidative modification markers such as dityrosine, kynurenine, and N′-formylkynurenine and also reduced the intensity of glycated BSA bands in sodium dodecyl sulfate-polyacrylamide gel electrophoresis, indicating that it not only suppressed end-product formation but also preserved overall protein structural integrity [29]. FJP-1 inhibited the formation of cross-β structures in BSA-fructose, BSA-glucose, and BSA-galactose models, suggesting that this protein-protective effect is not confined to a single reducing sugar system [28].

Oxidative stress and glycation are closely coupled. Lipid oxidation and reactive oxygen species (ROS) can accelerate the cleavage of Amadori products and the generation of dicarbonyl compounds, thereby indirectly elevating AGE levels. Multiple studies indicate that polysaccharides can mitigate this effect by alleviating oxidative stress. In a bovine serum albumin (BSA)-fructose model, the purified black fungus polysaccharide fraction AAP-2S dose-dependently reduced fluorescent AGEs and significantly decreased protein oxidation markers such as dityrosine, kynurenine, and N′-formylkynurenine, suggesting that its antiglycation effect

is closely associated with antioxidant protection [32]. Significant positive correlations were also observed between the capacities of the purified acidic polysaccharide fraction FJP-1 to scavenge 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and hydroxyl radicals and its inhibition of fructosamine and fluorescent AGE formation, with Pearson correlation coefficients ranging from 0.55 to 0.99, supporting an association between antioxidant capacity and antiglycation activity in this preparation [28]. In addition, the crude *Coptis chinensis* polysaccharide preparation CCP showed *in vitro* scavenging activity against hydroxyl radicals, superoxide anions, and DPPH radicals, and reduced AGE-associated fluorescence in the liver and pancreas while improving histopathological abnormalities in streptozotocin-induced diabetic mice [33]. Early work on ethanol-fractionated pumpkin polysaccharide preparations likewise showed that their fractions attenuated AGE formation while also reducing protein oxidative damage [34]. Together, these findings support antioxidant protection as a plausible contributing pathway, although radical-scavenging assays and *in vivo* AGE reductions do not by themselves establish direct inhibition of AGE formation.

Transition metals such as Fe^{2+} and Cu^{2+} can generate ROS through Fenton reactions, thereby catalyzing glycation and protein oxidation. Chelation of these metal ions may therefore slow the overall process. AAP-2S showed measurable Fe^{2+}-chelating ability *in vitro*, which provides a parallel explanation for its antioxidant and antiglycation effects [32]. Studies of *κ*-carrageenan and chitosan likewise suggest that negatively charged carboxyl or sulfate groups may participate in metal binding and thereby reduce oxidative stress in the system [29,30]. Metal chelation is better viewed as an auxiliary mechanism that usually acts together with broader antioxidant pathways.

Overall, the available evidence does not support a single mechanism common to all polysaccharides. GO or MGO depletion and the identification of polysaccharide-dicarbonyl adducts provide the clearest evidence of direct chemical interception and may preferentially affect AGE products derived from the intercepted precursor. Protein binding, site shielding, and conformational protection may act more broadly by limiting glycation and subsequent protein cross-linking. However, the endpoints used across studies remain highly heterogeneous, and current data do not establish that cross-linked AGEs such as pentosidine are consistently more resistant to inhibition than CML or CEL. Results based only on antioxidant assays, metal chelation, or lower AGE levels in animal models should therefore be interpreted as supportive rather than direct mechanistic evidence. In food systems, the contribution of each pathway will also depend on protein type, pH, ionic strength, water activity, and thermal history.

3.2 Structure–activity relationships of polysaccharides in antiglycation

Because extraction, fractionation, and degradation usually alter several structural variables at the same time, no single descriptor can reliably predict antiglycation activity. Molecular weight illustrates this difficulty. Among pumpkin polysaccharide fractions, the lower-molecular-weight PPIII showed the strongest inhibition of dicarbonyl compounds and fluorescent AGEs [34]. Kiwifruit and hawthorn pectin oligosaccharides (POS), however, followed a different pattern: fractions below 700 u were almost inactive, whereas intermediate-sized fractions were generally more effective than either the smallest or the largest fractions [35,36]. An intermediate chain length may retain sufficient accessibility while still supporting multivalent protein interactions and steric shielding. These comparisons are nevertheless complicated by concurrent changes in monosaccharide composition, branching, solubility, and the release of low-molecular-weight sugars.

Charge-bearing groups appear to be another important, but context-dependent, determinant. In kiwifruit POS, activity was positively associated with GalA content and the GalA-to-Rha ratio, but negatively associated with Ara-to-Rha and Gal-to-Rha ratios [35]. Hawthorn fractions rich in uronic acids and GalA were likewise more active than the weakly acidic water-soluble fraction [36]. Carboxyl groups may contribute through metal chelation, protein association, and changes in chain hydration. Consistent with a macromolecular binding mechanism, CMC inhibited CML and CEL formation in an SPI-glucose system but showed little activity in a lysine-glucose model [31]. The contribution of anionic charge is therefore likely to depend on pH, ionic strength, protein composition, and the extent to which counterions screen polysaccharide-protein interactions.

Evidence from deliberately modified polysaccharides further indicates that these relationships are seldom monotonic. Sulfated derivatives of a hyperbranched β-glucan were more active than the native polymer in a BSA-fructose model, but derivatives with low-to-moderate degrees of substitution (0.27 and 0.55) were more effective than those with higher substitution levels (0.71 and 0.75) [37]. Because sulfation also changed molecular weight, particle size, zeta potential, and chain conformation, the activity difference cannot be attributed to sulfate density alone. In chitooligosaccharides (COS), activity increased with the degree of deacetylation (DD): at 200 μg/mL, the inhibition rates of fluorescent AGEs by

MD_{90}, MD_{70}, and MD_{50} were 31.14%, 28.81%, and 23.56%, respectively [38]. This trend is consistent with a greater availability of free amino groups for carbonyl interception and complements the detection of chitosan-GO/MGO adducts [29]. By contrast, marked differences in methyl esterification among comparable kiwifruit fractions did not produce corresponding differences in activity [35], while preparation-induced decreases in methylation and acetylation did not improve hawthorn POS activity in parallel [36]. Acetylation, deacetylation, sulfation, and methyl esterification should therefore be treated as structure-dependent variables rather than general activity-enhancing modifications.

The independent roles of branching, glycosidic linkage pattern, reducing ends, and higher-order conformation remain less clearly resolved. Lower branching indices were associated with stronger activity among pectic oligosaccharides, but branching changed together with GalA content and molecular size [35]. Enzymatic cleavage of β-(2→1)/β-(2→6) fructan linkages or α-(1→4) galacturonan domains reduced or even reversed the activity of *Polygonatum* preparations [39], suggesting that chain integrity may be more important than extensive depolymerization. However, hydrolysis also increases reducing ends and releases monosaccharides that may participate in glycation. Existing studies therefore do not isolate an independent effect of reducing-end density. Higher-order conformation may similarly affect multivalent protein binding and steric shielding, but it has not been varied independently of molecular weight, branching, charge, or temperature.

Translation to foods introduces a further level of uncertainty. Studies of chitosan, κ-carrageenan, and CMC show that functional groups, protein binding, viscosity, water retention, and restricted molecular mobility can remain relevant during heating [29–31]. However, no available study has compared a matched acetylation or sulfation series using AGE endpoints in the same heated food matrix. Structural modification can therefore be said to alter antiglycation activity *in vitro*, but it has not been established that acetylation or sulfation generally improves thermal stability or AGE inhibition in complex foods. The contribution of each structural feature must instead be considered together with polymer dose, protein and lipid composition, pH, ionic strength, water activity, thermal history, and effects on texture and sensory quality. The principal structure-mechanism relationships, reported endpoints, and remaining evidence limitations are summarized in Table 2.

