Food Chemistry: X 24 (2024) 101955

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

The mechanism of pectin in improving anthocyanin stability and the application progress of their complexes: A review

Chenyang Shi [1], Chongting Guo [1], Shan Wang, Weixuan Li, Xue Zhang, Shan Lu, Chong Ning *, Chang Tan *

Light Industry College, Liaoning University, Shenyang, Liaoning 110031, China

ARTICLE INFO

Keywords:
Anthocyanin
Complexes
Food processing
Functional characteristics
Interaction
Pectin
Stability

ABSTRACT

Improving anthocyanin stability is a major challenge for the food industry. Studies have revealed that the interaction with pectin through non-covalent bonds can improve the anthocyanin stability, thus showing the potential to alleviate the above challenges. However, the interactions are highly complex and diverse. Thus, analyzing the effect of this interaction on anthocyanin stability is essential to promote anthocyanin-pectin complexes application in functional foods. Pectin can interact with anthocyanins through covalent and non-covalent interactions, and these interactions are affected by their structure, the external environment, and the processing methods. Through their interaction with pectin, the thermal, color, and storage stability of anthocyanins are improved, enhancing their bioavailability in the gastrointestinal and facilitating their application range in food processing. This review provides a theoretical reference for improving anthocyanin stability and increasing the application range of anthocyanin-pectin complexes.

1. Introduction

Plants display various colors owing to the naturally occurring water-soluble flavonoid pigment called anthocyanin (Wang et al., 2022). Anthocyanins possess significant antioxidant properties and can effectively regulate oxidative stress and inflammatory responses in the body, with potential health benefits (Merecz-Sadowska et al., 2023). Anthocyanins are increasingly popular among consumers and food manufacturers because they are natural pigments that can be used in food processing. However, their stability is susceptible to the external environment (Chung et al., 2016), implying that their resistance to processing conditions, formulations, and storage conditions is relatively poor. Consequently, the application of anthocyanins in food, biology, medicine, cosmetics, and other industries is restricted (Yang et al., 2022). To increase the application range of anthocyanins, researchers have developed various strategies, including co-pigmentation, structural modification, and microencapsulation, to improve their stability (Feitosa et al., 2023; Gençdağ et al., 2022). In addition, the interaction of anthocyanins with macromolecules, such as proteins or polysaccharides, has shown the potential to alleviate this challenge (Zang et al., 2022).

Pectin is a complex and functionally rich biological macromolecule primarily comprising galacturonic acid (GalA) units in the cell walls of plants, such as vegetables, fruits, and cereals (Riyamol Gada Chengaiyan et al., 2023). Owing to its high-quality gelling and stabilizing properties, pectin can be used as a thickener, stabilizer, and emulsifier or as a packaging material in food and pharmaceutical applications (Yue et al., 2023). In addition, pectin is a soluble prebiotic that contributes to the growth of beneficial microorganisms in the intestinal tract and possesses various biological properties, such as antioxidant, anti-glycosylation, anticoagulant, and anti-inflammatory (Huang, Sun, et al., 2024; Sun et al., 2023); it also lowers serum cholesterol and activates immune response (Zhang et al., 2023). Based on its strong functional properties, researchers have also started searching for more uses for it, such as pectin-polyphenol interactions to improve the utilization value of both. (Çakır & Gülseren, 2017; Guo et al., 2023).

An increasing number of studies are focusing on the interactions between anthocyanins and pectin. According to studies, pectin and anthocyanins can interact electrostatically through pectin anions with the flavonoid cations of anthocyanins, and the interactions can be enhanced by hydrogen bonding and hydrophobic effects, which would improve anthocyanin stability (Fernandes, Oliveira, et al., 2020; Weiss et al.,

* Corresponding authors.
E-mail addresses: liweixuan@lnu.edu.cn (W. Li), ningchong@lnu.edu.cn (C. Ning), tanchang@lnu.edu.cn (C. Tan).
[1] Chenyang Shi and Chongting Guo should be considered joint first authors.

https://doi.org/10.1016/j.fochx.2024.101955
Received 13 September 2024; Received in revised form 29 October 2024; Accepted 30 October 2024
Available online 1 November 2024

2023). However, the fine structure of pectin predestined the Mechanism of pectin improving anthocyanin stability to be highly variable and complex (Koh et al., 2020b). Consequently, we reviewed the mechanism of the interaction between anthocyanins and pectin, the impact of the interaction on anthocyanin stability, and the advancement of the application of the anthocyanin-pectin complexes and projected the future development trend of the complexes.

2. Anthocyanins and pectin

2.1. Anthocyanins

Anthocyanins are flavonoid compounds, which are secondary metabolites produced through the biosynthetic pathway of phenylpropionic acid and flavonoids in plants. They are commonly found in some fruits (blueberries, strawberries, raspberries, black mulberries, and red cherries), vegetables (purple collard greens and sugar beets), and grains (sweet potatoes and sorghum) and confer various colors, such as red, blue, purple, and orange, to these plants (Wang et al., 2022).

Anthocyanins have a typical C6-C3-C6 skeleton comprising two aromatic rings (A and B) separated by an oxygen-containing six-membered heterocyclic ring (C) (Qi et al., 2023) (Fig. 1a). Anthocyanidins are the basic structures of anthocyanins. Plants contain six common anthocyanidins, namely pelargonidin, cyanidin, delphinidin, peonidin, petunidin, and malvidin (Blesso, 2019) (Fig. 1b). Anthocyanidins are unstable and are readily linked to sugars, such as L-arabinose, galactose, glucose, L-rhamnose monohydrate, xylose, rutinose, sophorose, or gentiobiose, through glycosidic bonds to form anthocyanins (Sendri & Bhandari, 2024; Wang et al., 2024) (Fig. 1c).

Anthocyanins are used in the food and biomedical industries because of their color and antioxidant properties. Anthocyanin-rich films can maintain food quality, extend food shelf life (Wang et al., 2019), and monitor the freshness and quality of protein-rich foods (such as fish, shrimp, milk, and cheese) (Yong & Liu, 2020). In addition, studies have demonstrated that anthocyanins in berries possess biological potential, such as benefiting antioxidant (Liu & Zhang, 2024), anti-inflammatory (Gao et al., 2023), hypoglycemic (Chen et al., 2023), hypolipidemic (Zhu et al., 2023), and inhibition of lipid peroxidation properties (Li et al., 2022). This biological potential may be affected by anthocyanin structure, such as the number of hydroxyl groups, degree of

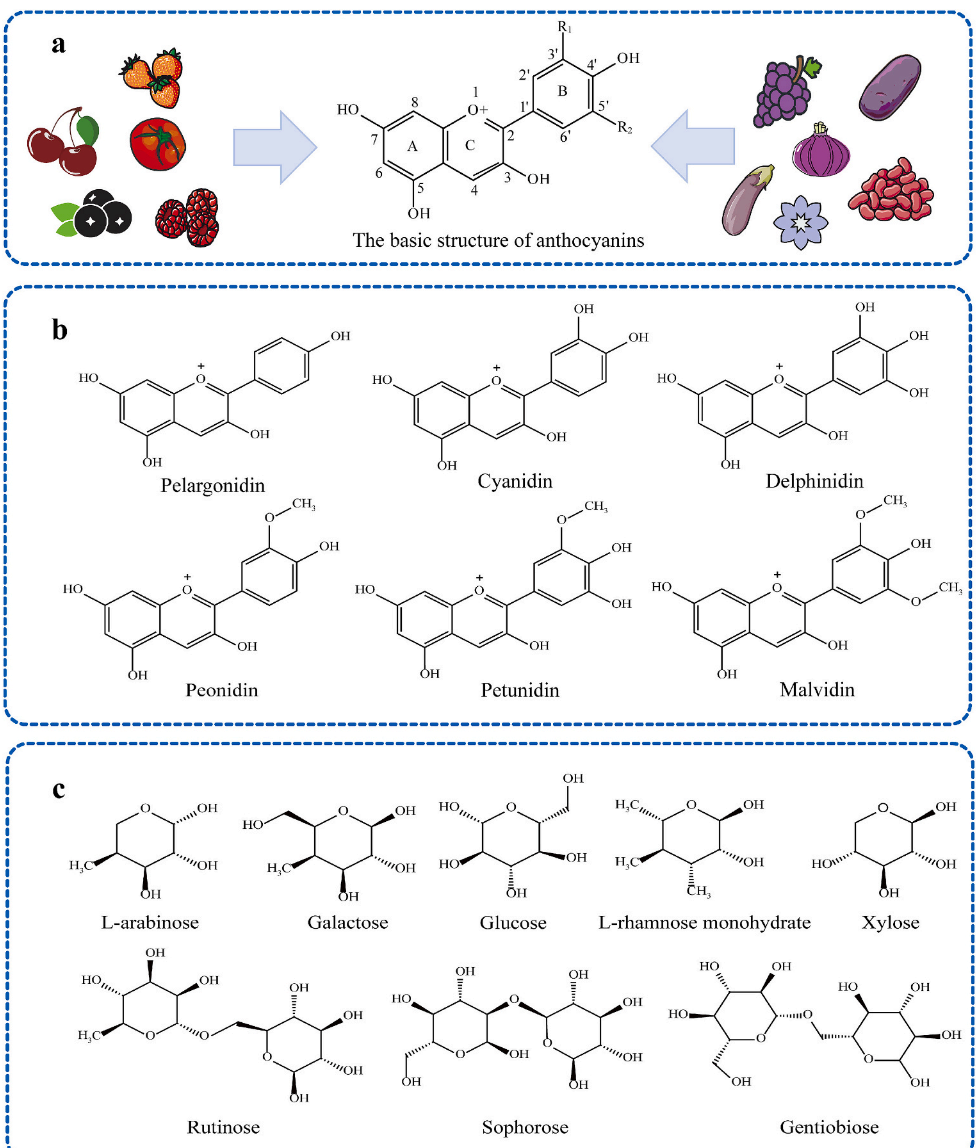

Fig. 1. Basic structures of anthocyanins. (a) Basic structure of anthocyanins, (b) Structural diagram of six common anthocyanidins, (c) Common monosaccharides and disaccharides that make up anthocyanins.

glycosylation and acylation, catechol residues on the B ring, and oxygen ions on the C ring (Gonçalves et al., 2021).

In food processing, using effective extraction technologies is essential for improving anthocyanin stability in food. Traditional methods for extracting anthocyanins from plants, such as impregnation and heat-assisted extraction, have been extensively used in the industry (Tena & Asuero, 2022). However, traditional extraction methods have disadvantages, such as toxicity of extraction solvents, environmental pollution, and a low yield of anthocyanins. To obtain high-quality anthocyanins from plant tissues in a shorter time and using fewer solvents, researchers have proposed emerging extraction techniques, such as pulsed electrical discharge systems (Zhou et al., 2022), high-pressure processing (Chen et al., 2023), ultrasound, and using natural deep eutectic solvents, as well as the combined application of several techniques (Lin et al., 2022).

However, anthocyanin stability is susceptible to internal and external factors, including anthocyanin structure, light, temperature, pH, metal ions, and enzymes (Chung et al., 2016). Anthocyanin stability is reportedly increased with increasing methylation and decreased with increasing number of hydroxyl groups on the B ring (Sadilova et al., 2006). Anthocyanins are easily degraded under light conditions and are easily oxidized and fade under heating or high-temperature conditions. In contrast, they are more stable under low-temperature and acidic conditions. Among phenolic compounds, anthocyanins change their structure with a change in charge at different pH values, achieving their color properties. In acidic environments (pH = 1), anthocyanins exist as flavonoid cations. At this time, anthocyanin structure is planar, making them highly soluble in water (Khoo et al., 2017). Under these conditions, anthocyanins appear red or purple. At pH 2–4, anthocyanins exist in the form of a blue quinone base. When the pH is 5–6, the non-planar structures of alcohol-type pseudobases and chalcones appear, that is, colorless compounds (Kang et al., 2021). When the pH exceeds 7, anthocyanins are degraded according to the substituents. Four anthocyanin forms may coexist in the pH range of 4–6, and the equilibrium between these forms is maintained by flavonoid cations.

