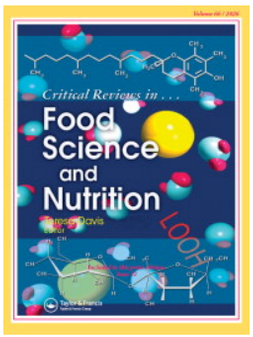

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REVIEW ARTICLE

Stabilization strategies for anthocyanins: recent advances

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ABSTRACT

Anthocyanins (ACNs), one of the most common natural pigments, have been extensively used in various fields, including food, pharmaceuticals, and cosmetics. Depending on the groups attached to the flavylium cation in ACNs, they give different colors to plants. Despite their good colorant and health-promoting properties, the use of ACNs is limited due to their labile structure under various conditions, such as pH, heat, light, and enzymes. Numerous studies have been reported on increasing the stability of ACNs through structural modification such as acylation, glycosylation, pyranization, copigmentation with phenolics and metal ions, complexes with other biomolecules, and encapsulation. This review aims to summarize the fundamental knowledge on methods for enhancing the stability of ACNs, drawing on the most recent research. Lastly, challenges and future work are also discussed.

KEYWORDS

Anthocyanins; copigmentation; encapsulation; extraction; stability

Introduction

Color is one of the vital sensory properties of a food product, playing a crucial role in determining its acceptability. This parameter is accepted as an indicator of the organoleptic properties of foods and, potentially, their safety, depending on the relevant legal regulations and the permissible limits of the colorant (Juhee et al. 2024). The color of food stimulates different perceptions before consumption, such as quality (Dominique et al. 2016), taste (Carlos et al. 2001), aroma (DuBose et al., 1980), and the willingness to consume (Kahn and Brian 2004). The relationship between color, taste, and aroma is indirect; color serves as a cognitive cue that shapes consumers' expectations before they taste. Colorants have been widely used in the food industry to preserve the color characteristics of products and enhance their appeal (Li et al. 2024). Food colorants can be categorized as natural (plant or animal origin), synthetic (like Allura red, tartrazine, and indigo carmine), and nature identical (e.g., synthetic carotenoids, similar natural ones but synthesized in a laboratory) (Netravati et al. 2022). Synthetic colorants are generally preferred due to their high stability under various conditions, including pH, temperature, light, and oxygen. Although they provide substantial technological advantages, their consumption is associated with different health problems, including neurological adverse effects, allergic reactions, and even carcinogenesis (Perez et al. 2022).

In parallel with the changes in consumption concepts, dietary preferences have shifted from merely satisfying hunger to embracing a nutritious diet (Liang et al. 2025). This shift paved the way for natural colorants, which are more nutritious, healthier, and safer. Natural food colorants are categorized into six groups: flavonoids, carotenoids, chlorophylls, betalains, heme groups, and miscellaneous colorants. Among them, polyphenols, anthocyanins (ACNs), carotenoids, betacyanin, betaine, and curcuminoids are the most studied and applied to food products (Ferreyra-Suarez et al. 2024). Anthocyanins are classified as a subgroup of flavonoids, a major class of polyphenolic compounds (Vidana Gamage et al. 2021). ACNs, vacuolar molecules, are secondary plant metabolites that give plants various colors, e.g., red, purple, and blue (Gamage and Choo 2023a, 2023b, 2023c). Their versatility in color expression is explained by the multistate system of ACNs, which includes flavylium cation (red), neutral quinonoid base (purple), anionic quinonoid base (blue), *cis*-chalcone (yellow), and *trans*-chalcone (colorless) (Wang et al. 2025). ACNs are conjugated acyl-glycosylated or glycosylated forms of anthocyanidins (ACDs) called aglycones (Gonçalves et al. 2021). Six aglycones are the most mentioned: cyanidin, delphinidin, malvidin, pelargonidin, peonidin, and petunidin. On the other hand, more than 700 ACNs have been reported, depending on the hydroxyl and methoxyl moieties (Li et al. 2022).

Although ACNs are found in high amounts in many plants, their extraction and industrial applications are limited due to their poor stability under process conditions, such as pH changes, high temperatures, enzymes, light, and oxygen (Albuquerque et al. 2020). Therefore, stability enhancement strategies for ACNs during processing and storage have gained increasing interest (Figure 1). Recently, various methods, including co-pigmentation (Co-P),

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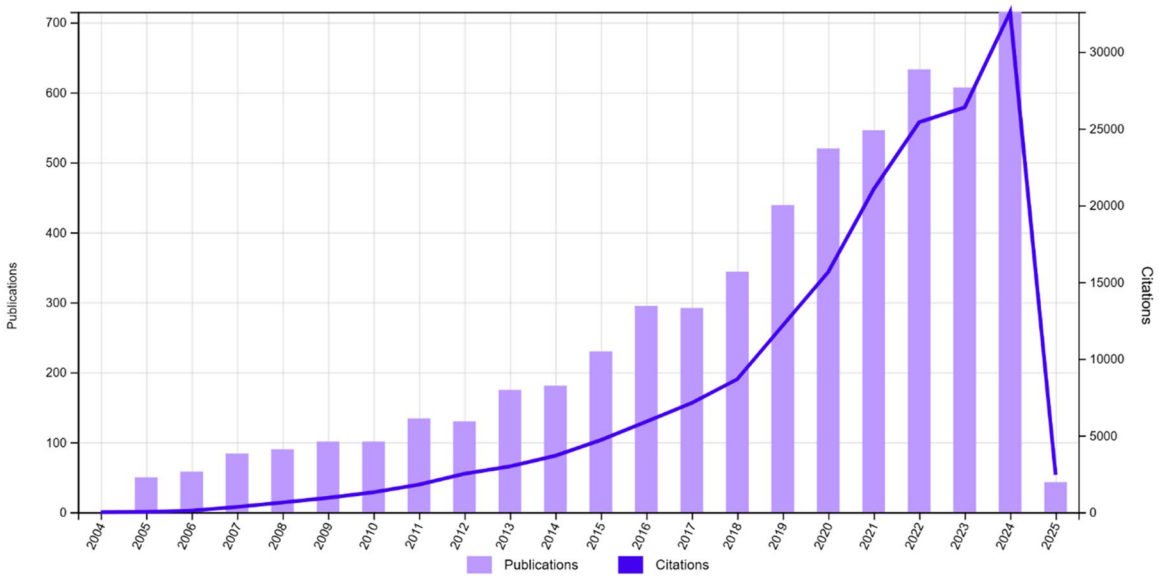

Figure 1. Published studies conducted about stability improvement of anthocyanins between 2005–2025 (Web of Science).

encapsulation, and chemical and biosynthetic modification, have been employed to enhance the stability of ACNs (Liu et al. 2025).

Co-P is a phenomenon that refers to the interaction between the flavylium cation of ACNs and copigments, such as flavanols, flavonols, and phenolic acids. A copigment (electron-rich) forms stable complexes with flavylium cation (electron-deficient); thus, ACNs are protected against nucleophilic attacks (Singh et al. 2025). Recently, biomacromolecules such as proteins and polysaccharides have also been used to enhance ACN stability (Cheng et al. 2024). Along with these biomacromolecules, some metal ions (Bahreini et al. 2024), cyclodextrins (CDs), and gums were also studied for the same purpose (Su et al. 2024). Furthermore, modifying the structure of ACNs with various methods, including glycosylation, acylation, and pyranization, is a promising approach for enhancing their stability (Xue et al. 2024). Encapsulation is another technique used for protecting ACNs, which involves entrapping functional compounds within wall materials (Jang and Koh 2024). Therefore, this study systematically reviews the characteristics of ACNs, factors affecting their stability, and the most recent studies aimed at enhancing the stability of ACNs. Moreover, this study examines current issues and illuminates prospects through both academic and industrial perspectives in this field.

Anthocyanins; an overview

Structure, types, sources, and applications

ACNs are water-soluble vacuolar polyphenolic pigments of the flavonoid group that give red-orange to blue-violet colors to leaves, flowers, and fruits of plants (Wallace and Giusti 2015). Different sources of ACNs are shown in Table 1. Chemically, ACNs are heterosides of an aglycone unit (ACDs) attached to glycosides. They occur in nature as glycosylated polyhydroxy and/or polymethoxy derivatives derived from the flavylium ion or 2-phenyl benzopyryllium.

ACNs consist of two aromatic rings connected by three carbons in an oxygenated heterocycle (Prior and Wu 2006). ACDs are found in the form of one or more sugars that can be acylated with different organic acids. The presence of sugar or hydroxyl groups in the rings is directly related to the solubility of the compound in solvents such as water, ethyl alcohol, or methyl alcohol (Escribano-Bailón et al. 2004). Approximately 30 different ACDs that can be glycosylated have been identified in nature, and they are distinguished from one another based on the degree and pattern of hydroxylation and methoxylation on their rings. With the number increasing day by day, the structures of > 700 ACNs in nature have been fully elucidated, and the structures of > 200 have been partially determined (Santos-Buelga and Gonzlez-Paramás 2019). ACNs differ in factors such as the number, location, and position of the attached sugars, the number of hydroxyl groups, and the nature of the aromatic and aliphatic acids attached to the sugars (Kong et al. 2003). Although ACDs are numerous, only six of them are the most common in nature, accounting for 90% of the total ACNs: cyanidin, pelargonidin, delphinidin, malvidin, peonidin, and petunidin (Castañeda-Ovando et al. 2009), as shown in Figure 2.

The central part of ACNs is aglycon (ACDs), the flavylium cation, which contains conjugated double bonds responsible for the ACNs to appear red. The number of hydroxyl and methoxyl groups in the B-ring differs between these aglycones. Their colors turn blue if the B ring contains too many hydroxyl groups and red if it contains too many methoxyl groups (Akther et al. 2020; He and Giusti 2010). ACNs are a popular natural colorant used in various food groups, including beverages, dairy products, bakery products, and confectionery, with colors varying depending on the pH (Cortez et al. 2017). ACNs are presented with the code E163. Cyanidin: E163a, delphinidin: E163b, malvidin: E163c, pelargonidin: E163d, peonidin: E163e, and petunidin: E163f (Khoo et al. 2017). In addition to providing colors ranging from pink to red, violet, and dark blue, the essential function of ACNs is that they also help pollination and seed dispersal by attracting other animals. They also serve as UV light

Table 1. Some of the anthocyanin-rich plants and major anthocyanins.

Source	Major anthocyanin	Amount	Standardized amounts (g/kg)	Reference
Mulberry	Cyanidin 3 glucoside	1.23-1.97 mg/g fw	1.23-1.97 fw	Zhang et al. (2025)
Black raspberry pomace	Cyanidin-3-rutinoside	6.57-7.75 mg/g dw	6.57-7.75 dw	Krgović et al. (2025)
Purple passion fruit peel	Total anthocyanins (cyanidin)	0.535 mg/g fw 0.156 mg/g dw	0.535 fw 0.156 dw	Gamarra-Castillo et al. (2025)
Chokeberry Fruit	Delphinidin chloride	264.37–494.35 mg/kg fw	0.264-0.494 fw	Gerçek et al. (2025)
Black goji berry	Petunidin-3-O-rutinoside(trans-p-coumaroyl)-5-O-glucoside	80.96 % dw	- dw	Gamage and Choo (2023a, 2023b, 2023c)
Haskap berries	Cyanidin	9.9 mg/g dw	9.90 dw	Martinez et al. (2021)
Kiwi berry	Cyanidin 3-O-sambubioside	8.942 mg/100 g dw	0.089 dw	Qiao et al. (2025)
Maqui berry	Delphinidin 3-O-glucoside-5-O-glucoside	6.40 – 8.69 g/kg dw	6.4–8.69 dw	Brauch et al. (2017)
Korean black raspberries	Cyanidin-3-O-glucoside	16.1–35 mg/g dw	16.1–35 dw	Kim et al. (2024)
Berberis crataegina DC.	Cyanidin-3-O-glucoside	85.48 mg/100 g fw	0.8548 fw	Demirci et al. (2022)
Blueberry	Malvidin-3-glucoside	38.7–122.8 mg/100 g fw	0.387-1.228 fw	Li et al. (2016)
Sweet cherry	Cyanidin-3-O-rutinoside	60 mg/100 g fw	0.6 fw	Grigoras et al. (2012)
Cornelian cherry	Pelargonidin 3-galactopyranoside	0–104.82 mg/100 g fw	0–1.048 fw	Kucharska et al. (2015)
Sour cherry varieties	Cyanidin-3-O-rutinoside	4–14 mg/100 g fw	0.04-0.140 fw	Homoki et al. (2016)
Haganta plums	Cyanidin 3-rutinoside	4.05 g/kg fw	4.05 fw	Usenik et al. (2013)
Jojo plums	Cyanidin 3-rutinoside	2.52 g/kg fw	2.52 fw	
Čačanska lepotica	Cyanidin 3-rutinoside	44.82–87.39 mg/100 g fw	0.4482-0.8739 fw	Trendafilova et al. (2022)
Black carrot	Cyanidin-3-xylosyl-feruloyl-glucosyl-galactoside	10.99 mg/g dw	10.99 dw	Carrillo et al. (2020)
Purple corn	Cyanidin 3-O-(6″-malonyl-glucoside)	398.2 mg/kg fw	0.3982 fw	Li et al. (2017)
Blue corn	Cyanidin 3-O-(6″-malonyl-glucoside)	40.1 mg/kg fw	0.0401 fw	Li et al. (2017)
Red cabbage	Cyanidin-3-diglucoside-5-glucoside	0.58 mg cy/g dw	0.580 dw	Wiczkowski et al. (2013)
Eggplant peel	Delphinidin 3-O-rutinoside	378 mg/kg fw	0.378 fw	Sadilova et al. (2006)
Black rice species	Cyanidin 3-glucoside	137.41, 19.39, 140.83 mg/100 g dm	1.3741 0.1939, 1.4083 dm	Sompong et al. (2011)
Purple potato (Itoman)	Cyanidin-3-p-hydroxybenzoyl sophoroside-5-glcoside	973.21 mg/kg fw	0.97321 fw	Kurata et al. (2024)
Black beans	Petunidin-3-O-glucoside	18.32 mg/g dw	18.322 dw	Mojica et al. (2017)
Black soybeans	Cyanidin 3-O-glucoside	1968.54 mg/100 g dw	19.6854 dw	Choi et al. (2020)

Abbreviations: Dw: dry weight, dm: dry matter, fw: fresh weight.