3.3 Interactions with polyphenols: potential synergy and attribution challenges

Polysaccharides and polyphenols may act at overlapping but not identical stages of AGE formation. Polyphenols are generally effective at scavenging reactive carbonyls and free radicals and can also chelate transition metals [2,14]. Polysaccharides may share some of these activities, but their macromolecular properties allow additional effects through protein binding, shielding of glycation-sensitive residues, and changes in viscosity, water distribution, and molecular mobility. Combining the two may therefore couple rapid chemical interception with matrix-level regulation. This mechanistic complementarity provides a rationale for combination strategies, but does not by itself demonstrate synergy.

Direct evidence for such combinations remains limited. Available food studies have generally tested polyphenols and polysaccharides or hydrocolloids as separate treatments rather than in a factorial design. In butter cookies, for example, catechin and hydrocolloids were evaluated individually; their different effects on AGE inhibition and product quality suggested possible complementary advantages, but did not establish a synergistic interaction [40]. A specific FMH-derived combination such as hawthorn pectin and green tea catechins should therefore be regarded as a testable formulation hypothesis rather than a validated intervention. Demonstration of synergy would require polysaccharide-only, polyphenol-only, and combined groups at matched doses, together with an explicit comparison against dose additivity.

Potential synergy must also be distinguished from unintended co-extraction. Examination of the primary studies showed substantial variation in purification and impurity control. The purified pectic fractions from *Actinidia arguta* contained 99.5%–99.8% carbohydrate, with no detectable protein and total polyphenols reported as absent in the compositional analysis [41]. The purified hawthorn fractions also had high carbohydrate contents, although residual phenolics were not quantified [36]. The *Dendrobium officinale* polysaccharide (DOP) preparation contained no detectable protein and only 0.04% total phenolics, making major interference from these components less likely [42]. However, none of these studies included a dedicated dephenolized comparator.

By contrast, residual phenolics were not quantified in several other preparations, including AAP-2S, FJP-1, and *Siraitia grosvenorii* polysaccharide (SGP) [28,32,43]. The *Polygonatum* samples were polysaccharide preparations rather than single homogeneous fractions, and their residual phenolic contents were not assessed [39]. More direct evidence of confounding was found in the chrysanthemum JHP samples, which retained 9.4–70.2 mg gallic acid equivalents/g of phenolics. JHP-1, the most active sample, also had the highest phenolic content [44]. Its activity should therefore be attributed to the polysaccharide-containing fraction rather than to the

Table 2 Structural and preparation-related factors associated with polysaccharide antiglycation activity.

Structural or preparation factor	Mechanistic relevance	Main AGE-related findings	Food-system relevance	Limitations	Ref.
Molecular weight and chain length	●Molecular accessibility ●Multivalent protein binding ●Steric shielding ●Viscosity and diffusion	A lower-molecular-weight pumpkin fraction showed stronger inhibition, whereas intermediate-sized kiwifruit and hawthorn POS were more active than both smaller and larger fractions	The effective size range may change with polymer dose, protein concentration, and viscosity	●Nonlinear and source-dependent relationship ●Composition and branching changed concurrently	[34–36]
Monosaccharide composition, uronic acids, carboxyl groups, and anionic charge	●Metal chelation ●Protein association ●Chain hydration ●Charge-mediated interactions	●Higher GalA or uronic acid content was associated with stronger inhibition ●CMC reduced CML/CEL through protein binding and dicarbonyl interception	Effects depend on pH, ionic strength, counterions, and protein type	Composition and charge density were rarely varied independently	[31,35,36]
Sulfate groups and degree of sulfation	●Anionic charge ●Protein interactions ●Changes in chain extension and conformation	●κ-Carrageenan reduced GO/MGO and CML/CEL ●Sulfated HBG derivatives were more active than native HBG, but low-to-moderate substitution was more effective than high substitution	κ-Carrageenan reduced AGE formation in cake	●No matched sulfation series tested during food heating ●Sulfation also changed molecular weight, particle size, zeta potential, and conformation	[30,37]
Free amino groups and degree of deacetylation	●Nucleophilic carbonyl trapping ●Competition for reducing-sugar or dicarbonyl species	●Chitosan formed detectable GO/MGO adducts ●COS activity followed MD_{90} > MD_{70} > MD_{50} (DD 90.8%, 70.8%, and 53.6%)	Chitosan reduced AGE markers in cake, but also affected viscosity, color, and texture	●Mechanism and deacetylation gradient were examined in separate studies ●Polymer sizes were not fully matched	[29,38]
Methyl esterification and acetylation	●Charge exposure ●Hydrophobicity ●Chain conformation ●Steric interactions	●Differences in methyl esterification did not alter activity in comparable kiwifruit fractions ●Lower methylation and acetylation did not improve hawthorn POS activity in parallel	Effects on thermal behavior and matrix compatibility remain unclear	●Direct negative or multivariable evidence ●No general activity-enhancing effect established	[35,36]
Branching and glycosidic linkage pattern	●Chain integrity ●Multivalent interactions ●Steric shielding	●Lower branching indices were associated with stronger pectic POS activity ●Cleavage of fructan or galacturonan domains reduced or reversed activity	Processing-induced hydrolysis may disrupt protective macromolecular interactions	Branching, molecular size, composition, and linkage integrity changed together	[35,39]
Reducing ends and higher-order conformation	●Intrinsic sugar reactivity ●Chain organization ●Protein binding and molecular accessibility	●Hydrolysis shortened polysaccharide chains while releasing monosaccharides ●Sulfation altered HBG conformation together with charge and molecular size	Processing may alter conformation while generating additional glycation substrates	Effects of reducing-end density and conformation have not been isolated experimentally	[37,39]
Protein binding and matrix structuring	●Shielding of Lys/Arg residues ●Reduced protein aggregation ●Altered water distribution and molecular mobility	●CMC protected SPI during heating ●Chitosan and κ-carrageenan showed dose-dependent effects on AGE formation and product quality	Matrix structuring can reduce AGE formation but may impair texture or acceptability at excessive doses	The practical optimum depends on formulation and cannot be predicted from chemical models alone	[29–31]

polysaccharide backbone alone. Fudan-Yueyang-*G. lucidum* (FYGL), an antioxidative proteoglycan from *Ganoderma lucidum*, is likewise a proteoglycan and cannot be used as evidence for the activity of a chemically pure polysaccharide [45].

These differences require source-specific attribution. When residual or bound phenolics are not quantified or controlled, the observed effect should be assigned to the tested preparation as a whole. Terms such as purified polysaccharide fraction, polysaccharide-containing fraction, proteoglycan, or polysaccharide–polyphenol conjugate should be used according to the composition actually reported. More definitive attribution requires phenolic and protein quantification and, where feasible, dephenolized or phenolic-matched controls. Residual phenolics in an isolated fraction represent a potential confounder, not evidence of synergy.