Owing to their poor stability during processing and digestion, anthocyanin application in food and human health is limited. Therefore, improving anthocyanin stability is a major challenge in the food industry. The interaction between anthocyanins and dietary macromolecules (such as proteins, starch, and pectin polysaccharides) is among the methods to improve anthocyanin stability (Cai et al., 2022).

2.2. Pectin

Pectin is a natural plant polysaccharide with a complex structure and rich functions; it is a crucial part of the primary cell wall and intercellular layer of higher plants (Christiaens et al., 2016). It is abundant in the cell walls of plants, such as vegetables, fruits, and grains. Most commercial pectins are derived from citrus, apples, and sugar beets, and some were extracted from berries such as raspberries, blueberries, strawberries, and red currants (Muñoz-Almagro et al., 2021; Sani & Alizadeh, 2022).

As a hydrophilic colloid, pectin comprises GalA molecules in the main chain, connected by α-1,4-glycosidic bonds (Chan et al., 2017). To date, almost 17 monosaccharides have been identified in the side chains (Table 1). These monosaccharides can interact with each other in more than 20 forms. Four structural domains, homogalacturonan (HG), rhamnogalacturonan I (RG-I), rhamnogalacturonan II (RG-II), and xylogalacturonan (XG), compose the pectin structure. They combine in certain proportions to form a complex pectin polysaccharide structure (Jin et al., 2021) (Fig. 2).

The HG is the largest domain of pectin polysaccharides, accounting for approximately 65 % of the pectin structure. This region is a linear polymer formed by α-1,4-glycosidic bonding to D-galacturonic acid, which is known as the “smooth region” (Chan et al., 2017). GalA residues in the HG can be methylated at C-6 and acetylated at O-2/O-3. According to the degree of esterification (DE) of the GalA carboxyl group, it is divided into high-esterified (DE > 50 %) and low-esterified (DE < 50 %) pectins, with the latter including amidated pectin (Chan et al., 2017). The O-3/O-4 of the GalA residue in the HG is reportedly replaced by xyloseto form the XG (Jin et al., 2021). Various neutral sugars are attached to the pectin backbone to form the major (RG-I) and minor (RG-II) pectin branches, which are known as the “furry region” of the pectin molecule (Lee et al., 2022). The RG-I region accounts for approximately 20–50 % of pectin. It comprises over 100 alternating α-1,2-L-rhamnose and GalA repeats, and it is the neutral side chain connected to the O-4/O-3 position of the α-L-rhamnose skeleton unit (Wu et al., 2020). Rhamnose can be substituted at the O-4 position by arabinose, galactose, or arabinogalactan side chain (Mohnen, 2008). RG-II comprises a skeleton of GalA residues (the same as HG); however, the skeleton is highly branched with side chains at C-2/C-3, including arabinose, fucose, galactose, rhamnose, glucose, glucuronic acid, and xylose (Lee et al., 2022).

Table 1
Monosaccharide composition of pectin polysaccharides.

monosaccharides	Abbreviation
galacturonic acid	GalA
L-arabinose	Ara
L-rhamnose monohydrate	Rha
galactose	Gla
glucose	Glc
D-mannose	Man
fucose	Fuc
xylose	Xyl
D-glucuronic acid	GlcA
Galactosamine	GalN
Glucosamine	GlcN
3-deoxy-d-manno-2-octulosonic acid	Kdo
3-deoxy-d-lyxo-2-heptulosaric acid	Dha
D-apiose	Api
L-aceric acid	AceA
O-methyl ester	Me
O-acetyl ester	Ac

Pectin contains various functional groups that interact with anthocyanins (Weber, 2022) and can improve anthocyanin stability by interacting with them (Koh et al., 2020b), achieving the “1 + 1 > 2” effect. Studies have shown that among polysaccharides, Pectin has the highest affinity with anthocyanins and can interact with anthocyanins to improve anthocyanin stability in the gastrointestinal tract (Fu et al., 2021). Padayachee et al. (2012) found that increasing pectin proportion in cellulose-pectin complexes caused increased anthocyanin adsorption from a carrot juice concentrate, indicating that the binding ability of pectin to anthocyanins was higher than that of cellulose, further proving its potential to increase anthocyanin stability. However, the interactions between pectin and anthocyanins are highly complex and largely depend on their fine structures (Koh et al., 2020b). Therefore, the interaction mechanism between anthocyanins and pectin and the factors affecting anthocyanin stability in anthocyanin-pectin complexes require further studies.

3. Interaction mechanism between anthocyanins and pectin

The interactions between anthocyanins and pectin are covalent and non-covalent. Both interactions significantly affect the physicochemical and functional properties of anthocyanin-pectin complexes, and further influence anthocyanin stability. When anthocyanins exist in plants in their natural form, they covalently interact with pectin. This interaction is produced by the formation of ether bonds between the hydroxyl groups of anthocyanins and pectin or by the formation of carbon-carbon glycosidic bonds between the carbon atoms of anthocyanins and pectin (Shahidi & Yeo, 2016; Zheng et al., 2024). In addition, covalent

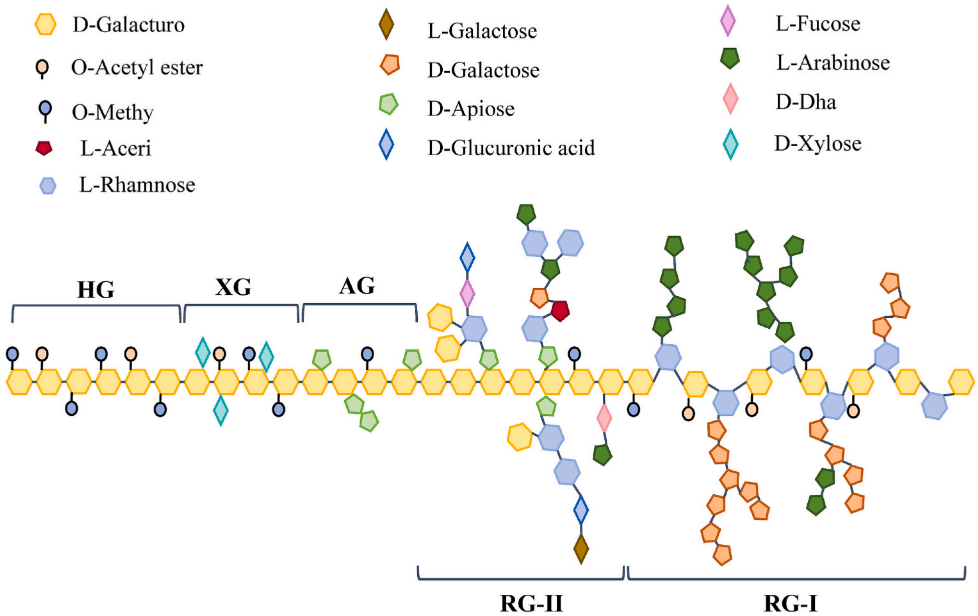

Fig. 2. Schematic structure of pectin.

interactions are strong interaction forces, and the formed complex is not easily decomposed.

Non-covalent interactions can be divided into four categories, namely electrostatic interactions, hydrophobic interactions, hydrogen bonding, and π-π stacking (Fig. 3). In slightly acidic solutions (such as at pH 3.4, apparent pKa ≈ 3.5–4.0), anthocyanins may exist in the form of flavonoid cations, and the free carboxyl groups of pectin can be partially deprotonated and negatively charged. Under this condition, the electrostatic interaction between anthocyanin flavonoids and pectin anions is the primary mechanism for the interaction between anthocyanins and pectin (Lin et al., 2016). When the methoxy group is on the B-ring of anthocyanins, the polarity is low, which may interact with the hydrophobic domain in the residue of the pectin RG structure, and the C—H bonds from alcohol hydroxyls and phenolic hydroxyls in the benzene ring of anthocyanins may be involved in the interaction between the two phytochemicals (Larsen et al., 2019). Buchweitz et al. (2013b) evaluated the effects of different pectins on strawberry anthocyanins and found that anthocyanins possibly interact with the amides, carboxyl groups, and hydroxyl groups in the GalA residue of pectin through hydrogen bonds. The stability of hydrogen bonds increases with an increase in the number of the hydroxyl groups on the B-ring of anthocyanin. Padayachee et al. (2012) proposed a plant cell-wall-binding model comprising anthocyanins and pectin. The initial anthocyanin binds to the active site and undergoes anthocyanin stacking, which is a method for combining anthocyanins and pectin. The anthocyanin structure changes from non-planar to planar at lower pH, promoting their self-association. When the pH changes from 4.0 to more acidic conditions, with the increased proportion of flavonoid cations, the possibility of π-π stacking of anthocyanin-pectin and anthocyanin-anthocyanin increases (Koh et al., 2020a).

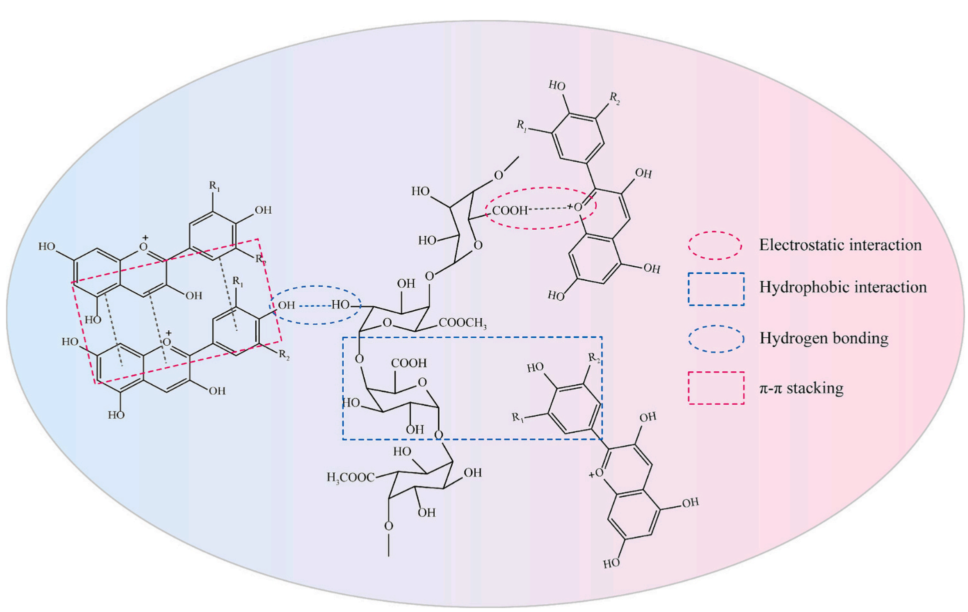

Fig. 3. Mechanism of interaction between anthocyanins and pectin.

4. Factors affecting the interaction between anthocyanins and pectin

Anthocyanins and pectin can interact covalently or non-covalently to enhance the anthocyanin stability; however, such interactions are susceptible to certain factors, such as the pectin and anthocyanin structures, the external environment (changes in pH, temperature, or ionic strength), and food processing technologies (such as high-pressure processing). These factors affect the structure or interaction mechanism of anthocyanins and pectin and thus affect their binding capacity (Table 2).

4.1. Anthocyanin structure

The number of hydroxyl groups in anthocyanins is a potential factor affecting the formation of hydrogen bonds or hydrophobic interactions with pectin. Studies have shown that, compared with cyanidin-3-glucoside (C3G) with catechol (two hydroxyl groups), delphinidin-3-glucoside (D3G) with pyrogallol (three hydroxyl groups) strongly interacts with pectin (Fernandes et al., 2014). An increased number of hydroxyl groups on the B-ring of anthocyanins enhances the interaction between anthocyanins and pectin. Pectin molecules form one, two, and three hydrogen bonds with P3G, C3G, and D3G, respectively, which increases anthocyanin stability (Buchweitz et al., 2013b). Koh et al. (2020b) obtained a similar result using malvidin-3-glucoside, C3G, and D3G to interact with blueberry pectin. Hydroxyl groups enhance the binding between anthocyanins and pectin, while methoxy groups have negative effects on binding (Lin et al., 2016). In addition, the sugar groups of anthocyanins affect their binding. Galactose and glucose, which are six-carbon sugars, exhibit higher binding affinities for pectin compared with those of arabinose and xylose, which are five-carbon sugars (Wei et al., 2020).

