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# Substituent group-modified pectins: Targeted modifications for enhanced functional properties

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ABSTRACT

*Background:* In nature, there are multiple substituent group-modified (SGM, e.g., alkylated, acetylated, amidated, and molecularly grafted groups) pectins that exhibit better functional potential than non-modified pectin, but their content is significantly much lower than normal pectins. Various methods for modifying pectin have been developed that rely on changing its degree of substitution (DS) to improve its targeted use, and the relationships between their modification methods, chemical structures and functional properties have yet to be fully explored.
*Scope and approach:* This article systematically reviews the modification methods and structural characterization of SGM pectins, as well as the mechanisms by which these modifications enhance their functional properties, including gelling, emulsifying, health-promoting effects, functional component delivery, and preservation. Future trends in the development of SGM pectins are also examined.
*Key findings and conclusions:* SGM pectins produced through various modification methods exhibit different types, degrees, and positions of substitution. These structural changes enhance the functional properties of pectins, including their physicochemical properties, health benefits, and practical applications. A new era of green, precise, and intelligent development of SGM pectins is anticipated. This information will support the targeted modification of pectins with specific functional properties and their application in high-quality pectin-based foods to meet diverse needs.

## 1. Introduction

Food components are important for human health (Emwas et al., 2021). Pectin, as a natural polysaccharide, is abundance in fruits and vegetables, up to 30% of the dry matter of the cell wall (Cui et al., 2021). Its extensive application in the food and pharmaceutical industries is due to its physicochemical and physiological properties, including gelling and emulsification, and its health-promoting effects. For example, pectin is commonly used as a thickener in jam and jelly, as a stabilizer in fruit juice and acidified milk beverages, and as a fat substitute in ice cream and meat products. In addition, it shows promise as a prebiotic for use in the alleviation of intestinal inflammation as well as in the prevention of weight gain and fat accumulation. In the pharmaceutical industry, pectin has been tested in drug delivery, tissue engineering, and wound healing (Chen et al., 2015). Interest in further developing pectin in functional foods has thus increased dramatically, such that the functional properties of pectin have become an intense focus of research.

Structurally, pectin is mainly composed of three domains: homogalacturonan (HG), rhamnogalacturonan type I (RG-I), and rhamnogalacturonan type II (RG-II). HG is a linear chain of 1,4-linked α-D-galacturonic acid (α-D-GalA) residues that can be partially methylated at C-6 or O-acetylated at C-3 and/or C-2. RG-I has a repetitive disaccharide [→2)-α-L-Rha (1 → 4)-α-D-GalA-(1→] skeleton, with side chains mainly composed of D-galactose and L-arabinose. RG-II consists of 12 different monosaccharides, with an HG backbone and polymers formed by 8–12 sugar residues (Niu et al., 2023). Similar to other macromolecular polymers, pectin also has a spatial conformation, which is influenced by its primary chemical structure (e.g., molecular weight, monosaccharide composition, and degree of esterification) and environmental factors (e.g., pH and temperature). The chemical structure of pectin determines its physicochemical properties and physiological activities. For example, high methoxyl pectin (HMP) forms a gel in the presence of sugar and low

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pH, while low methoxyl pectin (LMP), in the presence of divalent cations, forms a gel under a wide pH range. RG-I pectin exhibits better prebiotic activity than HG pectin, as the former is rich in neutral sugar side chains, which are crucial for the initial stage of intestinal microbiota fermentation and are preferentially utilized (Tang & de Vos, 2023).

In nature, there are multiple substituent group-modified (SGM) pectins that exhibit better functional potential than non-modified pectin in terms of gelling and emulsifying properties, health-promoting effects, delivery functions, and use as preservatives, but their content is significantly much lower than normal pectins (Liu et al., 2025). In the food industry, various methods for modifying pectin have been developed that rely on changing its degree of substitution (DS) to improve its targeted use. These modifications mainly mimic those found in nature, such as alkylation, acetylation, amidation, and molecular grafting at the carboxyl and ester bonds at C-6 and hydroxyl groups at C-2/C-3 of GalA. For example, the emulsifying properties of a pectin can be improved through modifications that favor noncovalent interactions, which increase the contact opportunities between pectin chains and in turn, the viscosity of pectin. In this case, the introduction of functional groups or molecules that differ in their hydrophilic or hydrophobic properties causes structural changes in pectin that alter its surface tension at the water/oil interface (Liu et al., 2020). Pectin modifications, which may improve its physicochemical properties and functional characteristics and, consequently, enhance the adaptability to different processing conditions and expand its range of applications, are important for its development and high-value utilization in the food industry. However, despite the many potential applications of SGM pectins, the relationships between their modification methods, chemical structures and functional properties have yet to be fully explored (Fig. 1).

This review examines the potential modifications of pectin, with a focus on the changes in the structural characteristics and functional properties achieved using processes such as alkylation, acetylation, amidation, as well as substitutions involving proteins and polyphenols. The underlying mechanisms are also discussed. By providing a better understanding of the potential relationships between the modification, chemical structure, and functional properties of pectin, this review can serve as a reference for the targeted modification of pectin according to specific functional requirements.

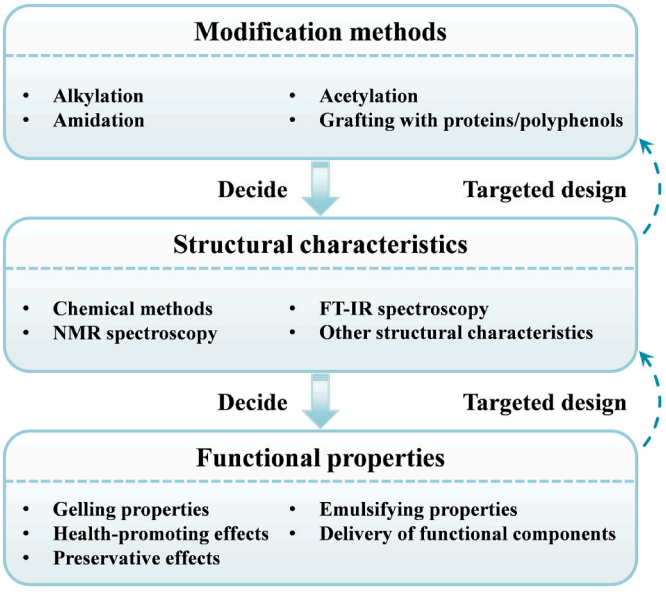


**Fig. 1.** Relationships among the modification methods, structural characteristics, and functional properties of substituent group-modified (SGM) pectins.

## 2. Targeted modifications

The low content and low DS of natural SGM pectins have limited their applications in the food industry. Targeted modification could efficiently provide SGM pectins with the desired type of substitution. At the same time, new SGM pectins can also be obtained, such as sulfated, quaternized, and thiolated pectin, to further expand the range of pectin-based applications (Table 1).

### 2.1. Alkylation

The carboxylic acid group at position C-6 of pectin can be replaced with carbon chains of different lengths via alkylation reactions. Pectin bearing methyl ester groups is the most common form of alkylated pectin (Fig. 2A). The Gal is an important indicator of many of the well-known properties of pectin, including gelling and emulsification. Natural pectin has a DM of 50.0–70.0%, depending on the source (Cui et al., 2021). High-DM pectin is prepared by reacting pectin with acidified methanol, which usually requires incubation at 0–5 °C or anhydrous conditions to minimize glycosidic bond cleavage. Alternatively, it can be obtained by reacting pectin with $CH_3I$ in dimethyl sulfoxide (DMSO) solution, although this method requires the extensive pre-depolymerization of pectin to increase its solubility, which facilitates $CH_3I$ replacement (Rosenbohm et al., 2003). The efficiency of these two methods is similar, with yields of 71.9%–79.8% and DMs of 75.9%–86.2%, but both involve acidic/alkaline reaction environments, leading to β-elimination and damage to the pectin chain. This drawback could be addressed by reaction of pectin with methanol at 65 °C or 20 °C on a cation exchange resin. The molecular weight and monosaccharide composition did not change significantly but a DM as high as 95.0% was possible (Peng et al., 2016).