4 FMH-Derived Polysaccharides for AGE Regulation

Polysaccharides from FMH sources already have a substantial research basis in fields such as antioxidant activity, immunomodulation, and the regulation of glucose and lipid metabolism [17,18]. In recent years, an increasing number of original studies have extended this work to AGE regulation [18]. Reported catalog-listed materials include *Ganoderma lucidum*, *Dendrobium officinale*, *Siraitia grosvenorii*, hawthorn, *Angelica sinensis*, *Polygonatum* spp., and chrysanthemum (Fig. 4). The available studies range from direct tracking of AGE

suppression to AGE-related injury and AGE–RAGE modulation [36,39,42–48]. The strength and directness of the evidence vary substantially across sources, as summarized in Table 3.

At present, *Ganoderma lucidum*, *Dendrobium officinale*, *Siraitia grosvenorii*, and hawthorn make up the most evidence-rich part of the literature. *Angelica sinensis*, *Polygonatum* spp., and chrysanthemum currently have thinner or more indirect support. Additional catalog-listed materials with established polysaccharide research but no direct AGE-focused evidence are considered in Section 4.3. Together, the sources discussed in this section span multiple polysaccharide classes, including proteoglycans, mannoglucans, pectins, fructans, and arabinogalactans.

4.1 FMH-derived polysaccharides with direct antiglycation evidence

These sources share a common feature: Investigators directly tracked AGE formation in relatively well-defined models and evaluated inhibitory effects using indicators such as fructosamine, fluorescent AGEs, CML/CEL, protein carbonyls, free sulfhydryl groups, dicarbonyl intermediates, or protein aggregation [36,42,43,45,48]. Even within this group, however, the relative strengths differ. *Ganoderma lucidum* and *Dendrobium officinale* are represented mainly by mechanistically clearer model studies, whereas *Siraitia grosvenorii* and hawthorn have already extended into real food systems and therefore show greater translational relevance.

4.1.1 *Ganoderma lucidum*

Ganoderma lucidum is one of the best-studied fungal materials in the FMH catalog, and its fruiting bodies and mycelia are rich in polysaccharides, triterpenoids, proteoglycans, and other bioactive constituents. In the context of AGE regulation, one representative study has focused on an antioxidative proteoglycan from *Ganoderma lucidum*, designated FYGL [45]. FYGL has a molecular weight of about 2.6×10^5 u and is a water-soluble, highly branched macromolecule. Its polysaccharide moiety is composed mainly of Ara, Gal, glucose (Glc), and Rha, and its major glycosidic linkages are 1→3, 1→2, and 1→6. Its protein moiety contains

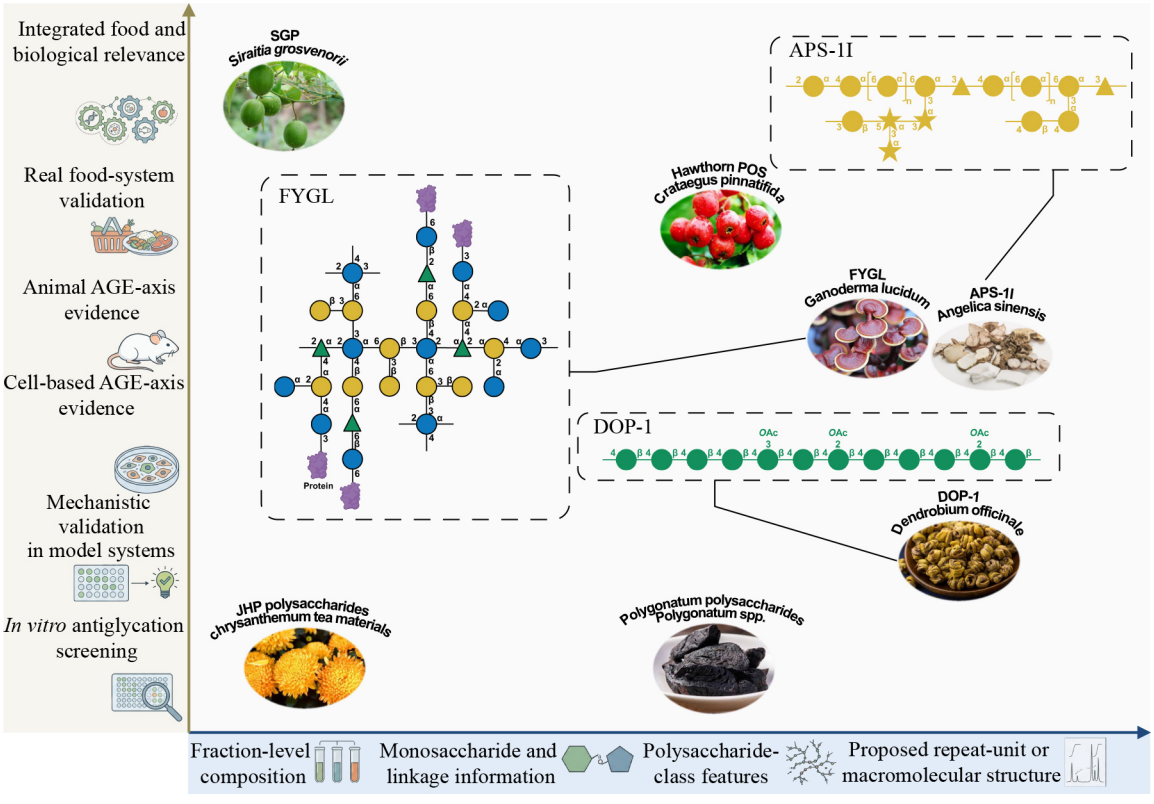

Fig. 4 Landscape of structural characterization depth and translational maturity among FMH-derived polysaccharides in AGE regulation. Representative FMH-derived polysaccharides are positioned according to structural characterization depth and translational maturity with respect to food-system and biological relevance. Dashed boxes indicate representative structural information available for selected sources.

Table 3 FMH-derived polysaccharide preparations with direct or preliminary evidence for AGE regulation.