4.2. Pectin structure

Pectin is vital in improving the stability and bioavailability of anthocyanins. The structural properties of pectin (such as its molecular weight, DE, proportion of neutral sugars, degree of polymer linearity, degree of side-chain branching, and complex three-dimensional conformation) affect its binding affinity for anthocyanins (Boulet et al., 2023). Bermúdez-Oria et al. (2019) found that the DE of the neutral sugar side chains of pectin may significantly influence its binding to anthocyanins. Fernandes, Brandão, et al. (2020) compared the structure of beet arabinose and other pectin polysaccharides to evaluate the interaction between arabinose-rich pectin polysaccharides and polyphenols and found that linear arabinose has a stronger binding ability with polyphenols. The results showed that the interaction between pectin and polyphenols are related to the degree of branching of the arabinoxylan structure and the polyphenols covalently connected to the arabinose skeleton. A higher degree of branching limits the interaction between arabinose and polyphenols, whereas covalent connections between polyphenols and polysaccharides limit further reactions (Waldron et al., 1997). Water-soluble apple pectin (63.23 %) and chelate-soluble peach pectin (55.66 %) exhibit a higher DE than those of other pectins. Jiang et al. (2024) have shown that pectin with a high DE also improves the stability of anthocyanins to a certain extent, which

Table 2
Research progress on the interaction between anthocyanins and pectin.

Anthocyanins	Pectins	Processing method	Primary acting forces	Key findings	References
Cyanidin-3-glucoside (C3G)	Citrus pectin	–	Electrostatic interaction, hydrophobic interaction, hydrogen bonding, and π-π stacking	The binding affinity of pectins with different structures to anthocyanins was different (30 % esterified pectin >30 % amidated pectin >70 % blockwise esterified pectin >70 % random esterified pectin).	(Fernandes, Oliveira, et al., 2020)
Anthocyanins	Beet pectin	Pectin was modified by enzyme or ultrasonic treatment	Hydrophobic interaction and hydrogen bonding	Pectin with higher molecular weight forms an insoluble anthocyanin-pectin complex.	(Larsen et al., 2019)
C3G, Pelargonidin-3-glucoside (P3G), Delphinidin-3-glucoside (D3G)	Citrus pectin, apple pectin, beet pectin	–	Hydrogen bonding and π-π stacking	Apple pectin and beet pectin increased the stability of P3G, and citrus pectin significantly increased the stability of D3G. The interaction of C3G and D3G with pectin was stronger than that of P3G.	(Buchweitz et al., 2013b)
Purple sweet potato anthocyanins	Sunflower pectin	40 kHz, 150 W ultrasonic treatment of sunflower pectin	Electrostatic interaction, hydrogen bonding, and π-π stacking	With the extension of the ultrasonic treatment time of sunflower pectin, the thermal stability of anthocyanins was significantly improved.	(Liu et al., 2024)
C3G	Citrus RG-I pectin	C3G-RG-I pectin complexes are subjected to high-pressure processing	Hydrophobic interaction and hydrogen bonding	High-pressure processing had a beneficial effect on the binding of C3G and RG-I pectin. After treatment (500 MPa/15 min), the binding rate was increased by 32.8 %, stability and antioxidant capacity of C3G was improved.	(Hou et al., 2022)
Strawberry anthocyanins	Strawberry pectin	High-pressure homogenization of Strawberry Pulp	Electrostatic interaction, hydrophobic interaction, and hydrogen bonding	The binding rate of water-soluble pectin fraction (48.80 %) and chelating agent soluble pectin fraction (50.25 %) to total anthocyanins was significantly higher than that of sodium carbonate soluble component (40.27 %).	(Xing et al., 2024)
C3G	Blueberry pectin	Ultrasonic treatment	Electrostatic interaction, hydrophobic interaction, and hydrogen bonding	Ultrasonic treatment destroyed the long chain and crystal structure of pectin, resulting in low molecular weight and a low DE. Pectin with higher linearity and lower DE had a stronger binding rate with C3G.	(Luo et al., 2024)
Mulberry anthocyanins	Pomegranate peel pectin	High-pressure homogenization	Electrostatic interaction, hydrophobic interaction, and hydrogen bonding	The binding rate of anthocyanins to three pectin components was increased by 34.22–34.59 % after 300 MPa high-pressure homogenization treatment, and the pH stability, thermal stability, and storage stability of anthocyanins were improved after treatment.	(Li et al., 2024)

may be attributed to hydrophobic interactions between anthocyanins and pectin. These findings indicate that the source of pectin affects anthocyanin binding properties.

Different extraction methods change the pectin structure, which affects its binding to anthocyanins. Fernandes et al. (2021) extracted grape pectin polysaccharides with a carbonate solution at 4 °C and found that the pectin had a high homogalacturonic acid region and a few neutral sugar side chains, which could combine well with malvidin-3-glucoside through hydrophobic interaction. Wang et al. (2023) used hot water extraction, high-temperature and -pressure extraction, three enzymes, and mixed enzymes to extract mulberry pectin and obtained six anthocyanin-pectin complexes. They found that the cellulase-assisted extraction of pectin polysaccharides had the highest binding rate to anthocyanins (71.81 %), followed by the mixed enzyme-assisted extraction (54.48 %). This is attributed to the fact that cellulase makes the cellulose oligomer partially adhere to the pectin component. In addition to pectin, anthocyanins also effectively bind to cellulose (Phan et al., 2017). Hot water, high-temperature and -pressure, and pectin-cleaving enzyme-assisted extraction methods caused partial esterification and high structural branching of pectin, which decreased the number of dissociated GalA residues and increased the spatial site resistance of pectin, hindering the ionic interactions between anthocyanins and pectin.

In addition to conventional pectin extraction methods, treating pectin with novel processing technologies can also affect the structure of pectin. Many studies have involved using novel processing technologies (such as ultrasonic treatment, electron beam irradiation, high-pressure homogenization) to modify pectin and investigating the binding effects of modified pectin and anthocyanins. Ultrasonic treatment does not destroy the main chain structure of pectin; however, it has a significant effect on the side chains (Chen et al., 2021). Moreover, residues of non-pectic polysaccharides might be partially removed during ultrasonic modification, increasing the purity of pectin. Liu et al. (2024) obtained modified pectin through the ultrasonic treatment of sunflower pectin at different times and combined it with anthocyanins extracted from purple sweet potatoes. They found that after ultrasonic treatment, the GalA content of pectin was increased, the side-chain of neutral sugars was broken, the DE was reduced, the negative charge was increased, and the hydrogen bonding and electrostatic interactions between pectin and anthocyanins were enhanced. The longer the ultrasonic treatment time of pectin, the lower the degradation rate of anthocyanins. The presence of ultrasound-modified pectin improved the thermal stability of anthocyanins at 90 °C significantly (Liu et al., 2024). This finding provides a theoretical basis for increasing the production value of anthocyanin-rich beverages as well as expanding the use of ultrasound-modified pectin in food applications. Xing et al. (2023) treated strawberry pulp with pasteurization, ultrasonic treatment, electron beam irradiation, and high-pressure processing and studied the changes in the properties of the three pectin components and their correlation with the anthocyanin retention rate in strawberry pulp. The results showed that ultrasonic treatment reduced the structural integrity of pectin, and the pectin glycosidic bonds became looser after electron beam treatment. The retention rate of anthocyanins after digestion was the lowest between the two treatments. Therefore, the retention rate of anthocyanins decreased with the disruption of pectin integrity. Xing et al. (2024) treated strawberry pulp with high-pressure homogenization and found that a modified pectin improved anthocyanin retention in strawberry pulp. This is attributed to the increase in the proportion of the pectin HG region, the decrease in the RG-I region and DE together contributing to the increase in anthocyanin and pectin binding rate.

The blueberry pomace remaining after processing commercial blueberry puree also contains anthocyanins; these anthocyanins likely adhered to the blueberry pomace fibers during and after processing. Hotchkiss et al. (2021) used microwave-assisted extraction to extract blueberry pectin from blueberry pomace, demonstrating that the pectin showed a randomly coiled shape, suggesting that an increase in the flexibility of the pectin molecule promotes anthocyanin binding. Therefore, the reprocessing of blueberry pomace can further improve the economic value and utilization of blueberries. In addition, pectin has been extracted from watermelon rind waste or apple pomace. The use of these processing by-products avoids the waste of raw materials and contributes to the development of functional foods.

Pectin conformation significantly affects its interaction with anthocyanins. The higher linearity of pectin may provide more binding sites for anthocyanins. Conversely, the interweaving of pectin side chains will increase spatial site resistance, which would reduce the number of binding sites for anthocyanins. Pectin, which has a high linearity and a low DE, interacts more closely with anthocyanins.

4.3. External environment

4.3.1. pH

In addition to pectin and anthocyanin structure, their interactions are also affected by the external environment, including pH, temperature, and ionic strength. At different pH values, anthocyanins and pectin have different morphological structures, indicating that pH affects their interactions. pH primarily affects the binding of pectin and anthocyanins by affecting the electrostatic interactions between them. Different pH values produce varying effects on the interactions between pectin and anthocyanins (Weber, 2022). At a medium acidic pH, the flavonoid cation form of anthocyanins dominates and binds to pectin through electrostatic interactions. At higher pH values, uncharged semi-aldehydes and quinones are more abundant, and other mechanisms may exceed electrostatic interactions. Liu et al. (2023) studied the thermal stability and antioxidant activity of sunflower pectin on purple sweet potato anthocyanins at different pH values and found that anthocyanins showed the highest thermal stability at pH 4 and a higher antioxidant activity at high pH than at low pH. In addition, the binding ability of different pectin components and anthocyanins is related to pH. The chelating agent-soluble pectin component has a strong binding ability with anthocyanins at pH 2.0–3.6, while the sodium carbonate-soluble pectin has a strong binding ability with anthocyanins at pH 3.6–4.5 (Lin et al., 2016).

4.3.2. Temperature

The temperature and duration of heating during food processing greatly influence anthocyanin stability (Cai et al., 2022). Buchweitz et al. (2013b) reported that the color stability of anthocyanin-pectin complexes was significantly higher than that of anthocyanin extracts during 18 weeks of storage in the dark at 20 °C. In addition, temperature affects the formation of chemical bonds. Hydrophobic interaction is an endothermic process that requires energy, while the generation of hydrogen bonds is an exothermic process (Jakobek & Matić, 2019). Therefore, temperature primarily affects anthocyanin stability by influencing the hydrogen bonds and hydrophobic interactions between pectin and anthocyanins. Fernandes, Le Bourvellec, et al. (2020) evaluated the thermal stability of anthocyanin-pectin complexes at different temperatures and found that increasing temperature adversely affected hydrogen bonds, causing a decreased binding rate between anthocyanins and pectin, and reduced thermal protection of anthocyanins.

4.3.3. Ionic strength

Ionic strength can affect the charges on pectin and anthocyanins. Koh et al. (2020a) found that the binding level of anthocyanins to pectin was decreased by 92 % when the concentration of citrate phosphate was increased from 25 mM to 200 mM at pH 4.0. This may be owing to an increased ionic strength, which shields the charge of pectin and anthocyanins, weakening the electrostatic interactions between them. Buchweitz et al. (2013a) also found that the addition of citric acid buffer reduced anthocyanin stability in a pectin model. In addition, the hydroxyl group on the B-ring of anthocyanins can form anthocyanin metal chelates with metal ions (such as calcium and iron ions) (Weiss et al., 2024), which may also affect the binding of anthocyanins and pectin. Pectin rich in iron ions has a higher binding affinity for flavonoids than those without iron ions because it can provide more binding sites for flavonoids, increasing the potential of pectin to interact with polyphenols (Chirug et al., 2018).

4.4. High-pressure processing

In addition to the influence of external natural factors, food processing of anthocyanin-pectin complexes (such as high-pressure processing) will also affect the interaction between them. Traditional food processing is inefficient in industrial applications; however, the combination of traditional methods with emerging technologies (such as high-pressure processing) for the extraction of by-products, such as pectin and anthocyanins, from fruit and vegetable waste shows great potential (Sani et al., 2023). However , the physicochemical properties and structures of pectin and anthocyanins were altered by high-pressure processing. On the one hand, high-pressure processing can promote the formation of π-π structure between anthocyanin molecules, resulting in increased anthocyanin self-association and co-coloration reaction (Tian et al., 2022); on the other hand, high-pressure processing exposes hydrophobic groups in pectin molecules, accelerates the occurrence of pectin demethylation, and causes changes in the pectin structure (Hou et al., 2021).