Conversely, demethylation, such as via acid or alkaline hydrolysis (Einhorn-Stoll & Kunzek, 2009) or methylesterase catalysis (Yoo et al., 2009), converts the original methyl ester groups of pectin into carboxyl groups. Acid/alkaline hydrolysis is convenient and fast but difficult to control. Enzymatic catalysis, as a specific reaction, produces pectin with a specific number and distribution of methyl esters (Li et al., 2024).

### 2.2. Acetylation

The acetylation of pectin usually refers to substitution of the hydroxyl groups at the C-2 and/or C-3 positions of pectin GalA with O-acetyl substituents ($CH_3CO$-) (Fig. 2B). In nature, acetylated pectin is found in many fruits and vegetables but the degree of acetylation (DAc) is very low, often <20.0% (Cui et al., 2021). Among the methods used to obtain highly acetylated pectin is a reaction in which acetic anhydride is the starting material and the reaction is catalyzed by pyridine or N-methylimidazole in different solvents (DMSO or formamide). However, acetylation is more likely to occur at the C-2 than at the C-3 position, perhaps due to the hindrance of the O-3-O-5' hydrogen bond on C-3 in the $2_1$ helical conformation of the GalA chain, while C-2 is more accessible. Single-factor experiments have shown that the use of a large excess of acetic anhydride ($Ac_2O$:GalA = 20:1) and pyridine:formamide (10:25) results in pectins with a very high DAc (approximately 154.0 units per reaction), whereas the DAc of pectin obtained in reactions using DMSO:N-methylimidazole and DMSO:pyridine systems is lower (135.0 and 102.0, respectively) (Renard & Jarvis, 1999). However, while the method is efficient and convenient, a large amount of acetic anhydride is needed, and recycling of the industrial-scale quantities of organic reagents is problematic. Long-chain fatty acid anhydrides (palmitic, oleic, and linoleic acid anhydrides) can react with pectin in an oil bath at 160 °C under solvent-free conditions. The substitution reactions using oleic acid and linoleic acid as substrates occur at the C-2 hydroxyl groups of GalA and result in a DS of 35.0%, while with palmitic acid a DS of 90.0% is possible (Monfregola et al., 2011). This method does not destroy the original structure of pectin, generates high-DS products, and

**Table 1**
Modification methods used to obtain substituent group-modified (SGM) pectins.

| Modifications | Reagent/Catalyst | Reaction conditions | Yield | Substitution degree | References |
|---|---|---|---|---|---|
| Alkylation | Methanol, $H_2SO_4$ | 5 °C, 24 d | – | DM: 92.0% | Rosenbohm et al. (2003) |
| | Methanol, cation exchange resin | 65 °C, 24 h | 85.5% | DM: 95.0% | Peng et al. (2016) |
| | $CH_3I$, tetrabutylammonium hydroxide, DMSO | RT, 2 d | – | DM: 84.0% | Rosenbohm et al. (2003) |
| | Alkyl bromide (C6, C12 or C18), tetrabutylammonium hydroxide, DMSO | RT, 24 h | – | DS: 0.7%–3.6% | Liang et al. (2015) |
| | Pectin methylesterases | 30 °C, pH 6.8, 5 min | – | DM: 6.3% | Yoo et al. (2009) |
| Acetylation | Acetic anhydride, pyridine or N-methylimidazole, DMSO or formamide | RT, 24 h | 50.0% | DAc: 102.0–154.0 | Renard & Jarvis, 1999 |
| | Fatty acid anhydrides (palmitic, oleic, linoleic acid anhydrides), $K_2CO_3$ | 160 °C, 15–25 min | – | DS: 1.8%–90.0% | Monfregola et al. (2011) |
| Amidation | Ammonia, ethanol | 5 °C, 4 h | – | DS: 12.7% | Einhorn-Stoll & Kunzek, 2009 |
| | Primary aliphatic amines, methanol | 5 °C, 12 h | – | DS: 10.0%–48.0% | Sinitsya et al. (2000) |
| | Ethylenediamine, EDC, N-hydroxysuccinimide | RT, pH 4, 8 h | – | DS: 31.6%–48.3% | Liang et al. (2020) |
| | Amino acids (glutamate, glycine, lysine), EDC, N-hydroxysuccinimide | Ice bath, pH 5, 24 h | – | DS: 4.9%–7.8% | Wang et al., 2022b |
| | Amino acids, MMTM | RT, 8 h | 71.4%–92.9% | DS: 4.5%–24.8% | Wang et al. (2024) |
| | Amino acids (glycine, glutamic acid, lysine), papain | −15 °C, pH 7, 24 h, $N_2$ | – | DS: 9.3%–13.0% | Zheng, Zhang, et al. (2022) |
| Grafting with proteins | Soy protein isolate, KBr | 60 °C, pH 7, humidity 79%, 5 d | – | DS: 25.0% | Ma, Chen, et al. (2020) |
| | Soy protein isolate, KBr | 60 °C, humidity 80%, 500 min, microwave (400W) | – | DS: 32.2% | Teng et al. (2023) |
| | Ovalbumin | 90 °C, pH 6, 50 min | – | DS: 38.9% | Yu et al. (2022) |
| | Ovalbumin | 60 °C, 70 min, sonicate (400W) | – | DS: 40.6% | Yu et al. (2022) |
| Grafting with polyphenols | Polyphenols (catechin, quercetin, rutin, hesperidin), epichlorohydrin | 40 °C, 5 h | – | – | Ahn et al. (2017) |
| | Naringenin, 4-dimethylaminopyridine | 60–65 °C, 6 h | – | DS: 37.1 μg naringenin/mg graft | Mundlia et al. (2019) |
| | Ferulic acid, laccase, methanol | 30 °C, 24 h | – | DS: 54.7 mg Gal Eq/g DW | Karaki et al. (2017) |
| | Ferulic acid, ascorbic acid, $H_2O_2$ | RT, 12 h | – | DS: 65.4% | Wang et al. (2020) |
| | Polyphenols (*p*-hydroxybenzoic acid, 3,4-dihydroxy-benzoic acid, gallic acid), lipase | 50 °C, 24 h | – | DS: 18.9%–20.3% | Liu et al. (2021) |
| Sulfation | Chlorosulfonic acid, formamide, propylene oxide | 80–90 °C, pH 10–11, 4 h | – | DS: 15.0% | Bae et al. (2009) |
| | Chlorosulfonic acid, formamide, pyridine | 4 °C, 12 h | – | DS: 1.5%–36.6% | Maas et al. (2012) |
| | Sulfur trioxide, pyridine, DMSO | 80 °C, 1–3 h | – | DS: 21.6%–31.5% | Hu et al. (2015) |
| | Monomethyl sulfate, pyridine | 80 °C, 0.5–3 h | 55.0%–76.0% | DS: 9.0%–21.0% (-$SO_3^-$ %) | Vityazev et al. (2010) |
| | $[N(SO_3Na)_3]$ | 90 °C, 90 min | – | DS: 1.0%–37.0% | Fan, Gao, et al. (2012) |
| Quaternization | 3-Chloro-2-hydroxypropyl- trimethylammonium chloride, NaOH | 40–70 °C, 17 h | – | DS: 0.4%–2.6% | Fan, Cao, et al. (2012) |
| | 2,3-Glycidyltrimethylammonium chloride | 60 °C, 3 h | 16.0%–36.0% | DS: 0.0%–3.1% | Šimkovic et al. (2008) |
| Thiolation | Cysteine, EDAC | 2 h and then 75 min with pH 5 | – | DS: 892.3 μmol thiol groups/g pectin | Majzoob et al. (2006) |
| | 4-Aminothiophenol, EDAC | Ice bath, 4 h | – | DS: 557.3 μmol thiol groups/g pectin | Perera et al. (2010) |
| | Thioglycolic acid, HCl | 80 °C, 150 min | – | ~600.0 μmol thiol groups/g pectin | Sharma & Ahuja, 2011 |

Note: DMSO, dimethyl sulfoxide; EDC, 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide; MMTM, 4-(4,6-dimethoxy-1,3,5-triazin-2-yl)-4-methyl-morpholin-4-ium chloride; EDAC, 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride.

is environmentally safe.

