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REVIEW

Advances in Anthocyanins from Edible Ornamental Flowers: Biosynthesis, Extraction, Stability, and Food Applications

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ABSTRACT: Anthocyanins (ACNs), a major class of water-soluble flavonoid pigments, are responsible for the vivid red, purple, and blue hues in many edible ornamental flowers. Recently, increasing attention has been directed toward these flowers not only for their aesthetic value but also for their nutritional and functional potential, such as antioxidant, anti-inflammatory, antidiabetic, anticancer, and cardioprotective activities. This review summarizes current knowledge on the source and biosynthesis pathways of ACNs in edible ornamental flowers, highlighting the key enzymes and regulatory genes involved. Factors affecting ACN stability, such as chemical structure, pH, temperature, light, oxygen, water activity, copigmentation, and microencapsulation are discussed in detail to provide insights into preserving their color and functionality in food systems. Eight extraction techniques, including solvent extraction (conventional method), and ultrasound-assisted, microwave-assisted, pulsed electric field-assisted, cold plasma-assisted and green solvent methods, are compared in terms of efficiency, sparing energy, environmental impact, and scalability. Among the 11 different types of edible flowers, the top four for total ACNs (g cyanindin-3-glucoside/kg DB) are rose (33.3), saffron (10.2), roselle (10.0), and butterfly pea flower (3.5), making them good sources of red to blue ACNs for exploring industrial scale-up. Finally, the review explores their diverse applications in the food industry as natural colorants, functional ingredients, and intelligent packaging films, offering potential for clean-label and health-oriented products. Overall, edible ornamental flowers represent a sustainable and multifunctional source of ACNs with promising applications in both nutrition and food technology. Future directions should focus on enhancing ACN stability, reducing extraction costs, and validating their efficacy through *in vivo* studies and industrial-scale trials.

KEYWORDS: Flower; anthocyanin; extraction; phytochemical; antioxidant; biosynthesis; degradation

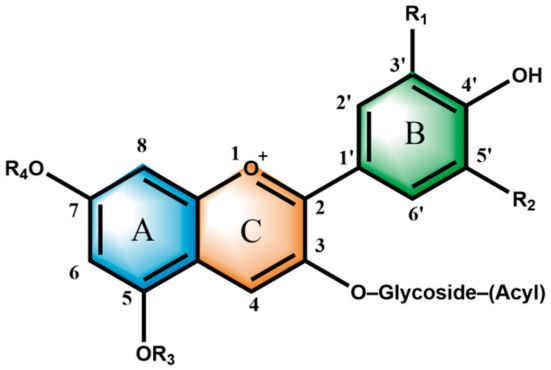
1 Introduction

Numerous ornamental plants produce flowers that are edible and have long been used in traditional diets in various regions [1,2]. Species, safety, and regulation of common edible flowers lists in Table 1. These flowers vary widely in morphology, aroma, phytochemical and pigment compositions, with ACNs being the primary pigments responsible for red, purple, blue, and magenta hues [3–5]. The edible flowers of osmanthus, lily, jasmine, chrysanthemum, marigold, and cactus appear white, yellow, orange, or red color, due to the presence of flavonoids, carotenoids, and betalains [6,7]. However, many of the ornamental flowers, such as oleander, jimsonweed, tulip, and hydrangea (Table 1), are inedible because they contain toxic or harmful components [8,9].

Table 1: Species, safety, and regulation of common edible and inedible flowers.

Items	Edible Flowers	Inedible Flowers
Scientific name	*Chrysanthemum morifolium*, *Clitoria ternatea*, *Crocus sativus*, *Dianthus caryophyllus*, *Hibiscus rosa-sinensis*, *Hibiscus sabdariffa*, *Hibiscus syriacus*, *Jasminum sambac*, *Lavandula angustifolia*, *Lilium lancifolium*, *Nelumbo nucifera*, *Ocimum sanctum*, *Opuntia ficus-indica*, *Osmanthus fragrans*, *Paeonia lactiflora*, *Paeonia suffruticosa*, *Prunus serrulata*, *Rosa rugosa*, *Tagetes erecta*, *Viola tricolor*	*Convallaria majalis*, *Datura stramonium*, *Hydrangea macrophylla*, *Nerium oleander*, *Papaver rhoeas* *Rhododendron simsii* *Tulipa gesneriana*
Safety	Generally safe	Intrinsic toxins: alkaloids, cyanogenic glycosides, cardiac glycosides, etc.
Regulatory status	Approved as food materials and compliant with regulations (e.g., China's NY/T 1506; the U.S. Federal Food, Drug, and Cosmetic Act along with 21 CFR Parts 172 and 182; and the European Union's EU 2015/2283 as well as EC No. 396/2005), including limits on pesticide residues, heavy metals, and microbial counts	Consumption prohibited

ACNs are natural water-soluble pigments widely distributed in flowers, fruits, leaves, and seeds of plant kingdom [10]. In plants, ACNs protect tissues from damage caused by excessive light, ultraviolet radiation, and oxidative stress. They also play a crucial role in attracting pollinators and seed dispersers, which enhances plant reproductive success. The basic structure of anthocyanin is the 2-phenylbenzopyrylium cation. ACNs are constituted by anthocyanidins, sugars, and/or organic acids, as shown in Fig. 1. The six most common anthocyanidins (aglycones) in foods are delphinidin, cyanidin, pelargonidin, malvidin, petunidin, and peonidin. The diversity of ACN structures, including variations in the types, numbers and sites of methoxyl, glycoside, and acyl groups, contributes to the wide range of colors observed in ornamental flowers [11]. The common sugars attached in 3, 5 and/or 7 positions in A and C rings as well as hydroxyl groups in B ring of ACN are glucose, galactose, arabinose, xylose, and their disaccharides or trisaccharides. Aromatic and aliphatic organic acids attached to the sugar moieties are caffeic, *p*-coumaric, sinapic, *p*-hydroxybenzoic, ferulic, malonyl, malic, succinic, and acetic [12]. These structural differences not only influence pigmentation but also affect ACN stability and bioactivity [13]. The intensity and hue of color are influenced by factors such as pH, metal ions and copigments present in the cellular environment. Since 2000, research on ACNs has been extremely popular, with more than 44,000 papers reported [14].



Anthocyanidin	R_1	R_2
Cyanidin	OH	H
Delphinidin	OH	OH
Pelagonidin	H	H
Malvidin	OCH_3	OCH_3
Peonidin	OCH_3	H
Petunidin	OH	OCH_3

Figure 1: Chemical structures of anthocyanins and anthocyanidins: R_3 and R_4 represent –H or a glycoside.

Edible ornamental flowers are rich in bioactive compounds including ACNs, flavonoids, phenolic acids, phytosterols, terpenoids, polysaccharides, and tannins, and have been demonstrated to exert beneficial effects on human health shown in Table 2. Epidemiological and experimental studies suggest that anthocyanin-rich foods and flowers may reduce the risk of chronic diseases, such as cardiovascular disease, diabetes, obesity, and certain types of cancer [15–17]. These protective effects are primarily attributed to their strong antioxidant activity, which allows them to scavenge reactive oxygen species and reduce oxidative damage in biological systems. Furthermore, ACNs may modulate signaling pathways involved in inflammation, lipid metabolism, and cellular stress responses. They significantly affect inflammation-related biomarkers including C-reactive protein, tumor necrosis factor alpha, interleukin-6, and adiponectin, as well as inhibit lipase, α-amylase, and α-glucosidase activities [18,19]. Recent evidence also suggests that ACNs may influence gut microbiota compositions, thereby contributing to overall metabolic health [20].

Table 2: Phytochemicals, color, and health benefits or functions of some edible ornamental flowers.

Flowers	Color	Phytochemicals	Functions or Health Benefits	References
Butterfly pea *Clitoria ternatea*	Blue	ACNs, flavonols, phenolic acids, phytosterols, and tocopherols	Antioxidative, anti-inflammatory, antidiabetic, antitumor and neuroprotective effects; Inhibit lipase, α-amylase, and α-glucosidase	[17,21–24]
Cherry blossoms *Prunus* species	Pink	ACNs, flavanols, polyphenols, and polysaccharides	Anti-inflammatory, antiviral, antidiabetic and anticancer effects α-glucosidase inhibition	[25–27]
Lavender *Lavandula* species	Violet	ACNs, phenolics, flavonoids, monoterpenes, tannins and phytosterols	Antioxidant, anti-inflammatory effects, antimicrobial and antifungal activities, sedative and anxiolytic activities, reduction of dementia and cancer cell growth	[28–30]
Lotus *Nelumbo nucifera*	Red, pink	ACNs, flavones, flavonols, polyphenols	Antioxidant, anti-inflammatory and hepatoprotective activities; reduce oxidative stress; alleviate muscle fatigue; inhibit enzyme activity, including β-secretase, acetylcholine esterase, angiotensin-converting enzyme, lipase, and β-glucosidase	[31–34]
Herbaceous peony *Paeonia lactiflora*	Pink, red	ACNs, polyphenols, flavonoids, essential oils	Antioxidant, cytoprotective and antibacterial effects; antiglycation and antityrosinase capacity	[35–38]
Rose *Rosa rugosa*	Red	ACNs, polyphenols, flavonoids, ascorbic acid, essential oil, carotenoids	Antioxidant, anti-inflammatory, antibacterial, antimutagenic and neuroprotective, and antianxiety activities	[39–42]
Roselle *Hibiscus sabdariffa*	Red	ACNs organic acids, flavonoids, phenolic acids, and ascorbic acid	Antimicrbial, antioxidant, antihypertensive, antidiabetic, hepatoprotective, nephroprotective, and antigenotoxic effects	[43–45]

ACNs in flowers are primarily concentrated in the vacuoles of petal epidermal cells. Owing to the thin cell walls, large vacuoles, low viscosity, and loosely organized tissue structure, cell wall disruption is relatively easy and solvent penetration is highly efficient. Consequently, compared with fruits, vegetables, or seeds, bioactive compounds in flowers are the easiest to extract. Flower petals therefore represent an ideal raw material for ACN extraction. Unlike previous reviews that focus primarily on ACNs from common fruits and vegetables, or single species of ornamental flower, this review targets various edible ornamental flowers as a distinct and underutilized source, offering a systematic comparison of their anthocyanin contents and characteristics, biosynthesis and regulatory mechanisms, stability factors, green extraction methods, food industry applications, and future research perspectives—an integrated perspective absent from the literature.

To achieve these objectives, the methodology employed for this article focused on identifying relevant papers published between 2015 and 2026. Searches were conducted across databases including Web of Science, Google Scholar, and PubMed. A comprehensive set of keywords was utilized, encompassing terms such as: flower, petal, anthocyanin, biosynthesis, extraction, solvent, ultrasound, microwave, deep eutectic solvent, cold plasma, supercritical fluid, stability, microencapsulation, health, bioavailability, intelligent film, and food applications.