After treatment of the anthocyanin-pectin complexes with high-pressure processing, the non-covalent effects (such as hydrogen bonding and hydrophobic interactions) between anthocyanins and pectin are altered. Hou et al. (2022) found that the high pressure treatment of anthocyanin-pectin complex improved the hydrophobicity and binding ability of anthocyanin and pectin. In addition, reducing the thermal degradation of anthocyanins and inhibiting their degradation in alkaline environments also play a role in high-pressure processing. In addition, the blueberry puree treated by high-pressure processing had more anthocyanin content and stronger antioxidant capacity than those of the puree obtained under traditional heat treatment (Zhang et al., 2021). Hou et al. (2022) found that strawberry juice with the anthocyanin-pectin complex after high-pressure processing treatment had high antioxidant activity. Tan, Kong, et al. (2021) found that high-pressure processing improves the adsorption adsorption between C3G and blueberry pectin. Through high-pressure processing, the particle size of the C3G-pectin complexes was reduced, which benefited the breaking of the macromolecular chain of pectin and the exposure of the charged groups of pectin, improving the ionic interactions between C3G and pectin. However, excessive pressure negatively effects the binding of C3G to pectin. The most favorable conditions for the protection of the stability of C3G are a pressure of 400 MPa and a 1:2 of C3G to pectin (Tan, Li, et al., 2021). Yun et al. (2023) found that low-sugar pomegranate jams with low-ester-amidated pectin had better color quality and higher total anthocyanin content after high-pressure processing. The hydrogen bonds formed between anthocyanins and low-ester-amidated pectin were higher than those of highly esterified pectin, and the total interaction energy and binding rate were higher. This explains the lower color change and browning index of the low-ester-amidated pectin-anthocyanin complexes. Therefore, the combination of high-pressure processing and pectin is used for producing anthocyanin-rich foods, including juices or jams, which is a good strategy to improve anthocyanin stability in food processing.

High-pressure processing is conducive to maintaining the interaction between anthocyanins and pectin, maintaining anthocyanin stability, and developing a new path for functional foods.

5. Effect of interactions on the anthocyanin stability and bioavailability

The interactions between anthocyanins and pectin significantly improve anthocyanin stability and increase their bioavailability in the gastrointestinal tract. Fig. 4 shows the effect of the interactions between anthocyanins and pectin on anthocyanin stability and bioavailability.

5.1. Stability

At different temperatures and pH, the color change of free anthocyanins during incubation was more obvious than that of anthocyanin-pectin complexes (Fu et al., 2023). Jiang et al. (2024) found that pectin could improve the thermal stability and reduce the thermal degradation rate of C3G. Similarly, after heating at 90 °C for 20 min, the anthocyanin retention rate in C3G-RG-I pectin complexes treated by high-pressure processing was 85.4–93.0 % higher than that of C3G alone (Hou et al., 2022). Ultrasonic modification changes pectin conformation. Modification of pectin with ultrasound also resulted in a significant increase in the thermal stability of the anthocyanins in the complexes (Luo et al., 2024). Therefore, ultrasonic modification significantly improves the thermal stability of anthocyanins in anthocyanins-pectin complexes. In summary, juice beverages containing anthocyanin-pectin complexes may retain more anthocyanins during heat sterilization. Copper ions partially bind to the catechol or pyrogallol component of anthocyanins, resulting in their degradation. The retention rate of anthocyanins was increased after adding pectin (Hou et al., 2022). Therefore, the addition of pectin protects anthocyanins from further degradation by metal ions, and this protection is enhanced by high-pressure processing.

5.2. Bioavailability

Although anthocyanins are used as natural coloring agents or functional ingredients in food, the extent to which anthocyanins in food are absorbed and utilized in the body reflects their health value. However, The *in vivo* absorption of anthocyanins is not efficient, and according to studies, their bioavailability in the human body is quite limited. Specifically, only a trace amount of anthocyanins ingested from food is able to enter the blood circulation, which is approximately only 1 % of the total amount ingested (Xue et al., 2022). In more detail, the actual utilization of anthocyanins in the human body has been estimated to be in the range of 0.26 % to 1.8 % (Cladis et al., 2020). Therefore, Improving the bioavailability of anthocyanins has become a major challenge in increasing their benefits in the human body. Studies have shown that the binding of macromolecules to anthocyanins enhances their stability during intestinal digestion and plays a protective role (Zang et al., 2022).

The addition of pectin increases the bioavailability of polyphenols in cherry laurel after *in vitro* digestion and fermentation (García-Pérez et al., 2024). Wang et al. (2023) obtained mulberry pectin polysaccharides containing a high proportion of galacturonic acid with high temperature and pressure extraction, and combined the pectin with anthocyanins to form a complex. The found that no evident release of anthocyanins was observed after digestion in the stomach and small intestine. Thus, the addition of pectin improved the bioavailability of anthocyanins in the small intestine. After gastrointestinal digestion, the anthocyanin-pectin complexes increase anthocyanin stability and allow them to reach the colon, improving their biological efficacy (Jakobek & Matić, 2019). Koh et al. (2020b) found that chelating agent-soluble pectin could prevent anthocyanin degradation and that the number of pectin-bound anthocyanins increased with an increase in the number of hydroxyl groups on anthocyanins. Electrostatic interactions and hydrogen bonding occurred between anthocyanins and pectin, contributing to anthocyanin stability in gastrointestinal simulations. Therefore, when humans ingest foods containing anthocyanins and pectin, the bioavailability of anthocyanins may increase, possibly increasing the anthocyanin concentration reaching the colon. Xing et al. (2024) found that the molecular weight and microstructural compactness of pectin were decreased in high-pressure homogenization-treated strawberry pulps, the HG region of water-soluble pectin was increased, the DE of chelating agent-soluble pectin was decreased, and the

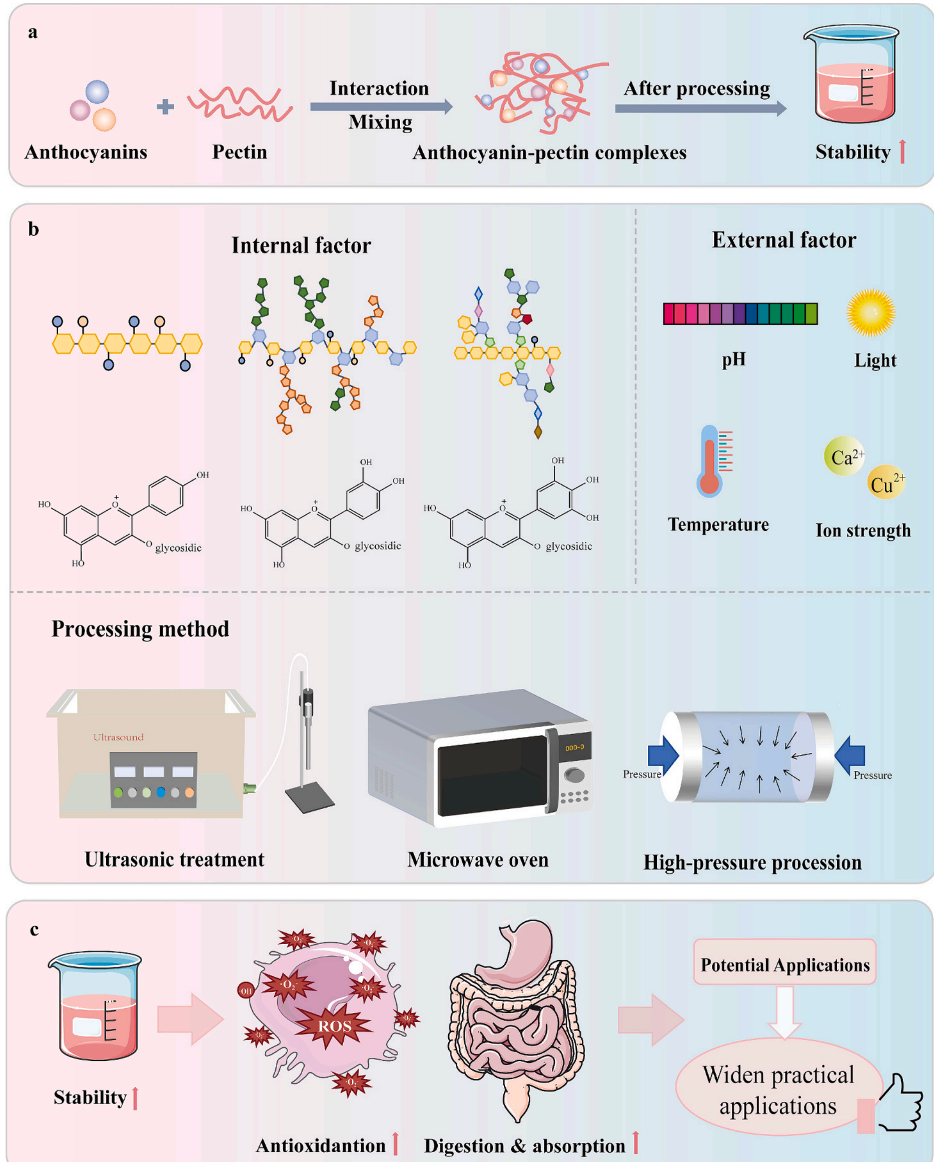

Fig. 4. Effect of interaction on anthocyanin stability and bioavailability. (a) The interaction between anthocyanins and pectin improves anthocyanin stability, (b) Factors affecting the interaction of anthocyanins and pectin, (c) Effects of interactions on anthocyanin properties.

modification of pectin effectively enhanced anthocyanin retention during digestion. The anthocyanin-pectin complexes improve the color and thermal stability of anthocyanins and enhance anthocyanin stability in the gastrointestinal tract, improving the bioavailability of anthocyanins.

6. Application in food processing

The interaction between anthocyanins and pectin increases anthocyanin stability and their range of applications in food (Fig. 5). The application of anthocyanin-pectin complexes in food is currently reflected in the following aspects: adding pectin to anthocyanin-rich foods to maintain food quality (Virgen-Ortiz et al., 2020), using the gelling and color change properties of pectin and anthocyanins, respectively, at different pH values to make intelligent pH indicator film to detect food freshness (Huang, Wang, et al., 2024), or combining high-pressure processing and other technologies to improve the functional characteristics of anthocyanins in food (Tan, Li, et al., 2021). Table 3 summarizes the applications of anthocyanin-pectin complexes in food field.

6.1. Maintaining food quality

Treatment of foods with pectin oligosaccharides can maintain their quality attributes, such as reducing the extent of fruit rot or extending their shelf life. Virgen-Ortiz et al. (2020) found that pectin oligosaccharides significantly increased the total polyphenol and anthocyanin contents in strawberries. Therefore, strawberries treated with pectin-oligosaccharides had a more evident red color and superior 2,2-diphenyl-1-picrylhydrazyl (DPPH) and 2,2-azino-bis(3-ethyl-benzothiazoline-6-sulfonate) (ABTS) free radical scavenging rate, which could maintain the quality attributes of strawberries during cold storage. Villegas et al. (2016) treated Cabernet Sauvignon grapes with pectin-derived oligosaccharides, which showed the same effect as ethephon in increasing the total anthocyanin content of the grapes after 30 days. Pectin-derived oligosaccharides can positively affect grape quality without adding agricultural chemicals. Ochoa-Villarreal et al. (2011) found that pectin-derived oligosaccharides could induce the mRNA expression of phenylalanine ammonia-lyase to enhance the color and anthocyanin content of grape berries.