### 2.3. Amidation

Amidated pectin can be extracted from lime or orange, but its content and DS from these sources are unclear (Larsen, Cahu, Isay Saad, Blennow, & Jespersenet, 2018). Synthetic pectin amidation involves replacement of the C-6 carboxyl or methoxy group in GalA to form an amide group (-CO-NHR-) (Fig. 2C). Amidated pectin with a high DS can be obtained by several modification methods. In the traditional method, which is also used to commercially produce amidated pectin, alkaline de-esterification of the methoxy groups is achieved using ammonia in anhydrous ethanol (Einhorn-Stoll & Kunzek, 2009), which introduces amide groups. Primary aliphatic amines, hydroxylamines, and amino acids can also be used to prepare amidated pectin. The introduction of primary aliphatic amines links various carbon free radicals or functions with pectin macromolecules (Sinitsya et al., 2000). The use of hydroxylamine results in partial degradation of pectin due to the alkaline reaction conditions and, thus, a decrease in its molecular weight (Rha et al., 2011). As most hydroxylamines used in the reaction are toxic, this method is not suitable for the food industry (Liang et al., 2020). In contrast, the amidation of pectin with amino acids, typically in aqueous solution for 4–12 h at 40 °C, is safe, although only a few neutral and alkaline amino acids (e.g., glycine, lysine, and arginine) can be used successfully under these conditions and the reaction efficiency (DS = 6.5%) is low (Chen et al., 2020). Moreover, the alkaline heating

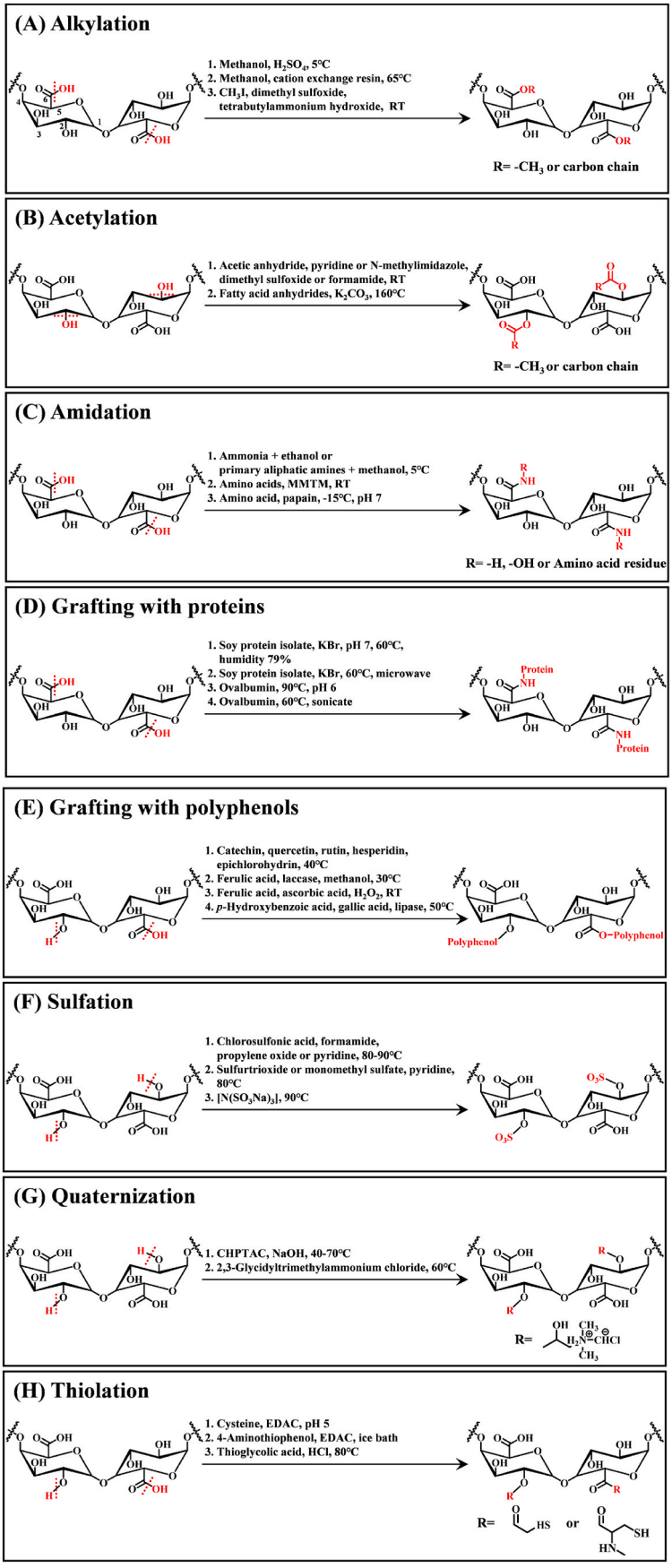


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**Fig. 2.** Reaction types and preparation methods of SGM pectins. (A) Alkylation; (B) Acetylation; (C) Amidation; (D) Grafting with proteins. Different lowercase letters represent the reaction conditions that can independently induce the reaction (RT, room temperature; MMTM, 4-(4,6-dimethoxy-1,3,5-triazin-2-yl)-4-methylmorpholin-4-ium chloride; CHPTAC, 3-chloro-2-hydroxypropyltrimethylammonium chloride; EDAC, 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride).
Reaction types and preparation methods of SGM pectins. (E) Grafting with polyphenols; (F) Sulfation; (G) Quaternization; (H) Thiolation.

conditions result in the destruction of pectin during the reaction process. Various catalytic methods with higher efficiency and wider applicability have thus been developed. For example, MMTM can be used to catalyze the amidation of pectin with 20 different amino acids. The highest DS (13.5–24.8%) is achieved with alkaline amino acids, followed by neutral (6.0–11.9%) and acidic (4.5–6.4%) amino acids (Wang et al., 2024). Amidated pectin (glycine/glutamic acid/lysine pectin) can also be prepared using papain under ultra-low-temperature conditions, which protects the pectin chain; the DS ranges from 9.3% to 13.0% (Zheng, Zhang, et al., 2022).