2 Biosynthesis and Its Regulation

2.1 Biosynthesis of Anthocyanin

The ACN biosynthetic pathway is a vital branch of the flavonoid biosynthesis pathway and is relatively conserved among higher plants. This intricate process involves a series of enzymatic reactions (Fig. 2), which are primarily divided into three stages: the formation of the basic ACN skeleton, the synthesis of ACN precursors, and the modification of these precursors into various ACNs [46].

The first stage involves a general phenylpropanoid pathway common to many secondary metabolites. It begins with the deamination of phenylalanine to cinnamic acid, catalyzed by phenylalanine ammonia-lyase [47]. Cinnamic acid is then hydroxylated by cinnamate 4-hydroxylase to form p-coumaric acid, which is subsequently activated by 4-coumarate-CoA ligase to yield 4-coumaroyl-CoA [48,49].

The second stage encompasses the conversion of 4-coumaroyl-CoA to dihydrokaempferol. Specifically, chalcone synthase catalyzes the condensation of 4-coumaroyl-CoA with three molecules of malonyl-CoA to produce naringenin chalcone, the first flavonoid intermediate in the pathway, which provides the fundamental carbon skeleton for subsequent compounds [50]. Chalcone is then isomerized by chalcone isomerase to form naringenin, which is further hydroxylated by flavanone 3-hydroxylase to generate dihydrokaempferol [51].

The third stage involves the formation of various anthocyanidins through three distinct branching pathways. Dihydrokaempferol serves as the common substrate for flavonoid 3′-hydroxylase and flavonoid 3′, 5′-hydroxylase, producing dihydroquercetin and dihydromyricetin, respectively [52]. These dihydroflavonols are then reduced by dihydroflavonol 4-reductase to their corresponding colorless leucoanthocyanidins. Finally, anthocyanidin synthase catalyzes the oxidative dehydration of these leucoanthocyanidins, resulting in the formation of the chromophoric yet unstable pelargonidin, cyanidin, and delphinidin [53].

Functioning at the terminal stage of the pathway, ACN O-methyltransferase modulates the relative abundance of major ACNs by catalyzing the methylation of cyanidin and delphinidin to produce peonidin, malvidin, and petunidin, respectively [54]. In plant cells, these anthocyanidins are typically unstable and do not persist as free aglycones [55]. Further modifications, including methylation, glycosylation, and acylation,

of these six anthocyanidins yield a diverse array of ACN derivatives, which thereby enhancing the stability and altering the spectral properties of the final pigments [56]. ACN glycosylation, primarily catalyzed by UFGT, serves as a crucial stabilization step. Subsequent acylation, mediated by ACN acyltransferase, conjugates aromatic or aliphatic acids to the glycosylated ACNs. This acylation modification further alters their spectral properties and is closely associated with the shift of flower color toward blue or red hues [57].

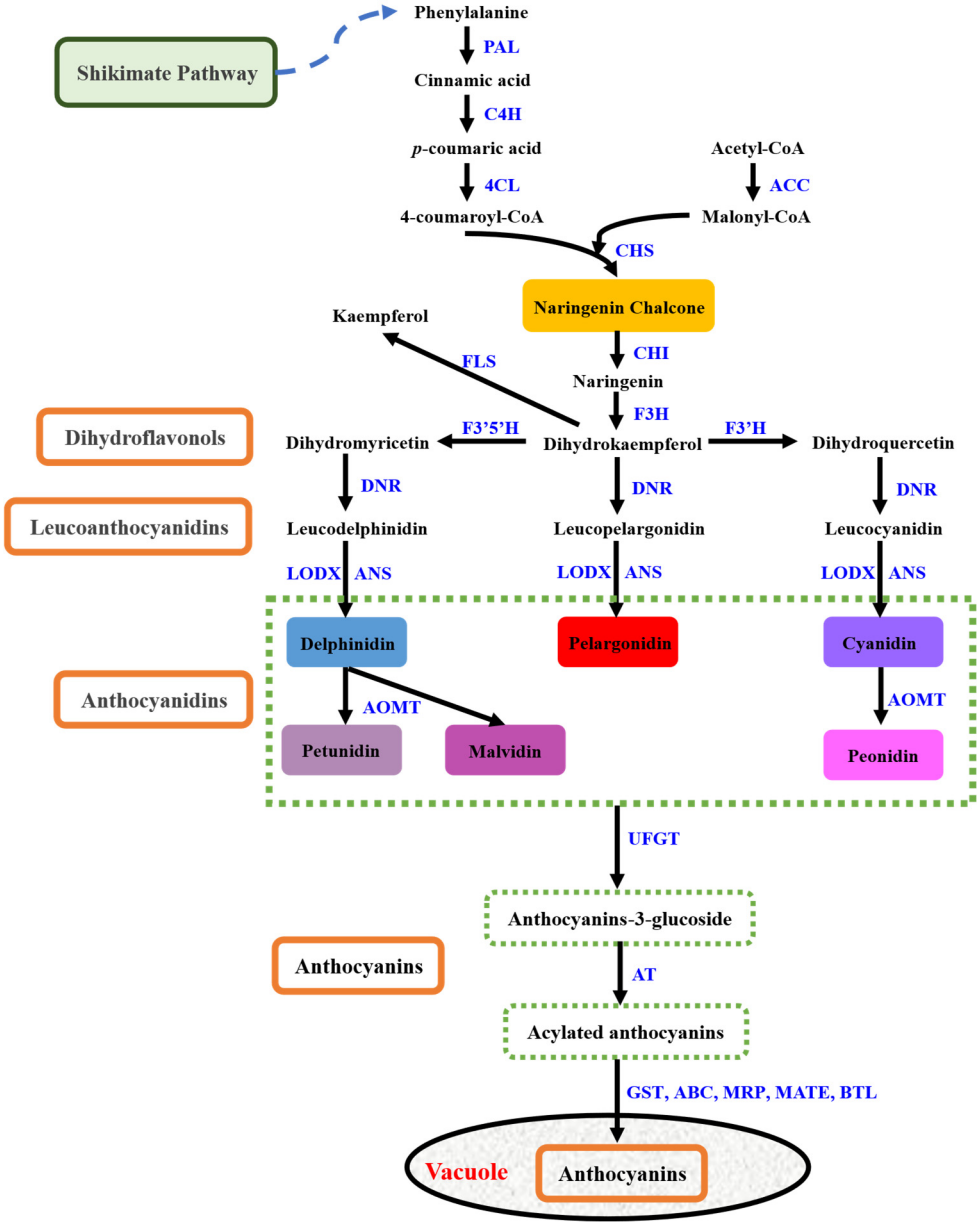


Figure 2: ACN Biosynthetic Pathway. Note: Enzymes are indicated by blue letters. The typical colors of compounds are also shown, though the actual color depends on various factors. PAL: phenylalanine ammonia-lyase; C4H cinnamate 4-hydroxylase; 4CL: 4-coumarate-CoA ligase; CHS: chalcone synthase; CHI: chalcone isomerase; F3H: flavanone 3-hydroxylase; F3′H: flavonoid 3′-hydroxylase; F3′5′H: flavonoid 3′,5′-hydroxylase; DFR: dihydroflavonol 4-reductase; ANS: anthocyanidin synthase; AOMT: anthocyanin O-methyltransferase; UFGT: UDP-glucose-flavonoid 3-O-glycosyltransferase; AT: anthocyanin acyltransferase; GST: glutathione S-transferase; ABC: ATP-binding cassette; MRP: multidrug resistance-associated protein; MATE: multidrug and toxic compound extrusion; BTL: bilitranslocase.

Finally, the ACNs are transported into and accumulated within the vacuole, facilitated by specific transporter proteins and transport vesicles [58]. This vacuolar sequestration is crucial for plant coloration, as the compartmentalization and concentration of these pigments directly determine their visual manifestation [59]. To date, five major classes of transporter proteins including glutathione S-transferase and ATP-binding cassette proteins are also known as multidrug resistance-associated proteins, multidrug and toxic compound extrusion transporters, and bilitranslocase homologues [59,60].

2.2 Regulation in Biosynthesis of Anthocyanin

The biosynthesis of ACNs is primarily regulated at the transcriptional level through the action of transcription factors on structural genes [61]. To date, several transcription factor families, including MYB, bHLH, WD40, Zinc finger, and WRKY, have been identified as key regulators of ACN metabolism [62,63]. Furthermore, detailed studies on species including *Chrysanthemum morifolium*, *Dianthus caryophyllus*, *Lilium* spp. and *Rosa* spp. have confirmed the presence of ACN-regulating gene families that correspond to these transcription factor types, as shown in Table 3.

Table 3: ACN-related transcription factor gene families in some edible ornamental flower.

Species	Transcript Factors	Regulated Key Enzymes	Effect	References
Chrysanthemum morifolium	*CmMYB6-MrbHLH1*	CmDFR	Positive	[64]
	CmMYB6-CmbHLH2	CmDFR	Positive	[65]
	CmMYB9a	CmCHS, Cmmdfr, CmFNS	Positive	[66]
	CmMYB9a	CmFLS	Negative	[66]
	CmMYB12	CmFNS, CmCHS, CmDFR, CmANS, CmUFGT	Negative	[67]
	CmMYB21	NtDFR	Negative	[68]
	CmMYB4, *CmMYB5*	NtCHS, NtF3H, NtDFR, NtANS, NtF3′H	Negative	[69]
Dianthus caryophyllus	*DcMYB1-DcbHLH1*	DcCHS, DcDFR	Positive	[70]
	DcWRKY15	DcCHS, DcF3H	Positive	[71]
	DcMYB2	DcbHLHl	Negative	[70]
Lilium spp.	*LvMYB5-LvbHLH13*	LvF3′H, LvDFR, Lv3GT	Positive	[72]
	LhMYB12	LhCHS, LhDFR	Positive	[73]
	LhMYB18	AtDFR	Positive	[74]
	LhMYBSPLATTER-LhbHLH2	LhF3H, LhDFR, LhUFGT, LhGST	Positive	[75]
	LhWRKY44	LhF3H, LhGST	Positive	[76]
	LvWRKY75	LvCHS, LvDFR, LvANS, Lv3GT, LvF3′H	Positive	[77]
	LvbZIP44	LvMYB5	Positive	[78]
	LhHB4	LhMYBSPLATTER, LhWRKY44	Negative	[79]
Osmanthus fragrans	*OfMYB3*, *OfMYB4*	F3H, F3′H, DFR, ANS	Positive	[80]
	Of WRKY3	OfCCD4	Positive	[81]
	OfMYB1, *OfMYB2*	F3H, F3′H, DFR, ANS	Negative	[80]