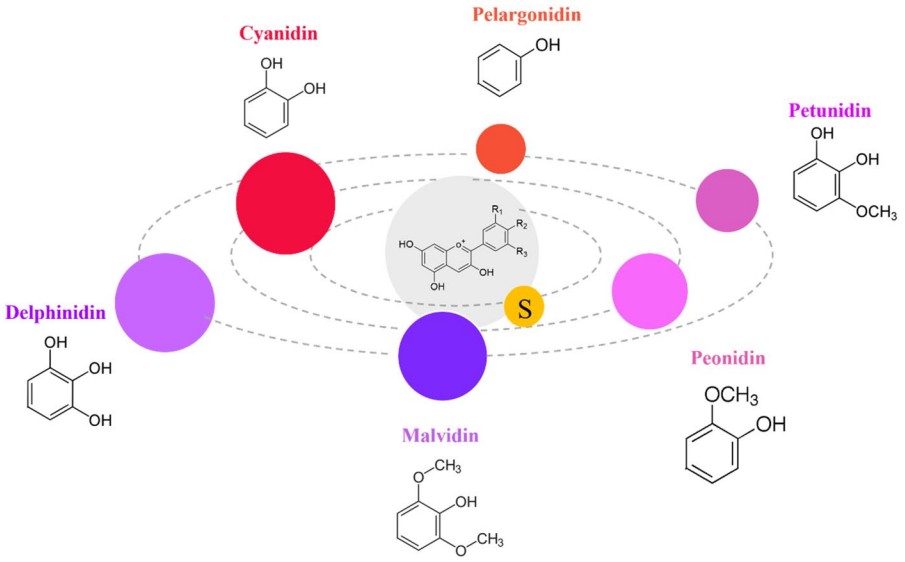

Figure 2. Anthocyanin universe.

protectors for plants, antioxidants, antimicrobials, and protectors against certain insects (Kong et al. 2003). ACNs positively affect human health in terms of antioxidant activity (*AxAc*), anti-inflammatory effect, diabetes prevention, and protection against cardiovascular diseases (Belwal et al. 2020).

Extraction

Since ACNs are susceptible to numerous external factors and can be easily degraded, the extraction methods employed are crucial. For example, ACN concentration decreases at high temperatures and pH (Cacace and Mazza 2003). ACN extraction methods are grouped under two main headings in the literature. The former are the methods used for identifying and characterizing ACNs, and the latter are the methods that can be adapted for use in the food industry. The most efficient extraction solutions for ACNs are organic solvents such as water, ethanol, methanol, and acetonitrile, acidified with formic acid, phosphoric acid, or citric acid (Ongkowijoyo et al. 2018). Pretreatments applied before extraction help release ACNs from cell organelles and

Table 2. Extraction techniques and solvents used for anthocyanins (ACNs).

Source	Extraction method	Extraction parameters	Solvent	Outcomes	References
Blackcurrant	Pulsed Electric Field (PEF)	Electric field = 1318 V/cm pulses = 315		Total ACN (T-ACN) increased by 6%, and antioxidant activity (*AxAc*) increased by 45%	Gagneten et al. (2019)
Blue pea flower	Microwave Assisted Extraction (MAE)	30 min, 50 °C, Power 800 W, sample to solvent 1:15	Ethanol	T-ACN =9.61 mg CGE/g was obtained	Gamage and Choo (2023a, 2023b, 2023c)
Blueberry powder	MAE	700–1100 W at the 1st stage, 100–500 W at the 2nd stage transition temperatures = 30–46 °C		The highest ACN acquisition (84.82%), the lowest ACN degradation (8.13%) under microwave power of 800 W	Liu et al. (2019a)
Butterfly pea flower	Ultrasonication	37 min extraction time, and 61% ethanol, sample solvent = 1:40	Ethanol	Pigment extraction significantly increased	Sai-Ut et al. (2024)
Date Palm Fruits	PEF	Frequency = 10 Hz, time = 100 µs, pulses number = 30, electric field strength = 1, 2, and 3 kV/cm	Ethanol	ACN yield increased from 0.75 to 1.23 (mg/L), *AxAc* from 40% to 58%, and carotenoid content from 2.85 to 4.93 (µg/mL)	Siddeeg et al. (2019)
Dried blackcurrant (*Ribes nigrum* L.) pomace	Ultrasonication	5 − 30 min at 50% amplitude	Ethanol (50%)	~27 % higher T-ACN. Higher DPPH inhibition and reducing power.	Nawawi et al. (2025)
Eggplant (*Solanum melongena* L.) peel	Enzyme-assisted extraction	Temperature (37.32 °C), enzyme concentration = 5%, extraction time = 1 h, Water, ethanol and citric (50:48:2 (v/v))	Ethanol (%50)	Enzyme addition increased T-ACN (578.66 mg C3G/L) up to a certain level; then, no increase observed	Amulya and Ul Islam (2023)
Garcinia indica Choisy Fruit Waste	Ultrasonication	40 °C for 2 min (40 kHz) at 15 s pulse intervals	Ethanol (50%)	Increased ACN yield by 15-fold	Shastry and Sriramareddy (2023)
Malus 'Royalty' Fruits	Ultrasonication	Temperature = 20 °C, time = 40 min, ultrasonic power = 300 W, Solid-liquid ratio = 1:6 (g/mL)	Ethanol (70 %)	Changing the solid-liquid ratio from 1:2 to 1:5 increased ACN yield.	Liu et al. (2022)
Pear fruit peel	Ultrasonication	162 W at 71 °C for 11 min, sample to solvent ratio = 1:30 g/ml	Ethanol (57%)	Cyanidin-3-galactoside yield was significantly higher	Belwal et al. (2019)
Purple passion fruit	MAE	Power = 300 W	Water	T-ACN was 71.80 mg C3G/L, and recovery rate was 65.40 %	Gamarra-Castillo et al. (2025)
Purple sweet potato	MAE	Power = 320 W, time = 500 s, Solid-to-liquid ratio = 1:3 (g/mL)	Ethanol (30%)	The residue obtained was in its original appearance	Liu et al. (2019b)
Rhodomyrtus tomentosa (Ait.) Hassk	MAE	Power 200 W, material/solvent ratio of 1:3	Ethanol (50%)	MAE provides efficient and quick ACN extraction.	Pham et al. (2022)
Rose flower petal	Ultrasonication	10 min sonication time (40 kHz, 400 W) at 50 °C	DES and ethanol	Significantly high extraction rate	Li et al. (2023)
Mangosteen pericarp	HHP	500 MPa at 20 ± 1 °C for 2–10 min	Ethanol (50 %)	Cyanidin-3-O-sophoroside and cyanidin-3-O-glucoside were the highest in HPP-10 min	Ijod et al. (2025)
Açai	HHP	600 MPa at 65 °C for 5, 10, 15, 20 and 25 min	Water	The HHP increased extraction of anthocyanins in açaí pulp.	de Jesus et al. (2020)
Tamarillo	Supercritical fluid extraction (SCFE) and Ultrasound	30 to 60 min, 40–60 °C, and 150 to 180 bars of pressure	Ethanol and distilled water (1:1)	Ultrasound had the higher ACN yield than SCFE.	Rohilla et al. (2022)
Black bean	Supercritical CO_2 Extraction (SCFE)	300 bar, 60 °C for 60 min	Ethanol/distilled water (50/50, v/v)	Supercritical fluid extraction showed the highest ACN amount. ACNs extracted by SFE had an outstanding bioactivity.	Hsieh-Lo et al. (2020)

Abbreviations: T-ACN: Total ACN, CGE: Cyanidin glucoside equivalent, C3G: Cyanidin 3-O-glicoside.

increase accessibility. One of these methods is reducing particle size, which increases surface area and facilitates the easy passage of solid particles into the liquid medium. Drying and lyophilization can also be used (Lorenzo et al. 2018). Maceration and Soxhlet extraction are the most common traditional extraction methods of ACNs. Some disadvantages of these methods, such as long extraction times, low purity, low selectivity, high solvent consumption, and acceleration of thermal degradation, compel researchers to seek new methods (Selvamuthukumaran and Shi 2017). Ultrasound-assisted extraction (UAE) pulsed electric field (PEF), microwave-assisted extraction (MAE), high hydrostatic pressure, and supercritical fluid extraction (SFE) are among the new techniques being studied (Mane et al. 2015). Some of the different extraction methods and solvents used for ACNs were summarized in Table 2.

The mechanical effect of acoustic cavitation by ultrasound (US) triggers the plant's hydration, causing pores in the cell wall to expand and facilitating cell wall destruction; thus, it enhances mass transfer and increases the extraction efficiency (Galván D'Alessandro et al. 2014). Ultrasound-assisted extraction has been reported to yield high extraction efficiencies of ACN from different fruits and vegetables, such as butterfly pea flower (Sai-Ut et al. 2024), dried blackcurrant (*Ribes nigrum* L.) pomace (Nawawi et al. 2025), *Garcinia indica Choisy* fruit waste (Shastry and Sriramareddy 2023), Malus 'Royalty' fruits (Liu et al. 2022), pear fruit peel (Belwal et al. 2019), and rose flower petal (Li et al. 2023). In PEF extraction, the sample is exposed to an electric field between 1 and 10 kV/cm with a pulse. This electrical charge causes electroporation of cell membranes and thus making them more permeable. It yields 2.5 times more ACN than conventional extraction (Corrales et al. 2008). Several studies have reported that PEF applications increased the ACN yield and *AxAc*, including those of blackcurrant (Gagneten et al. 2019) and date palm fruits (Siddeeg et al. 2019). MAE has been used for the extraction of ACN from blue pea flowers (Gamage and Choo 2023a, 2023b, 2023c), blueberry powder (Liu et al. 2019a), purple passion fruit (Gamarra-Castillo et al. 2025), and *Rhodomyrtus tomentosa* (Ait.) Hassk. (Pham et al. 2022). They reported a higher ACN yield. Notably, Liu et al. (2019a) emphasized that MAE not only enhanced extraction yield but also minimized anthocyanin degradation. Amulya and Ul Islam (2023) reported that enzyme-assisted extraction increased the T-ACN to a certain level. In addition, HHP is another promising technique for achieving higher ACN yields from various sources, such as mangosteen pericarp (Ijod et al. 2025) and açaí (de Jesus et al. 2020). de Jesus et al. (2020) indicated no significant difference between 600 MPa HHP treatment at 25 °C and 85 °C. Rohilla et al. (2022) compared SFE with ultrasound regarding ACN extraction from tamarilla. They found out that the US had a higher yield than SFE. Hsieh-Lo et al. (2020) extracted ACNs from black beans using SFE. They reported that an increase in ACN content and bioactivity. They also mentioned that the ACN content was not affected by the pressure differences.

The combination of water and ethanol as an extraction solvent yields the best extraction results, depending on the samples' ACN composition. Since ACNs are more stable at low pH values, acidifying the extraction solvents results in a higher ACN content. When selecting the acid type, the final application of ACNs should be considered. Formic acid, for instance, is highly suitable for chromatographic analysis since it does not interfere with the absorbance at 520 nm. All the studies using novel techniques we reviewed reported an increase in ACN content. The US is the most preferred method due to its efficacy, ease of handling, speed, and low cost. In addition, applying US to the industry on any scale is feasible. The studies using PEF reported an increase in AxAc.

Further studies are focusing on the combined usage of novel technologies. Statistical modeling techniques are widely used in ACN extraction processes to increase efficiency, reduce costs, and determine optimal conditions. One of the most preferred methods is the Response Surface Methodology (RSM), which evaluates the effects of multiple process parameters (e.g., temperature, time, solvent ratio) on the response variable and enables the determination of optimal combinations. The most frequently used experimental designs in RSM include the Box–Behnken Design and the Central Composite Design.

Factors affecting the stability

ACNs, which have an important place among natural food colorants, are restricted in their industrial use because their stability is easily affected by factors such as temperature, light, pH, enzymes, oxygen, humidity, ascorbic acid, sugar, sulfite salts, and or sulfur dioxide (Vinha et al. 2018), as depicted in Figure 3.

Temperature is one of the most critical factors affecting ACN stability. In general, at > 60 °C, ACNs turn into a chamfered structure, their stability decreases, and they become colorless (Liu et al. 2018) (Figure 4a). Although the pH of the solution is low, temperatures above 40 °C cause the color of ACNs to change from red to orange (West and Mauer 2013). In extracts rich in phenolics, moderate heating inhibits the activity of polyphenol oxidase, preventing enzymatic degradation of ACNs (Patras et al. 2010). The first-order kinetic model expresses the change in ACN amount with temperature. A logarithmic decrease in ACNs is observed with an arithmetic temperature increase (Kırca et al. 2007).