### 2.4. Grafting with proteins

The carboxylic acid group at position C-6 of pectin can condense with the amino group of proteins, which can be exploited in grafting reactions (Fig. 2D). Protein–pectin complexes are widely present in nature and are mostly formed through covalent interactions but also through electrostatic, hydrophobic, and hydrogen bonds (Einhorn-Stoll et al., 2021). However, the grafting rate is very low; for example, the protein content in sugar beet pectin extracted by different methods ranges from 0.5% to 6.0% (Chen, Qiu, et al., 2018). Protein-grafted pectins with a higher grafting rate can be prepared using methods that are mainly based on the Maillard reaction (Murata, 2021), including dry-heating and wet-heating. Dry-heating methods usually require pre-dissolving the protein and pectin in an aqueous solution, followed by freeze-drying, with the reaction then carried out over several hours or even days at 60–80% humidity and 60 °C (Guo et al., 2019; Kan et al., 2021). However, this method is time-consuming and costly, and the grafting rates are low (20.0–25.0%). The reaction in the wet-heating method is carried out in aqueous solution at pH 6–8, with the reaction temperature increased to 90 °C to shorten the reaction time (<1 h) and improve the efficiency. With this method the grafting rate is 40.6% (Yu et al., 2022), but the high temperature may cause protein denaturation and pectin chain depolymerization. More recent, non-heat-dependent techniques have therefore been introduced in combination with the traditional Maillard reaction, including ultrasound and microwave (Teng et al., 2023). For example, pectin products with a grafting degree of 38.9% and a browning degree of only 1.2 were obtained using ultrasound (70 min at 60 °C).

### 2.5. Grafting with polyphenols

The grafting reaction between pectin and polyphenols occurs at the C-6 carboxyl group or the C-2 hydroxyl group (Fig. 2E). Polyphenol-grafted pectin is found in many fruits and crops in amounts that affect the physicochemical properties, digestibility, and bioavailability of food (Guo et al., 2022). The preparation of polyphenol-grafted pectins with high grafting rates is facilitated by chemical catalysts such as epichlorohydrin and 4-dimethylaminopyridine (Ahn et al., 2017; Mundlia et al., 2019), which avoid the instability of polyphenols during the grafting process. However, the DS of the obtained grafted pectin is relatively low (<5.0%), and the chemical grafting agents are often toxic, have poor biocompatibility, and are difficult to completely remove. Enzyme-mediated reactions with high efficiency and grafting rates have thus been developed, mainly laccase-catalyzed oxidation and lipase-catalyzed esterification (Jung & Wicker, 2012; Liu et al., 2021). Laccase is used to catalyze ferulic-acid-grafted pectin. It oxidizes ferulic acid to reactive semiquinone, which then promotes the formation of a ferulic acid dimer and grafting with pectin (Karaki et al., 2016). Lipase has a wide range of reaction substrates, including ferulic acid, gallic acid, and salicylic acid, in which the grafting rate can reach 10.0–20.0%. The enzyme catalyzes the hydrolysis of the methyl groups in pectin under aqueous conditions and promotes esterification between pectin and polyphenols in the organic phase (Huang et al., 2021). For example, under laccase catalysis, citrus pectin was grafted with ferulic acid in aqueous medium at 30 °C and pH 7.5, resulting in a grafted pectin with a phenolic content five times higher than that of natural pectin (Karaki et al., 2017). However, free radical-induced reactions are more economical, environmentally friendly, and of higher efficiency. For example, in the oxidation-reduction using ascorbic acid and hydrogen peroxide, semi dehydroascorbic acid ($As^{\cdot}$) and hydroxyl (OH) radicals are generated to capture H atoms from the hydroxyl groups of pectin, in turn guiding the formation of pectin macroradicals. This modification method is simple, economical, and has a high efficiency, with a grafting rate of up to 65.4% (Wang et al., 2020).

### 2.6. Other modification methods

Other types of substitution can be used to obtain substituted pectins not found thus far in nature. The sulfation of pectin occurs on the C-2 and C-3 hydroxyl groups of GalA and is achieved using chlorosulfonic acid or monomethyl sulfate as the sulfation reagent, in a reaction performed in various solvents (formamide, DMSO, trimethylamine, or pyridine) (Bae et al., 2009; Fan, Gao, et al., 2012; Hu et al., 2015; Vityazev et al., 2010) (Fig. 2F). The sulfated pectin thus obtained has a $-SO_3^-$ content of 9.0–39.0%. The quaternization of pectin also occurs on the C-2 and C-3 hydroxyl groups of GalA and is catalyzed by 3-chloro-2-hydroxypropyltrimethylammonium chloride or 2,3-glycidyltrimethylammonium chloride (Fan, Cao, et al., 2012; Qin et al., 2022; Šimkovic et al., 2009) (Fig. 2G). However, the DS of quaternized pectin is very low (0.1–2.6%). Pectin thiolation involves the C-6 carboxyl group or the C-2 and C-3 hydroxyl groups of GalA (Fig. 2H). The carboxyl group reaction is mainly achieved using 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDAC) as the activator and proceeds via the formation of amide bonds. The obtained thiolated pectins contain 17.8–201.3 μmol thiol groups per SGM pectin (Majzoob et al., 2006). An amide bond can also be formed by the oxidative cross-linking of 4-aminothiophenol using EDAC (557.3 and 158.8 μmol 4-aminothiophenol/g pectin) (Perera et al., 2010). Thiolation at the C-2 and C-3 hydroxyl groups involves esterification with mercaptoacetic acid in the presence of hydrochloric acid and results in ~600.0 μmol thiol groups/g SGM pectin (Sharma & Ahuja, 2011).

## 3. Chemical structure characteristics

The complex chemical structures of SGM pectins require multiple methods for their verification, including chemical methods, Fourier-transform infrared spectroscopy, and nuclear magnetic resonance spectroscopy. The substitution degrees (e.g. DM, DAc, and grafting rate) are key modification indicators of SGM.

### 3.1. Chemical methods

Chemical methods are used to qualitatively determine the success of substitution reactions and to calculate the DS. Detection is often achieved using colorimetric reagents to measure changes in the content of specific functional groups. For example, the DM of pectin can be determined via titration, such as using the indicator phenolphthalein to

titrate the free carboxyl groups in pectin solution with NaOH, followed by saponification and neutralization reactions (Müller-Maatsch et al., 2014). However, elemental analysis, in which N or S is introduced, is the most direct method to characterize pectin after its amidation, sulfation, quaternization, or thiolation (Bae et al., 2009; Chen et al., 2023; Fan, Cao, et al., 2012; Zheng, Huang, et al., 2022). Alternatively, after adding a chromogenic reagent, some functional groups develop color within a specific wavelength range, such that absorbance can be determined by spectrophotometry. This is often done in protein-grafted pectins, in which the protein content can be determined using OPA reagents (a mixture of o-phthaldialdehyde [methanol solution], sodium tetraborate, SDS solution, and β-mercaptoethanol), and then measuring the absorbance of the reaction product at 340 nm (Ma, Chen, et al., 2020). Similarly, the content of polyphenols in polyphenol-grafted pectins can be assessed using Folin & Ciocalteu reagent and then measuring the absorbance at 730 nm (Chen, Cheng, & Liang, 2015), and the content of thiol groups in thiolated pectin using Ellman's reagent (5,5′-dithiobis-(2-nitrobenzoic acid)) and measuring the absorbance at 412 nm (Chen, Ye, et al., 2018).