Table 3: *Cont.*

Species	Transcript Factors	Regulated Key Enzymes	Effect	References
Jasminum sambac	*JsMYB1*	JsPAL1, JsDFR1, JsUFGT	Positive	[82]
Lavandula angustifolia	*LaMYB73*, *LaMYB14*	NbF3′H, NbDFR, LaCHS, LaCHI	Positive	[83]
	LaMYB44	NbF3′H, NbDFR, LaCHS, LaCHI	Negative	[83]
Prunus serrulata	*PsMYB77*, *PsMYB17*, *PsMYB105*	PsDFR, PsUFGT	Positive	[84]
Rosa spp.	*RcMYB1-RcBHLH42-RcTTG1*, *RcMYB1-RcEGL1-RcTTG1*	RcCHS, RcCHI, RcF3H, RcF3′H, RcDFR, RcANS, RcUFGT, RcGT1	Positive	[85]
	RrMYB5-EGL3, *RrMYB10-EGL3*	RrDFR, RrANR, RrLAR	Positive	[86]
	RrMYB108, *RrC1*, *RrMYB114*	RrAOMT	Positive	[87]
Viola wittrockiana	*VwMYB27*	VwF3H	Positive	[88]
	VwMYB113b, *VwTT8b*	VwCHS, VwF3′H, VwDFR, VwANS	Positive	[89]
Main patterns	MYB positive (75%)	Synergistic bHLH (15%)	Emerging WRKY (10%)	Critical synthesis

In edible flowers, MYB transcription factors represent the dominant regulatory group (approximately 75%) governing ACN biosynthesis across most studied species, which primarily govern ACN biosynthesis by directly binding to the promoter regions of key structural genes (e.g., CHS, DFR, ANS, UFGT) and activating downstream regulatory networks [62]. As a highly conserved regulatory mechanism across species, MYB proteins often function either independently or cooperatively with bHLH partners to trigger ACN accumulation. For example, as a typical conserved regulator, CmMYB6 in *Chrysanthemum morifolium* activates the CmDFR promoter, and its activity is markedly strengthened by synergistic interaction with MrbHLH1, representing a widespread MYB–bHLH cooperative mode [64].

Despite the predominant positive regulatory roles of MYB proteins, certain MYB transcription factors exhibit opposite functions and act as repressors in the ACN biosynthetic pathway. However, some MYB transcription factors function as negative regulators of ACN biosynthesis. For example, heterologous expression of *CmMYB4* and *CmMYB5* significantly reduces ACN content [69]. Additionally, *CmMYB12* suppresses flavonoid biosynthesis by directly regulating CmFNS, while concurrently reducing ACN accumulation through the inhibition of CmCHS, CmDFR, CmANS, and CmUFGT expression [67]. Notably, high expression of *OfMYB1* and *OfMYB2* from *Osmanthus fragrans* effectively blocks the ACN biosynthesis pathway [80].

The bHLH transcription factors can act as either transcriptional activators or repressors, directly modulating structural gene expression to regulate ACN biosynthesis [63]. *LvbHLH13* positively regulates *LvMYB5* expression independently of complex formation, subsequently activating downstream structural genes such as LvF3′H, LvDFR, and Lv3GT through a cascade mechanism to promote ACN synthesis in *Lilium Viviana* [72]. *VwMYB113b* and *VwTT8b* from *Viola wittrockiana* bind to and activate the promoters of VwCHS and VwF3′H, respectively, indirectly enhancing ACN production [89]. Synergistic interactions between bHLH and MYB factors are well-documented. *CmbHLH2* interacts with *CmMYB6*, directly binds the CmDFR promoter, and synergistically upregulates its transcriptional activity to promote ACN synthesis [65].

Similarly, the *DcbHLH1–DcMYB1* complexes enhance transcriptional activation synergistically, regulating ACN biosynthesis and petal coloration [70].

Studies on WD40 proteins independently regulating ACN biosynthesis in edible flowers remain limited. Typically, WD40 repeat proteins function as auxiliary components within the MBW (MYB–bHLH–WD40) complex to co-regulate ACN synthesis [90]. For example, in *Rosa* spp., two distinct MBW complexes positively regulate ACN synthesis in a functionally redundant manner [85], *LhWRKY44* promotes ACN accumulation via the MBW pathway in *Asiatic hybrid lily* [76].

Recent research continues to identify novel transcription factors involved in ACN regulation. *DcWRKY15* positively regulates ACN biosynthesis by directly binding to and enhancing the expression of DcCHS and DcF3H [71]. *LvWRKY75* and *LvbZIP44* directly bind promoters of key ACN structural genes, activating downstream expression to modulate the biosynthetic pathway [77,78]. These findings underscore the expanding complexity of the transcriptional regulatory network governing ACN biosynthesis and highlight the need for further mechanistic exploration.

Beyond the conventional transcriptional regulatory network clarified above, advances in modern biotechnology and insights into metabolic pathway crosstalk have further deepened the practical application of ACN biosynthesis regulation. Targeted modification of core structural genes italicized as CHS, F3H and DFR as well as upstream transcription factors through CRISPR/Cas9 gene editing [91], heterologous overexpression [92] and multi-transgene stacking [93] has become a well-established strategy to enhance ACN accumulation. Meanwhile, the ACN biosynthetic pathway exhibits intensive substrate competition and crosstalk with parallel flavonoid branches [92], including flavonol, proanthocyanidin [94] and lignin [95] metabolic pathways; fine tuning of the MBW complex and WRKY/bZIP regulatory modules can redirect metabolic flux toward ACN synthesis by inhibiting competing branch pathways [94]. Furthermore, integrated multi-omics is widely adopted to excavate novel regulatory nodes, break the metabolic bottleneck of key rate-limiting enzymes, and realize precise directional regulation of ACN enrichment, which greatly promotes the industrial utilization and germplasm improvement of ACN-rich edible flowers [96].

3 Factors Affecting the Stability of Anthocyanins from Ornamental Flowers

The stability of ACNs from ornamental flowers is a critical factor for their application in foods, cosmetics, nutraceuticals, and cut flower longevity. Owing to the electron-deficient flavylium cation, ACNs are highly reactive and prone to chemical reactions that alter their molecular structure, resulting in color fading or discoloration. Factors affecting ACN stability include chemical structure, pH, temperature, water activity, enzyme, light exposure, oxygen, copigmentation, microencapsulation, and other environmental and processing conditions [97,98].

3.1 Chemical Structure

The six anthocyanidins (Fig. 1) differ in their molecular structures, particularly in the number and position of hydroxyl and methoxy groups, which significantly influence their stability. Delphinidin contains three hydroxyl groups, making it more polar and less stable at high pH than other anthocyanidins. Methoxylated anthocyanidins (e.g., malvidin and peonidin) are generally more stable than hydroxylated ones (e.g., delphinidin). Methylation of hydroxyl groups increases hydrophobicity and molecular stability.

Glycosylation of anthocyanidins generally enhances both stability and water solubility, with di- and tri-glycosides being more stable than mono-glycosides [99,100]. Acylation is a key stabilizing factor for ACNs and is especially common in ornamental flowers such as *Clitoria ternatea* and *Ipomoea tricolor* [13,101]. When organic acids (e.g., caffeic, *p*-coumaric, and malonic acids) are esterified to the sugar moieties, they

promote intramolecular copigmentation, thereby shielding the chromophore from water and nucleophilic attack [12]. Hence, blue polyacylated ACNs (ternatins) found in butterfly pea flowers exhibited markedly high stability against light, heat, and pH variations [98]. The stability of ACNs among the five materials followed the order: butterfly pea flower > purple sweet potato > red cabbage > grape skin > eggplant peel [102]. After ACNs from mulberry were acylated with succinic acid using pyridine as a catalyst, their thermal stability, light stability, and antioxidant activity were all enhanced [103]. Purified ACNs were acylated with lipase using lauric acid or dihydroferulic acid, achieving acylation yields of 19.8% and 8.5%, respectively [104].

3.2 Temperature

ACNs are thermally sensitive compounds. Elevated temperature and prolonged exposure accelerate the hydrolysis of glycosidic bonds and acyl groups, as well as the cleavage of the anthocyanidin nucleus [98,105,106]. Heat treatments, such as pasteurization, sterilization, baking, cooking, and extended storage at high temperatures, significantly reduce ACN content [107–110].

The thermal degradation kinetics of ACNs is commonly described using a first-order reaction model, as expressed in Eq. (1):

$$\ln\left(\frac{C_t}{C_0}\right) = -k \times \mathrm{t} \tag{1}$$

where C_0 is the initial ACN concentration, C_t is the remaining ACN concentration after heating for t hours at a given temperature and pH, k is the first-order degradation rate constant.

Thermal degradation kinetics showed that the k value of roselle calyx ACN extracts increased progressively with temperature elevation from 70 to 90°C at all tested pH values (1–7); for instance, at pH 4, it rose from 0.114 h^{-1} at 70°C to 0.336 h^{-1} at 90°C [111]. When the heating temperature was increased from 60°C to 90°C at 3.6 of pH, the k value of cherry blossom ACNs (from 0.041 to 0.182 h^{-1}) increased by 4.43-fold [112]. In contrast, butterfly pea flower showed the smallest increase in k value (from 0.0195 to 0.054 h^{-1}), at only 2.77-fold under the same heating conditions [4]. The k value (h^{-1}) of ACNs in rose juice model increased with storage temperature, rising from 0.354 at 4°C to 1.962, 3.828, and 7.938 at 25, 37, and 55°C, respectively, indicating accelerated degradation at higher temperatures [110]. Therefore, high-temperature short-time processing and cool storage are essential for minimizing thermal degradation and preserving color and functionality in food applications.

3.3 pH Value

The color and stability of anthocyanins from ornamental flowers are strongly affected by pH value. Under highly acidic conditions (pH < 3), the red flavylium cation predominates and exhibits the greatest stability. As pH increases, ACNs undergo structural transformations, including proton transfer, hydration, tautomerization, and cis–trans isomerization. These reactions lead to the formation of quinoidal base, carbinol pseudobase, and chalcone structures, resulting in color fading and degradation [101]. In Fig. 3, ACNs from butterfly pea, cherry blossom, and peony exhibit red, purple, orange, blue, and brown colors at different pH values (1–12). As the pH increased from 2.5 to 5.5 at a heating temperature of 60°C, the half-life (calculated by $\ln(2)/k$) of ACNs from butterfly pea flower and cherry blossom significantly decreased from 52.94 to 27.51 h and from 26.06 to 8.05 h, respectively [4,112]. Similarly, at 90°C, pH markedly affected the half-life of cherry blossom ACNs, which decreased from 5.95 to 2.08 h. In contrast, the half-life of butterfly

pea ACNs at high temperature (90°C) ranged from 13.87 to 15.07 h and was not significantly influenced by the change of pH values.

Figure 3: Color changes of ACN extracts from butterfly pea (**a**), lotus (**b**), cherry blossom (**c**), and peony (**d**) at various pH levels ranging from 1 to 12 [102,112,113].