FMH source	Fractions	Structural features	Study models	Main AGE-related findings	Limitations	Ref.
Ganoderma lucidum	FYGL (*in vitro* models) and *Ganoderma lucidum* polysaccharide preparation (animal study)	●Highly branched proteoglycan complex ●Molecular weight (MW) ~2.6 × 10^5 u	●BSA-fructose model ●MGO-BSA model ●Diabetic rats	●Reduced fructosamine, dicarbonyls, and fluorescent AGEs ●Reduced glycoxidation and protein aggregation ●Lowered AGE accumulation *in vivo*	●Proteoglycan ●Different preparations were used in the *in vitro* and animal studies ●Activity cannot be assigned to the polysaccharide moiety alone ●No food-system validation	[45,49]
Dendrobium officinale	DOP-1 (structural features) and DOP (antiglycation assays)	●Acetylated mannoglucan ●MW ~7.9 × 10^5 u ●Man/Glc-rich	●BSA-fructose model	●Strong direct antiglycation activity ●IC_{50} ~0.237 mg/mL ●Reduced fluorescent AGEs and specific AGE markers ●Lowered protein carbonyls and preserved sulfhydryl groups	●Antiglycation assays used DOP, whereas detailed structural characterization focused on DOP-1 ●Chemical model only ●No food-system validation	[42]
Siraitia grosvenorii	Purified SGP fraction	●Fine structure not fully reported	●Biscuit system ●BSA-fructose model ●Caco-2 cells	●Modest direct inhibition in the chemical model ●Reduced fluorescent AGEs and protein oxidation in biscuits ●Alleviated CML-induced epithelial injury	●Single baking model ●Cell results reflect downstream protection rather than AGE formation itself ●Protein and residual phenolics were not quantified	[43]
Hawthorn (*Crataegus pinnatifida* var. *major*)	WPS SPS-2 POS	●GalA-rich pectic fractions and oligosaccharides ●Activity depends on molecular weight and composition	●*In vitro* structure–activity screening ●Infant formula storage at 25, 45, and 65 °C	●Medium-MW POS showed the strongest *in vitro* antiglycation activity ●Reduced furosine, CML, CEL, and total AGEs mainly during storage at 65 °C	●Clear overall inhibition demonstrated mainly at 65 °C ●Efficacy during normal shelf-life storage was not established ●Single milk-based matrix	[36,48]
Angelica sinensis	AG APS-1 Ⅰ APS-2 Ⅱ	●Branched arabinoglucan and other homogeneous polysaccharides ●Different fractions show markedly different affinities for RAGE	●RAGE-binding and competition assays ●Insulin-resistant HepG2 cells ●Diabetic rats	●AG interfered with AGE–RAGE binding ●APS-1 Ⅰ showed stronger RAGE affinity than APS-2 Ⅱ ●APS-1 Ⅰ showed stronger downstream improvement in insulin resistance	●Mainly receptor antagonism/downstream protection ●No clear direct suppression of AGE formation ●Residual phenolics were not quantified	[46,47]
Polygonatum spp.	PS and comparative polysaccharide samples from multiple species	●Fructan- and pectin-containing polysaccharides ●Marked interspecies structural variation	●Comparative *in vitro* antiglycation assay ●Enzymatic hydrolysis tests	●Dose-dependent antiglycation activity ●The *P. sibiricum* sample showed the highest inhibition at 3 mg/mL ●Activity declined after disruption of fructan- or pectin-like structures	●Multi-species screening ●Not single homogeneous fractions ●No standardized single official source ●Residual phenolics were not assessed ●No food-system or animal AGE validation	[39]
Chrysanthemum tea materials	Polysaccharide-containing fractions JHP-1 to JHP-5	●Acidic polysaccharides with two main molecular-weight fractions ●Marked variation in phenolic content	●Comparative *in vitro* antiglycation assay	●JHP-1 showed the strongest activity ●IC_{50} ~0.61 mg/mL ●Activity was associated with lower molecular weight, less esterified uronic acids, and higher bound phenolics	●JHP-1 was not derived from the official FMH chrysanthemum source ●No dephenolized or phenolic-matched control ●Activity cannot be assigned to the polysaccharide backbone alone	[44]

multiple naturally occurring amino acids and is covalently linked to the polysaccharide backbone through O-linkages involving serine and threonine residues. Thus, FYGL is better described as a proteoglycan complex than as a pure polysaccharide.

In both BSA-fructose and MGO-BSA models, FYGL showed inhibitory effects at the early, intermediate, and late stages of glycation. At 750 μg/mL, the inhibition rates for fructosamine, dicarbonyl compounds, and fluorescent AGEs were approximately 27.08%, 31.49%, and 85.68%, respectively, with a particularly pronounced effect on late fluorescent AGEs [45]. Further analysis showed that FYGL could also protect the conformational integrity of BSA by suppressing glycation-induced amyloid fibrillation and maintaining the stability of protein secondary structure, as supported by thioflavin T fluorescence, circular dichroism, and sodium dodecyl sulfate-polyacrylamide gel electrophoresis analyses. These findings indicate that the active fraction from *Ganoderma lucidum* acts across multiple stages of glycation while also limiting the associated oxidative damage.

In addition to *in vitro* models, *Ganoderma*-derived polysaccharides have also been associated with the amelioration of AGE-related pathology in animal studies. Meng et al. [49] reported that, in diabetic rats induced by a high-fat diet combined with streptozotocin, treatment with *Ganoderma* polysaccharides reduced AGE levels in serum and myocardium, alleviated myocardial collagen cross-linking, and increased the activities of superoxide

dismutase and glutathione peroxidase. However, these *in vivo* findings are better interpreted as mitigation of AGE-related pathology than as evidence of direct antiglycation. Because glycemic control, lipid metabolism, and oxidative status changed concurrently, the reduction in tissue AGEs cannot be separated from secondary metabolic effects in this model.

4.1.2 *Dendrobium officinale*

Dendrobium officinale is a well-known tonic FMH material, and stem polysaccharides are generally regarded as its principal bioactive constituents. Li et al. [42] isolated a novel homogeneous polysaccharide, designated DOP-1, from *Dendrobium officinale* through water extraction, ethanol precipitation, enzymatic removal of starch and protein, and purification on a DEAE-52 ion-exchange column, followed by relatively complete structural characterization. DOP-1 had a molecular weight of about 7.9×10^5 u. It consisted mainly of mannose (Man) and Glc at a molar ratio of approximately 5.23:1 and belonged to the mannoglucan class. Methylation analysis showed that its backbone was composed primarily of →4)-β-*D*-mannopyranosyl-(1→ and →4)-β-*D*-glucopyranosyl-(1→ residues. Among them, 4-linked Man residues accounted for 74.09% and 4-linked Glc residues for 15.62%. In addition, small proportions of terminal Man, 3,4-linked branched Man, and 2,4- and 4,6-linked branched Glc residues were detected. Notably, part of the Man residues carried acetyl substitutions at the 2-O and 3-O positions, and this acetylation may represent one of the structural features that distinguish *Dendrobium officinale* polysaccharides from those of other sources. The same study also prepared an enzyme-purified parent fraction, DOP, from which DOP-1 was isolated. The two materials were used for different purposes: DOP-1 underwent detailed structural characterization, whereas DOP was selected for the subsequent antiglycation assays.

In a BSA-fructose model, DOP showed strong direct antiglycation activity, with an IC_{50} of approximately 0.237 mg/mL for total AGE formation. At higher concentrations, the inhibition of fluorescent AGEs approached 90%. DOP also significantly decreased vesperlysine, pentosidine, argpyrimidine, and crossline formation, inhibited protein carbonylation, and protected free sulfhydryl groups [42]. The tested DOP preparation contained no detectable starch or protein and only 0.04% total phenolics, making major phenolic confounding unlikely, although no dephenolized control was included. However, the detailed linkage pattern and positions of acetyl substitution were established for DOP-1 rather than DOP. The study therefore supports the antiglycation activity of purified DOP, but does not directly demonstrate that the specific structural features resolved for DOP-1 account for that activity. The available evidence still comes from a BSA-fructose model rather than a real food system.

4.1.3 *Siraitia grosvenorii*

Siraitia grosvenorii is a traditional FMH material native to Guangxi. In addition to triterpene sweet glycosides, polysaccharides are also important bioactive constituents of the fruit. Long et al. [43] systematically evaluated the antiglycation effects of a purified *Siraitia grosvenorii* polysaccharide fraction, designated SGP, in a baking system, a BSA-fructose *in vitro* model, and a Caco-2 intestinal epithelial cell model. This study focused mainly on functional validation and mechanistic analysis of SGP, whereas detailed molecular weight data, monosaccharide composition, and fine structural features were not reported systematically and still require further study.

In the BSA-fructose model, 1000 μg/mL SGP inhibited fructosamine, dicarbonyl compounds, and fluorescent AGEs by approximately 7.12%, 10.91%, and 33.44%, respectively. Its mechanism involved metal chelation, and molecular docking further suggested that SGP could competitively bind to Asp108 and Arg144 on BSA, thereby sharing reaction sites with fructose. However, its inhibitory effects on early and intermediate indicators remained relatively limited.