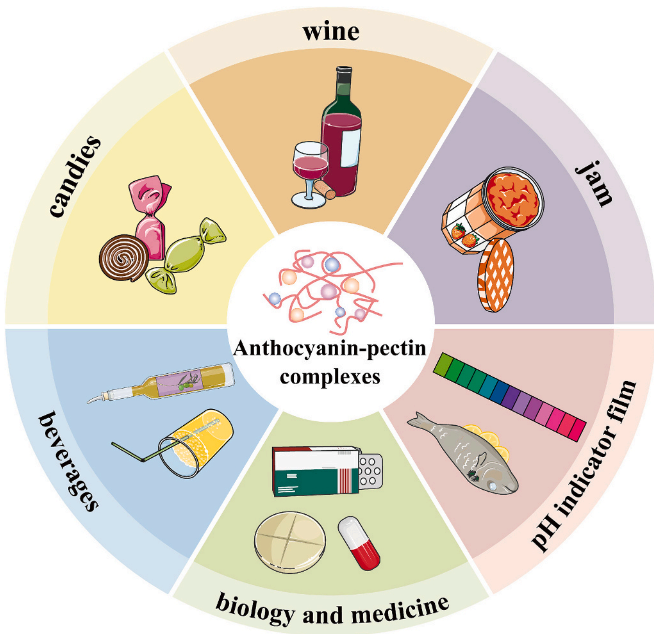

Fig. 5. Application of anthocyanin-pectin complexes in food processing.

6.2. Stabilizing wine color

Anthocyanin-pectin complexes are crucial in stabilizing pigments in wine. Grape pectin polysaccharides form soluble complexes with anthocyanins and enhance their spectral absorbance by promoting their self-association, producing a co-pigmentation effect similar to pigmentation (Weilack et al., 2023). Pectin enhances the red stability of wine by non-covalent interactions with anthocyanins. Therefore, the concentration of non-precipitable polymer pigments in pectin-containing wines increases with wine aging, which may positively affect the color stability of wines. In addition, the variety of raw materials significantly influences the interaction between anthocyanins and pectin. For example, the concentration of anthocyanins in Cabernet Sauvignon wines was decreased more than that of Pinot Noir wines was (Hensen et al., 2024), possibly owing to the synergistic effect of pectin with compounds such as yeast-derived proteins and other polyphenols (such as tannins).

6.3. Intelligent pH indicator film

The pectin-polyphenol active film can be used as an ideal active packaging material for refrigerated meat products. Guo et al. (2023) used watermelon-peel pectin and polyphenols to prepare active packaging films. The addition of polyphenols improved the barrier and mechanical properties, thermal stability, and light transmittance of the films. The pectin provides good gel properties for the composite film (Sani et al., 2021). The composite films delayed the decline in the quality of refrigerated mutton during ultracold storage, and the pectin-polyphenol films retained a dense microstructure and excellent mechanical properties after storage due to the formation of hydrogen bonds and other chemical bonds (Guo et al., 2023). Nastasi et al. (2023) used polyphenol-rich plant extracts (primarily comprising flavonoids and anthocyanins) to increase the stiffness of the pectin films and modulate the elongation at the break of the films; the high antioxidant activity of the composite film suggests that it can prolong the shelf-life of food products (Nastasi et al., 2023).

Anthocyanins exhibit different colors at different pH values. The use of anthocyanin-based pH-sensitive smart films not only effectively extends the shelf life of food products but also provides a system for tracking freshness (Eghbaljoo et al., 2023). Taheri-Yeganeh et al. (2024) found that the addition of anthocyanins and pectin could improve the thermal performance and mechanical properties (such as the increase in the film's strength and flexibility) of the film. The color change of the intelligent film was proportional to the color change of the anthocyanin solution at different pH values, and the freshness and spoilage of shrimp could be detected at 4 °C and 4 °C. Zeng et al. (2023) added black rice anthocyanins to a composite film composed of pectin and chitosan copolymers and found that the flavonoid cations of anthocyanin exhibited electrostatic interactions with the deprotonated carboxyl group of the pectin side chain and formed hydrogen bonds with chitosan and pectin, which enhanced the mechanical properties of the film. The color of the composite film changed from red to blue, indicating an increase in the degree of meat spoilage. Therefore, an intelligent pH indicator composite film containing anthocyanins can be used to monitor the freshness

Table 3
Progress of research on the application of anthocyanin-pectin complexes in the food field.

Application	Anthocyanins	Pectin	Results	References
Strawberry juice	C3G	RG-I pectin	After the heat treatment of strawberry juice at 90 °C/120 min, the retention rate of C3G in the C3G-RG-I pectin group (55.8 %) was higher than that in the C3G group (44.4 %), and the retention rate of C3G in the C3G-RG-I pectin group subjected to high-pressure processing reached 87.2 %.	(Hou et al., 2022)
Strawberry jams	Strawberry anthocyanins	Apple, citrus, and beet pectins	The pectin type affects the storage stability of anthocyanins in jam. 50 % esterified apple pectin, low-ester amidated citrus pectin, and beet pectin can enhance the color stability of jams.	(Holzwarth et al., 2013)
Strawberry spreads	Strawberry anthocyanins	Apple, citrus, and beet pectins	Sugar beet pectin enhanced the stability of anthocyanins in spreads more significantly.	(Holzwarth et al., 2013)
Jelly	Anthocyanins	Grape pectin	The color and encapsulation efficiency of total anthocyanins in microcapsule grape juice powder containing pectin were improved, and the recovery rate of anthocyanins in grape jelly containing higher concentrations of pectin was higher after *in vitro* digestion.	(Karadag et al., 2024)
Intelligent pH indicator film	*Ruellia tuberosa* L-derived anthocyanins	Pectin	The sensor is used to monitor the freshness of tilapia at room temperature and 4 °C. It has the best effect in phosphate buffer and has a long service life. In the 48 h test, the pH value of tilapia was decreased from 7.3 to 5, indicating that the freshness of fish was decreased.	(Nazaruddin et al., 2021)
Intelligent pH indicator film	Anthocyanin Extract from Purple Sugarcane Pericarp (PSPAEs)	Lemon peel pectin (LPP)	The LPP/PSPAEs composite film showed high blocking ability. 20–30 % of PSPAEs enhanced the mechanical properties and thermal performance of LPP film. In addition, LPP/PSPAEs composite film has excellent functional properties, including antioxidant properties and sensitive color response, which can be used to monitor food freshness.	(Jiang et al., 2022)
Intelligent pH indicator film	Purple cabbage extract (PCE)	Watermelon peel pectin(WMP)	Low PCE content (≤1.5 %) enhances the mechanical properties and thermal performance of the films. As the amount of PCE is added, the antioxidant and antimicrobial activities of WMP/PCE films become more favorable.	(Guo et al., 2022)

of meat products. Qiu et al. (2023) made an intelligent pH indicator film based on sodium alginate, apricot peel pectin, and rose anthocyanin extracts. Anthocyanins were homogeneously dispersed in the film-forming matrix, changing the mechanical strength and water vapor permeability of the film. This could be attributed to the hydrogen bonds and hydrophobic interactions between anthocyanins and pectin. In addition, the composite film showed excellent antioxidant properties, higher thermal stability, and stronger light-barrier properties. There was a strong correlation between the total volatile alkali nitrogen content of the meat samples and the total color difference of the film. Thus, the degree of decay of grass carp can be determined by the color change in the film.

6.4. Biological potentials

Anthocyanin-pectin complexes can produce functional properties, such as the regulation of liver lipid metabolism and inflammation caused by an obese diet. Fotschki et al. (2021) found that a combination of pectin-oligosaccharides and raspberry polyphenol extracts reduced the production of short-chain fatty acids in the cecum, which reduced liver fat, cholesterol, triglyceride content, and liver steatosis, benefiting liver lipid metabolism. Paturi et al. (2021) fed rats with pectin added to a polyphenol-rich black currant and green tea diet. After 28 days, the higher the pectin content of the diet, the lower the weight gain in the rats, which had significantly higher fecal nitrogen output, reduced protein digestibility, and increased plasma antioxidant capacity. Fu et al. (2021) combined potato anthocyanins with different polysaccharides (such as pectin, inulin, starch, and cellulose) and found that the binding mode of anthocyanins to different polysaccharides differed, the binding rate with pectin was the highest, and the anthocyanin-pectin complexes effectively improved the increase in lipopolysachharide-induced cell permeability. Therefore, pectin is the most suitable candidate for interaction with anthocyanins to improve gastrointestinal stability and barrier function.

The human bioavailability and intestinal accessibility of anthocyanin-loaded pectin nanoparticles were greatly improved compared with anthocyanins alone (Mueller et al., 2018). Karim et al. (2022) found that pectin chitosan-coated nanoliposomes loaded with P3G reduced palmitic acid-induced hepatocyte injury. High-pressure processing also affects the anti-inflammatory effects of anthocyanin-pectin complexes and the regulation of the intestinal microflora by affecting the non-covalent interaction between anthocyanins and pectin. Tan, Kong, et al. (2021) found that blueberry pectin and C3G complexes inhibited several mediators and cytokines involved in the inflammatory process to exert anti-apoptotic effects. High-pressure processing caused the alteration of the monosaccharide composition of the complexes and a better reduction in apoptotic cell death. In addition, after high-pressure processing, blueberry pectin and C3G complexes significantly alleviated diarrhea and hematochezia in mice with dextran sodium sulfate-induced ulcerative colitis, inhibited the expression of inflammation-related factor signals, and improved the composition of the intestinal microflora (Tan et al., 2022). The results showed that high-pressure processing of anthocyanin-pectin complexes improved the anti-inflammatory effect of ulcerative colitis mice, providing a new approach for treating ulcerative colitis. However, the composition of the intestinal flora of mice treated with the complex differed from that of mice without ulcerative colitis, indicating that the anthocyanin-pectin complexes may have a certain negative impact on the body (Tan et al., 2022). In addition, since the verification of etiology is complicated, further studies are needed to determine the clinical value of anthocyanin-pectin complexes. Hou et al. (2023) found that high-pressure processing reduced the pH of the fecal fermentation broth of RG-I pectin-C3G complexes and promoted the production of short-chain fatty acids. Compared with the control group, after high-pressure processing, the anthocyanin-pectin complexes had a rich flora composition, which promoted the growth of some beneficial bacteria.

In conclusion, anthocyanin-pectin complexes have good potential for the development of functional fruit and vegetable juices and food products. However, the effects of these complexes on the human intestinal microflora and the absorption of other nutrients need to be further investigated through *in vivo* experiments or clinical trials.

7. Conclusion and foresight

We reviewed the interaction mechanism between anthocyanins and pectin and the factors affecting anthocyanin stability in anthocyanin-pectin complexes and analyzed the practical applications of these complexes. There are primarily non-covalent interactions between anthocyanins and pectin, including electrostatic interaction, hydrophobic interaction, hydrogen bonding, and π-π stacking. The high linearity and low DE of pectin and the higher number of hydroxyl groups of anthocyanins will make their binding more closely. In addition, the pH, temperature, and ionic strength affect anthocyanin stability by affecting their interactions with pectin. High-pressure processing also improves the stability of the anthocyanin-pectin complexes and increases the stability and bioavailability of anthocyanins. Anthocyanin-pectin complexes have been studied to maintain food quality, stabilize wine color, monitor food freshness, and serve as functional ingredients for food addition.

However, whether anthocyanins and pectin can achieve the "$1 + 1 > 2$" effect requires further exploration, such as determining the relationship between the change in functional groups and biological activity in the interaction process of different anthocyanin monomers and pectin, mechanisms underlying interactions between anthocyanins and pectin in food applications, the bioavailability and sustained release effect in the practical application process, the influence of some new processing techniques on the interaction between pectin and anthocyanin, and the influence of complexes on sensory acceptance. Further studies are required to evaluate the practical significance of anthocyanin-pectin complexes in food processing and product development. Additionally, the *in vivo* side effects or negative biological effects of complexes need to be further investigated using *in vitro* modeling or clinical trials. Studying the interactions between anthocyanins and pectin may improve food quality, stability, and nutritional value. This review provides a reference for further research and applications of the interaction between anthocyanins and pectin.

Funding

This research was supported by Youth Funds for the National Natural Science Foundation of China (No. 32302084), Fundemental Research Funds for Public Universities in Liaoning (No. JYTQN2023192, JYTMS20230762) and Yingkou Science and Technology Bureau (No. YKSCJH2023-005).