The vacuolar pH in plant cells is tightly regulated and determines the predominant ACN form. Similar pH-dependent behavior is observed in food systems, where ACNs show enhanced stability and red coloration in acidic products such as yoghurts, jams, and acid juices, but reduced stability and bluish or colorless tones in neutral or weakly alkaline products such as dairy beverages and bakery products [108,114]. The pH control in extraction, formulation, and food processing plays a critical role in preserving the color and stability of ACNs. Hence, acidification or buffering is commonly employed in food systems to maintain desirable anthocyanin stability, functionality, and visual quality.

3.4 Water Activity

Water activity strongly influences ACN stability by affecting molecular mobility and reaction kinetics. In general, ACN degradation increases with rising Aw due to enhanced hydration, oxidation, and hydrolytic reactions. The stability of different forms of purified pelargonidin-based ACNs was investigated during storage at pH 3.4, 25°C, and under dark conditions for 242 days to evaluate the effect of water activity (0.44–1.00) on ACN stability. The results showed that, in general, the degradation rate of ACNs decreased with decreasing water activity, with half-life values ranging from 56 to 934 days [106]. However, when the water activity of blackberry juice was adjusted to 0.34, 0.76, and 0.95 using quartz sand and heated at 100–140°C, lower water activity was found to be unfavorable for ACN stability [115].

3.5 Enzyme

Enzymes such as β-glycosidase, peroxidase, and polyphenol oxidase decrease the stability of ACNs. β-Glycosidase cleaves the glycosidic bonds, releasing unstable, poorly soluble anthocyanidins. ACNs are oxidized by polyphenol oxidase and peroxidase into colorless compounds [97]. For example, the vivid purple flowers of *Brunfelsia calycina* turn white due to the action of endogenous β-glucosidase and peroxidase within the vacuole [116]. Red rose petals contain high levels of tannins, especially epicatechin gallate and gallocatechin gallate, which can inhibit endogenous peroxidase. This enzymatic inhibition helps preserve ACN stability and color *in vivo* [117].

Cellular structures of plant materials are disrupted during food processing operations such as cutting, mixing, drying, and maceration. This releases enzymes that come into contact with ACNs and catalyze oxidation reactions. Therefore, enzyme inactivation via blanching or other techniques (e.g., pH adjustment, oxygen reduction) can improve the pigment retention [118,119].

3.6 Light and Oxygen

Light, particularly UV and visible light, induces photo-oxidation and structural degradation of ACNs. Ornamental flower pigments are especially susceptible during storage in transparent packaging. Protection from light (opaque containers, UV-blocking films) markedly improves stability [120]. Compared with dark conditions, ACNs from *Hibiscus rosa-sinensis* flowers exhibited a shorter half-life (2.79 days) and a higher degradation rate constant (0.25 day^{-1}) under light exposure [109]. The ACN content in aqueous rose extract rapidly decreased over 6 days of light exposure, reaching 50% at 2.5 days and 19.68% by day 6 [110].

The unsaturated structure of ACNs makes them vulnerable to oxidative degradation, both through direct reaction with oxygen and via oxidizing enzymes. Their stability is significantly enhanced by storage under vacuum or nitrogen [97]. The rose extract containing 0.5% hydrogen peroxide was incubated at 25°C for 50 min, and the total anthocyanin content (TAC) was found to gradually decrease with increasing time [110].

3.7 Sulfite and Ascorbic Acid

Sulfite or sulfur dioxide is widely used in foods as preservatives, reductants, and anti-browning agents, particularly in fruit products, wines, and beverages. It inhibits microbial growth and enzymatic browning by reacting with oxygen and carbonyl compounds. However, sulfites strongly affect ACNs by forming colorless C-2 or C-4 sulfonate adducts, leading to bleaching and loss of red or purple color [121]. This reaction is reversible under acidic conditions but may cause permanent color degradation during processing and storage Therefore, the use of sulfites must be carefully controlled in ACN-rich foods to balance color retention, antioxidant protection, and regulatory safety limits.

Although ascorbic acid is a nutritious antioxidant, its presence often promotes ACN degradation and color loss during processing and storage, especially at higher temperatures and neutral pH in the presence of oxygen [99,122]. It can react directly with ACNs or generate reactive oxygen species, leading to cleavage of the flavylium ring and bleaching of red–purple pigments [97]. Therefore, the addition of ascorbic acid must be carefully controlled in ACN-rich foods to maintain color stability.

3.8 Co-Pigmentation

Co-pigmentation is a molecular association phenomenon in which colorless or pale-yellow organic compounds (co-pigments) interact non-covalently with ACN pigments, primarily in their colored flavylium cation form. This interaction, driven mainly by hydrophobic π–π stacking and/or hydrogen bonding,

stabilizes the ACN molecule against nucleophilic attack by water [123]. As a result, a bathochromic shift (red-to-blue shift in the absorption maximum), increased color intensity, and improved stability against degradation caused by pH, heat, and light are observed [97].

Co-pigmentation of ACNs is generally classified into four types based on the interacting components: self-association, metal complexation, intramolecular co-pigmentation, and intermolecular co-pigmentation.

(1) Self-association refers to stacking interactions between two or more ACN molecules without the involvement of other co-pigments. This phenomenon can be observed in concentrated ACN solutions, where it leads to enhanced color intensity at high concentrations [124].

(2) Metal complexation describes the interaction between ACNs and metal ions (e.g., Al^{3+}, Fe^{3+}, and Mg^{2+}), often resulting in the development of intense blue coloration. Among ACNs only those derived from cyanidin, delphinidin, and petunidin are capable of metal chelation, due to the presence of free hydroxyl groups in the B ring. The vivid blue color of cornflower (*Centaurea cyanus*) petals arises from a supramolecular metalloanthocyanin consisting of an ACN (succinylcyanin), flavone co-pigments, and Fe^{3+}/Mg^{2+} ions [125]. Purified ACNs from iris flowers were complexed with Al^{3+} and Cu^{2+} at pH 5–6, resulting in the formation of blue and green ACN–metal chelates [126].

(3) Intramolecular co-pigmentation occurs through stacking interactions between the hydrophobic acyl moiety covalently bound to the sugar and the flavylium nucleus, thereby reducing ACN hydrolysis. For example, Dangles et al. demonstrated an interaction in ACNs from Ipomoea nil between the pelargonidin chromophore and the caffeoyl groups, with the glycosyl unit acting as a spacer [127]. An intramolecular interaction between the cyanidin chromophore and coumaric acid (a co-pigment) has also been reported [119].

(4) Intermolecular co-pigmentation refers to the association between anthocyanins and distinct co-pigment molecules, such as organic acids, phenolic acids, flavones, proteins, and polysaccharides [123,128]. This represents the most prevalent and extensively investigated form of co-pigmentation, as it plays a crucial role in enhancing color intensity and improving the stability of non-covalent ACN complexes within food matrices.

Three organic acids (tartaric, malic, and citric acids) showed chromatic effects on ACNs from *Hibiscus syriacus* flowers and enhanced their thermal stability. After heating at 90°C for 4 h, ACN retention increased by 23.05%, 13.67%, and 13.32%, respectively, compared with the control. Molecular docking and related analyses confirmed that organic acids form stable complexes with ACNs through hydrogen bonding and hydrophobic interactions [129]. Pectin–cyanindin-3-glucoside (C3G) complexes exhibited greater stability against heat, light, and intestinal digestion than C3G alone. Moreover, complexes treated with high hydrostatic pressure showed superior stability compared with those without high hydrostatic pressure [130].

Highly purified *Hibiscus sabdariffa* ACNs were interacted with three animal proteins (whey protein, casein, and ovalbumin). Experimental results showed changes in protein secondary structures, such as α-helix, β-sheet, and β-turn, and elucidated the docking active sites between proteins and ACNs. Interaction with these proteins improved the stability of ACNs during simulated digestion, with whey protein showing the strongest protective effect [131]. Casein protected lotus ACNs from degradation and improved their stability against light, heat (80°C for 2 h), and oxidation (H_2O_2 treatment). During simulated digestion, ACN retention and DPPH and ABTS scavenging activities increased in the presence of 0.1–0.2 mg/mL casein. Furthermore, casein enhanced the bioavailability of lotus ACNs in a zebrafish model [113].

3.9 Micro-/Nanoencapsulation

As mentioned above, ACNs exhibit health-promoting effects; however, their practical application in foods and nutraceuticals is limited by poor stability, resulting in color loss, degradation, and reduced bioactivity during processing and storage. Furthermore, due to low absorption and rapid metabolism in the human body, ACNs generally show low bioavailability. To overcome these limitations, micro-/nanooencapsulation has emerged as an effective strategy for the development of ACN delivery systems [97].

Micro-/nanoencapsulation is a technique in which active compounds are entrapped, coated, or embedded within a protective matrix or shell at the micrometer scale (1–1000 μm) or nanometer scale (<100–200 nm). It effectively enhances ACN stability against heat, light, oxygen, and pH variations, while improving bioaccessibility and enabling controlled release. Various micro-/nanoencapsulation techniques, including spray drying, freeze drying, ionic gelation, and liposomes, have been widely used [132]. Based on a meta-analysis of 45 studies, spray drying was the most commonly used method for ACN encapsulation (33.33%), followed by freeze drying (27.08%), gelation (20.83%), and lipid-based particles (14.58%). Carbohydrates were the dominant wall materials, with maltodextrin (19.56%) and gums (15.22%) being the most frequently used biopolymers [133]. Encapsulated ACNs from various berries retained 67–80% after 3–6 months of storage at 25°C in darkness when water activity was ≤0.33 [134].

3.9.1 Spray Drying

Spray drying is widely employed for the microencapsulation of ACNs because of its rapid processing, cost-effectiveness, simple operation, industrial scalability, high encapsulation efficiency, and favorable storage stability. Nevertheless, the exposure of atomized droplets to high inlet air temperatures (150–220°C) during drying may result in some degree of thermal damage to heat-sensitive anthocyanins [97].

Carrier selection is a critical factor influencing the encapsulation efficiency, stability, and release behavior of ACN microcapsules. An ideal carrier should possess good film-forming ability, high solubility, low hygroscopicity, and compatibility with ACNs, while providing effective protection against heat, light, oxygen, and pH variations. Proteins and polysaccharides, as stated in Section 3.8, can enhance ACN stability through intermolecular co-pigmentation. Carbohydrates such as maltodextrin are widely used due to their low cost and good drying performance, although their limited emulsifying capacity often requires combination with other materials. Gum Arabic and modified starches offer superior emulsifying and protective properties but are more expensive. Composite carrier systems are frequently employed to balance protection efficiency, processability, and cost [133].