Compared with studies confined to chemical models, the main value of SGP lies in extending the evidence to both food and cellular systems. In a biscuit baking system, SGP reduced fluorescent AGEs and protein oxidation products while improving product crispness, indicating preliminary application potential in baked foods. Specific data are discussed in Section 5.1. In a Caco-2 intestinal epithelial cell model, SGP alleviated CML-induced cellular injury, decreased intracellular reactive oxygen species levels and RAGE expression, and upregulated the tight junction protein zonula occludens-1 (ZO-1) and mucin 2 (MUC2) [43]. The biscuit model reflects direct suppression in a food system, whereas the Caco-2 model reflects protection against CML-induced cellular injury.

4.1.4 Hawthorn (*Crataegus pinnatifida* var. *major*)

The hawthorn material examined in these studies was the fruit of *Crataegus pinnatifida* var. *major*, and its fresh pulp contains as much as 6.4% pectin. It is one of the few FMH sources supported by a relatively continuous line of evidence from *in vitro* structure-activity analysis to validation in real food systems. Zhu et al. [36] isolated a water-washed pectin fraction (WPS), a salt-washed pectin

fraction (SPS-2), and related components from hawthorn through water extraction, ethanol precipitation, Sevag deproteinization, and DEAE-cellulose-52 column chromatography. WPS contained 97.9% carbohydrate but only 0.8% uronic acid, and its monosaccharide composition was dominated by Glc (25.6%), Gal (36.5%), Ara (14.6%), and Rha (10.5%). SPS-2 contained 98.6% carbohydrate and as much as 74.9% uronic acid, and consisted mainly of GalA (72.3%), Ara (17.3%), and Rha (3.6%). The characteristic absorptions at 1730–1760 cm^{-1} and 1600–1630 cm^{-1} in Fourier transform infrared spectroscopy further confirmed that SPS-2 was a pectic substance.

On this basis, SPS-2 was degraded by enzymatic treatment or ultrasound-assisted enzymatic treatment to obtain POS with different molecular weights. After ultrafiltration using membranes with molecular weight cutoffs of 700 u and 3000 u, low-molecular-weight POS (< 700 u), medium-molecular-weight POS (700–3000 u), and high-molecular-weight POS (> 3000 u) were obtained. Among them, the enzymatically generated medium-molecular-weight POS had the highest GalA content (84.6%), together with 8.7% Ara and 2.1% Rha, and showed the strongest antiglycation activity at 1.5 mg/mL. By contrast, the low-molecular-weight fraction almost completely lost activity. The medium-molecular-weight fraction generated by ultrasound-assisted enzymatic degradation was weaker than the product obtained by enzymatic degradation alone, because the proportion of polygalacturonans decreased from 85.1% to 61.9%, whereas the proportions of Ara and rhamnogalacturonans increased [36].

Food-system validation has been reported in infant formula under ambient and accelerated storage conditions [48]. Clear inhibition was observed mainly at 65 °C, whereas efficacy during normal shelf-life storage was not established; detailed results are discussed in Section 5.1. Hawthorn POS is therefore one of the few FMH-derived materials supported by structural characterization, *in vitro* activity screening, and real-food testing, although its translational evidence remains limited to a single milk-based matrix and severe accelerated storage.

Within this direct-evidence tier, *Ganoderma lucidum* has the richest mechanistic analysis, while *Dendrobium officinale* provides detailed structural characterization and strong *in vitro* activity, although these data were obtained from related but distinct fractions. *Siraitia grosvenorii* and hawthorn are among the few sources that have already entered validation in real food systems.

4.2 FMH-derived polysaccharides with preliminary or indirect AGE-regulatory evidence

Angelica sinensis, *Polygonatum* spp., and chrysanthemum have all yielded AGE-related findings, but the current evidence is thinner or less direct than that for the sources discussed in Section 4.1. Most available studies focus on downstream protection along the AGE–RAGE axis or on comparative screening in relatively simple models. Even so, their structural features remain distinctive enough to warrant attention.

4.2.1 *Angelica sinensis*

Angelica sinensis is a traditional Apiaceae medicinal root with long-standing dietary and medicinal use. Its polysaccharides are structurally diverse, and multiple homogeneous fractions have already been isolated and characterized. Sui et al. [46] isolated a branched arabinoglucan, designated AG, with a molecular weight of about 5.1 ku. Structural analysis showed that the backbone of AG was composed of (1→4)-α-*D*-glucopyranosyl residues, with glucopyranosyl branches at the O-6 position and terminal β-*L*-arabinofuranosyl residues. Using RAGE-overexpressing cells and competitive binding assays, the authors demonstrated that AG could interact directly with RAGE and inhibit AGE-RAGE binding, with an IC_{50} of about 138.7 mg/L. In streptozotocin-induced diabetic rats, AG treatment reduced renal AGE and RAGE expression and alleviated renal dysfunction and inflammatory responses.

Liu et al. [47] further isolated two homogeneous polysaccharides from *Angelica sinensis*, APS-1I and APS-2II, with molecular weights of 17.0 and 10.0 ku, respectively, and found a marked difference in their affinities for RAGE. APS-1I was a heteropolysaccharide with a backbone composed of α-1,6-Glcp, α-1,3,6-Glcp, α-1,2-Glcp, α-1,4-Galp, and α-1,3-Rhap residues, and its two side chains contained multiple linkages, including α-1,3,5-Araf, α-1,3-Araf, α-1,4-Galp, β-1,3-Galp, and β-1,4-Glcp. By contrast, APS-2II was a linear glucan containing only α-1,6-Glcp, α-1,3-Glcp, α-1,2-Glcp, and terminal α-Glcp residues. Their dissociation constants for RAGE were about 2.02 and 85.92 μmol/L, respectively. The stronger binder, APS-1I, also showed a stronger capacity to ameliorate hepatic insulin resistance in insulin-resistant HepG2 cells and diabetic rats, and it suppressed the RAGE-JNK/p38-IRS signaling pathway.

4.2.2 *Polygonatum* spp.

Polygonatum is a traditional tonic rhizome widely used in Chinese medicine and diet therapy. Zhao et al. [39] systematically compared the structural features and antiglycation activities of polysaccharides from nine *Polygonatum* spp. Their results showed clear interspecies differences. The polysaccharides from *Polygonatum*

macropodium were composed mainly of fructans with a molecular weight of about 3.3 ku, and their fructose content reached 86.5%. By contrast, the other eight sources, including the officially recorded materials *Polygonatum sibiricum*, *Polygonatum kingianum*, and *Polygonatum cyrtonema*, contained both fructans and pectins. Their fructan fractions ranged from 2.5 to 4.1 ku and contained 24.3%–48.0% fructose, whereas the pectin fractions exceeded 4.1×10^5 u and contained 23.0%–34.7% GalA and 17.4%–32.4% Gal, together with smaller amounts of Rha, Ara, xylose (Xyl), and Glc. All samples had esterification degrees below 50%, and the lowest value was observed for *P. macropodium*.

Antiglycation assays showed that the polysaccharide preparation from *P. sibiricum* gave the highest inhibition rate at 3 mg/mL, at about 30.2%. After enzymatic treatments with exo-inulinase, invertase, and pectinase, the activity decreased rather than increased, indicating that the integrity of the fructan and pectin-like structures was important for activity. These results support the antiglycation potential of *Polygonatum* polysaccharides but they do not yet establish any single official source as the dominant active material. The current evidence comes mainly from multi-species comparative work rather than from a standardized source-specific study.