ACNs exist in different chemical forms, depending on the pH of the medium (Figure 4b). The flavylium cation is dominant at pH 1, causing the color to appear purple-red. In the pH range of 2–4, quinoidal red-blue compounds are formed due to rapid proton loss. Colorless carbinol pseudo base and chalcone derivatives are formed between pH 5 and 6. At pH ≥ 7, ACNs degrade, depending on the substituent groups (Fleschhut et al. 2006). As the pH increases, the amount of anhydrous base also increases, and under more acidic conditions, the dominant species becomes the red flavylium ion (Cooper-Driver 2001). The stability of ACDs is affected by the presence of hydroxyl and methoxyl groups in the B ring, which reduces the stability of the aglycone in neutral environments. Therefore, the most stable aglycone is

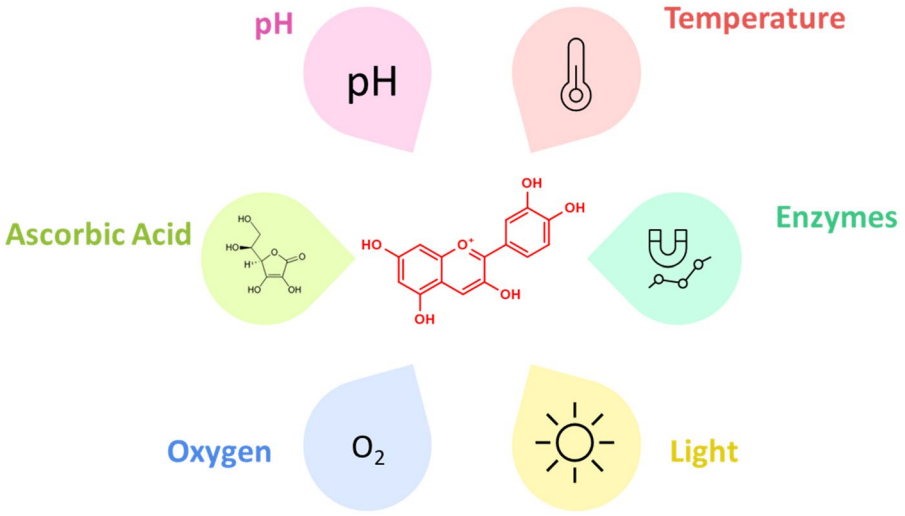

Figure 3. Major factors affecting the stability of anthocyanins.

pelargonidin (Fleschhut et al. 2006). Unlike aglycones, monoglycosides and mostly diglycosides are more stable at neutral pH values because sugar molecules prevent the conversion of unstable molecules into phenolic acids and aldehyde compounds (Fleschhut et al. 2006). Light causes the formation of 2,4,6-trihydroxybenzaldehyde from the benzopyrylium core and the C-2-linked phenyl ring of ACNs, along with benzoic acid, leading to the degradation of ACNs and fading of the color (Carlsen and Stapelfeldt 1997). A linear relationship exists between light exposure and ACN degradation (Amr and Al-Tamimi 2007). Polyphenol oxidase indirectly causes ACN degradation by oxidizing phenolics to quinones. This reaction turns ACNs into brown compounds (Terefe et al. 2010). Oxidation of ascorbic acid causes the formation of free radicals that can break down the pyrylium ring of ACNs. In addition, ascorbic acid condenses with ACNs and triggers the loss of the flavylium cation. This ascorbic acid activity can occur in aerobic and anaerobic environments (Howard et al. 2014). Temperatures above 40°–60° causes changes in the structure of ACNs, thereby decreasing stability. In some cases, mid-heating prevents enzymatic degradation of ACNs by inactivating polyphenol oxidase. At the first step of thermal degradation, sugar molecules of ACN are removed, and ACNs turn into ACD. At the final stage, ACDs turn into different phenolic acids. The stability of ACNs is easily affected by changes in pH. ACNs are red at low pH values due to the dominance of flavylium cation; they start to degrade above neutral pH. The structure of ACNs is an important factor in their stability. While sugar moieties increase stability, hydroxyl and methoxyl groups in the B ring do the opposite.

Anthocyanin stabilization strategies

Co-pigmentation

Co-pigmentation, the interaction between ACNs and copigment, is primarily governed by various mechanisms, including hydrophobic interactions, π–π stacking, hydrogen bonding, and *Van der Waals* forces. This interaction leads to a hyperchromic effect and bathochromic shift, which collectively enhance the color stability and intensity (Singh et al. 2025). Through copigmentation, electron exchange occurs between the electron-deficient flavylium cation and the electron-rich copigment, resulting in stable complexes that protect ACNs against nucleophilic attack by water at the C2 position (Trouillas et al. 2016). Copigments, mostly colorless or yellowish-colored molecules, possess rich *p*-orbital electrons and a planar structure and are naturally found in plant cells (Teixeira et al. 2013).

The copigmentation can occur in different ways, including self-assembly, inter-, and intra-molecular Co-P, and metal complexes (Figure 5a). ACNs act as copigments and improve the stability in the self-assembly Co-P. Herein, an interaction is observed instead of the covalent bonds (Chen et al. 2023). While in the intramolecular Co-P, the copigments and ACNs interact through covalent bonds. In the intermolecular Co-P, ACN, and copigment form a stable complex through non-covalent interactions (π–π stacking), hydrogen bonds (*H*-bonds), and hydrophobic forces (Yücetepe et al. 2024). Table 3 summarizes some of the Co-P studies.

The most common copigments are phenolic compounds because they are electron-rich molecules, unlike the flavylium cation. Also, they have the same planar structure as ACNs. Some of the most studied phenolic copigments are rutin, chlorogenic acid, caffeic acid, and quercetin. The increasing concentration of the copigment had a positive effect on the stabilization efficiency. Wang et al. (2024) reported that EGCG was the most effective copigment, and Xu et al. (2015) reported that quercetagetin had higher stability than EGCG at the same concentration. Hernández-Herrero et al. (2015), Fan et al. (2019), and Demirci (2021) reported that the addition of rutin increased the thermal stability of ACNs. Singh et al. (2025) and Bimpilas et al. (2016) found that rosmarinic acid was the least effective copigment among other copigments they studied.

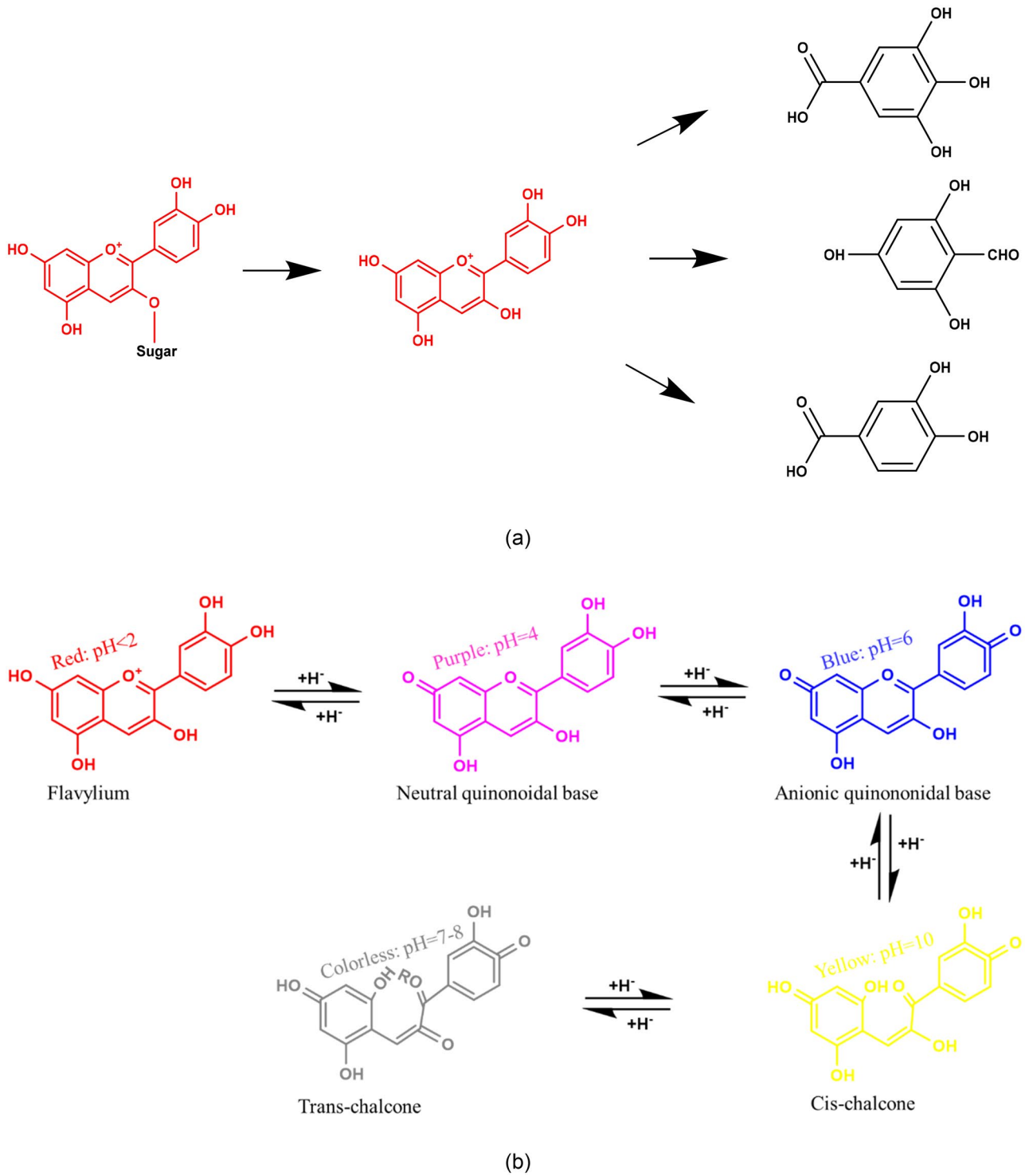

Figure 4. (a) Thermal degradation of anthocyanins; (b) Color shift of anthocyanin molecule under different pH.

Self-association (Se-As)

Se-As is a special condition in which the ACN molecules undergo hydrophobic interaction and vertical positioning in a left-sided spiral manner (Figure 5a). This special bonding protects ACNs from nucleophilic attacks, improving their stability (Xue et al. 2024). Se-As was observed to be stronger with the increasing number of hydroxyl or methoxy groups on the B-ring. Cyanidin-derived ACNs (two hydroxyls on B-ring) had higher dimerization constants than those of pelargonidin-derived ACNs (single hydroxyl on B-ring) (Chatham et al. 2020).

In a study by González-Manzano et al. (2008), Se-As was investigated in wine-like products containing different grape ACNs, including malvidin, delphinidin, and peonidin glucosides. They reported that Se-As leads to an increase in C*ab, indicating a more intense color. They also found that the greater the number of methoxyl groups on the B-ring, the greater the magnitude of the Se-As. Leydet et al. (2012) reported that the flavylium cation and the quinoidal base of the six most abundant 3-glucoside ACNs self-associate, increasing the acidity and decreasing the hydration reaction. Han and Xu (2015) investigated the effect of ACN structures

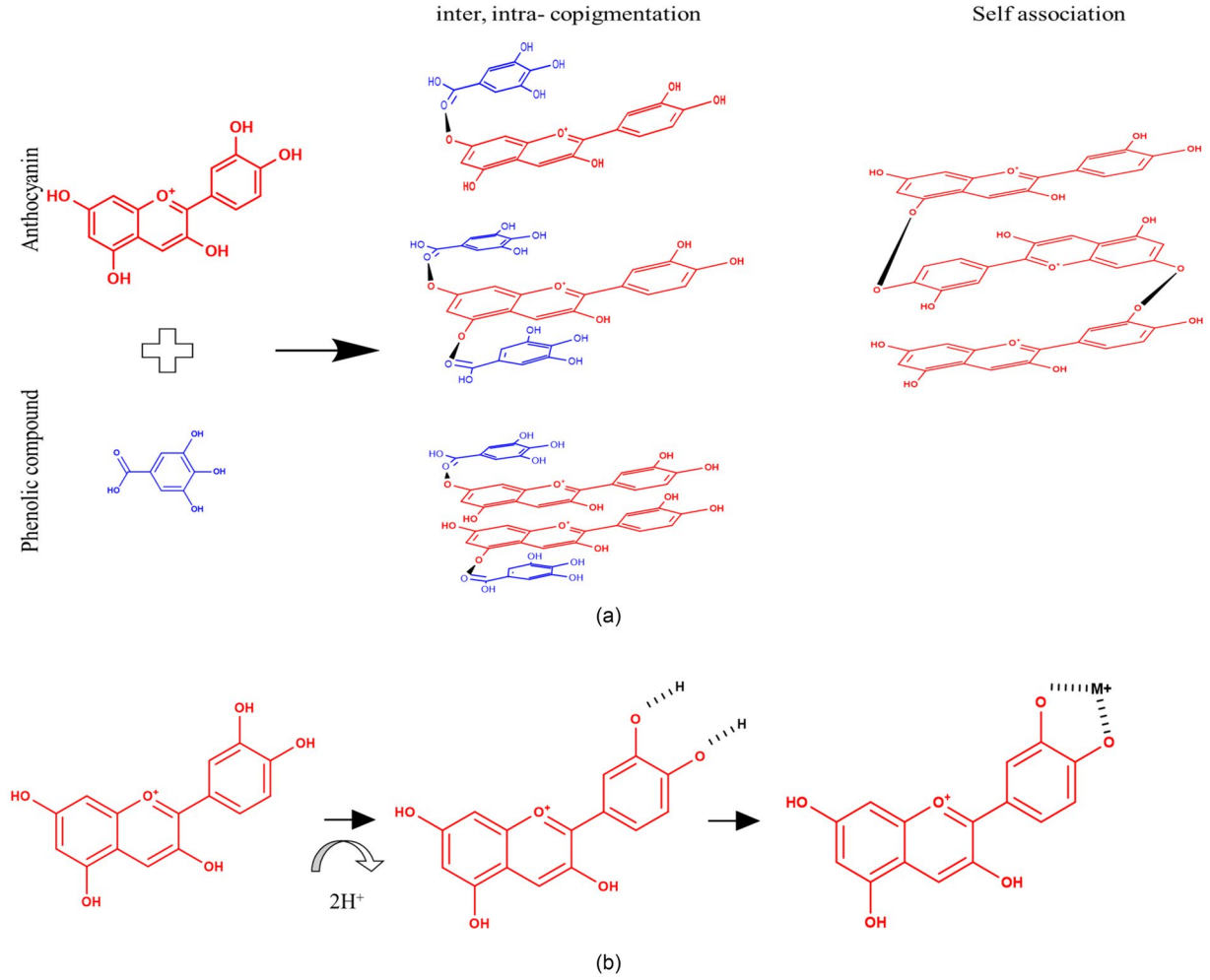

Figure 5. (a) Types of anthocyanin copigmentation and (b) Anthocyanin:metal complex formation.

on Se-As and color in an aqueous alcohol model. The addition of hydroxyl at the C3 position weakened Se-As, and the addition at the C5 position facilitated Se-As. Adding hydroxyl and methoxyl moieties at C3 and C5 simultaneously enhanced the Se-As and the color.

ACNs can form a stable complex on their own by making hydrophobic interactions. This activity is directly related to the hydroxyl or methoxyl groups on the B ring. The Se-As phenomenon is mainly studied in wine-like alcoholic beverages, resulting in an intense color. The studies indicated that the most common 6 ACN-3 glucosides can self-associate.

Intermolecular copigmentation

Intermolecular Co-P is a non-covalent bonding of ACNs with a potent copigment through π-π stacking, *H*-bonds, *van der Waals* forces, and hydrophobic and ion interactions (Figure 5a).