### 3.2. FT-IR spectroscopy

FT-IR spectroscopy is a powerful tool for characterizing the structural changes in SGM pectins based on the absorptions of the chemical bonds or functional groups of the polysaccharides. For alkylated pectin, the absorption peaks at 1740 and 1630 $cm^{-1}$ are those of the methyl ester (-$COOCH_3$) and free carboxyl (-COOH) groups of pectin. The ratio of the peak area at 1740 $cm^{-1}$ to the sum of the peak areas at 1740 and 1630 $cm^{-1}$ is commonly used to estimate the DM of pectin and indicates the involvement of the carboxyl group of pectin in the reaction. Acetylated pectin is detected by the appearance of a new absorption peak at 1745 $cm^{-1}$, representing the carbonyl C=O vibration from the acetyl group, with the relative intensity of the peak increasing with increasing DAc. The absorption of the stretching vibration of carbonyl C-O at 1245 $cm^{-1}$ is also significantly enhanced at a higher DAc (Huang et al., 2022). Amidated pectin is represented by three new absorption peaks, at 1765 $cm^{-1}$ (C=O vibrations), 1681 $cm^{-1}$ (amide I), and 1594 $cm^{-1}$ (amide II) (Sinitsya et al., 2000).

A structural characterization of molecular grafted pectin is also possible using FT-IR. For protein-grafted pectins prepared by the Maillard reaction, the intensities of the characteristic bands at 1651 and 1538 $cm^{-1}$, from the C=O stretching of amide I and the N-H vibrations of amide II, and at 1395 $cm^{-1}$, from the C-N stretching and N-H vibrations of amide III, are greatly reduced, with a new band appearing at 1645 $cm^{-1}$, attributable to the C=N stretching vibration of the Schiff base product (Ma et al., 2020a, 2020b). For polyphenol-grafted pectins formed by lipase catalysis, the characteristic absorption peaks vary depending on the polyphenol, occurring at 1265 $cm^{-1}$ (C-O groups), 1517 $cm^{-1}$ (stretching vibrations in the benzene ring), 1692 $cm^{-1}$ (C=O in the phenolic acid aromatic ring), and 2500–3600 $cm^{-1}$ (stretching vibrations in the benzene ring for -OH, hydrogen bonds and C-H) (Chen et al., 2022; Wang et al., 2020).

### 3.3. NMR spectroscopy

One of the most effective tools for qualitative and quantitative analyses of the composition and structure of SGM pectins is NMR. Moreover, $^1$H NMR allows for the simultaneous determination of the DM and DAc of pectins and thus simultaneous confirmation of successful alkylation and acetylation (Müller-Maatsch et al., 2014). Specifically, alkylated pectin is identified by the appearance of new peaks at 1.6 ppm ($COOCH_2CH$-), 1.4–1.1 ppm (-$COOCH_2CH_2(CH_2)_{n-3}$-), and 0.8 ppm (-$COO(CH_2)_{n-1}CH_3$) (Liu et al., 2017), and for amidated pectin the appearance of new peaks between 1.0 and 3.2 ppm, representing the amino acid chain regions. For example, in amidated pectin prepared with lysine, new peaks are observed at 3.0 (α-proton), 1.7, 1.3, 1.5 and 1.9 ppm (methylene proton) (Chen et al., 2020). The peaks of specific amino acids can be found at low ranges of the spectrum. For amidated pectin prepared with histidine, the peaks at 3.3 and 7.3 ppm are those of Hα and the hydrogen on the heterocyclic side chain of histidine, respectively (Wang et al., 2024). $^1$H NMR also allows the efficient detection of some polyphenol-grafted pectins. For example, a decrease in the ratio of the peak area of 3.7 ppm (-$OCH_3$ of GalA) to the total area of all of the hydrogen peaks in the grafts indicates the formation of ester bonds between pectin and hesperidin (Liu et al., 2025), while the appearance of a new peak at 6.0–8.0 ppm represents chemical shifts of hydrogen on the polyphenol benzene ring (Zhang et al., 2021).

### 3.4. Other structural characterization methods

Several methods can be used to characterize the subtle changes in SGM pectins. For example, the structure of GalA oligomers with acetyl groups at the O-2 and/or O-3 positions can be elucidated using hydrophilic interaction liquid chromatography-evaporative light-scattering detection-mass spectrometry, enabling the differentiation of pectin oligosaccharides with different methyl ester and acetyl group distributions (Remoroza et al., 2012). X-ray photoelectron spectroscopy can reveal the characteristic binding energies of the C and N of SGM pectins, as the C-N binding energy peak of amidated pectin is significantly higher than that of non-modified pectin. The strong peak belonging to N1s, detected in the spectral range of 404.0–396.0 eV, is related to the amide basic body and the amide group forming hydrogen bonds (Wang et al., 2024). Protein-grafted pectins can be characterized by SDS-PAGE, as the presence of a new, higher band indicates the formation of a Maillard-induced adduct (Chen et al., 2018), and by circular dichroism spectroscopy, based on a change the secondary structure change in protein-grafted vs. non-grafted pectin (Li et al., 2022; Ma, Hou, et al., 2020).

## 4. Enhanced functional properties

The chemical structure of SGM pectin determines its functional properties and thus its potential applications. Changes in the chain structure and spatial conformation resulting from modification alter the functional properties of pectin, including its gelling and emulsifying properties, health-promoting effects, ability to deliver functional components, and as a food preservative. Modifications could endow pectin with enhanced functional properties and thus improve its applicability (Table 2).

### 4.1. Gelling properties

The use of pectin as a gelling agent is one of its most important applications in the food industry. Pectin forms a gel in the presence of soluble solids under low pH or using $Ca^{2+}$ to form a gel network ("egg box" model), which is determined by the DM of pectin (Fig. 3A). For alkylated pectin, a high DS generally enhances its gelling properties. Unlike non-modified pectin (DM, 67.1%), alkylated pectin substituted with $C_6$, $C_{12}$, or $C_{18}$ long carbon chains that result in a DS of 0.7–4.5% can form a stable gel, with pectin and sucrose at final concentrations of 2.0 and 60.0 wt%, respectively. The gel strength increases with increasing DS and an increase in the chain length from 40.0 to 160.0 g, as hydrogen bonding and hydrophobic interactions play a major role in gel stability (Liu et al., 2017). The hydrophobicity of methyl/long carbon chains enables them to function in stable hydrophobic network junctions. Hydrophobic groups may also facilitate intermolecular dehydration, resulting in a more compact conformation that improves gel strength (Said et al., 2023). In demethylated pectin, the deprotonated carboxyl groups in the HG domain form cross-links with multivalent metal cations. For example, in the presence of 7.2 mM $CaCl_2$, untreated pectin (DM of 33.1%) does not form even a weak gel, while enzymatically demethylated pectin (DM of 17.4%) forms a strong, self-supporting gel (Zhang et al., 2024). Gel stability is also achieved