4.2.3 Chrysanthemum

In the Chinese Pharmacopoeia and the FMH catalog, chrysanthemum refers to cultivated varieties of *Chrysanthemum morifolium* and is widely consumed as both a tea material and a medicinal herb. Yuan et al. [44] compared the structures and activities of polysaccharide-containing fractions from five commercially available "chrysanthemum tea" materials, including snow chrysanthemum (*Coreopsis tinctoria*, JHP-1), wild chrysanthemum (*Chrysanthemum indicum*, JHP-2), and three cultivated chrysanthemum varieties (*C. morifolium* 'Huangju', JHP-3; *C. morifolium* 'Gongju', JHP-4; and *C. morifolium* 'Hangbaiju', JHP-5). The total uronic acid contents of these fractions ranged from 28.4% to 36.2%, and their total phenolic contents ranged from 9.4 to 70.2 mg gallic acid equivalents/g. Based on molecular size, each sample could be divided into two main fractions, namely F1 (4.29×10^5–5.88×10^5 u) and F2 (4.11×10^4–5.24×10^4 u). Monosaccharide analysis showed that GalA, Ara, and Gal were the dominant constituent monosaccharides in all samples.

Activity screening showed that JHP-1 from snow chrysanthemum had the strongest antiglycation activity, with an IC_{50} of about 0.61 mg/mL, close to the level of aminoguanidine, whereas JHP-3 to JHP-5 were clearly weaker. However, the most active material in this study, *Coreopsis tinctoria*, is not the official chrysanthemum source included in either the Chinese Pharmacopoeia or the FMH catalog. The official chrysanthemum entry therefore corresponds more closely to JHP-3 to JHP-5. Because no dephenolized or phenolic-matched control was included, the relatively high activity of JHP-1 cannot be assigned to the polysaccharide backbone alone and may partly reflect its higher content of bound phenolics.

4.3 Other FMH-derived polysaccharide sources with putative AGE-regulatory potential

Among the 106 currently recognized FMH materials, many polysaccharide sources have not yet been investigated directly for AGE regulation. The materials summarized in Table 4 are presented as illustrative candidates rather than as a ranking of efficacy or research priority. They were selected using four practical considerations: inclusion of the relevant source and edible part in the current FMH catalog; an established basis for polysaccharide extraction and structural characterization; structural features or reported bioactivities relevant to the mechanisms discussed in Section 3; and plausible compatibility with food formulation or processing [17,18]. Antioxidant, metal-chelating, hypoglycemic, or protein-protective activities can support initial candidate screening, but do not establish antiglycation activity in the absence of direct AGE-related endpoints.

Among tonic medicinal materials, sources such as *Poria cocos*, fragrant Solomon's seal (*Polygonatum odoratum*), lily bulb (*Lilium* spp.), *Codonopsis* root (*Codonopsis* spp.), jujube (*Ziziphus jujuba*), dwarf lilyturf tuber (*Ophiopogon japonicus*), and *Rehmannia* root (*Rehmannia glutinosa*) all have relatively solid polysaccharide research foundations. Their polysaccharides cover a broad structural range, including β-glucans, fructans, pectic polysaccharides, and heteropolysaccharides. Preliminary evidence has already been reported for activities such as free-radical scavenging, metal chelation, and protein protection, all of which can be linked mechanistically to the antiglycation pathways discussed in Section 3. Among these materials, dwarf lilyturf tuber and *Rehmannia* root were only added to the FMH catalog in 2024. Their polysaccharide research is therefore relatively recent, but initial data on structural characterization and bioactivity have already begun to emerge. Chinese yam (*Dioscorea opposita*), as a representative rhizomatous material, is also noteworthy. Its polysaccharides are dominated mainly by mucilage-related fractions and fructans, and substantial evidence has accumulated for antioxidant and hypoglycemic activities, although systematic studies specifically

Table 4 Illustrative candidate FMH-derived polysaccharide sources requiring direct AGE-focused validation [17,18].

FMH source	Major polysaccharides	Reported supporting bioactivities	Rationale for AGE-focused screening	Current gaps
Poria cocos	●β-Glucans ●Acidic heteropolysaccharides	●Antioxidant ●Hypoglycemic ●Gut-modulatory	●Glycoxidation control ●Substrate-load reduction	●No direct AGE endpoints ●No food-system validation
Fragrant Solomon's seal (*Polygonatum odoratum*)	●Fructans ●Neutral heteropolysaccharides	●Antioxidant ●Hypoglycemic	●Attenuation of oxidation-driven glycation ●Glycemic-control support	●No direct antiglycation assay ●No AGE-marker tracking
Lily bulb (*Lilium* spp.)	●Heteropolysaccharides ●Pectic/glucomannan-related fractions	●Antioxidant ●Immunomodulatory	●Protein protection under oxidative/inflammatory stress	●Indirect AGE relevance ●No food-system data
Codonopsis root (*Codonopsis* spp.)	●Pectic polysaccharides ●Arabinogalactan-rich fractions	●Antioxidant ●Immunomodulatory ●Tissue-protective	●Glycoxidative-injury attenuation ●Downstream protection	●No AGE-formation validation ●No standardized active fraction
Jujube (*Ziziphus jujuba*)	●Acidic heteropolysaccharides ●Pectic fractions	●Antioxidant ●Anti-inflammatory ●Metabolic improvement	●Attenuation of oxidative glycation amplification ●Insulin-sensitivity support	●No direct antiglycation assay ●Non-AGE-specific evidence
Dwarf lilyturf tuber (*Ophiopogon japonicus*)	●Fructans ●Acidic heteropolysaccharides	●Antioxidant ●Hypoglycemic ●Anti-inflammatory	●Suppression of oxidative/inflammatory AGE drivers	●Newly listed FMH source ●Early polysaccharide evidence
Rehmannia root (*Rehmannia glutinosa*)	●Heteropolysaccharides ●Oligosaccharide-rich fractions	●Antioxidant ●Gut or immune modulation ●Anti-aging	●Modulation of intestinal/metabolic AGE exposure	●Newly listed FMH source ●No direct AGE validation
Chinese yam (*Dioscorea opposita*)	●Mucilage-related polysaccharides ●Fructans	●Antioxidant ●Hypoglycemic ●Intestinal protection	●Glucose-derived precursor reduction ●Glycoxidative-injury protection	●No direct AGE-marker tracking ●No food-system validation
Kelp/kunbu (*Laminaria japonica* or *Ecklonia kurome*)	●Alginates ●Sulfated brown algal polysaccharides	●Antioxidant ●Metal chelation ●Protein protection	●Low-AGE formulation support ●Protein protection in food matrices	●Hydrocolloid-oriented evidence ●Not FMH-source-specific

targeting AGE formation remain scarce.

Among marine algal materials, kelp/kunbu (*Laminaria japonica* or *Ecklonia kurome*) provides another illustrative candidate. Evidence from alginates and sulfated brown algal polysaccharides in hydrocolloid-oriented studies suggests possible AGE-inhibitory, metal-chelating, and protein-protective effects. However, these findings were not obtained from studies designed around catalog-defined kelp/kunbu materials as FMH sources. They therefore justify targeted screening rather than assigning kelp a higher priority than other candidate materials.

These candidates should be evaluated through a common stepwise route: Preparation of compositionally defined fractions with appropriate protein and phenolic controls; screening in complementary sugar- and dicarbonyl-driven models using multiple AGE and protein-damage endpoints; confirmation in representative food matrices under realistic processing or storage conditions; and joint assessment of dose, product quality, sensory acceptance, and safety. This sequence would provide comparable evidence before practical priority is assigned.