Copigments form π-π complexes and co-chromatic interactions between ACN-related groups, protecting them from water attack and hindering the formation of colorless forms of ANCs (Chen et al. 2023; Trouillas et al. 2016). Co-P is affected by the number of hydroxyl (–OH) and methoxy (–OCH_3) groups. While the higher hydroxyl group facilitates *H*-bond formation, the higher methoxyl group promotes the π-π stacking of aromatic compounds with ACNs (Ijod et al. 2025). Copigments act as H-bond donors or acceptors, increasing the stability of ACNs. Intermolecular Co-P strength mainly depends on the ACN structure, type of copigment, concentration, pH, and temperature (García-Marino et al. 2013). A higher ratio of copigment: ACN results in a higher Co-P effect. Because both of the colored forms (flavylium cation and the quinonoid base) of ACNs are almost planar, they easily interact with planar copigments. Phenolic acids with different types and ligand numbers show different Co-P effects on ACNs. Hydroxycinnamic acids such as chlorogenic, caffeic, and p-coumaric are indicated as efficient copigments with flavonols. In contrast, hydroxybenzoic acids, such as gallic acid, benzoic acid, and vanillic acid have minimal effects (Wang et al. 2024).

Azman et al. (2022) investigated the effect of ferulic, caffeic, chlorogenic, and rosmarinic acid addition on the stability of dried blackcurrant pomace ACNs at pH 3 and 6 during storage. Rosmarinic acid was the most effective phenolic acid in enhancing color at pH 3 and 6 on day 0; however it could not maintain the stability during storage at 20 °C. Regarding half-life at pH 3 and 6, chlorogenic and ferulic acids were the best copigments, while caffeic acid was the weakest. Cyanidin-3-glycoside exhibited the highest stability compared to the other ACNs.

Table 3. Copigmentation (Co-P) of anthocyanins (ACNs) with phenolics and metals.

ACN	Copigment	Ratio (ACN:Copigment)	Results	References
ACNs of blueberry wine	Caffeic acid, syringic acid, and quercetin	1:1 M	Adding co-pigments improved blueberry wine's color properties (decreased L* and a* and an increased b*). Depending on the concentration, all copigments contributed to a higher ACN stability in blueberry wine.	Sun et al. (2022)
ACNs of red cabbage	Organic acids = tannic acid and oxalic acid, phenolic acids = rosmarinic acid and chlorogenic acid, flavonoid = naringin and amino acids = aspartic acid, methionine and proline	1:1, 1:2, 1:5, 1:10 & 1:20, for organic and amino acids. For phenolic acids molar ratio was 1:1, 1:2, 1:5, & 1:10, and for flavonoids molar ratio was 1:0.5, 1:1, 1:1.5, and 1:2 (w/w)	Co-P efficacy order was oxalic acid > chlorogenic and rosmarinic acid at 120 °C and 150 °C.	Singh et al. (2025)
Berberis crataegina DC. anthocyanins	Chlorogenic acid, quercetin and rutin	1:5, 1:10 and 1:20	At the highest temperature of 90 °C, the most effective Co-P agent was chlorogenic acid at 1:5 and 1:10 concentrations, while rutin was the most effective agent at 1:20 concentration.	Demirci (2021)
Blackberry wine residue ACNs (BWRA)	Protocatechuic acid, p-coumaric acid, caffeic acid, ferulic acid, quercetin, baicalein, rutin, and daidzein	1:2.5	Ferulic acid or rutin had the best Co-P activity. The Co-P occurred via non-covalent interactions, e.g., π-π stacking, hydrogen bonding, and *van der Waals* interaction.	Fan et al. (2019)
Blueberry fermented beverage ACN	(−)-epigallocatechin gallate (EGCG), ferulic acid, and gallic acid	1:40	EGCG exhibited a better Co-P than gallic and ferulic acid. The molecular docking model verified that ACNs and copigments interact by hydrogen bonds and π-π stacking.	Wang et al. 2024.
Bog bilberry syrup wine	Tannic acid and gallic acid extracted from Chinese gallnut	1:2.5 and 1:6	The copigments significantly helped to retain the red color. The wines copigmented with phenolic acids had 1.4–1.8 times higher total ACN.	Liu et al. (2019c)
Chinese bayberry ACNs	Ferulic acid, sinapic acid, and syringic acid	1:0, 1:1, 1:5, 1:10, 1:20, and 1:30	At higher ratio of copigments, *L** decreased, and *a** increased. The thermal stability of ACNs was significantly improved.	Zhu et al. (2020)
Grape skin	Quercetagetin, EGCG, Tea polyphenols, Myricitrin & Rutin	1:10, 1:20 and 1:40 for thermal 5:1, 1:1, 1:5 and 1:10 for light	With the quercetagetin, the half-life of ACNs was significantly extended. The quercetagetin was the most effective copigment compared to the others.	Xu et al. (2015)
Kyoho grape skin ACNs or cyanidin-3-O-glucoside	Tannic, ferulic, caffeic, syringic, tartaric, and phosphoric acids	1:10, 1:50, 1:100, and 1:150	The optimum molar ratio for increasing the absorbance of Cyanidin-Tannic acid, Cyanidin-ferulic acid, and Cyanidin-tartaric acid was 1:100, whereas for the other complexes was maximized at a molar ratio of 1:150. Kyoho grape skin ACNs and cyanidin-3-O-glucoside ferulic acid complexes showed high thermal stability.	Lv et al. (2022)
Plum ACNs	Rutin and ascorbic acid	20:15	The color stability was improved by the presence of rutin and decreased by the ascorbic acid.	Hernández-Herrero and Frutos (2015)
Purple sweet potato ACNs	KCl, $CaCl_2$, $MgCl_2$, $AlCl_3$, $ZnCl_2$, $FeSO_4$, $FeCl_3$, or $CuSO_4$	1 ml:0.2 M	K^+ did not show a significant hyperchromic effect. Fe^{3+} exhibited a significant hypochromic effect with a concentration of 0.0001 mol/L	Li et al. (2016)
Red cabbage ACNs	Al^{3+}, Ca^{2+}, Fe^{3+}, and Sn^{2+}	1:1 (v/v)	Adding metal ions accelerated the ACN degradation but delayed total phenolic loss. During spray drying, metal ions, excluding Al^{3+}, caused ACN losses, ranging from 7.3% to 10.6%.	Ratanapoompinyo et al. (2017)
Red wine	Rosmarinic acid and natural extracts rich in hydroxycinnamic acids from *Origanum vulgare* and *Satureja thymbra*	1000 ml:650 mg	The red color intensity was higher when adding either extract than rosmarinic acid. During storage, a decrease in monomeric and copigmented ACNs was observed.	Bimpilas et al. (2016)
Wine ACNs: delphinidin-3-glucoside, malvidin-3-O-glucoside and malvidin-3-O-acetyl glucoside	Epicatechin, epigallocatechin, quercetin, quercetin-3-O-glucoside, caffeic acid and syringic acid	1:1 M	The quercetin-3-O-glucoside and caffeic acid demonstrated superior Co-P effects. Co-P effect on delphinidin-3-glucoside was lower than that of malvidin-3-O-glucoside and malvidin-3-O-acetylglucoside.	Lyu et al. (2025.)

Another study, conducted by Wang et al. (2024), investigated the Co-P between ACNs in fermented blueberry beverage and three different phenolics: ferulic acid, (−)-epigallocatechin gallate (EGCG), and gallic acid. The binary complexes formed between ACNs and copigments through H-bonds and π-π stacking. The higher molar ratio of ACN to copigment resulted in a better color. Due to its strong ability to form hydrogen bonds and π–π stacking interactions, EGCG exhibited a stronger co-pigmentation effect than ferulic and gallic acid.

A study examined the intermolecular Co-P of ACNs with sinapic acid, tartaric acid, and catechin at concentration of 1:5 and 1:10 M for 77 days. Ijod et al. (2025) concluded that ACN: tartaric acid (1:5) showed the highest stability for total monomeric ACN content and half-life (59.5 days). Similarly, Patras et al. (2019) suggested that adding 0.2% (v/v) tartaric acid to 1 L of ACNs reduced their degradation after 20 wks from 25% to 16%. Klisurova et al. (2019) investigated the effect of ten phenolics on the stability of black chokeberry ACNs. They revealed that syringic acid, rosmarinic acid, catechin, and epicatechin were good candidates for Co-P, except for chlorogenic acid. They found the hyperchromic effects of rosmarinic acid, syringic acid, and catechin to be 52.02%, 43.24%, and 39.73%, respectively.

Intermolecular Co-P is formed through non-covalent bonding. Like Se-As, the interactions of ACNs and copigments are affected by the number of -OH and -OCH3 groups. Rosmarinic acid, EGCG, chlorogenic acid, ferulic acid, and tartaric acid are reported to be good copigment.

Intramolecular copigmentation

In the intramolecular Co-P, ACNs and copigments form a more stable complex through covalent bonds (Wang et al. 2024). Intramolecular Co-P and Se-As interactions interconnected and, in some cases, difficult to differentiate (Trouillas et al. 2016). Structural modification of ACNs changes the potential combination with other molecules. Thus, ACN derivatives obtained through acylation or metal-ion complexation are more prone to intramolecular Co-P. For instance, hydroxycinnamic acids have better efficacy if they bond with the acylated pigment. Because the acylation offers sufficient flexibility for the pigment and copigment, both molecules easily contact and form a non-covalent intramolecular interaction (Trouillas et al. 2016).

Metal complexes

The stability of ACNs is enhanced by forming complexes with various metal cations, such as iron, aluminum, and copper. Metal cations contribute to stability by forming an ortho-dihydroxyl order in the ACN B ring (Figure 5b). The Co-P with positively charged alkaline or poor metals ($^{+2}$, $^{+3}$) offers the most stable color (Enaru et al. 2021). The metal ions compete with H^+ to attach to the pyrogallol or catechol moieties on the B-ring, changing the form of ACNs from red flavylium to purple-blue quinoidal base anion. The latter form of ACNs stacks with other flavylium molecules to form a stable structure (Tang and Giusti 2020). This complex is formed with cyanidin, delphinidin, and petunidin ACDs but not with pelargonidin, malvidin, and peonidin (Cortez et al. 2017; Tachibana et al. 2014).

When investigating the effect of aluminum salts (0.057, 0.2288, and 0.4576 M) on cyanidin and delphinidin derivatives isolated from eggplant, raspberry, red cabbage, aronia, black currant, and black carrot plants, it was reported that aluminum-ACN complexes were formed in all plants and ACN species in the pH range of 3–6. Each ACN showed bathochromic and hyperchromic interactions when treated with aluminum cations. Higher aluminum salt did not create a significant difference at low ACN concentrations. In the study where sample ACN amounts were taken as 25, 50, and 100 µM, the optimum salt concentration was reported as 100-500X ACN. As the pH increased, ACN degradation and metalloanthocyanin complexes weakened (Sigurdson and Giusti 2014).

Similarly, Tachibana et al. (2014) investigated the effects of iron, aluminum, and calcium anions ($FeCl_3$, $FeCl_2$, $AlCl_3$, and $CaCl_2$) on the stabilities of cyanidin-3-glucoside, pelargonidin-3-glucoside, and delphinidin-3-glucoside. Fe^{+3} anion significantly increased the thermal stability of cyanidin and delphinidin, not pelargonidin, which lacks a hydroxyl group in the B ring. Only the calcium salt did not significantly affect the thermal stability of cyanidin-metal complexes. The order of increasing thermal stability was Fe^{2+}> Al^{3+}>Fe^{3+}. The addition of pectin, alginate, and carrageenan contributed positively (Tachibana et al. 2014). In another study examining the effect of metal Co-P on the thermal stability of red cabbage ACNs before encapsulation, metal anion (Al^{+3}, Ca^{+2}, Fe^{+3}, and Sn^{+2}) ACN complexes were formed at a 1:1 ratio and encapsulated using a spray dryer to examine thermal degradation parameters. Except for the aluminum cation, all other metals decreased the half-life of ACNs compared to the control. When *k* values were compared, the sample containing Sn^{+2} anion was the highest (Ratanapoompinyo et al. 2017).

In the metal: ACN complexes, metal ions compete with the H for the pyrogallol or catechol moieties on the B-ring, preventing color changes. Aluminum, iron, and calcium are the most studied metal ions. A higher amount of metal ions in the metalloanthocyanin complexes that contain low ACNs did not cause a significant change. Calcium salts did not affect the thermal stability of the compound. The addition of pectin, carrageenan, and alginate contributed to the stability of product.

Complexes with other molecules

Recent studies have suggested that other molecules, such as amino acids, peptides, or polysaccharides, can stabilize ACNs by forming stable complexes (Table 4.). Peptides with a higher tryptophan content exhibit stronger interactions with ACNs through *H*-bonds and electrostatic forces (Zhang et al. 2023). In a study examining the effect of milk α and β-caseins on malvidin-3-O-glucoside ACN, caseins were added to grape skin ACNs at a 1:1 ratio of 0.05, 0.1, and 0.15 mg/mL. Then, these samples were subjected to heating, oxidation, and light. During the heat treatment, the least degradation (46%) was observed in the sample containing 0.1% casein, while this rate was 74.19% in the control group. ACN loss in the control group was 96.18% in the oxidation

Table 4. Complexes of anthocyanins (ACNs) with other molecules.