**Table 2**
Enhanced functional properties of SGM pectins.

| Functional properties | Modifications | Promoting effects | References |
|---|---|---|---|
| Gelling properties | Alkylation | ↑Gel hardness (4-fold); ↑G' (about 3.7-fold) | Liu et al. (2017) |
| | | ↑Maximum peak temperature; ↓Content of $Ca^{2+}$ required to form gel; ↑Gel hardness (1.3-fold) | Zhang et al. (2024) |
| | Amidation | ↑Viscosity (3.4-fold); ↑Gel hardness (from 0 to 0.19 N) | Wang et al. (2022) |
| Emulsifying properties | Alkylation | ↑Emulsifying capacity (1.6-fold); ↑Emulsifying stability (from 0 to 97.1%); ↓Droplet size (8.5-fold) | Liang et al. (2015) |
| | Acetylation | ↓Interfacial tension (1.5-fold); ↑Zeta potential (1.1-fold); ↓Droplet size (2.1-fold); ↑Viscosity (1.3-fold) | Ai et al. (2022) |
| | Grafting with proteins | ↓Droplet size (fresh emulsions) (1.2-fold); ↓Droplet size (after 7 d) (9-fold) | Lin et al. (2020) |
| | Grafting with polyphenols | ↓TSI (11.8-fold); ↓Droplet size (1.2-fold); ↓Zeta potential (1.2-fold); ↑Adsorption layer thickness (6-fold); ↑Contact angle (1.2-fold) | Liu et al. (2025) |
| Health-promoting effects | Alkylation | ↓Total cholesterol (1.8-fold); ↓Low-density lipoprotein cholesterol (1.9-fold); ↓High-density lipoprotein cholesterol (1.5-fold) | Brouns et al. (2011) |
| | | ↑SCFAs (2.9-fold); ↑Acetic acid (2.7-fold); ↑Propanoic acid (3.4-fold); ↑Butyric acid (4.9-fold) | Dongowski et al. (2002) |
| | Amidation | ↓Triacylglycerols (1.3-fold); ↓Cholesterol in hepatic (2.3-fold) | Marounek et al. (2007) |
| | Grafting with polyphenols | ↓Relative cell survival rate (1.2-fold); ↓Hemolysis rate (from 100% to ~0%) | Ren et al. (2023) |
| | Sulfation | ↑Activated partial thromboplastin time (from 0 to 51.9 IU/mg); ↑Thrombin time (from 0 to 15.2 IU/mg) | Hu et al. (2015) |
| Delivery of functional components | Alkylation | ↑Dense texture; ↑Drug loading level (1.6-fold); ↑Encapsulation efficiency (1.6-fold); ↓Cumulative release rate (8.7-fold) | He et al. (2017) |
| | | ↑Swelling ratio; ↑Encapsulation efficiency (1.1-fold); ↑Load capacity (1.1-fold); ↑Retention rate under natural light conditions (1.1-fold) | Cai et al. (2022) |
| | Amidation | ↑Bio accessibility (1.4-fold) | Zheng et al. (2023) |
| | Thiolation | ↑Swelling degree in simulated saliva; ↑Mucosal adhesion (2.6-fold); ↑*In vitro* drug release dose (1.1-fold) | Özbaş et al. (2022) |
| Preservative effects | Amidation | ↑Retention of β-carotene; ↑Vitamin C content; ↑Color characteristics | Sakooei-Vayghan et al. (2020) |
| | Grafting with proteins | ↓Weight loss; ↑Retention of carotenoids; ↑Hardness (4-fold); ↑Chewiness (3-fold) | Rossi Marquez et al. (2017) |
| | Grafting with polyphenols | ↑Antibacterial activity; ↑Phenolic substances reduction (1.9-fold); ↑Hardness (1.8-fold) | Huang et al. (2023) |

through van der Waals interactions, hydrogen bonds, and electrostatic interactions. Gel formation by LMP depends not only on the degree of demethylation but also on the intermolecular and intramolecular distribution patterns of the unesterified GalA residues in a single polyelectrolyte chain. In general, the closer the distribution of unesterified GalA residues on the pectin chain, the greater the likelihood that the pectin chain will be cross-linked by metal cations, resulting in a firmer, more stable gel (Yapo & Koffi, 2013).

The introduction of an amide group also enhances the gelling properties. Amidated LMP prepared by traditional methods requires less $Ca^{2+}$ for gel formation and can be used to obtain thermally reversible gels that can be heated and re-cured after cooling (Guillotin et al., 2006). The rapid saturation of a small amount of dissociated free carboxyl groups in amidated pectin with $Ca^{2+}$ may lead to a decrease in the number of ionic interactions. The formation of hydrogen bonds involving amide groups in amidated pectin promotes gelling, yielding gels that are more stable than those formed by unsubstituted pectin (Alonso-Mougán et al., 2002; Kastner et al., 2017). Similar to alkylated pectin, in the presence of $Ca^{2+}$ (pectin:$CaCl_2$ = 50:1, w/w), amidated pectin modified with lysine (DS, 6.4%) and glycine (DS, 7.8%) forms gels that are stronger than those formed by the original pectin even after 24 h (Wang et al., 2022).

The good gelling properties of SGM pectins account for their widespread use in food processing and production. For example, amidated pectin can affect the formation of a continuous surimi gel matrix during heating-induced gelatinization, resulting in changes in the viscosity, mobility, and other aqueous-phase properties that affect the mechanical properties of surimi (Uresti et al., 2003). Good gelling properties also allow SGM pectins to be used as raw materials for 3D printing technology, which could expand their roles in various fields, especially food analysis and monitoring, closely related to human health (Song, Chen, et al., 2023).

### 4.2. Emulsifying properties

The emulsifying properties of SGM pectins account for their wide-ranging use in food production, particularly in acidic dairy products and fruit juices. For example, HMP stabilizes acidic dairy products and prevents their coagulation by forming a spatial network structure. Both alkylation and acetylation have been shown to improve the emulsifying properties of pectin. The introduction of carbon-chain/acetyl groups increases the hydrophobicity of pectin as well as the contact opportunities between pectin chains, leading to a higher viscosity and thus a better stability of the emulsions. More hydrophobic SGM pectins also have better amphiphilicity, allowing firm adsorption at the oil-water interface due to the abundance of anchor points, in turn improving emulsification (Fig. 3B). For instance, an increase in the emulsifying capacity (from 35.5% to 38.0–55.1%) and emulsion stability (from 0 to