Spray drying of aqueous *Hibiscus rosa-sinensis* petal extract with maltodextrin was optimal at 180°C and 15° Brix, yielding the highest powder recovery (17.85%), TAC (64.81 mg C3G/L), and water solubility (99.58%). The powder showed high color stability in acidic foods, which achieved the best sensory scores [135]. Using a 3.2% (w/v) starch–alginate carrier blend and an inlet temperature of 170.7°C, spray drying of *Hibiscus sabdariffa* L. achieved maximum solids recovery (60.8%) and ACN retention (96.0%) [136]. Spray drying of *Hibiscus sabdariffa* L. using maltodextrin and gum Arabic at 144°C and 7 mL/min produced ACN powder with 100.22 mg/g content and 93.87% encapsulation efficiency. The powder had low moisture, high solubility, acceptable density, poor flowability, and good compressibility. Scanning electron microscopy revealed small spherical (2–10 μm), wrinkled, irregular particles with rough surfaces [137]. Under optimal spray-drying conditions (134°C and a 1:3 maltodextrin-to-core ratio), tulip petal ACNs formed uniform, crack-free microcapsules, retaining 92.94%, 52.14%, 42.78%, and 14.13% of ACNs in apple juice after 6 weeks of storage at 4, 20, 30, and 40°C, respectively [138].

3.9.2 Freeze Drying

Freeze drying is widely applied in the microencapsulation of ACNs, as the low-temperature and vacuum conditions effectively prevent thermal and oxidative degradations, thereby preserving ACN structure, color, and antioxidant activity while improving storage stability and bioaccessibility. However, this technique has notable drawbacks, including high equipment and energy costs and long processing times [132].

Microencapsulation of saffron petal ACNs with alginate and maltodextrin by freeze-drying enhanced their storage stability (half-life) and *in vitro* gastric bioavailability, with particle sizes of 188–304 μm [139]. Freeze-dried saffron petal extracts were encapsulated with gum Arabic and maltodextrin (M7 and M20), showing no significant differences in ACN stabilization ($p < 0.01$) and maintaining stable ACN content after 10 weeks of storage [140]. Similarly, freeze-dried saffron petal extracts encapsulated with cress seed gum, gum Arabic, and maltodextrin (M7 and M20) showed no significant differences in TAC immediately after production or after 10 weeks of storage at 35°C [141].

Rose ACNs microencapsulated by freeze drying using gum Arabic and maltodextrin as wall materials showed uniform laminated structures, high retention of ACNs (95.12%) and phenolics (91.44%), and longer thermal half-lives at 70–90°C, indicating that freeze drying is more suitable than spray drying [142]. Compared with free ACNs, encapsulation of rose ACNs with β-cyclodextrin significantly increased retention by 9.24%, 9.21%, and 2.57% under heating at 70–90°C, light exposure, and strong oxidant (H_2O_2) conditions, respectively [110]. Aqueous okra flower extracts were encapsulated with maltodextrin using freeze-drying, microwave-drying, and spray-drying, all achieving > 99% encapsulation efficiency, with freeze-drying providing the highest ACN bioaccessibility (Cyanin, C3G, Cyanidin-3-rutinoside) [143].

3.9.3 Ionic Gelation

Ionic gelation is a microencapsulation technique based on electrostatic interactions between charged polymers and multivalent counter-ions, leading to the formation of a three-dimensional gel network that entraps bioactive compounds. It can be achieved using dripping–extrusion or atomization techniques. ACN extracts are first dispersed in a polymer solution (e.g., alginate, pectin or chitosan) under acidic conditions, followed by the addition of crosslinking ions such as Ca^{2+} or triphosphate, resulting in rapid gel formation and the production of microcapsules or nanoparticles [144,145].

This mild, low-cost, and eco-friendly process preserves anthocyanin structure and bioactivity while enhancing stability against pH variations, light, and oxidation. Ionic gelation also provides high encapsulation efficiency, operational simplicity, and food-grade compatibility [132]. Roselle ACN was microencapsulated by ionic gelation via dripping–extrusion and atomization, using a double emulsion (ACN/edible oil/pectin) followed by calcium chloride cross-linking. The resulting microparticles (78–1100 μm) had encapsulation efficiencies of 67.9–93.9% and showed markedly improved thermal and storage stability, as well as enhanced color retention [146]. Moreover, ionic gelation treatment significantly improved the gastrointestinal stability and enteric protection of roselle ACNs. Incorporation into pectin jelly candy was successful, achieving up to 73% retention of bioactive compounds, demonstrating strong potential for functional confectionery applications [147]. Encapsulation of black carrot ACNs using 1% pectin and 1% alginate markedly enhanced their stability and antioxidant capacity during cold storage for four weeks. ACN retention reached 91.7% in biopolymer beads and remained up to 62% in fortified yoghurt, with substantial preservation of antioxidant activity. These results demonstrate the effectiveness of ionic gelation in protecting black carrot ACNs in acidic food systems and their suitability as natural colorants in dairy applications [144].

Ionic gelation–based capsules commonly exhibit low mechanical strength and sensitivity to pH and ionic conditions, resulting in limited stability; however, these limitations can be alleviated through polymer complexation. In particular, coating alginate beads with cationic polymers such as chitosan markedly improved gel strength, surface charge, and ACN retention, enabling pH-responsive release and enhanced pigment protection, while gelatin coating effectively formed a protective protein layer that modified moisture content and structural integrity, thereby improving the functional performance of ionic gelation–derived ACN carriers in food systems [148,149].

3.9.4 Liposome

A liposome is a spherical vesicle, ranging in size from a few nanometers to several micrometers, composed of one or more phospholipid bilayers enclosing an aqueous core [132]. Liposomes are commonly used as delivery systems for bioactive compounds in food, pharmaceutical, and cosmetic applications [97,150]. Preparation methods typically include thin-film hydration, ethanol injection, and supercritical carbon dioxide techniques to control particle size and stability [151,152].

For ACN encapsulation, liposomes offer several advantages: they protect ACNs from environmental stressors such as light, oxygen, heat, and pH changes; improve dispersibility in aqueous systems; and can enhance bioaccessibility and controlled release during digestion [153]. Compared with free ACNs from roselle, liposome-encapsulated ACNs exhibited markedly enhanced antioxidant activity and a stronger inhibitory effect on melanogenesis [154]. Black carrot ACNs were encapsulated in < 50 nm liposomes, and increasing lecithin (1–4% w/w) enhanced encapsulation efficiency and stability, particularly of acylated forms, protecting them from ascorbic acid degradation over 24 h [122].

Liposomes have limitations, including limited physical stability (e.g., aggregation or leakage) and susceptibility to lipid oxidation; coating or gelling them with polysaccharides or proteins is an effective strategy to enhance their stability. Natural polysaccharides self-assemble with ACN-loaded liposomes via electrostatic interactions and hydrogen bonding to form nanoparticles, with gum Arabic coating offering the greatest stability and effectively enhancing ACN integrity, antioxidant activity, and *in vitro* bioaccessibility [155]. Layer-by-layer modification of ACN nanoliposomes with pea protein isolate significantly improved encapsulation efficiency, structural stability, and resistance to thermal, light, and digestive stresses, providing enhanced protection [156]. Liposome–casein hydrogels protect ACNs from acid-induced degradation, preserve their structure, and enhance stability, antioxidant activity, digestive performance, and bioavailability, offering a promising strategy for functional anthocyanin delivery in food and nutraceuticals [157]. The structure of ACNs encapsulated in liposomes and their further processing with polysaccharides or proteins is illustrated in Fig. 4.

Based on the above discussion, strategies to enhance the stability of ACNs from ornamental flowers include selecting acylated ACNs, applying heat treatment or blanching at relatively low temperatures and acidic pH, and storing products under low temperature, low water activity, and low-oxygen conditions in the absence of light. In addition, interactions with proteins, carbohydrates, and organic acids through co-pigmentation, as well as encapsulation techniques, can be employed to effectively protect ACNs.

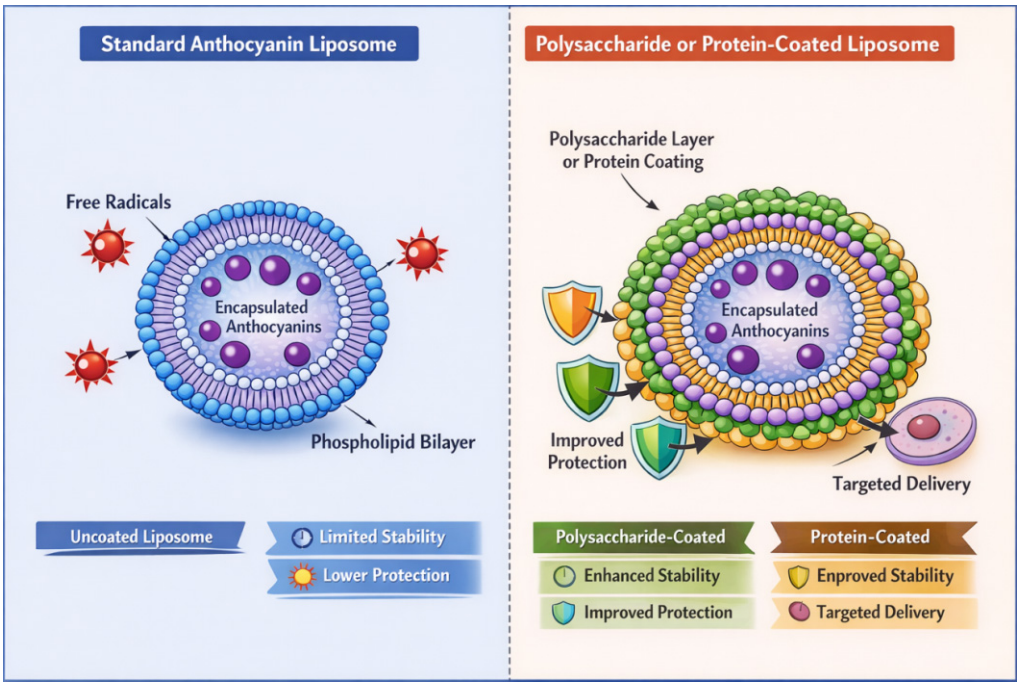


Figure 4: Schematic diagram of ACN-loaded liposomes; Left: standard liposome with ACNs encapsulated in the core; Right: ACN-loaded liposome coated or gelled with polysaccharides or proteins.

4 Extraction Method

The efficiency, safety, and cost of ACN extraction are crucial for their application in the food, pharmaceutical, and cosmetic industries. Different extraction methods vary in their efficiency, environmental impact, and influence on ACN stability. Therefore, selecting an appropriate extraction technique requires a comprehensive understanding of their advantages, disadvantages, and influencing factors. Fig. 5 illustrates the pretreatment, extraction, and post-extraction processes of ACNs from edible flowers.