ACN	Copigment (s)	Ratio (ACN:Copigments)	Results	References
ACNs in pomegranate juice	Aspartic acid, phenylalanine, and Valine	1:5 (w:w)	Aspartic acid copigmentation (Co-P) resulted in a significant increase in color density and hyperchromic effect. Valine was the most effective copigment, providing the highest stabilities for individual ACNs, color density, and hyperchromic effect.	Türkyılmaz et al. (2025)
Blueberry ACNs	Bovine serum albumin (BSA)	The concentrations of copigment were 0.05, 0.10, 0.15, and 0.20 mg/mL	BSA copigmented ACNs had better antioxidant capacity.	Zang et al. (2022)
Blueberry ACNs	Whey protein isolates (WPI) and BSA	Equal proportions	Adding 0.15 mg/mL WPI and BSA significantly prevented color fading and increased the stabilities of the ACNs. WPI performed better than BSA in terms of stabilities and free radical scavenging activity.	Zang et al. (2021)
Blueberry ACNs	β-glucan (BG), konjac glucomannan (KGM), and xanthan gum (XG)	0.5:0.05, 0.4 (v/v)	Three polysaccharides retained the color, stability, and antioxidant capabilities of ACN under thermal treatments (XG > konjac glucomannan > β-glucan). TGA and DSC studies confirmed that the introduction of three polysaccharides, especially XG, could improve the thermostability of ACN	Dong et al. (2023)
Purple carrot ACNs	L-phenylalanine, l-tyrosine, l-tryptophan and a polypeptide (ε-poly-l-lysine)	0.025:0.1:0.011% (ACN:copigments:Ca2+)	Amino acid addition increased the color stability. L-tryptophan was the best amino acid.	Chung et al. (2017)
Black soybean seed coat ACNs	soy protein isolate (SPI)	1:1, v/v	SPI preheated at 121 °C increased ACNs' thermal and oxidation stabilities.	Chen et al. (2019)
Grape skin ACNs	α and β-caseins	1:1 ratio	The least (46%) degradation was observed in the sample containing 0.1 casein, while this rate was observed as 74.19% in the control group. The loss caused by light was measured as 92.21% in the control and 65.13% in the 0.1 mg/mL casein sample	He et al. (2016)
ACN in purple corn	Polysaccharides, organic acids, and colloids	0%, 5%, 10%, 15%, 20%, 25% for saccharides, 0%, 0.02%, 0.04%, 0.06%, 0.08%, 0.1% for organic acids and 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% for colloids	The retention of total ACN was 37.29% for fructose and 52.18 % for glucose. Monosaccharides showed better Co-P activity than disaccharides. The retention rates of ACNs were 71.47% for 0.06% tannic acid and 68.21% for 0.1% tartaric acid.	Pang et al. (2024)
Berberis crataegina DC. ACNs	α and β-cyclodextrin (CD)	1:5, 1:10 and 1:20	When the k values were compared at 1:5 concentration, no statistical difference was observed between the two agents at all temperature values. At 90 °C, β-CD was more effective. At 1:10 and 1:20 concentrations, α-CD was observed to be the more effective agent at all temperature values.	Demirci (2021)
ACNs	Gum Arabic (GA)	0.51:10 mg/mL	With GA addition, the change in a* and b* values were not significant, and the color values remained constant.	Guan and Zhong (2015)

process, but this rate decreased to 78.49% in the 0.1 mg/mL casein sample. Finally, the loss was measured as 92.21% in the control and 65.13% in the 0.1 mg/mL casein sample upon exposure to light. The activities of the samples containing 0.15 mg/mL casein were less than those containing 0.1 (He, Xu, et al. 2016).

Zang et al. (2022) examined the addition of bovine serum albumin to blueberry ACNs. They reported that copigmented samples had higher *AxAc*. Chung et al. (2017) used four different amino acid-based copigment, including l-phenylalanine, l-tyrosine, l-tryptophan, and a polypeptide (ε-poly-l-lysine) to evaluate their effects on purple carrot ACNs. All amino acids enhanced the stability, with tryptophan being the most effective. The addition of soy protein isolate (SPI) to black soybean seed coat ACNs, with a ratio of 1:1, increased thermal and oxidation stability (Chen et al. 2019). In another study, Türkyılmaz et al. (2025) used aspartic acid, phenylalanine, and valine to increase the stability of ACNs in pomegranate juice. Valine was the most effective copigment, providing the highest stabilities for individual ACNs, and aspartic acid increased the color intensity and hyperchromic effect. Guan and Zhong (2015) investigated the effects of gum Arabic (GA) on the stability of ACNs. For Co-P, a 0.51 mg/mL ACN sample was mixed with 10 mg/mL GA at pH 5 and heat-treated at 80 °C and 126 °C for 80 min. In the control group, b^* value increased significantly while a^* value decreased. In the sample with GA, the changes in a^* and b^* values were not significant, and the color values remained

constant. With the addition of GA, the k values at 80 and 126 °C decreased by 61% and 45.3%, respectively.

In a study using citrus, apple, and sugar beet pectin (SBP) as co-pigments, Buchweitz et al. (2013) examined the stability of strawberry ACNs. When potassium sorbate was added as a preservative, the ratios were 500 mg/kg ACN, 1% (w/w) pectin, and 0.2% (w/w) sorbate. During the shelf life, apple pectin and SBP reduced ACN loss, while citrus pectin was ineffective. For the control group, the half-life was 38 days, and 90% pigment loss was observed at the end of 18 wks. This value ranged from 48.2 and 52.9 in the samples with apple pectin added; during this period, it was between 47.2 and 48.5 days in SBP. There was only a 4–5 day improvement in the samples with citrus pectin (Buchweitz et al. 2013). Fernandes et al. (2016) evaluated the effect of pectic polysaccharides on the stability of oenin ACN; it was co-pigmented with low-molecular pectic polysaccharides obtained from citrus fruits at the ratios of 1:0, 1:5, 1:10, 1:20, 1:30, and 1:40. The binding of pectic polysaccharides to the oenin molecule strengthens the color. ACNs obtained from two types of black beans, Idaho and Otomi, were copigmented with β-CD for use as a sports drink. β-CD was added to the samples at a rate of 2%. Samples were prepared with 25 mg pure ACN obtained from Idaho, 65 mg pure ACN obtained from Otomi, and 1.5 g liquid solution obtained from the shell of Otomi. The thermal stability of the samples during light treatment and shelf life was expressed with first-order kinetic model. ACN losses were low in all samples in the dark and were even lower in samples containing β-CD. With β-CD, the half-life increased from 9.8 days to 15.2 days in Otomi samples and from 7.5 days to 9.4 days in Idaho samples. During the shelf life, the half-life of all samples containing β-CD increased. In the Idaho sample, the value increased from 31.8 to 77.8 weeks; in the Otomi sample, it increased from 36.10 wks to 96.42 wks (Aguilera et al. 2016). Dong et al. (2023) used three polysaccharides, including β-glucan, konjac glucomannan, and xanthan gum (XG) as a Co-P agent for blueberry ACNs. All three polysaccharides retained color and stability, and *AxAc*, while the effectiveness order was XG > konjac glucomannan > β-glucan.

In a similar study, Quan et al. (2020) investigated the thermal degradation parameters of purple sweet potato ACNs by enriching them with β-CD. Potato ACNs were copigmented with 500 mg/L and 2500 mg/L β-CD solutions. After 30 min heat treatment at 100 °C, thermal degradation was higher in the sample containing 500 mg/L β-CD than in the control. However, this value decreased in the sample containing 2500 mg/L β-CD. While the total loss was 42.5% in the control, it was 50.2% in the sample containing 500 mg/L β-CD and 34.7% in the sample containing 2500 mg/L β-CD. The k value was 1103 min^{-1} and the $t½$ value was 36.3 min in the control samples. The k value was measured as 1413 in the sample containing β-CD at a low concentration, while it was measured as 0.988 min^{-1} in the sample at a high concentration. It is understood from the K and t ½ values that a more stable product is obtained with increasing concentration (Quan et al. 2020). Pang et al. (2024) used polysaccharides, organic acids, and colloids to increase the stability of ACN in purple corn. Retention of total ACN was 37.29% for fructose and 52.18% for glucose. Monosaccharides showed better Co-P activity than disaccharides. Demirci (2021) added α and β-CD into *Berberis crataegina* DC. ACNs with ratios of 1:5, 1:10, and 1:20 and evaluated the thermal stability at 70, 80, and 90 °C. At a 1:5 ratio, there was no statistically significant difference in the k values at all temperatures. At 90 °C, β-CD was more effective. At concentrations of 1:10 and 1:20, α-CD was observed to be the more effective agent at all temperatures. Howard et al. (2014) performed Co-P of aronia ACNs with β-CD and investigated the stability change. The addition of β-CD during the pasteurization process reduced ACN losses. While the highest concentration (3%) of β-CD did not provide significant protection at low pH values, it reduced losses at higher pH values. After 8 months of storage, the number of ACNs in samples containing 3% β-CD was 49% higher than the control. Samples containing 3% β-CD preserved a large portion of their total ACNs, such as 95%, over a period of 2–8 months.

To increase the thermal stability of ACNs, whey proteins, caseins, polysaccharides, gums, and some amino acids were used. While Guan and Zhong (2015) reported that GA addition did not significantly change the a* and b* values, Dong et al. (2023) reported an increase in thermal stability of ACNs with the addition of XG, konjac glucomannan, and β-glucan, where the XG is the best. According to the study conducted by Chung et al. (2017), L-tryptophan was the best amino acid; on the other hand, Türkyılmaz et al. (2025) indicated that valine was the most effective. The concentration of these molecules in the matrix was lower compared to the Co-P studies. Demirci (2021), Aguilera et al. (2016), and Howard et al. (2014) reported that the addition of β-CD increased the thermal stability of ACNs. Anthocyanins can form non-covalent complexes with sugars, proteins, gums, and cyclodextrins. ACN:protein interactions improve stability through hydrophobic association and hydrogen bonding, while polysaccharide gums enhance the stability by forming protective colloidal matrices. ACN: sugar complexes increase water solubility and color retention. Despite the numerous advantages of these complexes, the ratios, methods, and solvents used in the process should be further investigated for industrial applications and environmental sustainability.

Structural modification of anthocyanins

The modification of the ACN structure contributes to the improvement of ACNs. Some modification methods include acylation, glycosylation, and pyranization.

Acylation

Acylation of ACNs can be explained as an acyl donor attaching to the core structure of ACNs, preventing them from nucleophilic attack (Lin et al. 2022), as shown in Figure 6a. The acylation usually happens at the hydroxyl groups of ACNs; introducing the aromatic and aliphatic acyl groups of fatty acids or aromatic acids into the ACN molecules improves their thermostability (Yang et al. 2019).

Short-chain aliphatic acids (acetic, propionic), dicarboxylic acids (oxalic, malic, succinic), and aromatic acids (ferulic, *p*-coumaric, gallic) have been used as acyl donors (Zhang et al. 2020a). Acylation efficiency is affected by the number

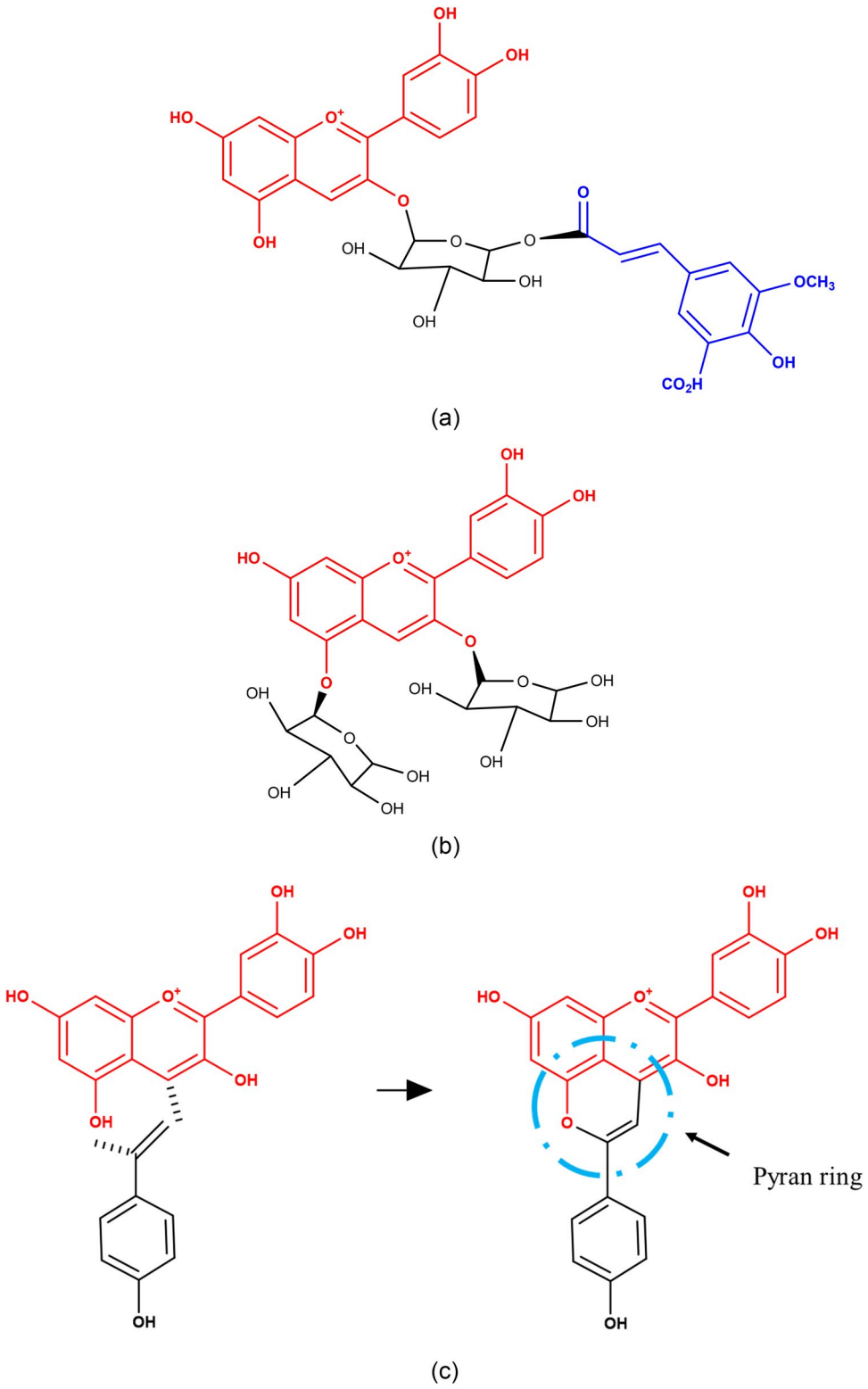

Figure 6. (a) Acylation, (b) Glycosylation, and (c) Pyranization of anthocyanins.

of acyl groups in the molecule. As the monoacyl groups can only protect one side of the benzopyridine ring of ACNs, the other side becomes vulnerable to nucleophilic attacks from water, resulting in lower stability. However, diacylation and polyacylation protect both sides of ACNs, which provides higher stability under the same conditions (Mendoza et al. 2018). Some acylation studies in the literature are presented in Table 5.