Some materials discussed in the broader literature are not included in the main list considered here. *Coptis chinensis* is not among the 106 officially recognized FMH materials. Research materials such as walnut diaphragm and longan peel do not correspond to the officially listed edible parts, namely walnut kernel and longan aril. Black fungus, despite being a common edible mushroom, is absent from the current FMH catalog.

5 Food-System Applications and Engineering Considerations of FMH-Derived Polysaccharides

Once FMH-derived polysaccharides are incorporated into complex food matrices, their performance can no longer be judged by a single *in vitro* antiglycation value. Instead, they must be evaluated together with processing behavior, storage stability, and product quality. Compared with BSA-sugar chemical models, real foods present far more complex reaction environments. Proteins, lipids, reducing sugars, and water participate simultaneously, while ionic strength and pH may also vary substantially across matrices. These factors jointly influence AGE accumulation pathways. Accordingly, evaluation should extend beyond fluorescent AGEs to multiple indicators, including furosine, CML, CEL, 5-hydroxymethylfurfural (HMF), α-dicarbonyl compounds, protein oxidation products, color, texture, and sensory scores [40,50]. Therefore, the application value of FMH-derived polysaccharides in foods must be judged within specific systems rather than inferred solely from inhibition rates in simplified *in vitro* models.

5.1 Reported performance of FMH-derived polysaccharides in real food systems

Direct food-system evidence is currently limited to hawthorn POS in infant formula during storage and SGP in biscuits during baking.

Infant formula is highly susceptible to Maillard

reactions during processing and prolonged storage, making it a representative dairy matrix for practical AGE control. Zhu et al. [48] added hawthorn POS to infant formula at 5% (*w*/*w*) and examined three storage conditions: 25 °C for 12 months, 45 °C for 12 weeks, and 65 °C for 48 days. At 25 °C, furosine changed little and CML, CEL, and total AGEs were hardly formed in any group, preventing a meaningful assessment of sustained AGE inhibition under ambient storage. At 45 °C, the increase in furosine was smaller in the POS group than in the blank and galactooligosaccharide/fructooligosaccharide groups, but no significant overall inhibition of AGE formation was established. Clear differences emerged at 65 °C. After 48 days, the POS group contained 0.66 ng/mg CEL, 0.89 ng/mg CML, and 2.08 ng/mg total AGEs, compared with 1.08, 1.26, and 3.41 ng/mg, respectively, in the blank control. POS also slowed the formation of lipid oxidation products and was associated with lower cytotoxicity, although it did not alter protein degradation products. These results support the effectiveness of hawthorn POS under severe accelerated storage stress, but they do not demonstrate sustained inhibition during normal shelf-life storage. Longer-term studies under commercially relevant conditions are still needed to evaluate AGE control, formulation stability, and retention of POS structure and activity.

Biscuits are typical high-risk foods for AGE formation because of their high sugar content, low moisture, and intensive thermal processing. Long et al. [43] added 1%, 2%, and 4% SGP to cocoa biscuit formulations and evaluated AGE levels and product quality after baking at 170 °C for 5 min. Fluorescent AGEs increased by 54.55% in blank biscuits but only by 52.83%, 46.80%, and 39.27% after the addition of 1%, 2%, and 4% SGP, respectively. Protein oxidation products such as dityrosine, kynurenine, and N′-formylkynurenine were also reduced. SGP also altered texture-related biscuit properties. Moisture content decreased from 5.59% to 3.62%, hardness increased, and crispness increased to 1.08–1.27 times that of the blank group. These results show that, in baking systems, FMH-derived polysaccharides can affect both AGE formation and product texture.

5.2 Engineering value of FMH-derived polysaccharides as food ingredients

FMH-derived polysaccharides can serve as both AGE-mitigation agents and structural ingredients in food formulations. Their engineering value lies not only in reducing AGE formation but also in contributing to water retention, thickening, gelation, emulsification, stabilization, and texture optimization. Related hydrocolloid studies further suggest that the advantage of polysaccharide ingredients often lies in their dual contribution to hazard control and product-quality maintenance [18,29]. This dual functionality may offer formulation advantages over inhibitors that provide no structural contribution.

Although direct food-engineering validation of FMH-derived polysaccharides remains limited, studies on non-FMH hydrocolloids such as chitosan, pectin, and sodium alginate provide useful engineering references. Studies in fish patties, fish sausages, sponge cakes, and roasted beef patties collectively show that polysaccharides or hydrocolloids can reduce CML/CEL, fluorescent AGEs, or other thermally induced hazards while largely maintaining color, texture, and sensory acceptability [18,29,51]. For example, adding 1.5% chitosan or pectin to roasted beef patties reduced levels of AGEs and heterocyclic amines by approximately 53.8%–68.1%, while exerting generally limited effects on pH, cooking loss, texture, color, and sensory properties [51]. In fish sausages, an enzymatic glycosylation strategy coupling transglutaminase with chitosan oligosaccharides reduced CML by 36.4% and was accompanied by favorable changes in texture and water distribution [52]. These dual effects suggest that polysaccharides should be viewed not merely as added inhibitors, but as part of structural formulation design. Although these engineering experiences do not directly validate FMH-derived polysaccharides, they provide useful methodological references for the further application of hawthorn, *Siraitia grosvenorii*, and other FMH-derived polysaccharides.

In product development, polysaccharides are rarely used in isolation but may be combined with polyphenols, natural antioxidants, or other functional ingredients. Hu et al. [40] found in butter biscuits that catechin showed the strongest inhibition of AGEs and HMF, but caused greater color and flavor penalties. In contrast, pectin and chitosan showed weaker direct inhibition but were more favorable for sensory quality. The authors therefore proposed that combining natural antioxidants with hydrocolloids may be more suitable for balancing hazard control and consumer acceptability. Because direct studies of combination strategies involving FMH-derived polysaccharides remain scarce, these approaches should be treated as formulation hypotheses requiring factorial comparison with the individual components.

5.3 Key factors affecting the performance of FMH-derived polysaccharides in food applications

In real foods, inhibitory effects and product performance usually show clear dose dependence, but the dose that gives the strongest inhibition is not always the dose that gives the best product quality. Wang et al. [30] found in cakes that 2% *κ*-carrageenan produced the strongest AGE

inhibition, with fluorescent AGEs reduced by 69.69%, but sensory quality and overall acceptability also decreased. After considering overall product quality, the authors regarded 1% as a more suitable practical dose. Wang et al. [29] similarly found in sponge cakes that 0.5% chitosan achieved a better balance between AGE inhibition and product quality. These cases show that excessive addition may lead to trade-offs in texture, color, or flavor. The timing of addition and the processing route, such as premixing, addition before or after heating, or combination with enzymatic treatment, may also alter the final outcome. Dose is only one variable; application success also depends on the matrix into which a polysaccharide is incorporated and the components with which it interacts.

Interactions between polysaccharides and proteins, lipids, or reducing sugars determine whether polysaccharides can truly influence AGE formation pathways. Wei et al. [31] found in plant-based meat analogues that CMC inhibited AGE formation in an SPI-glucose model, but showed little effect in a lysine-glucose model. This suggests that its effect is mediated mainly by interactions with soy protein, occupation of reactive protein sites, and improved thermal stability, rather than by simple competition with small-molecule amino groups. The main action sites of polysaccharides may therefore differ across food matrices. In dairy systems, their effects may be more closely related to intermediate control and system stabilization, whereas in plant-based or meat products, protein-site occupation and structural protection may be more important [31,43]. To advance the application of FMH-derived polysaccharides, future studies must therefore focus on their compatibility with target food matrices, rather than extrapolating only from *in vitro* model results. Beyond matrix compatibility, retention of activity during processing and storage also affects the final application value of polysaccharides.