Prior to ACN extraction, drying is usually carried out to prevent deterioration resulting from microbial activity and biochemical reactions, as well as to reduce the transportation cost of raw materials. There are many methods of food drying, such as hot-air drying, infrared drying, drum drying, spray drying, vacuum drying, and vacuum freeze-drying. The temperature and duration of drying, as well as the presence of oxygen, relate to the stability of ACNs and other bioactive compounds in the flowers during the process. Cherry petals dried by vacuum freeze-drying showed superior appearance, greater contents of total anthocyanins, polyphenolics (TPC), and flavonoids (TFC), and higher antioxidant activities than those obtained using the other six drying methods [158]. Sun drying and hot-air drying of fresh roselle calyces resulted in decreased brightness and redness of the aqueous extracts. Compared with the fresh calyces, hot-air drying at 70°C for 4 h resulted in ACN losses of 8.6–12.4%, whereas sun drying (6 days) caused much higher ACN losses, ranging from 39.8% to 45.5% [159]. Heat-pump drying is a new energy-efficient drying technique that operates at relatively low temperatures. When lavender flowers are dried using this energy-saving heat-pump method (24 h at 22°C), they show significantly higher TAC and TPC, as well as greater antioxidant activities, compared with those dried for 24 h at 50°C by the hot-air drying method [29]. Furthermore, grinding is commonly employed to reduce particle size of samples.

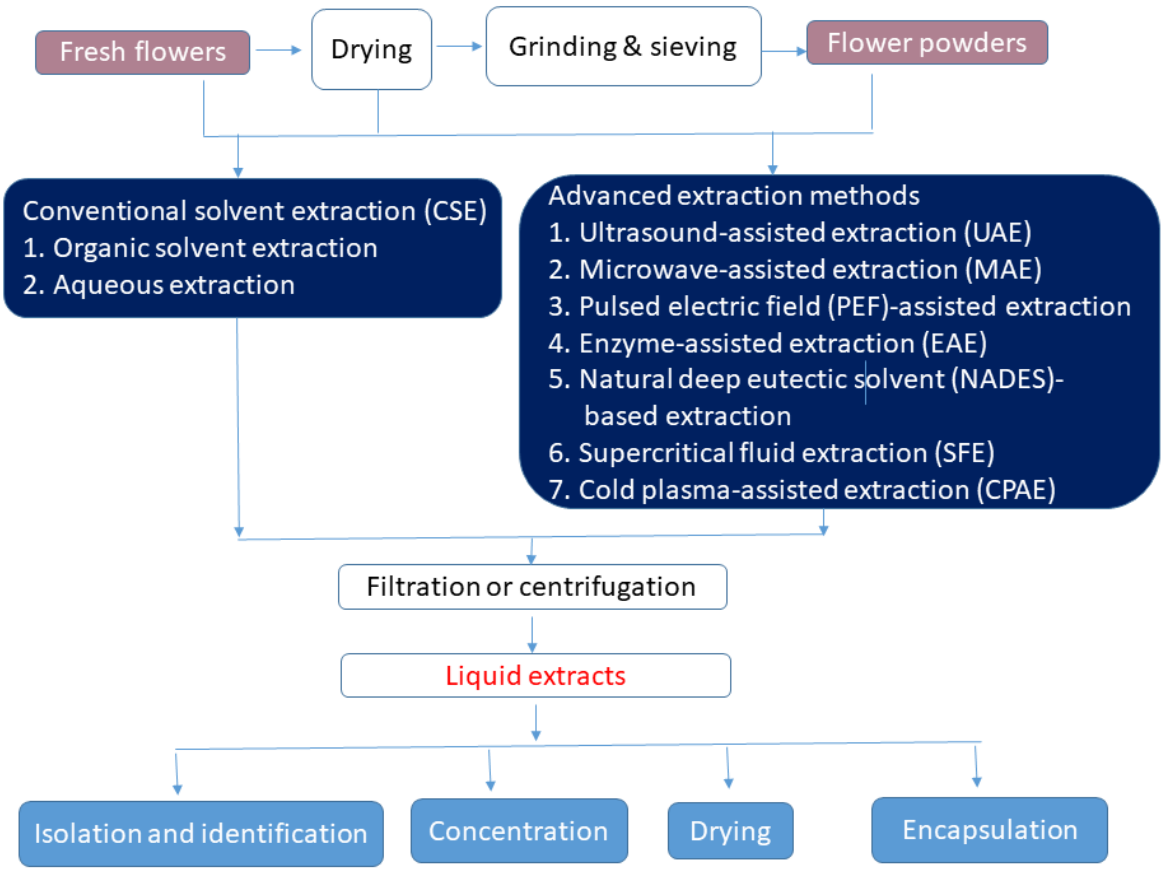


Figure 5: Schematic diagram of the pretreatment, extraction, and post-extraction processes for ACNs from edible flowers.

In this section, two categories are to be discussed in detail: conventional solvent extraction (CSE) methods and advanced extraction methods as illustrated in Fig. 5. Different varieties of edible flowers possess unique tissue characteristics and anthocyanin structures; therefore, the most suitable or optimal extraction methods vary among them. Tables 4–8 list the adequate or optimal extraction conditions for ACNs from the flowers of butterfly pea, roselle, rose, lavender, and other ornamental plants, respectively. The TAC values in these tables are preferably presented in the form of g C3G/kg DB. However, TAC values can be expressed in different forms, such as g C3G/kg WB, g C3G/L, g/kg extract, etc., depending on the different analytical methods used and when certain conversion factors are unknown. Under the extraction conditions for ACNs, these tables also present the TPC, TFC, and antioxidant activities of edible flowers. It should be noted that various bioactive substances may have distinct optimal extraction conditions compared to ACNs due to differences in their structures, polarities, and other properties. Among the 11 different types of edible flowers in Tables 4–8, the top four for total ACNs (g C3G/kg DB) are rose (33.3), saffron (10.2), roselle (10.0), and butterfly pea flower (3.5), making them good sources of red to blue ACNs for exploring industrial scale-up. Similarly, among more than 50 varieties and cultivars of edible flowers from Yunnan Province, *Rosa rugosa* Thunb (Mohong) ranked highest in TAC (Table 8) [2].

Table 4: Extraction methods for ACNs and antioxidant activities in butterfly pea flowers.

Extraction Conditions	TAC	TPC	Antioxidant Activity (DPPH Scavenge)	References
Optimal conditions for flower and powder forms: 90 min and 30 min using 90°C of water at 60 rpm and 50 mL/g of LSR	1.09–1.14 g C3G/kg DB	28.1–28.6 g GAE/kg DB	21.1–26.7 g TE/kg DB	[160]
Optimal conditions: 37.2% ethanol, 45°C, 50.75 min, 50 mL/g of LSR	2.67 g C3G/kg DB	159.2 g GAE/kg DB	25.23% of DPPH inhibition	[161]
Optimal conditions by UAE: 40°Cwater for 45 min, 10 mL/g of LSR at 160 W	1.77 g C3G/kg DB	7.35 g GAE/kg DB	63.8% of DPPH inhibition	[162]
CSE: Stir, 45°C, 45 min, 20 mL water/g petal powder MAE: 45–50°C, 2 min, 20 mL water/g petal powder	7.92 g C3G/L 6.14 g C3G/L	0.095 g GAE/kg 0.298 g GAE/kg	Antioxidant activity: CSE > MAE	[163]
(1) No enzyme: 50°C for 30 min at 6 mL water/g of LSR, then 50% ethanol for 30 min Optimal conditions in EAE: (2) Cellulase & pectinase: 1% (3) Viscozyme: 1%	2.17 g C3G/kg DB 2.64 g C3G/kg DB 3.16 g C3G/kg DB major: cyanidin-3-(*p*-coumaroyl) glucose and cyanidin-3-(*p*-coumaroyl)-rutinoside	37.3 g GAE/kg 44.7 g GAE/kg 44.7 g GAE/kg	86.7 μmol TE/g 108.1 μmol TE/g 120.4 μmol TE/g	[164]
(1) MAE: 385 W, 45 s (2) MAE plus EAE: 1.26% Viscozyme, pH 3.5, 52°C, 20 min	1.84 g C3G/kg DB 3.47 g C3G/kg DB.	44.9 g GAE/kg 68.6 g GAE/kg	87.1 μmol TE/g 122 μmol TE/g	[165]
UAE: 80°C, 50 min, 14.3 mL/g of LSR (1) Water (2) NADES: choline chloride/glycerol (1/2) with 30% water	211.63 mg D3G/L 374.65 mg D3G/L	No data	93 μmol TE/mL 156 μmol TE/mL	[166]

Note: D3G: delphinidin-3-glucoside; GAE: gallic acid equivalent; TE: trolox equivalent; LSR: liquid-to-solid ratio.

Table 5: Extraction methods for ACNs and antioxidant activities in roselle flowers.

Extraction Conditions	TAC	TPC	Antioxidant Activity (DPPH Scavenge)	References
Optimal extraction: 60°C of hot water for 30 min	4.04 g C3G/kg DB	23.58 g FAE/kg DB	35.78 g TE/kg DB; 41.93 g TE/kg DB of reducing power	[4]
Infusion by boiling water 80% ethanol, 25°C, I h, 150 rpm	12.30 g/kg extract DB; 12.96 g/kg extract DB	Total phenolic acids: 5.01 g/kg extract DB 5.60 g/kg extract DB	Inhibit of lipid peroxidation	[43]
Boiling for 15 min	3.2–9.5 g C3G/kg; Major: D3S & cyanidin-3-sambubioside	26–39 g GAE/kg	No data	[159]
(1) CSE: 80% ethanol, 72 h at 32°C, 20 mL/g of LSR. (2) Optimal conditions of UAE 40–60 min at 32°C, 20 mL/g of LSR, 80% ethanol, 40 KHz and 180 W	0.90 g C3G/kg; DB 1.85 g C3G/kg; DB	65.3 g GAE/kg DB 13.0 g GAE/kg DB	52.89% of DPPH inhibition 74.58% of DPPH inhibition	[45]
60% ethanol, 24 h at RT UAE, 5 min at 30°C& 20 KHz MAE 10 min, 60% ethanol UAE plus MAE, 15 min	14.46 g/kg 13.47 g/kg 16.34 g/kg 17.36 g/kg	182.9 g GAE/kg 163.2 g GAE/kg 177.0 g GAE/kg 208.3 g GAE/kg	230 mmol TE/kg 145 mmol TE/kg 188 mmol TE/kg 254 mmol TE/kg	[167]
MAE: Optimal conditions 72°C, 15 min, 70% ethanol, 40 mL/g of LSR	D3S: 100–680 mg/kg; Cyanidin-3-sambubioside: 50–350 mg/kg	No data	No data	[168]

Table 5: *Cont.*

Extraction Conditions	TAC	TPC	Antioxidant Activity (DPPH Scavenge)	References
(1) CSE: water, 100°C 5 min, 100 rpm (2) UAE: 75% acidified ethanol, 10 min, room temperature (3) EAE by pectinase (4) EAE by cellulose (5) EAE by mixed enzymes	3.2 g C3G/kg DB 9.4 g C3G/kg DB 9.4 g C3G/kg DB 9.8 g C3G/kg DB 10.0 g C3G/kg DB Major: D3S & C3G	24 g GAE/kg 85 g GAE/kg 71 g GAE/kg 79 g GAE/kg 84 g GAE/kg Major: chlorogenic, gallic, & caffeic acids	340 mmol TE/kg 310 mmol TE/kg 300 mmol TE/kg 385 mmol TE/kg 100 mmol TE/kg	[169]
UAE: 25°C, 20 min (1) Water (2) 70% ethanol (3) NADES: sodium acetate/formic acid	6.44 mg D3S/g 6.80 mg D3S/g 10.62 mg D3S/g	141 mg GAE/g 141 mg GAE/g 233 mg GAE/g	313 mmol TE/g 354 mmol TE/g 343 mmol TE/g	[170]
NADES: choline chloride/citric acid choline chloride/glycerol choline chloride/ethylene glycol	187 mg/L 96 mg/L 131 mg/L	No data	No data	[171]

Note: D3S: delphinidin-3-sambubioside.