CRediT authorship contribution statement

Chenyang Shi: Writing – original draft, Visualization, Investigation, Formal analysis. **Chongting Guo:** Writing – review & editing, Conceptualization. **Shan Wang:** Resources. **Weixuan Li:** Validation. **Xue Zhang:** Validation. **Shan Lu:** Investigation. **Chong Ning:** Supervision, Project administration. **Chang Tan:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

Data availability

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

References

Bermúdez-Oria, A., Rodríguez-Gutiérrez, G., Fernández-Prior, Á., Vioque, B., & Fernández-Bolaños, J. (2019). Strawberry dietary fiber functionalized with phenolic antioxidants from olives. Interactions between polysaccharides and phenolic compounds. *Food Chemistry, 280*, 310–320. https://doi.org/10.1016/j.foodchem.2018.12.057

Blesso, C. N. (2019). Dietary anthocyanins and human health. *Nutrients, 11*, 2107. https://doi.org/10.3390/nu11092107

Boulet, J.-C., Abi-Habib, E., Carrillo, S., Roi, S., Veran, F., Verbaere, A., … Vernhet, A. (2023). Focus on the relationships between the cell wall composition in the extraction of anthocyanins and tannins from grape berries. *Food Chemistry, 406*, Article 135023. https://doi.org/10.1016/j.foodchem.2022.135023

Buchweitz, M., Speth, M., Kammerer, D. R., & Carle, R. (2013a). Impact of pectin type on the storage stability of black currant (Ribes nigrum L.) anthocyanins in pectic model solutions. *Food Chemistry, 139*, 1168–1178. https://doi.org/10.1016/j.foodchem.2013.02.005

Buchweitz, M., Speth, M., Kammerer, D. R., & Carle, R. (2013b). Stabilisation of strawberry (Fragaria x ananassa Duch.) anthocyanins by different pectins. *Food Chemistry, 141*, 2998–3006. https://doi.org/10.1016/j.foodchem.2013.04.117

Cai, D., Li, X., Chen, J., Jiang, X., Ma, X., Sun, J., … Bai, W. (2022). A comprehensive review on innovative and advanced stabilization approaches of anthocyanin by modifying structure and controlling environmental factors. *Food Chemistry, 366*, Article 130611. https://doi.org/10.1016/j.foodchem.2021.130611

Çakır, B., & Gülseren, İ. (2017). Dissolution kinetics of polyphenol bearing calcium pectate hydrogels in simulated gastric or intestinal media and their anti-carcinogenic capacities. *Food Hydrocolloids, 70*, 69–75. https://doi.org/10.1016/j.foodhyd.2017.03.026

Chan, S. Y., Choo, W. S., Young, D. J., & Loh, X. J. (2017). Pectin as a rheology modifier: Origin, structure, commercial production and rheology. *Carbohydrate Polymers, 161*, 118–139. https://doi.org/10.1016/j.carbpol.2016.12.033

Chen, T.-T., Zhang, Z.-H., Wang, Z.-W., Chen, Z.-L., Ma, H., & Yan, J.-K. (2021). Effects of ultrasound modification at different frequency modes on physicochemical, structural, functional, and biological properties of citrus pectin. *Food Hydrocolloids, 113*, Article 106484. https://doi.org/10.1016/j.foodhyd.2020.106484

Chen, Z., Ma, J., Li, P., Wen, B., Wang, Y., Ma, Y., & Huang, W. (2023). Preparation of hypoglycemic anthocyanins from mulberry (Fructus mori) fruits by ultrahigh pressure extraction. *Innovative Food Science & Emerging Technologies, 84*, Article 103255. https://doi.org/10.1016/j.ifset.2022.103255

Chirug, L., Okun, Z., Ramon, O., & Shpigelman, A. (2018). Iron ions as mediators in pectin-flavonols interactions. *Food Hydrocolloids, 84*, 441–449. https://doi.org/10.1016/j.foodhyd.2018.06.039

Christiaens, S., Van Buggenhout, S., Houben, K., Jamsazzadeh Kermani, Z., Moelants, K. R. N., Ngouémazong, E. D., … Hendrickx, M. E. G. (2016). Process–structure–function relations of pectin in food. *Critical Reviews in Food Science and Nutrition, 56*, 1021–1042. https://doi.org/10.1080/10408398.2012.753029

Chung, C., Rojanasasithara, T., Mutilangi, W., & McClements, D. J. (2016). Stabilization of natural colors and nutraceuticals: Inhibition of anthocyanin degradation in model beverages using polyphenols. *Food Chemistry, 212*, 596–603. https://doi.org/10.1016/j.foodchem.2016.06.025

Cladis, D. P., Debelo, H., Lachcik, P. J., Ferruzzi, M. G., & Weaver, C. M. (2020). Increasing doses of blueberry polyphenols alters colonic metabolism and calcium absorption in Ovariectomized rats. *Molecular Nutrition & Food Research, 64*. https://doi.org/10.1002/mnfr.202000031

Eghbaljoo, H., Alizadeh Sani, M., Sani, I. K., Maragheh, S. M., Sain, D. K., Jawhar, Z. H., … Jafari, S. M. (2023). Development of smart packaging halochromic films embedded with anthocyanin pigments; recent advances. *Critical Reviews in Food Science and Nutrition*, 1–17. https://doi.org/10.1080/10408398.2023.2280769

Feitosa, B. F., Decker, B. L. A., Brito, E. S. D., Rodrigues, S., & Mariutti, L. R. B. (2023). Microencapsulation of anthocyanins as natural dye extracted from fruits – A systematic review. *Food Chemistry, 424*, Article 136361. https://doi.org/10.1016/j.foodchem.2023.136361

Fernandes, A., Brandão, E., Raposo, F., Maricato, É., Oliveira, J., Mateus, N., … de Freitas, V. (2020). Impact of grape pectic polysaccharides on anthocyanins thermostability. *Carbohydrate Polymers, 239*. https://doi.org/10.1016/j.carbpol.2020.116240

Fernandes, A., Brás, N. F., Mateus, N., & de Freitas, V. (2014). Understanding the molecular mechanism of anthocyanin binding to pectin. *Langmuir, 30*, 8516–8527. https://doi.org/10.1021/la501879w

Fernandes, A., Oliveira, J., Fonseca, F., Ferreira-da-Silva, F., Mateus, N., Vincken, J.-P., & de Freitas, V. (2020). Molecular binding between anthocyanins and pectic polysaccharides – Unveiling the role of pectic polysaccharides structure. *Food Hydrocolloids, 102*. https://doi.org/10.1016/j.foodhyd.2019.105625

Fernandes, A., Raposo, F., Evtuguin, D. V., Fonseca, F., Ferreira-da-Silva, F., Mateus, N., … de Freitas, V. (2021). Grape pectic polysaccharides stabilization of anthocyanins red colour: Mechanistic insights. *Carbohydrate Polymers, 255*, Article 117432. https://doi.org/10.1016/j.carbpol.2020.117432

Fernandes, P. A. R., Le Bourvellec, C., Renard, C. M. G. C., Wessel, D. F., Cardoso, S. M., & Coimbra, M. A. (2020). Interactions of arabinan-rich pectic polysaccharides with polyphenols. *Carbohydrate Polymers, 230*, Article 115644. https://doi.org/10.1016/j.carbpol.2019.115644

Fotschki, B., Juśkiewicz, J., Jurgoński, A., & Sójka, M. (2021). Fructo-oligosaccharides and Pectins enhance beneficial effects of raspberry polyphenols in rats with nonalcoholic fatty liver. *Nutrients, 13*, 833. https://doi.org/10.3390/nu13030833

Fu, W., Li, S., Helmick, H., Hamaker, B. R., Kokini, J. L., & Reddivari, L. (2023). Complexation with polysaccharides enhances the stability of isolated anthocyanins. *Foods, 12*, 1846. https://doi.org/10.3390/foods12091846

Fu, W., Li, S., & Reddivari, L. (2021). Complexation with polysaccharides enhanced polyphenol gastrointestinal stability and activity. *Current Developments in Nutrition, 5*, 314. https://doi.org/10.1093/cdn/nzab037_024

Gao, Q. C., Ma, R., Shi, L., Wang, S. L., Liang, Y., & Zhang, Z. Y. (2023). Anti-glycation and anti-inflammatory activities of anthocyanins from purple vegetables. *Food & Function, 14*, 2034–2044. https://doi.org/10.1039/D2FO03645b

García-Pérez, P., Tomas, M., Rivera-Pérez, A., Patrone, V., Giuberti, G., Cervini, M., Capanoglu, E., & Lucini, L. (2024). Pectin conformation influences the bioaccessibility of cherry laurel polyphenols and gut microbiota distribution following in vitro gastrointestinal digestion and fermentation. *Food Chemistry, 430*, Article 137054. https://doi.org/10.1016/j.foodchem.2023.137054

Gençdağ, E., Özdemir, E. E., Demirci, K., Görgüç, A., & Yılmaz, F. M. (2022). Copigmentation and stabilization of anthocyanins using organic molecules and encapsulation techniques. *Current Plant Biology, 29*, Article 100238. https://doi.org/10.1016/j.cpb.2022.100238

Gonçalves, A. C., Nunes, A. R., Falcão, A., Alves, G., & Silva, L. R. (2021). Dietary effects of anthocyanins in human health: A comprehensive review. *Pharmaceuticals, 14*, 690. https://doi.org/10.3390/ph14070690

Guo, Z., Wu, S., Lin, J., Zheng, H., Lei, H., Yu, Q., & Jiang, W. (2023). Active film preparation using pectin and polyphenols of watermelon peel and its applications for super-chilled storage of chilled mutton. *Food Chemistry, 417*, Article 135838. https://doi.org/10.1016/j.foodchem.2023.135838

Guo, Z., Zuo, H., Ling, H., Yu, Q., Gou, Q., & Yang, L. (2022). A novel colorimetric indicator film based on watermelon peel pectin and anthocyanins from purple cabbage for monitoring mutton freshness. *Food Chemistry, 383*, Article 131915. https://doi.org/10.1016/j.foodchem.2021.131915

Hensen, J.-P., Hoening, F., Bogdanovic, T., Schieber, A., & Weber, F. (2024). Pectin forms polymeric pigments by complexing anthocyanins during red winemaking and ageing. *Food Research International, 188*, Article 114442. https://doi.org/10.1016/j.foodres.2024.114442

Holzwarth, M., Korhummel, S., Siekmann, T., Carle, R., & Kammerer, D. R. (2013). Influence of different pectins, process and storage conditions on anthocyanin and colour retention in strawberry jams and spreads. *LWT - Food Science and Technology, 52*, 131–138. https://doi.org/10.1016/j.lwt.2012.05.020

Hotchkiss, A. T., Chau, H. K., Strahan, G. D., Nuñez, A., Simon, S., White, A. K., … Hirsch, J. (2021). Structure and composition of blueberry fiber pectin and xyloglucan that bind anthocyanins during fruit puree processing. *Food Hydrocolloids, 116*, Article 106572. https://doi.org/10.1016/j.foodhyd.2020.106572

Hou, Z., Chen, S., & Ye, X. (2021). High pressure processing accelarated the release of RG-I pectic polysaccharides from citrus peel. *Carbohydrate Polymers, 263*, Article 118005. https://doi.org/10.1016/j.carbpol.2021.118005

Hou, Z., Luan, L., Hu, X., Chen, S., & Ye, X. (2022). Beneficial effects of high pressure processing on the interaction between RG-I pectin and cyanidin-3-glucoside. *Food Chemistry, 383*, Article 132373. https://doi.org/10.1016/j.foodchem.2022.132373

Hou, Z. Q., Luan, L. Q., Hu, X. X., Chen, S. G., & Ye, X. Q. (2023). Innovative processing technology for enhance potential prebiotic effects of RG-I pectin and cyanidin-3-glucoside. *Food Hydrocolloids, 134*, Article 108045. https://doi.org/10.1016/j.foodhyd.2022.108045

Huang, K., Wang, L., Deng, Y., Zheng, H., Wu, S., Li, Z., Lei, H., Yu, Q., & Guo, Z. (2024). Development of amine-sensitive intelligent film with MIL-100(Fe) as function filler based on anthocyanins/pectin for monitoring chilled meat freshness. *International Journal of Biological Macromolecules, 270*, Article 132463. https://doi.org/10.1016/j.ijbiomac.2024.132463

Huang, L., Sun, Q., Li, Q., & Li, X. (2024). Screening and characterization of an anti-inflammatory pectic polysaccharide from Cucurbita moschata Duch. *International Journal of Biological Macromolecules, 264*, Article 130510. https://doi.org/10.1016/j.ijbiomac.2024.130510