Marquez-Rodriguez et al. (2021) reported that the acylation of delphinidin 3-O-sambubioside from *Hibiscus sabdariffa* L. by octanoic acid increased the stability and solubility. They also mentioned that lipophilization took place at the primary alcohol of ACN. Leonarski et al. (2025) used octanoic acid to acylate the cyanidin-3-o-glucoside. They had similar results regarding stability and lipophilicity. In a study where aromatic acids, including *p*-coumaric acid and caffeic

Table 5. Acylation of anthocyanins (ACNs).

ACN	Method	Results	References
Blueberry (*Vaccinium ashei*) pomace ACNs	Novozyme 435 lipase	The enzymatic acylation increased the lipophilicity, thermostability, and photostability of blueberry pomace ACNs.	Yang et al. (2023)
Rose ACNs	Novozyme 435 lipase	The acylation of ACNs improved stability against temperature, light, and pH. The acylated ACNs showed high antioxidant activity (*AxAc*).	Li et al. (2023)
Cyanidin-3-O-glucoside in raspberry ACNs	Novozymes 435	*AxAc* of cyanidin-3-O-glucoside by octanoic acid was up to 47.1%. The acylation improved lipophilicity, *AxAc*, and stability of cyanidin-3-O-glucoside. The acylated forms maintained the pH-color response characteristics.	Lin et al. (2022)
Blueberry ACNs	Solid-phase grafting method	The stability of ACNs was increased after the acylation reaction. The grafting of maleic acid protected the pH-color response characteristics.	Fei et al. (2021)
Blackcurrant (*Ribes nigrum*) ACNs	Lipase acrylic resin from *Candida antarctica* expressed in *Aspergillus niger*	Acylation with lauric acid improved the thermostability and lipophilicity. Acylation also inhibited lipid peroxidation in lipophilic conditions.	Yang et al. (2019)
Blueberry ACNs	Novozyme 435	The color stability and antioxidation activity of ACNs were improved. Acylated ACNs exhibited more potent *AxAc* and higher color stability during storage at 25 °C, 40 °C and 60 °C	Liu et al. (2020)
Disaccharide ACN delphinidin 3-O-sambubioside from *Hibiscus sabdariffa* L.	*Candida antarctica* lipase B	The acylation with the C8 aliphatic chain increased the stability and solubility of pigment in octanol media. The blue color of the quinoidal base is significantly stabilized at neutral and moderately alkaline pH.	Marquez-Rodriguez et al. (2021)
Cyanidin-3-O-glucoside extracted from black rice bran	*Candida antarctica* lipase B	The acylation increased the half-life time for cyanidin-3-O-glucoside at different pH values (3, 5, and 7).	Leonarski et al. (2025)

acid, were used for the acylation of blueberry ACNs, color stability and antioxidation activity were improved. The graft occurred at the 6-OH position of galactoside and glucoside, and at the 5-OH position of arabinose. (Liu et al. 2020). Fei et al. (2021) acylated blueberry ACNs with maleic acid through solid-phase grafting, decreasing color loss from 50.81% to 23.19%. Similarly, they reported that the acylated groups were grafted onto the –OH of the glycosyl. Yang et al. (2019) and Yang et al. (2023) used lauric acid for the acylation of blackcurrant and blueberry ACNs, respectively. They both agreed that lauric acid acylation improved the thermal stability of ACNs.

In the acylation, the stability of ACNs is increased by attaching an acyl donor (fatty acids or aromatic acids) to the core of ACNs. This formation protects the ACNs against hydrophilic attacks. Acylation efficacy is directly related to the acyl groups in the molecules. While monoacyl groups can protect only one side, di- or polyacyls can protect both sides, resulting in a higher stability. Acylating ACNs with fatty acids increased their thermal and photostability as well as lipophilicity. *Candida antarctica* lipase B (Novozyme 435) is the most commonly used enzyme in the acylation of ACNs.

Glycosylation

ACNs are present in plants in glycosylated forms. ACNs comprise an aglycone and one or more sugars attached to 3, 5, 7, 3′, and 5′ hydroxyl groups, with the 3 positions on the C ring being the most common (Cheng et al. 2014). For example, cyanidin 4-glucoside was found in the flower petals of *Hibiscus esculentus*, and ACNs with glycosylation at C3′- and C4'–OHs without any C3–OH were found in the red onion and blue flowers of *Nymphaea caerulea*. The glycosidic bonds, including O- and C-glycosidic, are identified in ACD glycosylation, with the most dominant being O-glycosidic. Glycosylation significantly impacts the stability of ACNs depending on the number, nature, and position of the sugars (Zhao et al. 2014). The molecular scheme of glycosylation is shown in Figure 6b. Glycosylation reactions at different sites result in different colors. While the A-ring glycosylation results in a more purple color, the C-ring glycosylation results in a more red and purple color. Glycosylation can affect the molecular size, polarity, and spatial structure of ACNs (Guo et al. 2022). Kim et al. (2011) investigated the color stability of glycosylated ACNs from *Acanthopanax sessiliflorum*. They monitored that sugar moieties linked to cyanidin were glucose and xylose after acid hydrolysis of the purified ACNs. They concluded that glycosylation provides a protective barrier for ACDs, enhancing their color stability. Glycosylation mostly occurs at C3 of ACNs by O-glycosidic bonds, and the number and the position of sugar moieties affect the stability of ACNs. Depending on the glycosylated ring, ACNs present different colors.

Pyranization

Pyranoanthocyanins (P-ACNs) are modified ACN molecules that contain an additional pyran D-ring. This ring is formed by bonding between the OH groups at the C4 and C5 positions (Figure 6c). P-ACNs were discovered in red wine.

Table 6. Pyranization of anthocyanins (ACNs).

ACN	Cofactor	Proanthocyanin	Method	Results	References
Cranberry ACNs	Caffeic acid	Phenol-pyranoanthocyanins (P-ACNs)	*Lactobacillus* fermentation	Lactobacillus fermentation accelerated the formation of proanthocyanins from cranberry ACNs. Cranberry PACNs exhibited higher antioxidant properties and stability.	Han et al. (2024)
ACNs derived from pelargonidin, cyanidin, and malvidin	Caffeic acid	10-catechyl-P-ACNs	Incubation at 45 °C	10-catechyl-P-ACNs displayed better heat stability. Proanthocyanins retained at least 90 % of absorbance after 4.5-h heat treatment at 90°C.	Voss et al. (2023)
Blueberry wine	Vinylcatechol, vinylphenol	Malvidin-4-vinylcatechol, delphinidin-3-arabinoside-4-vinylcatechol, cyanidin-3-galactoside/glucoside −4-vinylcatechol, cyanidin-3-O-arabinoside-4-vinylcatechol, malvidin-3-O-glucoside/galactoside-4-vinylcatechol, and C3G-4-vinylphenol	Yeast fermentation (*Metschnikowia pulcherrima* with Hydroxycinnamate decarboxylase)	Vinylphenolic P-ACNs provide a stable color in blueberry wine. Yeast with Hydroxycinnamate decarboxylase enhanced the vinylphenolic P-ACNs formation. Proanthocyanins formed by fermentation displayed light and temperature stability.	Tang et al. (2024)
Blueberry wine	Vinylcatechol, vinylsyringol, vinylguaiacol	Cyanidin-3-O-galactoside/glucoside-4-vinylcatechol, cyanidin-3-O-galactoside/glucoside-4-vinylsyringol, malvidin-4-vinylguaiacol, and malvidin-4-vinylcatechol	Non-Saccharomyces yeasts fermentation	Among all the yeasts studied, *Wickerhamomyces anomalus* Y5 showed the best performance. Pyranization by yeast fermentation may improve the color stability.	Zhou et al. (2024)
Cyanidin-3-glycosides from black carrot	4-vinylphenol and 4-vinylguaiacol, decarboxylated p-coumaric and ferulic acid		Incubation for up to 96 h at 45 °C in the dark	P-ACN formation with 4-vinylphenols was more efficient than that of hydroxycinnamic acids. The 1:5 molar ratio of ACN to cofactor had higher proanthocyanin yields.	Miyagusuku-Cruzado et al. (2023)

Vitisin A and B, flavanol-P-ACNs, phenolic-P-ACNs, and methyl-P-ACNs are some of the common types of P-ACNs (Han et al. 2024). Secondary small molecules such as acetaldehyde and pyruvic acid, and hydroxycinnamic acids, including caffeic acid, *p*-coumaric acid, and ferulic acid can react with ACNs to form various P-ACNs after decarboxylation, which is catalyzed by phenolic acid decarboxylase. Phenolic acid decarboxylase enzyme breaks down the phenolic acid and produces 4-vinyl derivatives through non-oxidative decarboxylation. In yeasts, the hydroxycinnamic acid decarboxylase enzyme catalyzes the same reaction. Although the enzymes consist of identical amino acid sequences, the yeast-originated enzyme needs a cofactor called flavin mononucleotide (Deng et al. 2024). In traditional pyranization, either enzymes from yeast or bacteria are used to improve stability of ACNs. Some studies used the end product of enzymatic reactions and had better results. Some relevant studies are summarized in Table 6. Zhou et al. (2024) used 10 non-*Saccharomyces* yeasts to enhance the formation of P-ACNs in blueberry wines. They found that the caffeic acid was the most dominant phenolic acid. The main ACNs in blueberry wines were not pyranized. The most effective non-*Saccharomyces* yeast was *W. anomalus*, which converts cyanidin 3 glucoside and malvidin 3 glucoside into C3G-4-vinylcatechol and C3G-4-vinylsyringol, malvidin-4-vinylguaiacol, and malvidin-4-vinylcatechol, respectively, after 5 days of fermentation (Zhou et al. 2024).

Deng et al. (2024) expressed phenolic acid decarboxylase from *B. amyloliquefaciens* and surface-displayed it on *S. cerevisiae*. Due to the limited generation of 4-vinyl derivatives by yeast in wines, using phenolic acid decarboxylase on yeasts promotes vinylphenolic P-ACN formulation and results in better stability. In a study, ferulic acid, decarboxylated *p*-coumaric, and two 4-vinylphenols in different concentrations were used as cofactors for P-ACN formation. 4- vinylphenol compounds (4-vinylphenol and 4-vinylguaiacol) exhibited higher P-ACN formation yields than those of hydroxycinnamic acids. 1:5 and 1:10 molar ratios of ACN cofactor significantly promoted the P-ACN formation, while 1:30 caused ACN degradation (Miyagusuku-Cruzado et al. 2023). Gao et al. (2023) investigated hydroxycinnamate decarboxylase activity of 84 different yeast strains for the formation of stable vinylphenolic P-ACNs during fermentation of mulberry wine. The strains with high hydroxycinnamate decarboxylase activity promoted the synthesis of stable pigments, including cyanidin-3-O-glucosid e-4-vinylcatechol, and cyanidin-3-O-rutinoside-4-vinylcatechol,

thereby enhancing the color stability. *Escherichia coli* co-cultures are also used to produce P-ACNs. The highest pyranocyanidin-3-O-glucoside-phenol production titer was and 19.5 mg/L, and the highest pyranocyanidin-3-O-glucoside-catechol production titer was 13 mg/L. P-ACNs produced by *Escherichia coli* co-cultures were significantly more stable than those of plant-produced ACNs (Akdemir et al. 2019).

Pyranization refers to the modification of ACN molecules by forming an additional pyran D-ring at the C4 and C5 positions using different molecules such as acetaldehyde and pyruvic acid, caffeic acid, p-coumaric acid, and ferulic acid. The reaction is catalyzed by phenolic acid decarboxylase and hydroxycinnamic acid decarboxylase, where the latter one needs a cofactor called flavin mononucleotide. Deng et al. (2024) reported improved stability by expressing phenolic acid decarboxylase in yeasts used in wine production. The efficiency of pyranization depends on the hydroxycinnamate decarboxylase activity in the same microbial species. In addition, some studies have used different microorganisms such as *E. coli* (Akdemir et al. 2019) and *W. anomalus* (Zhou et al. 2024). They both reported the formation of P-ACNs, while Zhou et al. (2024) mentioned that the main ACNs in blueberry wines were not pyranized. Pyranization is the formation of an additional pyran ring on the anthocyanin structure, through reactions with small molecules, including caffeic acid or vinylphenols. Pyranoanthocyanins frequently exhibit color changes—moving from bright red to orange-brown hues—and the formation process is sometimes slow, requiring particular fermentation or aging conditions. Furthermore, the commercial scaling of controlled synthetic pyranization remains a challenge.

Encapsulation

Encapsulation is defined as entrapping bioactive compounds (bioactives) inside a wall material. Encapsulation techniques not only offer improved stability, but also increase the bioavailability of ACNs (Figure 7). The wall materials used for encapsulation of ACNs mainly include carbohydrates (e.g., maltodextrin, β-CD, chitosan, and starch), proteins (e.g., whey protein, soy protein, ovalbumin, and gelatin), and gums (e.g., XG and GA), as summarized in Table 7. Encapsulation is achieved with the aid of specialized equipment, including spray dryers, freeze-dryers, and electrospinning devices. In addition, water-oil emulsions and liposomes can also be mentioned. Finally, nano- or micro-carriers can be prepared using ionic gelation, an encapsulation method based on atomization or extrusion (Sharif et al. 2020). Several studies were reported on the encapsulation and stability enhancement of ACNs in black carrot (Ersus and Yurdagel 2007), blueberry pulp (Flores et al. 2014), and black carrot (Guldiken et al. 2018) with spray drying, blackberry (Yamashita et al. 2017) with lyophilization, and hibiscus (de Moura et al. 2018) with emulsions.

Microencapsulation

Microencapsulation refers to the technique of entrapping bioactive compounds within a wall material to form micro-sized particles (Mehta et al. 2022), thereby protecting the encapsulated material from environmental stresses, enhancing stability, and enabling the controlled release (Butstraen and Salaün 2014). Freeze drying is a suitable microencapsulation technique for heat-labile bioactives, such as ACNs (Mansour et al. 2020). Another technique is spray drying, which has gained prominence due to its potential for easy scale-up, low operating costs, and the ability to obtain final products as powders. Since ACNs are hydrophilic natural pigments, they are usually compatible with watery gel formulations, including starches, GA, and maltodextrin, as well as proteins like soy and whey protein (da Rosa et al. 2019; Otálora et al. 2025).

Polysaccharide-based wall materials. Polysaccharide-based wall materials used for anthocyanin encapsulation include starches and natural gums, modified carbohydrates, pectin derivatives, and phenolic structure-supporting compounds such as lignin.