Table 6: Extraction methods for ACNs and antioxidant activities in rose flowers.

Extraction Conditions	TAC	TPC	Antioxidant Activity (DPPH Scavenge)	References
25 cultivars Methanol with 0.3% HCl, at 4°C in dark	0.20–12.07 g C3G/kg WB; Major: cyanidin-caffeoyl-glucoside, cyanidin-coumaroyl-glucoside, cyanidin-glucoside, pelargonidin-glucoside	0.2–26 g GAE/kg WB TFC: 0.1–7.1 g QE/kg WB	304–1403 mmol TE/kg WB	[3]
13 cultivars 95% ethanol with 1.5 N HCl, 15 mL/g of LSR, standing at 4°C for 13 h	0.008–0.250 g/kg WB	41.9–243 g GAE/kg WB TFC: 0.35 g/kg WB	Total antioxidant activity: 38.1–222.2 mmol TE/kg	[40]
Methanol with HCl	1.64–1.80 g/kg WB; Major: peonidin 3,5-diglucoside	22–25 g/kg WB; Major: ellagitannins	No data	[172]
80% ethanol with 0.1 N HCl (1) UAE: 40 mL/g of LSR, 30°C, 15 min (2) Soxhiet extraction: 100 mL/g of LSR, 2.5 h (3) Condensing reflux extraction: 40 mL/g of LSR, 150 min (4) Maceration extraction: 40 mL/g of LSR, 25°C, 48 h	(1) 32.0 g C3G/kg (2) 30.0 g C3G/kg (3) 33.3 g C3G/kg (4) 29.6 g C3G/kg	No data	No data	[173]

Table 7: Extraction methods for ACNs and antioxidant activities in lavender flowers.

Extraction Conditions	TAC	TPC	Antioxidant Activity (DPPH Scavenge)	References
80% ethanol, 30 min with ultrasound bath	0.2–0.3 g/kg	66.5–84.6 g/kg	IC_{50} of reducing power: 25–33 μg/mL	[174]
Boiling water for 5 min	0.40–0.61 g C3G/kg DB	164–252 g GAE/kg DB	61–127 μmol TE/g DB	[175]
Methanol with HCl (85:15, V/V), 24 h at RT	0.099 g/kg DB	Total phenol acids: 5 g/kg DB		[176]
NADES (choline chloride: formic acid) plus UAE (40°C, 60 min)	No data	9.76 g GAE/kg	8.86 g TE/kg	[177]

Table 8: Extraction methods of ACNs and antioxidant activities in some edible ornamental flowers.

Flowers	Extraction Conditions	TAC	TPC	Antioxidant Activity (DPPH Scavenge)	References
Cherry blossoms	(1) Aqueous extraction: 90°C, 30 min at 50 mL/g of LSR and 100 rpm (2) 60% ethanol with 1% HCl: 40°C, 30 min, 50 mL/g of LSR and 100 rpm	0.13 g C3G/kg DB 0.19 g C3G/kg DB	79.8 g GAE/kg DB 72.6 g GAE/kg DB	140 g TE/kg DB 121 g TE/kg DB	[112]
Cherry blossoms	80% methanol with 1% HCL (V/V), 4°C for 2 h and 6 mL/g of LSR	0.1–1.6 g/kg WB; major: C3G and cyanidin-3-O-(6-O-malonyl-β-glucoside)	No data	No data	[84]
Chinese hibiscus	Optimal conditions: 20 mL/g of LSR, pH 4.6 of citrate-phosphate buffer, 4 h at 25°C	0.46 g C3G/kg WB	33.74 mg GAE/100 mL	85.15% of DPPH inhibition	[109]
Lotus	70% methanol with 2% formic acid, 10 mL/g of LSR, stirring at 4°C for 36 h in dark	0.24–0.59 g/kg WB; major: 3-O-glucosides of malvidin, delphinidin, & petunidin.	0.74–1.30 g/kg WB of flavones and flavonols; most abundant: kaempferol derivatives	No data	[31]
Lotus	Stir at 90°C of water for 1 h; 100 mL/g of LSR	No data	12.1–26.6 g GAE/kg	7.2–9.4 μmol TE/kg DB	[34]
Okra (*Abelmoschus esculentus*)	Optimal conditions: 60°C of water for 40.5 min, and 42.5 mL/g of LSR	0.57 g C3G/kg DB; major: cyanidin-3-rutinoside and C3G	No data	No data	[143]
Tree peony (*Paeonia suffruticosa*)	Optimal condition of MAE-DES: 57°C, 12 min, 43 g/g of LSR, betaine/1,2-propanediol	2.15 g C3G/kg	321.6 g GAE/kg	No data	[178]
European peony (*Paeonia officinalis*)	EAE plus UAE: EAE: cellulose, 40°C, pH 4.8; UAE: 30 min, 150 W, 40 kHz, 50% amplitude, 70% ethanol, 50 mL/g of LSR	0.72 g C3G/kg DB	39.85 g GAE/kg; TFC: 23.7 g QE/kg	81% of DPPH inhibition	[179]
Saffron	Optimal condition: microwave pretreatment (energy density, 0.16–0.54 kJ/mL), 3.33 mL/g of LSR at 65°C	10.19 g C3G/kg DB; major: delphinidin	31.33 g GAE/kg	2.40 mmol TE/g dry extract	[180]
Saffron	CSE: acidic ethanol (50%, pH 2), 25°C, 8 h, 40 mL/g of LSR Optimal conditions of MAE 48°C, 9.3 min, 77.5 mL acidic ethanol (50%, pH 2)/g tepal of LSR	CSE: 136.96 g C3G/kg MAE: 105.32 g C3G/kg.	No data	No data	[181]
50 edible flowers	UAE: 25 mL/g of LSR, 70% ethanol, 60°C for 45 min	*Rosa rugosa* Thunb (Dianhong) had the highest TAC, 177 g C3G/kg	*Prunus mume* had the highest TPC, 244 g GAE/kg. *Osmanthus fragrans* Lour had the highest TFC, 68 g RE/kg	*Rosa rugosa* Thunb. (Mohong) exhibited the strongest DPPH and ABTS radical scavenging activities	[2]

4.1 CSE

CSE, which employed (acidified) methanol, ethanol, and water as solvents, is the most widely used and fundamental method for obtaining ACNs from edible ornamental flowers. Its advantages are its simplicity,

low equipment cost, and suitability for laboratory-scale studies. However, the major disadvantages include long extraction time, high solvent consumption, and potential degradation of ACNs due to exposure to high temperatures, oxygen, or light. Additionally, organic solvents may pose environmental and health risks. The extraction yield of ACNs and other bioactive compounds from edible flowers is influenced by factors such as solvent type, pH, temperature, extraction time, particle size, LSR, and agitation, as discussed below.

4.1.1 Cultivar and Harvesting Time of Flower

The cultivar of edible ornamental plants affects flower color, and flower color is closely related to pigment composition and anthocyanin content. In general, flower cultivars with redder or darker coloration tend to contain higher levels of ACNs indicating that they are richer sources of ACNs. Red cultivars of *Nelumbo nucifera* and *Hibiscus sabdariffa* contain higher ACN levels than pink cultivars, whereas yellow, white, and red/white pied cultivars contain little to no ACNs [31,45]. Among various rose cultivars, anthocyanin content followed the order: red > light red > pink > white. The TAC of roses increased from the bud stage to the fully open flower stage and then decreased during senescence [182]. Petals of sacred lotus harvested at the onset of rainy season exhibited higher TPC and antioxidant activities than those harvested at other times [34].

4.1.2 Kinds of Solvent and pH

Regarding extraction, it is essential to understand the polarity characteristics of the target compounds in raw materials. Polar compounds dissolve in polar solvents, whereas nonpolar compounds dissolve in nonpolar solvents. Different solvents and pH levels significantly impact ACN extraction for ornamental flowers [43,183]. ACNs in flowers possess certain polarity; therefore, they are traditionally extracted using methanol, ethanol, acetone, or water as solvents [98]. In addition, aqueous organic solvents are often acidified with hydrochloric acid to stabilize the flavylium cation structure of anthocyanins and to destroy cell structure, thereby enhancing anthocyanin yield [176]. Ethanol or water, being less toxic and more environmentally friendly, is increasingly preferred in food-grade ACN extraction. Organic solvents can alter the cellular structure of floral tissues at low temperatures, thereby facilitating the extraction of ACNs; in contrast, when water is used as the solvent, elevated temperatures are required to achieve efficient extraction [43,84]. The extraction efficiencies and advantages of different solvents for anthocyanins are shown in Table 9.

Table 9: Comparative analysis of solvent extraction for ACNs from edible flowers.

Solvent	Relative Polarity	Extraction Efficiency	Advantage
Methanol	76	Highest	Analytical purposes (e.g., HPLC); extracts both polar and semi-polar anthocyanins with high yields.
Ethanol	65	Higher	Industry standard; high penetration into cells; denaturation of cell membrane; Inhibition of polyphenol oxidase; generally recognized as safe.
Water	100	Medium-high	Non-toxic, edible, cheapest, ideal for food-grade extracts
Acetone	36	Medium	Excellent for breaking hydrophobic interactions between ACNs and cell walls; inactivation of oxidizing enzymes.

The extraction efficiency of ACNs from butterfly pea flower powder decreased in the following order: ethanol > methanol > water > ethyl acetate > acetone > diethyl ether [183]. Although aqueous extraction (90°C for 30 min) showed superior ACN recovery from intact CT flowers compared with 60% ethanol extraction (40°C for 30 min), ethanol extraction was more effective for powdered samples, indicating that sample physical structure strongly influences ACN extractability [160]. Compared with acidified ethanol extraction (40°C for 30 min), hot water extraction (90°C for 30 min) yielded 68.23% and 71.41% of the TAC for cherry petals and powders, respectively, while the TPC levels were similar or higher [112].