Thermal processing, low-moisture baking, and long-term storage can simultaneously change the rate of AGE formation and the activity profile of polysaccharides themselves. Hu et al. [40] noted in butter biscuits that pectin at higher addition levels could reduce protein-bound AGEs, but this reduction was accompanied by a marked increase in HMF. The authors related this result to a decrease in dough pH. This indicates that the same ingredient in the same system may produce divergent outcomes, such as lower AGEs but higher HMF. The cake study by Wang et al. [30] also showed that changes in AGE inhibition, product structure, and sensory scores were not fully synchronized across different doses. Zhu et al. [50] further showed, using kiwifruit POS in infant formula, that ingredients during accelerated storage affect not only AGE accumulation, but also water activity, lactose glass transition, and browning degree. Accordingly, the suitability of a polysaccharide in practical applications cannot be judged from a single endpoint or time point.

Formulation optimization should therefore jointly consider AGE markers, texture, color, flavor, overall acceptability, and processing stability rather than maximize the inhibition of a single AGE endpoint. FMH-derived polysaccharides have shown potential in real food systems, but food-type specificity, dose optimization, and processing adaptation remain underexplored. Their development into scalable low-AGE food ingredients will depend not only on efficacy, but also on whether they can deliver stable, acceptable, and reproducible performance in specific systems. Addressing these issues is essential for further standardization and industrial translation.

6 Limitations and Future Perspectives

The evidence summarized above supports further investigation of FMH-derived polysaccharides for food AGE control. However, current studies remain insufficiently comparable for confident source selection, mechanistic interpretation, or practical application [17,25].

Most current evidence on the regulation of AGEs by FMH-derived polysaccharides still comes from simplified models. BSA-sugar chemical models and a limited range of cellular models are useful for mechanistic screening, but they lack the complexity of real food matrices and cannot simulate human digestion, absorption, and metabolism [19,53]. Rodent models provide a degree of *in vivo* relevance, but they are also affected by species differences, exaggerated doses, and interpretive confounding caused by co-exposure designs. A substantial gap therefore remains between activity in experimental models and effectiveness under real dietary exposure conditions [8,53].

FMH-derived polysaccharides are not static materials, and their structural features often change markedly during processing and preparation. Although several structure-activity tendencies have been summarized, most remain local observations. Studies that analyze processing conditions, structural changes, and AGE-regulatory effects as a continuous chain are still scarce [17,25]. Since herbal processing, extraction, thermal treatment, and storage conditions can all alter molecular weight, monosaccharide composition, and branching features, results obtained from different sources or preparation methods are often difficult to corroborate. This limitation further constrains broader generalization of structure–activity relationships [54].

Analytical comparability remains limited across studies, even within similar food systems. Current studies differ substantially in their selection of AGE markers. The coverage of fluorescent AGEs, CML, CEL, pyrraline, MG-H1, and other markers varies across studies. Meanwhile, the distinction among free, bound, and total AGEs, as well as sample pretreatment procedures, still lacks unified standards [20,55,56]. Such analytical heterogeneity not only reduces cross-study comparability, but also makes it difficult to integrate conclusions based on different endpoints into consistent application guidance.

Human-relevant evidence remains the most consequential gap. Existing dietary AGE intervention studies are generally small and heterogeneous, and the absorption, metabolism, excretion, and health effects of exogenous AGEs are jointly shaped by food matrix, intestinal environment, and individual physiological status [8,19,53]. Accordingly, high-quality evidence for long-term dietary intervention conclusions remains limited, and clinical extrapolation should remain cautious [26,56].

Future work should therefore focus on measurement comparability, mechanistic validation, and translation.

Given the diversity of polysaccharide preparations and food matrices, a minimum reporting framework is more practical than a single universal protocol. At the material level, studies should report the source species and material part, batch information, extraction and purification procedures, molecular-weight distribution, monosaccharide composition, homogeneity, relevant charged or substituted groups, and residual protein and total phenolic contents [17,18]. At the model level, the complete composition of the reaction system or food matrix, polysaccharide dose, pH, water activity, mixing sequence, and thermal or storage history should be specified. AGE measurements should define whether free, bound, or total fractions are determined and describe the corresponding pretreatment and hydrolysis procedures. Fluorescence may be retained for screening, but it should be complemented by CML and CEL, at least one cross-linked or pathway-specific AGE such as pentosidine or MG-H1, and, where relevant, reactive dicarbonyls or early glycation products. Analytical reports should also provide information on standards or internal standards, calibration, recovery, limits of detection and quantification, normalization, replicates, and quality-control procedures [20,21,55,56]. Linking these measurements with protein oxidation, digestive fate, and intestinal exposure would further improve their translational relevance.

Safety should be evaluated separately from the traditional dietary use of the source material. Current reviews do not establish a universal dose limit or a class-wide safety profile for FMH-derived polysaccharides, and the consumption history of an FMH material does not by itself establish the safety of a purified polysaccharide fraction used at a high inclusion level [17,18]. Tolerance is likely to depend on the source, molecular characteristics, purity, co-extracted components, processing residues, target food, and consumer population. Future food-application studies should therefore examine gastrointestinal tolerance, particularly where fermentability, water-binding capacity, or viscosity increases at high inclusion levels, together with possible interactions with proteins, minerals, and other nutrients. Reported immunomodulatory activity should not be interpreted as evidence of clinical immunogenicity; nevertheless, immune-related endpoints should be considered where relevant. Contaminants, residual solvents, batch consistency, and responses in sensitive populations also require attention. Dose-response assessment in the intended food matrix is therefore needed before general safety conclusions can be drawn.

Future studies should also connect processing-induced structural changes with AGE-inhibitory activity. Tracking molecular weight, composition, branching, and activity across raw-material treatment, thermal processing, storage, and reheating would help explain discrepancies among existing findings and better reflect the practical use of FMH-derived polysaccharides as food ingredients [17,25,54].

Future research should also extend from measuring AGE formation alone to understanding the intestinal fate of AGEs after exposure. Unabsorbed AGEs interact in complex ways with the gut microbiota, intestinal barrier, and systemic inflammatory responses. The microbiota may metabolize certain dicarbonyl intermediates, but it may also amplify AGE-related toxicity through the lipopolysaccharide-RAGE axis [57,58]. For FMH-derived polysaccharides, which can themselves serve as carbohydrate substrates for the gut microbiota, future evaluation systems should more systematically include endpoints such as gut microbiota composition, intestinal barrier integrity, and intestinal permeability, rather than remaining limited to plasma AGE levels or a single fluorescence indicator [26,56].

Translational progress will also require research models and methodological tools that better approximate real dietary exposure. Emerging approaches such as human stem-cell-derived systems, intestinal organoids, organ-on-chip platforms, and physiologically based kinetic modeling coupled with quantitative *in vitro*-to-*in vivo* extrapolation (PBK-QIVIVE) provide more human-relevant alternatives. These approaches can evaluate polysaccharide effects under conditions closer to real dietary exposure and realistic dose levels [17,53].

Simple proof of activity is no longer sufficient. The priority is to convert scattered findings into evidence that supports source selection, mechanistic interpretation, and application in real food systems. Connecting standardized AGE measurements with source-specific structural characterization, processing-responsive activity tracking, and human-relevant exposure models would help move FMH-derived polysaccharides toward reproducible use in low-AGE food formulation.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Competing interests The authors declare no conflicts of interest.

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