- starches and natural gums: gum arabic (Hay et al. 2025, Shaddel et al. 2018, Li et al. 2023, Sakulnarmrat et al. 2022), pitaya peel mucilage (Otálora et al. 2025), sodium alginate (Zhang et al. 2020; Gull et al. 2025), inulin (Sakulnramrat et al., 2022).
- modified carbohydrates: modified starch, maltodextrin (Hay et al. 2025, Pashazadeh et al. 2025, Otálora et al. 2025, Yamashita et al. 2017, Gull et al. 2025, Sakulnarmrat et al. 2022).
- pectin derivatives: pectin (Sakulnarmrat et al. 2022), high-methyl pectin (Pan et al. 2022),
- lignin (Meenu et al. 2025).

Pashazadeh et al. (2025) investigated the efficacy of various encapsulation techniques, including lyophilization, spray drying, and microwave drying, on ACNs from okra flowers, a common agricultural byproduct in different parts of the world. They used maltodextrin (4.0–7.0 dextrose equivalent) as the wall material and reported EE > 99% for all the techniques applied; lyophilization had the best ACN bioaccessibility (Pashazadeh et al. 2025). In another study, a model ice cream was produced using ACNs from mangosteen fruit peel encapsulated into pitahaya peel mucilage and maltodextrin. SEM data revealed that the microcapsules were spherical and smooth, indicating that they were suitable for food applications. Mucilage microcapsules improved the retention of the delphinidin-3-O-arabinoside compared to that of unencapsulated samples (Otálora et al. 2025). Cai et al. (2019) improved blueberry ACNs' stability by microencapsulation using carboxymethyl starch/XG. After 30 days of storage at 37 °C, the amount of retained ACNs was 76.11% by the microcapsules. They also revealed that the encapsulation with a carboxymethyl starch/XG ratio of 30/1 showed superior *AxAc*. Zhang et al. (2020a, 2020b) manufactured ACN-loaded sodium alginate microcapsules using different methods. Encapsulation increased the light and thermal stabilities of ACNs from grape skin. They also mentioned that encapsules produced by spray drying were more stable. Yamashita et al. (2017) used maltodextrin to encapsulate ACN-rich blackberry by-product extract. The encapsulated

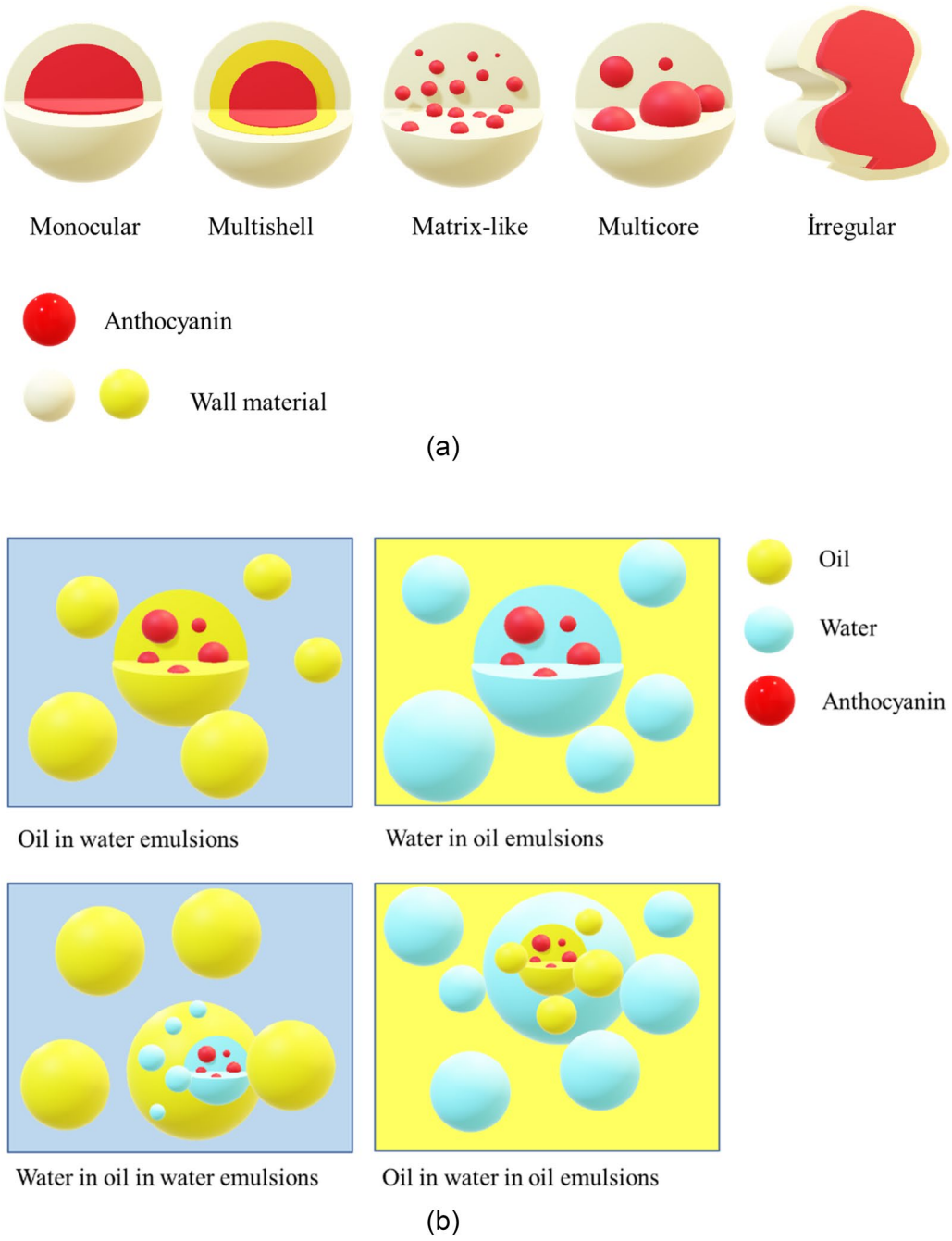

Figure 7. (a) Types of carriers and (b) types of emulsions.

samples had a high ACN content and a low moisture content, as well as hygroscopicity, a_w, and solubility. In a study where non-conventional wall materials, including Psyllium husk, Cassia tora gum, and Mutamba gum, were combined with GA or maltodextrin, the *in vitro* digestion of ACN-rich extracts from grumixama fruits was examined. A 1% combination of non-conventional wall materials increased the release rate of total ACNs and water absorption. Microcapsules produced with GA and 1% *Cassia tora* gum exhibited the highest ACN bioaccessibility (Junior et al. 2025).

Protein-based wall materials. Protein-based wall materials used for anthocyanin encapsulation include soy protein (Pan et al. 2022), whey protein isolate (Flores et al. 2014), gelatin (Shaddel et al. 2018), and synthetic peptide (Li et al. 2023).

Pan et al. (2022) combined high methyl pectin (HMP) with SPI or whey protein isolate (WPI) for the encapsulation of blueberry ACNs. Combining SPI and HMP increased encapsulation efficiency (EE) and decreased the hygroscopicity of the microcapsules. Li et al. (2024) investigated *AxAc* and the ability to modulate gut microbiota of ACNs encapsulated with fructooligosaccharides and whey protein. Encapsulation increased *AxAc* and gastric stability and improved the fermentability. ACN-loaded microcapsules lowered the pH, promoted gas production, and increased short-chain fatty acid production. They also change the gut biota in favor of beneficial ones, including *Faecalibacterium* and *Akkermansia*. In another study, Li et al.

Table 7. Encapsulation of anthocyanins (ACNs).

	ACN	Wall material (s)	Ratio	Results	References
Microencapsulation	ACNs extracted from *Antidesma erostre*	Native Gidyea gum, gum Arabic (GA) and maltodextrin	Maltodextrin, maltodextrin/GA (3:1) and maltodextrin/Gidyea gum (3:1)	The maltodextrin combination with either gum showed superior encapsulation efficiency (EE) and ACN retention. Spray-drying provided better color stability than freeze-drying.	Hay et al. (2025)
	ACNs from okra flower	Maltodextrin (4–7 dextrose equivalent)	The ratio of ACN to MD was 9:1	Encapsulation efficiency was >99%. Lyophilized samples had the highest ACN bioaccessibility.	Pashazadeh et al. (2025)
	ACNs form mangosteen fruit peel	Pitahaya peel mucilage (PPM) and maltodextrin (DE-20)	Two g of ACN with 100 mL of either the PPM, MD, or PPM/MD (1:1)	Microcapsules were spherical. Mucilage microcapsules improved the retention of the delphinidin-3-O-arabinoside	Otálora et al. (2025)
	Blueberry ACNs	Soy protein isolates/high methyl pectin combination	0% WPI + 1% HMP, 10% WPI + 2% HMP, 10% WPI + 4% HMP, 4% SPI + 1% HMP, 4% SPI + 2% HMP, 4% SPI + 4% HMP, 10% WPI, and 4% SPI, denoted 10W1H, 10W2H, 10W4H, 4S1H, 4S2H, 4S4H, 10 W, and 4S	SPI/HMP combination increased EE. 4% SPI + 2% HMP combination exhibited superior *AxAc* and ACN release behavior.	Pan et al. (2022)
	ACNs extracted from grape skin	NaAlg	The ratio between wall material and ACNs was 1:15	The light and thermal stabilities of ACNs increased by encapsulation, and spray-dried samples were the most stable.	Zhang et al. (2020b).
	Blueberry pomace extract	Whey protein isolate (WPI)	The ratio of 8:67:25 of ethanol:water: WPI	Encapsulation provided a two-fold increase in total phenolics and a slight increase in *AxAc*.	Flores et al. (2014)
	Black raspberry ACNs	Gelatin and GA	Wall material and the core material concentrations at ratios of 1:1:0.5, 1:1:0.75, and 1:1:1, the concentration of polymer solutions (2.5%, 5.0%, and 7.5%, w/v) as well as pH (3.5, 4.0, 4.5 and 5.0).	The microcapsules exhibited a smooth surface and a spherical shape. The average sizes ranged from 45.25 to 109.49 µm. The retention rate of microencapsulated ACNs up to 36% after 2 months at 37 ± 2 °C	Shaddel et al. (2018)
	ACN-rich blackberry (*Rubus* spp.) by-product extract	Maltodextrins with 10 and 20 dextrose equivalent (DE)	30% total solids concentration	Encapsulated samples had high ACN and low moisture content, hygroscopicity, aw, and solubility. The sample manufactured with MD 10DE had better results.	Yamashita et al. (2017)
	Saffron petal's ACNs	Maltodextrin and GA	Extract:wall material ratio (w/w) of 1:5	There was no significant decrease in ACN amount of the encapsulated samples during storage. Both gums had quite similar results in protecting ACNs.	Khazaei et al. (2014)
	ACN from mulberry	Synthetic peptide	10 mg peptides and 1 mg ACNs	Encapsulation showed superior enhancement in temperature and pH stability and *AxAc*, as well as stability against heavy metals. Fmoc-MAAAAAA (FM) exhibited the most promising results.	Li et al. (2023)
	Saffron petal ACN extract	Sodium alginate (SA), maltodextrin (MD)	ACN extract and wall material ratio was 1:5 w/w	SA:MD capsules displayed the highest EE by 80.10%, ACN stability by 153 mg/g, and lowest ΔE value after storage (35 days). All the wall materials applied increased the half-life of encapsulated ACNs	Gull et al. (2025)
	Mangosteen pericarp ACN-rich extract	Maltodextrin combined with GA, inulin, and pectin	The ratio of ACNs to wall material was 200 mL to 800 mL	The thermal stability of encapsulated samples was high at temperatures <200 °C, and thermal degradation was decreased. Incorporating powders into yogurt produced naturally colored products with good shelf life but slight suppression in the multiplication of *Lactobacillus bulgaricus*.	Sakulnarmrat et al. (2022)

(*Continued*)

Table 7. Continued.

	ACN	Wall material (s)	Ratio	Results	References
Nanoencapsulation	Anthocyanin extract from purple yam	Whey protein isolate and maltodextrin	MD: WPI ratio was 1:3, 1:1, and 3:1 (w/w). Anthocyanin was added 30% (w/w).	MD: WPI (1:3) was retained more bioactive components. WPI (1:3) had the lowest L value (78.13), which indicates a darker.	Tamaroh and Sari (2024)
	Blueberry ACN extracts	Ferritin	A volume ratio of 1:11	The free ACNs were more stable at pH 3 and 40 °C. Encapsulation prevented ACN degradation under weakly acidic pH (pH 6), ultraviolet light, high temperature (60 °C), and oxidant conditions.	Huang et al. (2023)
	ACNs of *Echium amoenum* petal	Maltodextrin/modified starch combination	MD/MMS: 1/0, 1/0.25, 1/0.5, 1/1, w/w%	The encapsulation efficacies were between 93.1 and 97.4%. The encapsulation by MD/MMS 1:1 improved the stability of ACNs by 43.8%. Also, microencapsulated ACNs increased the antioxidant activity (*AxAc*).	Mehran et al. (2020)
	Cyanidin 3-O-glucoside	Artificial peptide, named C6M1 (RLWRLLWRLWRRLWRLLR)	C6M1/C3G molar ratio as 1:4, 1:8, 1:16, 1:24, 1:32, 1:64	EE was 77.06%. C6M1 increased the ACN stability against pH changes, metallic ions, and hot temperature, while maintaining the free radical scavenging capacity.	Yao et al. (2021)
	ACNs from red raspberry pomace	β-lactoglobulin	The ratio of ACN to wall material was $1–13\times10^{-4}$ M to 10 mg/ml	EE % was ~77%. With increasing concentration of ACNs *AxAc* also increased.	Salah et al. (2020)
	ACNs from black wheat bran, black plum and blueberry	Lignin	Lignin to anthocyanin ratio was 10:1, 10:3, 10:5, and 10:10 w/w	Encapsulation efficiency was from 92.32 to 72.26%. ACN-loaded NPs were light stable during 28 days of storage at room temperature.	Meenu et al. (2025)
	ACNs from Aronia	Chitosan	ACN:chitosan ratio was 3:3.5–9:3.5	EE was 65.7%, zeta potential was +42.7 mV. Nano encapsulated ACNS showed slower degradation and stronger antioxidant activity in the simulated gastrointestinal digestion and storage	Wang et al. (2021)
	Bilberry-derived ACNs	Chitosan - pectin	A mass ratio of CS-PC to ACN was 2:0, 2:1, 2:2, 2:3 and 2:4	Well dispersed spheres nanocarriers were observed when the mass ratio of chitosan/pectin/anthocyanin was 1:1:3. EE was 66.68%. Nano encapsulation enhanced the storage stability under light and dark conditions.	Zhao et al. (2020)
	ACNs from blackberry	Pectin-lysozyme	The ratio of pectin, lysozyme, anthocyanin was 1:2:0.4 (m:m:m)	EE was 79%. The ACN degradation was lower than isolated ACNs. The stability of ACN-nanoparticles was during digestion.	Rosales et al. (2023)
	ACNs from blackberry	Pectin-lysozyme	The ratio of pectin, lysozyme and anthocyanin was 1:1:0.2 (v/v/v)	EE and loading capacity were 73% and 15%, respectively. ACN-loaded nanoparticles have superior physical stability in different pH ranges.	Rosales et al. (2021)

(2023) encapsulated ACNs into synthetic peptide-based gels. The results revealed a significant enhancement in thermal and pH stability. Flores et al. (2014) found that phenolic content and antioxidant activity of blueberry pomace increased (a two-fold increase) during storage. In a similar study evaluating the efficacy of the gelatin-gum arabic wall material for the double emulsion of black raspberry ACNs, Shaddel et al. (2018) revealed that encapsulated ACNs had high retention (up to 36%) compared to the control during 2-month storage.