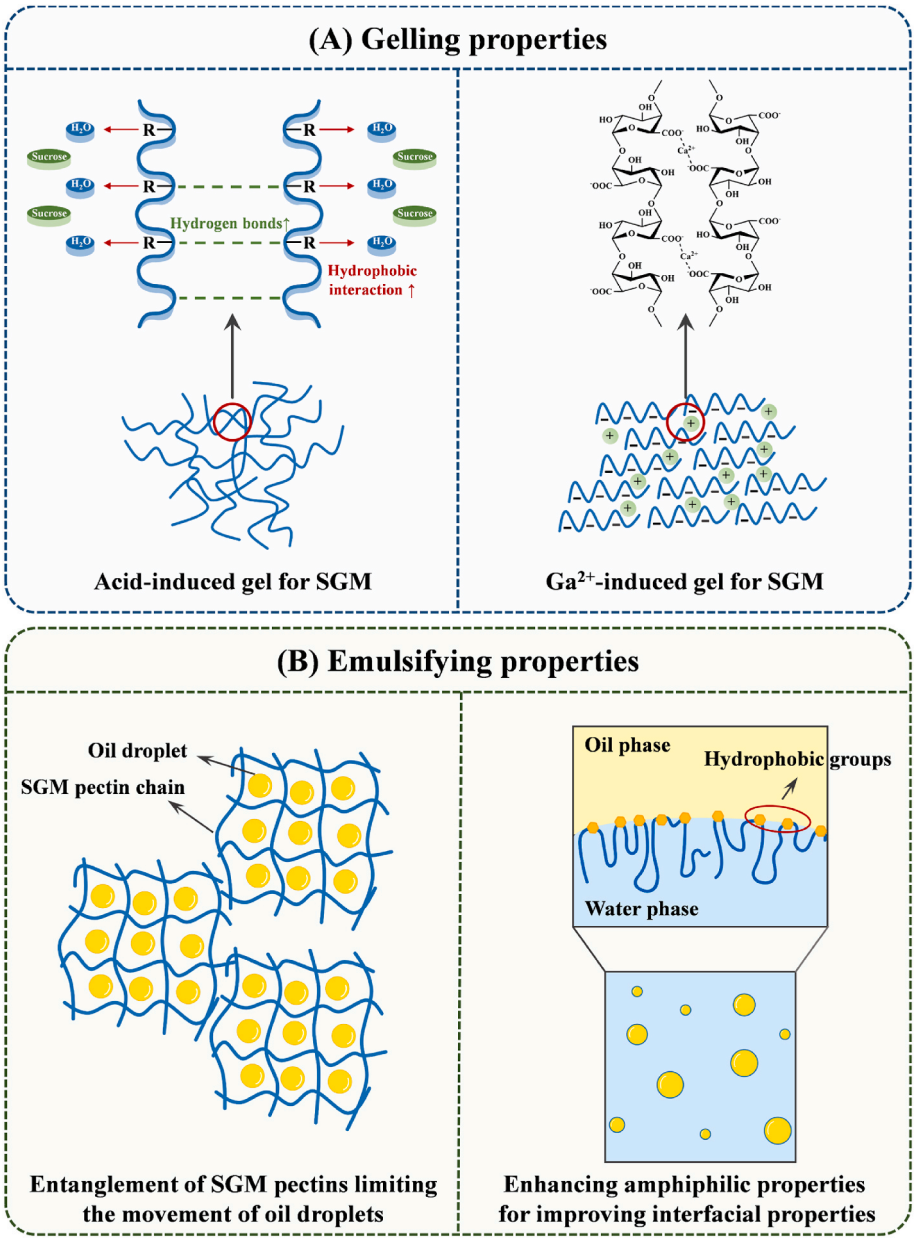


**Fig. 3.** The mechanism underlying the enhanced functional properties of SGM pectins. (A) Gelling properties; (B) Emulsifying properties.

85.6–97.1%) of pectin and a reduction in the emulsion particle size (from 60.1 to 7.1–7.8 μm) were achieved after alkylation with $C_6$, $C_{12}$, and $C_{18}$ (Liang et al., 2015).

Pectin grafted with protein/polyphenols shows good amphiphilic properties and thus improved emulsifying performance (Li et al., 2022). In a previous study, the droplet size of an emulsion stabilized with whey protein isolate-grafted sugar beet pectin decreased from 0.6 (emulsions stabilized by non-grafted pectin) to 0.5 μm. Good emulsion stability after 7 days of storage at 60 °C was determined, with the droplet size of the emulsions stabilized with grafted pectin increasing only slightly (from 0.5 to 0.7 μm) and that of emulsions stabilized with non-grafted pectin increasing significantly (from 0.6 to 6.4 μm) (Lin et al., 2020). In addition to the covalent interactions of grafted pectin, hydrophobic interactions between chains and noncovalent interactions such as hydrogen bonding make the spatial conformation of grafts more compact, increasing the amount of pectin adsorbed on the oil-water interface and improving the interfacial affinity of the grafts (Qi et al., 2017). These properties explained the good stability of emulsions prepared with hesperidin-grafted pectin within the first 24 h, evidenced by a Turbiscan stability index of ~0.8 vs. 9.4 for emulsions prepared with non-grafted pectin. The droplet size also decreased significantly, to 0.9 μm vs. 1.4 μm (Liu et al., 2025).

### 4.3. *Health-promoting effects*

Pectin is a natural plant extract that can be used in the prevention and treatment of diseases, such as by reducing blood lipids and through its antioxidation and anticoagulation effects. The different types of modification can be applied to enhance its physiological activity, yielding functional foods with positive health characteristics. Some highly substituted pectins act as efficient cholesterol-lowering agents. For example, the introduction of methoxy/acetyl groups enhances hydrophobicity, resulting in a change in the conformation of its polysaccharide chains, such that more polar groups are exposed, viscosity is increased, and a network then forms in the aqueous phase that helps capture cholesterol and bile salts (Chen, He, et al., 2023). Reductions in

total cholesterol and low-density lipoprotein cholesterol of 6.5 and 9.3 mmol/L have been obtained with pectins with a DM of 70.0%, compared to the significantly lower reductions (3.7 and 4.9 mmol/L) achieved with pectin with a DM of 35.0% (Brouns et al., 2011). Underlying the human health benefits conferred by DM pectin is an effect on the gut microbial community. Thus, LMP with a DM of 34.5% stimulates the production of short-chain fatty acids (SCFAs) (110.6 μmol/g, dry matter of cecum contents), particularly acetate, propionate, and butyrate, whereas HMP with a DM of 70.8–92.6% yields an SCFA content of only 88.7–98.4 μmol/g (dry matter of feces) (Dongowski et al., 2002). The difference might be due to the release of pectin lyase, methylesterase, and other enzymes by the probiotics. LMP is hydrolyzed faster, both *in vitro* and *in vivo*, than HMP and is more easily digested by the gut microbiota, such that the growth of *Bifidobacterium* and *Bacteroidetes* species is promoted (Kumar & Tingirikari, 2023). Amidated pectin modified with octadecyl groups has been shown to significantly reduce serum levels of cholesterol in a dose-dependent manner. In one study, as the feeding content of amidated pectin increased (0.0–60.0 g/kg), cholesterol decreased, from 3.3 to 1.2 μmol/mL. Octadecyl amide pectin significantly reduced liver cholesterol (from 16.7 to 8.6 μmol/g) and serum levels of triglycerides (from 2.4 to 1.5 μmol/mL). In a study in rats, hydrophobic SGM pectin with octadecyl groups significantly altered cholesterol homeostasis, suggesting its potential as a clinically effective cholesterol-lowering drug (Marounek et al., 2007).

An additional property of SGM pectins is their good biocompatibility. In cytotoxicity tests using hesperetin grafted onto pectin through free radical induction, the relative survival rate of L929 fibroblasts was >80%, indicating that the grafted pectin had no cytotoxicity. The good blood compatibility of this grafted pectin was evidenced by a hemolysis rate of almost zero, while red blood cells were intact and maintained their normal shape (Ren et al., 2023). Potent anticoagulant activity was demonstrated for sulfated pectin, attributed to the high negative charge density generated by the sulfate groups, which presumably neutralized the positively charged amino acid residues of coagulation proteins. For example, a high DS would induce a high negative charge density, which would inhibit the activity of antithrombin (Bae et al., 2009; Fan, Gao, et al., 2012; Maas et al., 2012). The anticoagulant properties of sulfated pectin account for its ability to increase the activated partial thromboplastin time and the thromboplastin time, unlike natural pectin (Hu et al., 2015).

### 4.4. Delivery of functional components

The biocompatibility, low toxicity, and biodegradability of pectin have raised interest in its use for the delivery of functional components. However, delivery systems prepared from natural pectin are limited by its poor swelling and corrosion in the case of gels, and its instability due to demulsification in the case of emulsions. Pectin modification, including alkylation and amidation, results in physicochemical properties that enable the precise delivery of functional components with minimal loss. For alkylated pectins, their improved gelling properties can be exploited to achieve the targeted release of functional components. Micro gel beads prepared with alkylated pectins have a hydrophobic microstructure domain that ensures their stability largely prevents the release of the embedded components in the stomach while promoting controlled release in the intestine (Bostanudin, 2022; He et al., 2017). Demethylated pectin cross-linked with metal cations can be used to create a gel-based targeted delivery system consisting of thick shells and multi-layer internal structures that maintains its integrity in the gastrointestinal environment simulated *in vitro*. For example, in one study, the release rate of curcumin embedded in gel beads prepared using the alkali method, the enzyme method, or the high hydrostatic pressure assisted enzyme method was <1.0% during the gastric and intestinal digestion phases but increased significantly during the colon digestion phase (16 h), with a cumulative release rate of 50.0% (Cai et al., 2022).