Jakobek, L., & Matić, P. (2019). Non-covalent dietary fiber - polyphenol interactions and their influence on polyphenol bioaccessibility. *Trends in Food Science & Technology, 83*, 235–247. https://doi.org/10.1016/j.tifs.2018.11.024

Jiang, H., Zhang, W., Cao, J., & Jiang, W. (2022). Effect of purple sugarcane peel extracts on properties of films based on lemon peel waste pectin and the application in the visible detection of food freshness. *Food Hydrocolloids, 133*, Article 107982. https://doi.org/10.1016/j.foodhyd.2022.107982

Jiang, X., Bi, J., Liu, X., Liu, M., Xie, H., Verkerk, R., & Dekker, M. (2024). Effect of different pectin sources and structures on the stability of cyanidin-3-O-glucoside (C3G). *Lwt, 205*, Article 116473. https://doi.org/10.1016/j.lwt.2024.116473

Jin, M.-Y., Li, M.-Y., Huang, R.-M., Wu, X.-Y., Sun, Y.-M., & Xu, Z.-L. (2021). Structural features and anti-inflammatory properties of pectic polysaccharides: A review. *Trends in Food Science & Technology, 107*, 284–298. https://doi.org/10.1016/j.tifs.2020.10.042

Kang, H.-J., Ko, M.-J., & Chung, M.-S. (2021). Anthocyanin structure and pH dependent extraction characteristics from blueberries (Vaccinium corymbosum) and chokeberries (Aronia melanocarpa) in subcritical water state. *Foods, 10*, 527. https://doi.org/10.3390/foods10030527

Karadag, A., Ozkan, K., & Sagdic, O. (2024). Development of microencapsulated grape juice powders using black 'Isabel' grape peel pectin and application in jelly formulation with enhanced in vitro bioaccessibility of anthocyanins. *Journal of Food Science, 89*, 2067–2083. https://doi.org/10.1111/1750-3841.16999

Karim, N., Shishir, M. R., Li, Y., Zineb, O. Y., Mo, J., Tangpong, J., & Chen, W. (2022). Pelargonidin-3-O-glucoside encapsulated pectin-chitosan-Nanoliposomes recovers palmitic acid-induced hepatocytes injury. *Antioxidants, 11*, 623. https://doi.org/10.3390/antiox11040623

Khoo, H. E., Azlan, A., Tang, S. T., & Lim, S. M. (2017). Anthocyanidins and anthocyanins: Colored pigments as food, pharmaceutical ingredients, and the potential health benefits. *Food & Nutrition Research, 61*, 1–21. https://doi.org/10.1080/16546628.2017.1361779

Koh, J., Xu, Z., & Wicker, L. (2020a). Binding kinetics of blueberry pectin-anthocyanins and stabilization by non-covalent interactions. *Food Hydrocolloids, 99*, Article 105354. https://doi.org/10.1016/j.foodhyd.2019.105354

Koh, J., Xu, Z., & Wicker, L. (2020b). Blueberry pectin and increased anthocyanins stability under in vitro digestion. *Food Chemistry, 302*, Article 125343. https://doi.org/10.1016/j.foodchem.2019.125343

Larsen, L. R., Buerschaper, J., Schieber, A., & Weber, F. (2019). Interactions of anthocyanins with pectin and pectin fragments in model solutions. *Journal of Agricultural and Food Chemistry, 67*, 9344–9353. https://doi.org/10.1021/acs.jafc.9b03108

Lee, H.-B., Kim, Y.-S., & Park, H.-Y. (2022). Pectic polysaccharides: Targeting gut microbiota in obesity and intestinal health. *Carbohydrate Polymers, 287*, Article 119363. https://doi.org/10.1016/j.carbpol.2022.119363

Li, J., Li, R., Peng, Y., Tian, J., & Zhou, L. (2024). Effect of high-pressure-homogenisation on the interaction between pomegranate peel pectin fractions and anthocyanins in acidic environment. *Food Chemistry, 457*, Article 140110. https://doi.org/10.1016/j.foodchem.2024.140110

Li, N., Liu, X., Zhang, J., Lang, Y.-Z., Lu, L., Mi, J., … Ran, L.-W. (2022). Preventive effects of anthocyanins from Lyciumruthenicum Murray in high-fat diet-induced obese mice are related to the regulation of intestinal microbiota and inhibition of pancreatic lipase activity. *Molecules, 27*, 2141. https://doi.org/10.3390/molecules27072141

Lin, S., Meng, X., Tan, C., Tong, Y., Wan, M., Wang, M., Zhao, Y., Deng, H., Kong, Y., & Ma, Y. (2022). Composition and antioxidant activity of anthocyanins from Aronia melanocarpa extracted using an ultrasonic-microwave-assisted natural deep eutectic solvent extraction method. *Ultrasonics Sonochemistry, 89*, Article 106102. https://doi.org/10.1016/j.ultsonch.2022.106102

Lin, Z., Fischer, J., & Wicker, L. (2016). Intermolecular binding of blueberry pectin-rich fractions and anthocyanin. *Food Chemistry, 194*, 986–993. https://doi.org/10.1016/j.foodchem.2015.08.113

Liu, S., & Zhang, Y. (2024). Antioxidant properties and electrochemical activity of anthocyanins and anthocyanidins in mulberries. *Journal of Food Measurement and Characterization, 18*, 3569–3576. https://doi.org/10.1007/s11694-024-02426-9

Liu, Y., Tong, Y., Tong, Q., Xu, W., & Wang, Z. (2023). Effects of sunflower pectin on thermal stability of purple sweet potato anthocyanins at different pH. *International Journal of Biological Macromolecules, 253*, Article 126663. https://doi.org/10.1016/j.ijbiomac.2023.126663

Liu, Y., Tong, Y., Tong, Q., Xu, W., & Wang, Z. (2024). Effect of ultrasonic modification on the binding ability of pectin to anthocyanin. *Journal of the Science of Food and Agriculture, 104*, 3614–3623. https://doi.org/10.1002/jsfa.13245

Luo, F., Zhang, Z., Lu, F., Li, D., Zhou, C., Li, Y., Niu, L., Xu, Y., Feng, L., Dai, Z., & He, W. (2024). Ultrasound modification of pectin and the mechanism of its interaction with cyanidin-3-O-glucoside. *Food Hydrocolloids, 152*, Article 109898. https://doi.org/10.1016/j.foodhyd.2024.109898

Merecz-Sadowska, A., Sitarek, P., Kowalczyk, T., Zajdel, K., Jęcek, M., Nowak, P., & Zajdel, R. (2023). Food anthocyanins: Malvidin and its glycosides as promising antioxidant and anti-inflammatory agents with potential health benefits. *Nutrients, 15*, 3016. https://doi.org/10.3390/nu15133016

Mohnen, D. (2008). Pectin structure and biosynthesis. *Current Opinion in Plant Biology, 11*, 266–277. https://doi.org/10.1016/j.pbi.2008.03.006

Mueller, D., Jung, K., Winter, M., Rogoll, D., Melcher, R., Kulozik, U., … Richling, E. (2018). Encapsulation of anthocyanins from bilberries - effects on bioavailability and intestinal accessibility in humans. *Food Chemistry, 248*, 217–224. https://doi.org/10.1016/j.foodchem.2017.12.058

Muñoz-Almagro, N., Ruiz-Torralba, A., Méndez-Albiñana, P., Guerra-Hernández, E., García-Villanova, B., Moreno, R., Villamiel, M., & Montilla, A. (2021). Berry fruits as source of pectin: Conventional and non-conventional extraction techniques. *International Journal of Biological Macromolecules, 186*, 962–974. https://doi.org/10.1016/j.ijbiomac.2021.07.016

Nastasi, J. R., Fitzgerald, M. A., & Kontogiorgos, V. (2023). Tuning the mechanical properties of pectin films with polyphenol-rich plant extracts. *International Journal of Biological Macromolecules, 253*, Article 127536. https://doi.org/10.1016/j.ijbiomac.2023.127536

Nazaruddin, N., Afifah, N., Bahi, M., Susilawati, S., Sani, N. D. M., Esmaeili, C., … Safitri, E. (2021). A simple optical pH sensor based on pectin and Ruellia tuberosa L-derived anthocyanin for fish freshness monitoring. *F1000Research, 10*, 422. https://doi.org/10.12688/f1000research.52836.2

Ochoa-Villarreal, M., Vargas-Arispuro, I., Islas-Osuna, M. A., González-Aguilar, G., & Martinez-Téllez, M. A. (2011). Pectin-derived oligosaccharides increase color and anthocyanin content in flame seedless grapes. *Journal of the Science of Food and Agriculture, 91*, 1928–1930. https://doi.org/10.1002/jsfa.4412

Padayachee, A., Netzel, G., Netzel, M., Day, L., Zabaras, D., Mikkelsen, D., & Gidley, M. J. (2012). Binding of polyphenols to plant cell wall analogues – Part 1: Anthocyanins. *Food Chemistry, 134*, 155–161. https://doi.org/10.1016/j.foodchem.2012.02.082

Paturi, G., Butts, C. A., Joyce, N. I., Rippon, P. E., Morrison, S. C., Hedderley, D. I., & Lister, C. E. (2021). Pectin influences the absorption and metabolism of polyphenols from blackcurrant and green tea in rats. *Foods, 10*, 813. https://doi.org/10.3390/foods10040813

Phan, A. D. T., Flanagan, B. M., D'Arcy, B. R., & Gidley, M. J. (2017). Binding selectivity of dietary polyphenols to different plant cell wall components: Quantification and mechanism. *Food Chemistry, 233*, 216–227. https://doi.org/10.1016/j.foodchem.2017.04.115

Qi, Q., Chu, M., Yu, X., Xie, Y., Li, Y., Du, Y., … Yan, N. (2023). Anthocyanins and Proanthocyanidins: Chemical structures, food sources, bioactivities, and product development. *Food Reviews International, 39*, 4581–4609. https://doi.org/10.1080/87559129.2022.2029479

Qiu, L., Zhang, M., Huang, M., Chitrakar, B., & Chang, L. (2023). Fabrication of sodium alginate/apricot peel pectin films incorporated with rose anthocyanin-rich extract for monitoring grass carp (Ctenopharyngodon idellus) freshness. *Food Packaging and Shelf Life, 39*, Article 101150. https://doi.org/10.1016/j.fpsl.2023.101150

Riyamol Gada Chengaiyan, J., Rana, S. S., Ahmad, F., Haque, S., & Capanoglu, E. (2023). Recent advances in the extraction of pectin from various sources and industrial applications. *ACS Omega, 8*, 46309–46324. https://doi.org/10.1021/acsomega.3c04010

Sadilova, E., Stintzing, F. C., & Carle, R. (2006). Thermal degradation of Acylated and Nonacylated anthocyanins. *Journal of Food Science, 71*, C504–C512. https://doi.org/10.1111/j.1750-3841.2006.00148.x

Sani, I. K., & Alizadeh, M. (2022). Isolated mung bean protein-pectin nanocomposite film containing true cardamom extract microencapsulation /CeO2 nanoparticles/ graphite carbon quantum dots: Investigating fluorescence, photocatalytic and antimicrobial properties. *Food Packaging and Shelf Life, 33*, Article 100912. https://doi.org/10.1016/j.fpsl.2022.100912

Sani, I. K., Geshlaghi, S. P., Pirsa, S., & Asdagh, A. (2021). Composite film based on potato starch/apple peel pectin/ZrO2 nanoparticles/ microencapsulated Zataria multiflora essential oil; investigation of physicochemical properties and use in quail meat packaging. *Food Hydrocolloids, 117*, Article 106719. https://doi.org/10.1016/j.foodhyd.2021.106719

Sani, I. K., Masoudpour-Behabadi, M., Alizadeh Sani, M., Motalebinejad, H., Juma, A. S. M., Asdagh, A., … Mohammadi, F. (2023). Value-added utilization of fruit and vegetable processing by-products for the manufacture of biodegradable food packaging films. *Food Chemistry, 405*, Article 134964. https://doi.org/10.1016/j.foodchem.2022.134964

Sendri, N., & Bhandari, P. (2024). Anthocyanins: A comprehensive review on biosynthesis, structural diversity, and industrial applications. *Phytochemistry Reviews*. https://doi.org/10.1007/s11101-024-09945-9