Maltodextrin and gum arabic are commonly combined to enhance encapsulation efficiency, though they offer limited thermal protection compared to protein–based complexes. While soy protein and whey protein are still among the most widely used protein wall materials, studies using synthetic proteins have also been reported. Although microencapsulation improves anthocyanin stability under mild conditions, process optimization is crucial since carrier ratio and drying temperature significantly influence retention of ACNs. ACNs are heat-labile compounds; therefore, lyophilization remains one of the most effective techniques for enhancing the bioaccessibility of ACNs. Spray drying is the most widely used microencapsulation technique due to its simplicity and scalability, yet it exposes anthocyanins to thermal degradation. Some promising studies explore the potential usage of novel wall materials such as pitaya peel mucilage and Native Gidyea gum. Microcapsules prepared from polysaccharide materials provide effective protection against oxidation and dehydration. In contrast, protein-based wall materials offer stronger molecular interactions with ACNs through hydrophobic interactions and hydrogen bonding, thereby enhancing pH and thermal stability. Polysaccharides are preferred for their processability and low cost, whereas proteins offer better encapsulation efficiency and color retention during storage.

Nanoencapsulation

Nanoencapsulation is technique based on entrapping a bioactive compound within a wall material, to form nano-sized particles. Nanoencapsulation offers two distinct shell/core structure types: nanocapsules, which are characterized by bioactives enclosed in a membrane, and nanospheres, which are characterized by bioactives uniformly distributed in the polymeric matrix (Naz et al. 2025). The smaller particle size obtained by nanoencapsulation prevents particles from aggregating, making them suitable for foods that require good stability during storage (Anjum et al. 2025). The wall materials potentially used in nanoencapsulation are polysaccharides, including pectin, chitosan, maltodextrins, corn syrup solids, gums, maltodextrin starch, and β-CDs; lipids, including vegetable oils, beeswax, lecithin, and medium-chain triglycerides; and proteins, including soy and zein, casein, egg, and whey proteins (Singh et al. 2023). Nanocapsules can be prepared using various methods, including nano spray drying, electrospinning, emulsification, and electrostatic complexation (Rosales and Fabi 2022).

Polysaccharide-based wall materials. In a study using ACN-loaded NPs, Gull et al. (2025) employed sodium alginate and maltodextrin as wall materials to encapsulate the saffron petal ACN extracts. Sodium alginate:maltodextrin capsules displayed the highest EE by 80.10% and ACN stability by 153 mg/g. All the wall materials applied increased the half-life of encapsulated ACNs. Wang et al. (2021) manufactured chitosan nano capsules to increase the stability of aronia ACNs. They monitored the stability of ACNs during simulated gastrointestinal digestion and storage. They reported higher AxAc and lower ACN degradation. They also mentioned that chitosan nanocapsules increased the physical and oxidative stability of ACNs. In a similar study, Zhao et al. (2020) prepared chitosan nanocapsules incorporating pectin. They also reported similar EE to Wang et al. (2021). Their findings also showed an increase in stability. In addition to the storage stability, they reported that the nanocarriers protected ACNs from acrylamide, heat shock, oxidative stress, and UV light. Rosales et al. (2023, 2021) prepared nano capsules with pectin-lysozyme to enhance the stability of blackberry ACNs. They reported EE over 70% in both studies. They also reported that the stability of ACNs increased in the acidic environment. Furthermore, the digestion stability was also increased by the encapsulation.

Polysaccharide-based wall materials, including chitosan, maltodextrin, alginate, and pectin, have been extensively studied due to their availability, biocompatibility, cost, and structural versatility. Among polysaccharide-based nanocarriers, chitosan is one of the most preferred materials, providing high encapsulation efficiency due to its strong electrostatic affinity. Hybrid systems combining different polysaccharides, such as chitosan–alginate or pectin–starch complexes, have demonstrated better overall stability and improved resistance to thermal and pH degradation.

Protein based wall materials. Salah et al. (2020) prepared ACN-loaded β-lactoglobulin nanoparticles (NPs) by the desolvation method combined with ultrasound. Before encapsulating raspberry ACNs, β-lactoglobulin NPs were manufactured by heating at 85 °C for 30 min. Nanoencapsulation increased *AxAc* and stability during digestion. In another study, Yao et al. (2021) fabricated peptide NPs to encapsulate ACNs. C6M1, which consists of 18 amino acids, was used. They reported that the peptide's secondary structure was converted from α-helix to β-sheet during the process. Additionally, nanoencapsulation enhanced the stability of ACNs against changes in pH, temperature, and the presence of metallic ions. Cyanidin 3-O-glucoside-loaded sericin NPs were prepared to improve the stability of ACNs and monitor the effects on wound healing. Molecular results showed that specific amino acids, phenylalanine, and tyrosine, with a hairpin structure, had a significant role in the peptide-ACN interaction. ACN-peptide NPs exhibited enhanced bioactivity, particularly in their reactive oxygen species scavenging ability, which is crucial for wound

healing (Zhang et al. 2023b). Huang et al. (2023) manufactured ferritin nanocapsules to entrap blueberry ACN extracts. Interestingly, the free ACNs were more stable at pH 3 and 40 °C. The nanoencapsulation prevented ACN degradation under weakly acidic pH (pH 6), ultraviolet light, high temperature (60 °C), and oxidant conditions.

Whey protein isolate, β-lactoglobulin, soy protein, ferritin, sericin, and synthetic peptides have been studied as protein-based wall materials for ACN stabilization. Additionally, Meenu et al. (2025) reported that nanoencapsulation of ACNs using lignin, a phenolic structure-supporting compound, increased stability, AxAc, and antimicrobial activity compared to purified ACNs. They produced a packaging material using ACN-lignin NPs and reported that nanocapsule-containing packages offered a longer shelf life than the control. β-lactoglobulin forms stable protein–ACN complexes through hydrophobic interactions and hydrogen bonding, resulting in enhanced color protection against environmental factors such as heat, light, and pH changes. On the other hand, ferritin acts as a nanocage with its unique structure, providing a good thermal and oxidative stability, as well as targeted delivery; however its high cost constrains practical application. The functionality of proteins is influenced by changes in ionic strength and pH. Thus, integrating proteins with different wall materials, such as polysaccharides or lipid-based materials, in hybrid systems eases the overcoming of these problems and enhances ACN stability by combining hydrophobic and electrostatic interactions. Finally, engineered peptides offer improved stability against pH fluctuations, thermal changes, and metal ions; however, their cost and scalability remain limiting factors in food applications.

Lipid-based wall materials. Guan et al. (2025) manufactured lecithin, cholesterol, and sodium cholate liposomes loaded with black wolfberry ACNs. Flexible nanoliposomes significantly improved EE and storage stability of bioactives compared to conventional liposomes. After 10 wks of storage at 25 °C in a light-protected environment, the retention rates of BWA and EGCG in flexible nanoliposomes were 62.47% and 60.01%, respectively, with an average retention rate 1.73 times higher than in conventional liposomes. In another ACN-loaded liposome study, Guldiken et al. (2018) produced lecithin liposomes loaded with ACN-rich black carrot extract. They reported that the degradation of the extract (30%–90%), phenolic content (10%–29%), and *AxAc* (4%–33%) of liposomes varied depending on the lecithin content. Overall, every wall material has its own advantages and disadvantages. While the polysaccharide wall materials are available, inexpensive, and biodegradable, proteins offer better stability and bioavailability of ACNs. However, proteins are easily affected by environmental changes such as pH, temperature, and ionic strength. Lastly, lipid-based nanocarriers are prone to oxidation during the process or storage.

Conclusion and future work

Overall, the present review clearly concludes that ACN stability is predominantly governed by environmental factors, such as temperature, pH, light, enzymes, and ascorbic acid, which limit its industrial applications. This review demonstrates that stabilization strategies should be evaluated not only in terms of physicochemical preservation, but also with respect to functional performance, bioavailability, industrial applicability and environmental sustainability. Current studies we reviewed have been proposes multiple stabilization techniques, including Co-P, structural modification, complexes with different molecules, and encapsulation. However, most studies were conducted on isolated systems under controlled conditions, which limited emphasis on real food matrices or large-scale production.

The most common copigments used in Co-P are phenolic compounds because they are electron-rich molecules and have the same planar structure as ACNs. Some of the most studied phenolic copigments are rutin, chlorogenic acid, caffeic acid, and quercetin. While hydroxycinnamic acids, such as chlorogenic, caffeic, and p-coumaric, have been reported as efficient copigments with flavonols, hydroxybenzoic acids, including gallic acid, benzoic acid, and vanillic acid, have been reported to have minimal effects. Rosmarinic acid, EGCG, chlorogenic acid, ferulic acid, and tartaric acid were reported to be good copigment in the intermolecular copigmentation. The increasing concentration of the copigment positively enhanced the stability. The Co-P decreased the L* values and increased the a* values. Se-As is mainly studied in wine-like alcoholic beverages and observed to be stronger with the increasing number of hydroxyl or methoxy groups on the B-ring. The interactions between ACNs and copigments, particularly in terms of bonds and molecular positioning, should be studied further to elucidate the mechanism.

Metal ions can be attached to the B-ring of the flavylium cation and protect it. Metal:ACN complexes can significantly enhance color intensity and induce bathochromic shifts; however, color instability during storage and potential toxicity limit their food-grade applications. Iron, aluminum, and calcium are the most studied metal ions. A higher amount of metal ions in the metalloanthocyanin complexes that contain low ACNs did not cause a significant change. The addition of pectin, carrageenan, and alginate contributed to the stability of metalloanthocyanin complexes. New phenolics, metals, or their combinations could provide promising results.

Similar to copigments, other molecules, such as proteins, polysaccharides, and gums also showed promising results in enhancing ACN stability under various conditions. While the stability mechanism of amino acids mostly depends on making new bonds, other molecules, such as polysaccharides, and gums are forming a protective environment for the ACNs. The peptides with higher tryptophan content showed stronger interactions with ACNs. The addition of GA did not significantly affect the L* and a* values. The addition of BSA and polysaccharides increased the stability and *AxAc*. Monosaccharides were reported to have better Co-P activity than polysaccharides. The mechanism behind these complexes should be studied and clarified.

Another approach for increasing stability is structural modification. Acylation, glycosylation, and pyranization were the most mentioned modifications in the literature. A cofactor was bonding with the O atoms of ACNs in the acylation and glycosylation, and a new ring occurs in the pyranization. Acylation of free hydroxyl groups decreases water solubility and enhances lipophilicity, resulting in improved solubility in lipid matrices. The effectiveness of acylation also depends on the type of acyl donor and the reaction selectivity. Diacylation and polyacylation protect both sides of ACNs, resulting in higher stability than monoacylation. The additional sugar groups have been reported to increase the water solubility of ACNs. Also, the number and position of sugar groups attached to the flavylium cation may affect the digestion and absorption of ACN.

Caffeic acid, ferulic acid, p-coumaric acid, and vinylphenol-type phenolics, including vinylcatechol and vinylsyringol derivatives, were some of the most used cofactors in pyranization. The phenolic acid decarboxylase activity of microorganisms promoted the pyranization reactions, resulting in an enhanced stability of ACNs. Thus, recent studies focused on the new types of microorganisms that can promote P-ACN formation. New studies on novel molecules for acylation and pyranization, as well as enzymes and fermentative microorganisms for pyranization, could be conducted. The formation of an extra pyran ring in the ACN structure often increases the stability, but it is synthetically hard to control. Future studies should be conducted on the controllable and scalable structural modifications.

The encapsulation of ACNs increased the stability and AxAc. Maltodextrin was one of the most common polysaccharide-based materials used solely or in combination with other wall materials. The combination of MD with sodium alginate, gum arabic, or WPI increased the stability, AxAc, and bioavailability. The use of chitosan as a wall material exhibited slower degradation and stronger AxAc during storage and in simulated gastrointestinal digestion. Additionally, a combination of chitosan and pectin resulted in enhanced stability under dark conditions. Although nanoencapsulation offers superior protection, controlled release, and enhanced bioavailability, its application in real food systems remains limited due to higher production costs, scale-up challenges, and regulatory uncertainties. The encapsulation by emulsions can increase the lipophilicity of ACNs. Novel wall materials, such as lignin, artificial peptides, native Gidyea gum, and Pithaya peel mucilage, have shown promising encapsulation efficiency. From a sustainability perspective, the valorization of food by-products and food waste can be utilized as wall materials, thereby minimizing the environmental footprint.

What is more? The combination of these techniques is becoming a trend—for instance, Co-P before encapsulation or acylation before metal Co-P. Thus, the overall stability will indeed increase. Another approach will be searching for the possibility of increasing the stability of ACNs before extraction. Is it possible to modify ACNs in the plant using biotechnology? Furthermore, all the complexes with ACNs should also be monitored *in vitro*, *in vivo*, and even in human studies.

Author contributions

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