Amidated pectin can be used to prepare different delivery systems (including hydrogels and emulsion gels). Its rigid groups (amide planes and benzene ring structures) provide structural support for the gel, due to the more ordered polymer arrangements and combinations during the gelation process, resulting in gels with a higher gel strength despite less gelation (Zheng, Huang, et al., 2022). In one study, compared to a hydrogel prepared with LMP (0.4%), the bioaccessibility of curcumin in a gel formed using amidated pectin (8.0%) was 18.0% (Zheng et al., 2023); the gel was also highly resistant to pepsin hydrolysis. The delivery potential of thiolated pectins can be attributed to their good mucosal adhesion (Sharma & Ahuja, 2011), including in applications requiring mucosal adhesive particles (Martins et al., 2017) or in combination with other macromolecules to produce adhesive based patches (Özbaş et al., 2022) or form an *in situ* gel (Hintzen et al., 2012). For example, in one study, brimonidine tartarate prepared with a thiolated pectin was used as an *in situ* gelling preparation in rabbit eyes to evaluate possible eye irritation caused by *in situ* gel administration. The thiolated pectin reduced intraocular pressure within 1 h and for up to 5 h, compared to a maximum of 3 h for non-thiolated pectin (Mittal & Kaur, 2014).

### 4.5. Preservative effects

Fruits and vegetables play crucial roles in modern diets due to their nutritional value, but their perishable nature makes them prone to rapid spoilage. Although traditional preservation methods are effective to some extent, they often have shortcomings in maintaining quality and safety (Du et al., 2024). Interest in SGM pectins as a food preservative reflects their ability to maintain and maximize food quality, particularly fruits and vegetables, by reducing water migration, lowering oxidation reaction rates, and preventing enzymatic browning (Valdés et al., 2015). Amidated pectin, when utilized as a film base, significantly enhanced the retention of β-carotene (>20.0 mg/g dry matter) and vitamin C (~50.0 mg/g dry matter) in dried apricots, while also improving their color characteristics (Sakooei-Vayghan et al., 2020). For protein-grafted pectins, whey protein-pectin films prepared by transglutaminase catalysis have been used in the processing of fresh cut apples, potatoes, and carrots. The coating formed by a cross-linked mixed film can prevent microbial growth while preserving the phenolic compounds and carotenoids present in fruits and vegetables. Whey protein–pectin coatings significantly reduce weight loss in apples while maintaining their crispness and chewiness (Rossi Marquez et al., 2017). In a study on polyphenol-grafted pectins, epigallocatechin gallate grafted onto pectin through a free radical-mediated reaction to prepare a coating for application to the surfaces of grapes. In addition to its good wetting and adhesion properties, the coating significantly reduced weight loss in fruits (by 25.3% vs. 49.1% in noncoated grapes) and phenol content, while inhibiting lipid oxidation and microbial growth during grape ripening (Huang et al., 2023). A study that prepared a film using pectin modified with ethyl gallate reported good preservation effects on golden pomfret fillets, as after being stored at 4 °C for 10 days they showed no signs of decay. In a determination of the malonaldehyde content, as an indicator of the degree of lipid oxidation, the value in coated golden pomfret was 0.1 mg/kg vs. 0.3 mg/kg in the non-treated group (Song, Zhang, et al., 2023).

Different modification methods induce distinct changes in the chemical structures of pectin (e.g., DM and the position and type of substituents), which would further influence its functional properties. For example, alkylation can increase the hydrophobicity of pectin, providing enhanced gelling properties in certain applications, while de-esterification may enhance its water solubility, making it suitable for different food or pharmaceutical preparations. Therefore, understanding the specific effects of different modification methods on the structure of pectin can help optimize its application performance in food, medicine, and other fields, ultimately achieving the design and development of functional modified pectin. Amidated pectins show better gelling

properties than SGM pectins produced by the other major substitution methods. On the one hand, the introduction of amide groups enables amidated pectins to form a gel with the participation of a small amount of $Ca^{2+}$. Compared with the sugar acid gel formed by alkylated pectin, it has wider potential applications in low-sugar foods. On the other hand, amidated pectin can be used to form a thermoreversible gel, which enables it to be melted and modified according to temperature, especially for food production and packaging of bioactive substances. Although amidated pectins, protein–pectin grafts, and polyphenol–pectin grafts all have enhanced emulsifying properties, proteins, as excellent emulsifiers, are more helpful. Moreover, compared to other SGM pectins, protein and pectin as two natural biomolecules show simpler mutual binding. Polyphenol–pectin grafts show special advantages with regard to health benefits. Polyphenols, as secondary metabolites widely present in plants, have multiple physiological functions, including antioxidant properties, promoting gut microbiota balance, and improving human health. The connection with polyphenols will therefore enhance the functional properties of pectins.

## 5. Perspectives

Different modification methods result in pectins that differ in their structural characteristics and therefore in their physicochemical properties and functions. Understanding these relationships is crucial to obtaining pectins with the desired functional properties. Future research on SGM pectins should focus on the following aspects.

First, efficient targeted modification methods are needed to obtain SGM pectins that meet different application requirements. The development of green and energy-saving methods is in line with the current emphasis on sustainability. Special attention should be paid to modifications using novel catalysts as well as reaction conditions that avoid the use of organic solvents.

Second, detailed structural information of modified pectin is still lacking, which limits a systematic understanding of the reaction sites and processes involved in modification reactions and the mechanisms that give rise to pectins with the desired functional properties (Niu et al., 2023). Microscopic imaging techniques, fluorescent labeling, and molecular simulation may be efficient methods for the chemical characterization of SGM pectins, including their DS, substitution sites, and microstructure.

Third, a prerequisite for the development of pectin-based foods with enhanced functional properties is knowledge of the mechanisms underlying the functional properties of SGM pectins (Zhang et al., 2023). This information will facilitate the production of customized, modified pectins with specific functional properties that are applicable in different industries and for different groups of consumers, resulting in a larger pectin market.

Fourth, the rapid development of artificial intelligence (AI) can be expected to lead to new insights into the relationship between the structure and function of pectin and thus to an efficient design of pectins targeted for specific applications (Shokrani et al., 2023). The establishment of a database of pectin structure and function for computational biology studies aimed at simulation and optimization will allow the rapid characterization of pectin structures and precise predictions of their corresponding functions, further improving the design efficiency of SGM pectin.

Finally, the safety of SGM pectins as functional additives must be evaluated carefully. To date, pectin and amidated pectin have been approved by the United States Food and Drug Administration and the European Commission (Moslemi, 2021). However, many other recently developed SGM pectins have not yet been proven to be safe. Continuous attention to the potential impacts of the long-term intake of modified pectin on human health, and the possibility of allergic reactions to pectin or its modified forms (especially in food applications) in some individuals is required, and it will be necessary to determine the metabolic pathways of modified pectin in the body and its safety in interacting with biomolecules.

To ensure the safety of SGM pectins, comprehensive toxicity assessments of SGM pectins will be required, to determine their safe intake limits. Biological experiments, including experiments in animal models and cells *in vitro*, will be required to verify their safety and effectiveness for food and drug applications. Finally, it will be necessary to establish relevant standards and regulations for SGM pectins, to ensure that their production and use comply with safety requirements.

## 6. Conclusions

This review systematically examined the modification methods, structural features, and enhanced functional properties of SGM pectins. Different modifications induce changes in the structure and thus in the function of pectin. The demand for SGM pectins with specific functional properties is driving the development of tools for their precise structural characterization and targeted design. Future research should be directed at targeted, efficient and green modification techniques, methods allowing a precise structural characterization, the mechanisms underlying the targeted function of modified pectin, and the use of AI in predicting the structure and function of SGM pectins. The safety of SGM pectins must also be confirmed. This information would promote the high-value development and application of pectin for use in the food industry.

## Declaration of competing interest

The authors declare no competing financial interest.

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## Data availability

Data will be made available on request.

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