Shahidi, F., & Yeo, J. (2016). Insoluble-bound Phenolics in food. *Molecules, 21*, 1216. https://doi.org/10.3390/molecules21091216

Sun, H., Chen, R., Meng, F., Bai, H., Tian, L., Lu, J., … Gong, M. (2023). Extraction, characterization, antioxidant and hypoglycemic of Pectic polysaccharides from cantaloupe (Cucumis melo L.) peels. *Starch - Stärke, 76*, 157. https://doi.org/10.1002/star.202300157

Taheri-Yeganeh, A., Ahari, H., Mashak, Z., & Jafari, S. M. (2024). Monitor the freshness of shrimp by smart halochromic films based on gelatin/pectin loaded with pistachio peel anthocyanin nanoemulsion. *Food Chemistry: X, 21*, Article 101217. https://doi.org/10.1016/j.fochx.2024.101217

Tan, C., Kong, Y., Tong, Y., Deng, H., Wang, M., Zhao, Y., Wan, M., Lin, S., Liu, X., Meng, X., & Ma, Y. (2021). Anti-apoptotic effects of high hydrostatic pressure treated cyanidin-3-glucoside and blueberry pectin complexes on lipopolysaccharide-induced inflammation in Caco-2 cells. *Journal of Functional Foods, 86*, Article 104709. https://doi.org/10.1016/j.jff.2021.104709

Tan, C., Li, D., Wang, H., Tong, Y., Zhao, Y., Deng, H., Kong, Y., Shu, C., Yan, T., & Meng, X. (2021). Effects of high hydrostatic pressure on the binding capacity, interaction, and antioxidant activity of the binding products of cyanidin-3-glucoside and blueberry pectin. *Food Chemistry, 344*, Article 128731. https://doi.org/10.1016/j.foodchem.2020.128731

Tan, C., Wang, M. Y., Kong, Y. W., Wan, M. Z., Deng, H. T., Tong, Y. Q., … Meng, X. J. (2022). Anti-inflammatory and intestinal microbiota modulation properties of high hydrostatic pressure treated cyanidin-3-glucoside and blueberry pectin complexes on dextran sodium sulfate-induced ulcerative colitis mice. *Food & Function, 13*, 4384–4398. https://doi.org/10.1039/d1fo03376j

Tena, N., & Asuero, A. G. (2022). Up-to-date analysis of the extraction methods for anthocyanins: Principles of the techniques, optimization, technical Progress, and industrial application. *Antioxidants, 11*, 286. https://doi.org/10.3390/antiox11020286

Tian, X., Zou, H., Yang, P., Ma, Y., Li, Y., Zhao, L., … Liao, X. (2022). Effects of high pressure processing and thermal treatment on the interaction between α-Lactalbumin and Pelargonium-3-glucoside. *Molecules, 27*, 4944. https://doi.org/10.3390/molecules27154944

Villegas, D., Handford, M., Alcalde, J. A., & Perez-Donoso, A. (2016). Exogenous application of pectin-derived oligosaccharides to grape berries modifies anthocyanin accumulation, composition and gene expression. *Plant Physiology and Biochemistry, 104*, 125–133. https://doi.org/10.1016/j.plaphy.2016.03.020

Virgen-Ortiz, J. J., Morales-Ventura, J. M., Colín-Chávez, C., Esquivel-Chávez, F., Vargas-Arispuro, I., Aispuro-Hernández, E., & Martínez-Téllez, M. A. (2020). Postharvest application of pectic-oligosaccharides on quality attributes, activities of defense-related enzymes, and anthocyanin accumulation in strawberry. *Journal of the Science of Food and Agriculture, 100*, 1949–1961. https://doi.org/10.1002/jsfa.10207

Waldron, K. W., Ng, A., Parker, M. L., & Parr, A. J. (1997). Ferulic acid dehydrodimers in the cell walls of Beta vulgaris and their possible role in texture. *Journal of the Science of Food and Agriculture, 74*, 221–228, 10.1002/(SICI)1097-0010(199706)74:2<221::AID-JSFA792>3.0.CO;2-Q.

Wang, J., Zhao, Y., Sun, B., Yang, Y., Wang, S., Feng, Z., & Li, J. (2024). The structure of anthocyanins and the copigmentation by common micromolecular copigments: A review. *Food Research International, 176*, Article 113837. https://doi.org/10.1016/j.foodres.2023.113837

Wang, M., Zhang, Z., Sun, H., He, S., Liu, S., Zhang, T., Wang, L., & Ma, G. (2022). Research progress of anthocyanin prebiotic activity: A review. *Phytomedicine, 102*, Article 154145. https://doi.org/10.1016/j.phymed.2022.154145

Wang, S., Xia, P., Wang, S., Liang, J., Sun, Y., Yue, P., & Gao, X. (2019). Packaging films formulated with gelatin and anthocyanins nanocomplexes: Physical properties, antioxidant activity and its application for olive oil protection. *Food Hydrocolloids, 96*, 617–624. https://doi.org/10.1016/j.foodhyd.2019.06.004

Wang, S., Zhang, X., Ai, J., Yue, Z., Wang, Y., Bao, B., Tian, L., & Bai, W. (2023). Interaction between black mulberry pectin-rich fractions and cyanidin-3-O-glucoside under in vitro digestion. *Food Hydrocolloids, 134*, Article 108110. https://doi.org/10.1016/j.foodhyd.2022.108110

Weber, F. (2022). Noncovalent Polyphenol–Macromolecule Interactions and Their Effects on the Sensory Properties of Foods. *Journal of Agricultural and Food Chemistry, 70*, 72–78. https://doi.org/10.1021/acs.jafc.1c05873

Wei, J. Q., Li, D. N., & Meng, X. J. (2020). Effect of binding to pectin on the stability of anthocyanins from Aronia melanocarpa berries. *Food Science, 41*, 65–72. https://www.spkx.net.cn/CN/10.7506/spkx1002-6630-20190125-329.

Weilack, I., Mehren, L., Schieber, A., & Weber, F. (2023). Grape-derived pectic polysaccharides alter the tannin and pigment composition of cabernet sauvignon red wines. *Current Research in Food Science, 6*, Article 100506. https://doi.org/10.1016/j.crfs.2023.100506

Weiss, V., Okun, Z., & Shpigelman, A. (2023). Utilization of hydrocolloids for the stabilization of pigments from natural sources. *Current Opinion in Colloid & Interface Science, 68*, Article 101756. https://doi.org/10.1016/j.cocis.2023.101756

Weiss, V., Okun, Z., & Shpigelman, A. (2024). Ternary anthocyanin-iron ion-pectin interactions: Structure-dependent formation and spectral properties as potential tools for more stable blue colorants. *Food Hydrocolloids, 153*, Article 110035. https://doi.org/10.1016/j.foodhyd.2024.110035

Wu, D. M., Zheng, J. Q., Mao, G. Z., Hu, W. W., Ye, X. Q., Linhardt, R. J., & Chen, S. G. (2020). Rethinking the impact of RG-I mainly from fruits and vegetables on dietary health. *Critical Reviews in Food Science and Nutrition, 60*, 2938–2960. https://doi.org/10.1080/10408398.2019.1672037

Xing, Y., Wang, K., Zhang, M., Law, C.-L., Lei, H., Wang, J., & Xu, H. (2023). Pectin-interactions and the digestive stability of anthocyanins in thermal and non-thermal processed strawberry pulp. *Food Chemistry, 424*, Article 136456. https://doi.org/10.1016/j.foodchem.2023.136456

Xing, Y., Yuan, Q., Gui, X., Jian, L., Wang, K., Ma, Q., Wang, J., & Xu, H. (2024). Mechanistic understanding of the improvement of the digestive retention of anthocyanins by modified pectin after high-pressure homogenization of strawberry pulp. *Innovative Food Science & Emerging Technologies, 92*, Article 103559. https://doi.org/10.1016/j.ifset.2023.103559

Xue, H., Sang, Y., Gao, Y., Zeng, Y., Liao, J., & Tan, J. (2022). Research Progress on absorption, metabolism, and biological activities of anthocyanins in berries: A review. *Antioxidants, 12*, 3. https://doi.org/10.3390/antiox12010003

Yang, W., Guo, Y., Liu, M., Chen, X., Xiao, X., Wang, S., Gong, P., Ma, Y., & Chen, F. (2022). Structure and function of blueberry anthocyanins: A review of recent advances. *Journal of Functional Foods, 88*, Article 104864. https://doi.org/10.1016/j.jff.2021.104864

Yong, H., & Liu, J. (2020). Recent advances in the preparation, physical and functional properties, and applications of anthocyanins-based active and intelligent packaging films. *Food Packaging and Shelf Life, 26*, Article 100550. https://doi.org/10.1016/j.fpsl.2020.100550

Yue, Y., Wang, B., Xi, W., Liu, X., Tang, S., Tan, X., Li, G., Huang, L., Liu, Y., & Bai, J. (2023). Modification methods, biological activities and applications of pectin: A review. *International Journal of Biological Macromolecules, 253*, Article 127523. https://doi.org/10.1016/j.ijbiomac.2023.127523

Yun, Y., Li, J., Pan, F., Zhou, Y., Feng, X., Tian, J., Cai, S., Yi, J., & Zhou, L. (2023). A novel strategy for producing low-sugar pomegranate jam with better anthocyanin stability: Combination of high-pressure processing and low methoxyl & amidated pectin. *Lwt, 179*, Article 114625. https://doi.org/10.1016/j.lwt.2023.114625

Zang, Z., Tang, S., Li, Z., Chou, S., Shu, C., Chen, Y., Chen, W., Yang, S., Yang, Y., Tian, J., & Li, B. (2022). An updated review on the stability of anthocyanins regarding the interaction with food proteins and polysaccharides. *Comprehensive Reviews in Food Science and Food Safety, 21*, 4378–4401. https://doi.org/10.1111/1541-4337.13026

Zeng, F., Ye, Y., Liu, J., & Fei, P. (2023). Intelligent pH indicator composite film based on pectin/chitosan incorporated with black rice anthocyanins for meat freshness monitoring. *Food Chemistry: X, 17*, Article 100531. https://doi.org/10.1016/j.fochx.2022.100531

Zhang, S., Waterhouse, G. I. N., Xu, F., He, Z., Du, Y., Lian, Y., … Sun-Waterhouse, D. (2023). Recent advances in utilization of pectins in biomedical applications: A review focusing on molecular structure-directing health-promoting properties. *Critical Reviews in Food Science and Nutrition, 63*, 3386–3419. https://doi.org/10.1080/10408398.2021.1988897

Zhang, W., Shen, Y., Li, Z., Xie, X., Gong, E. S., Tian, J., … Liu, R. H. (2021). Effects of high hydrostatic pressure and thermal processing on anthocyanin content, polyphenol oxidase and β-glucosidase activities, color, and antioxidant activities of blueberry (Vaccinium Spp.) puree. *Food Chemistry, 342*, Article 128564. https://doi.org/10.1016/j.foodchem.2020.128564

Zheng, S., Zhang, Y., Chen, Q., Fu, X., Huang, Q., Bin, Z., Dong, H., & Li, C. (2024). Exploring the synergistic benefits of insoluble dietary fiber and bound phenolics: Unveiling the role of bound phenolics in enhancing bioactivities of insoluble dietary fiber. *Trends in Food Science & Technology, 149*, Article 104554. https://doi.org/10.1016/j.tifs.2024.104554

Zhou, X., Wu, Y., Wang, Y., Zhou, X., Chen, X., & Xi, J. (2022). An efficient approach for the extraction of anthocyanins from Lycium ruthenicum using semi-continuous liquid phase pulsed electrical discharge system. *Innovative Food Science & Emerging Technologies, 80*, Article 103099. https://doi.org/10.1016/j.ifset.2022.103099

Zhu, C.-W., Lü, H., Du, L.-L., Li, J., Chen, H., Zhao, H.-F., Wu, W.-L., Chen, J., & Li, W.-L. (2023). Five blueberry anthocyanins and their antioxidant, hypoglycemic, and hypolipidemic effects in vitro. *Frontiers in Nutrition, 10*. https://doi.org/10.3389/fnut.2023.1172982