4.1.3 Extraction Temperature and Time

Both temperature and time of extraction are critical factors influencing the efficiency of ACN extraction. In general, either high-temperature short-time or low-temperature long-time method is adopted for ACN extraction from edible ornamental flowers. Appropriate heat treatments for some edible ornamental flowers can enhance ACN yield by reducing solvent viscosity, increasing diffusion rates, and facilitating the disruption of cell walls and vacuolar membranes, thereby improving mass transfer from petal tissues to the solvent. For example, the optimum conditions for anthocyanin extraction from butterfly pea flowers were 37.2% ethanol, 45°C, 50.75 min, and an LSR of 50 mL/g [161]. When extracted with water at 30–90°C for 30 min, the TACs of butterfly pea and cherry blossoms reached their highest levels at 90°C. Furthermore, prolonged extraction at 90°C (60–120 min) resulted in a pronounced decrease in ACN content, likely due to the thermal instability and oxidation of anthocyanins [112,160]. However, the optimal extraction temperature and duration for roselle calyces was 60°C for 30 min [4]. Owing to differences in floral tissue and cellular structures, as well as solvent properties, optimal extraction conditions must be determined experimentally, with careful consideration of the balance between mass transfer efficiency and ACN stability.

4.1.4 Particle Size, LSR, and Others

Particle size strongly influences ACN extraction efficiency by affecting mass transfer and solvent accessibility. Reducing particle size increases the specific surface area and shortens the diffusion path length, thereby facilitating solvent penetration and the release of ACNs from vacuolar tissues. Hence, moderate grinding can markedly enhance extraction efficiency. However, excessively fine particles may lead to particle agglomeration, increased slurry viscosity, and enhanced exposure to oxygen or high temperature, which can negatively affect ACN stability and recovery. The finest cherry petal powder resulted in the highest TAC, TPC, and antioxidant activity among all particle sizes (<0.25 mm~14 mm), owing to enhanced mass and heat transfer [112].

An increased LSR value enhances the concentration gradient and prevents solvent saturation, thereby promoting ACN diffusion into the solvent. However, excessive solvent volumes increase solvent consumption and dilute the extract without a proportional improvement in recovery. The common LSR used ranges from 5:1 to 50:1 (mL/g) [5,109]. For example, Chinese hibiscus was extracted in a citric acid–phosphate buffer (pH 4.6) at 25°C for 4 h using different LSRs ranging from 10 to 25 mL/g, and the results showed that an LSR of 20 mL/g was optimal [109].

Appropriate agitation (60–200 rpm) improves solvent–solid contact and reduces boundary layer resistance, accelerating mass transfer and ACN release, whereas excessive agitation may elevate dissolved oxygen levels and promote oxidative degradation [184]. Oxygen and light reduce ACN stability through oxidative reactions and photodegradation. Therefore, minimizing oxygen exposure by nitrogen flushing or vacuum conditions, as well as shielding from ultraviolet or strong visible light, is often necessary during extraction.

4.2 Advanced Extraction Methods

Green technology is a current development trend focused on sustainability, safety, and resource efficiency throughout sampling, preparation, measurement, and waste management. The Green Analytical Procedure Index is a comprehensive tool used to evaluate how environmentally friendly an analytical method is—from sample collection to final determination [185]. Therefore, research and development of extraction methods for isolating ACNs or other bioactive compounds from edible flowers have increasingly focused on green, sustainable, safe, and efficient approaches, such as ultrasound-, microwave-, and pulsed electric field-aided techniques. These advanced extraction methods are illustrated in detail below. A comparison of the extraction efficiency, cost, scalability, and suitability for industrial manufacturing of different extraction methods for anthocyanins is shown in Table 10.

Table 10: Comparison of various extraction methods for ACNs in terms of extraction efficiency, cost, scalability, and feasibility for industrial production.

Extraction Methods	Extraction Efficiency	Cost	Scalability	Industrial Feasibility
CSE	Moderate (degradation; long time)	Low (solvents, energy, labor)	High (simple tanks/stirrers)	High
UAE	High (cavitation breaks cells, short time)	Low–moderate (equipment cost, low solvent use)	High (multiple probe/flow-through systems)	High
MAE	High (rapid heating)	Moderate (equipment cost, low solvent)	Moderate (batch; continuous challenging for heat-sensitive compounds)	Moderate (good for small-to-medium scale; uneven heating risks)
PEF-Assisted	Moderate–high (electroporation at low temperature)	High (equipment cost)	Moderate	Moderate (high investment)
EAE	High (cell wall degradation, gentle, long time)	Moderate to high (enzymes costly)	Moderate (bioreactors)	Moderate
NADES	High–very high (excellent stability & biocompatibility)	Moderate (pure components)	Moderate (viscosity limits mixing)	Remains in the developmental phase
SFE	Low (polarity mismatch; requires co-solvent)	High (CO_2, equipment cost)	Moderate (batch; complex scale-up)	Low (for anthocyanins)
CPAE	Moderate (cell wall etching)	High (equipment cost)	Low (lab-scale only)	Very Low (still experimental)

4.2.1 UAE

UAE is an emerging non-thermal technique that uses ultrasonic waves (20–200 kHz of frequency) to generate cavitation bubbles in the solvent, leading to the disruption of cell walls and membranes and enhancing mass transfer between the solvent and the plant matrix. Compared with CSE, this method can greatly reduce extraction time, extraction temperature, and solvent consumption. Therefore, UAE is considered an efficient, simple, and energy-saving technique for extracting bioactive compounds from plants [186]. Özgür et al. compared three extraction methods (UAE, Soxhlet, and maceration) for ACN extraction from red rose petals. UAE achieved the highest TAC (32.0 g/kg) at 40 mL/g, 30°C, and 15 min. Soxhlet extraction yielded 30.0 g/kg (100 mL/g, 2.5 h), while maceration gave 29.6 g/kg (40 mL/g, 25°C, 48 h), using 80% ethanol with 0.1 N HCl as the solvent in all cases [173]. For roselle, using 80% ethanol at 32°C,

CSE for 72 h yielded 0.90 g C3G/kg while UAE for 40–60 min at 32°C, 40 kHz, and 180 W increased the TAC to 1.85 g C3G/kg [45]. Similarly, the TAC for roselle extracted by UAE was 2.94 times greater than that by CSE in Table 4 [169]. Ultrasound treatment (162.5 W, 20 kHz, 60°C, 30 min) significantly enhanced ACN extraction from intact CT flowers (+66.70%), whereas UAE of CT powders resulted in a lower TAC than the water extract obtained at 60°C for 30 min [160].

ACN yield during UAE is influenced by factors such as ultrasonic power, frequency, amplitude, temperature, extraction time, solvent type, and liquid-to-solid ratio. Optimization of these parameters is therefore essential. The optimal UAE conditions for butterfly pea petal powder were water extraction at 40°C for 45 min with an LSR of 10 mL/g and an ultrasonic power of 160 W, yielding 1.77 mg/g of TAC and 7.35 mg GAE/g of TPC [162]. Nevertheless, excessive ultrasonic power, high temperature, or prolonged sonication can lead to thermal degradation and structural modification of ACNs. Increasing both extraction temperature and electric power of UAE raised free radical levels and medium temperature, thereby accelerating the degradation of bioactive compounds in butterfly pea extracts [162,187]. Moreover, UAE can be combined with other advanced extraction methods (e.g., MAE or DESs) to improve both extraction yield and sustainability [167].

In summary, UAE is a non-thermal, efficient, and green extraction method that has been widely studied and well developed for extracting anthocyanins and other bioactive compounds from flower materials, as summarized in Table 10.

4.2.2 MAE

Microwaves are a type of electromagnetic radiation with frequencies ranging from approximately 300 MHz to 300 GHz. MAE utilizes microwave energy to heat the solvent and sample rapidly and uniformly, enhancing cell wall rupture and the diffusion of phytochemicals into the solvent [181]. The main advantages are short processing time, and reduced solvent consumption, and high extraction efficiency. For roselle, CSE with 60% ethanol for 24 h at room temperature yielded a TAC of 14.46 g/kg, whereas MAE for 10 min at 180 W increased TAC to 16.34 g/kg, and the combined UAE–MAE gave the highest TAC (17.36 g/kg) [167]. Adding a microwave pretreatment (65°C) to the CSE process (acidified water) reduced the extraction time by up to 12-fold and increased the extraction efficiency of TPC and TAC from saffron by more than 28%, even at low microwave energy densities (0.16–0.54 kJ/mL) [180]. Nevertheless, MAE extraction of butterfly pea flower powder (45–50°C for 2 min, LSR 20 mL/g) gave lower TAC and antioxidant activities but higher TPC and TFC than water CSE (45°C for 45 min), with a much shorter extraction time [163]. However, microwaves can easily cause localized overheating, which may accelerate ACN degradation, especially at high temperatures [181]. Proper control of microwave power and extraction time is critical to prevent the pigment loss. MAE is particularly suitable for thermally stable pigments and phenolic compounds, but for heat-labile ACNs, milder extraction conditions are recommended.

4.2.3 PEF-Assisted Extraction

PEF technology is an emerging non-thermal processing technique that has gained increasing attention for enhancing the extraction of heat-labile bioactive compounds, particularly ACNs, from plant materials. PEF involves the application of short, high-voltage electric pulses, typically in the range of 0.5–10 kV/cm, which induce electroporation of plant cell membranes. When the transmembrane potential exceeds a critical threshold, reversible or irreversible pores are formed in the membrane, leading to increased permeability and facilitating the release of intracellular bioactive compounds into the extraction medium [188].

In ACN extraction, PEF is mainly applied as a pretreatment prior to CSE. The ACN yield obtained by PEF–assisted extraction is markedly affected by electric field intensity, pulse number, pulse duration, and overall energy input. Some studies have reported that PEF pretreatment significantly improves ACN yield, shortens extraction time, and reduces solvent consumption in plant foods, including berries [189,190], grape [191], purple-fleshed potato [192], and red cabbage [193]. Owing to its mild processing conditions, PEF effectively preserves anthocyanin structure, color intensity, and antioxidant activity, which are often compromised during thermal extraction [194]. However, to date, very few studies have investigated the application of PEF for the extraction of ACNs from flowers. Rose petals suspended in a low-conductivity medium were treated with ten 10-μs pulses at 6 kV/cm and frequencies of 0.17–10 Hz. The results demonstrated that reducing the frequency to 0.17 Hz efficiently disintegrated the petal tissue, highlighting its potential to enhance petal extraction processes [195].

PEF-assisted extraction is well aligned with green processing strategies, as it allows the use of water or low-concentration ethanol as environmentally friendly solvents and can be integrated with other emerging technologies, such as enzyme- or ultrasound-assisted extraction, to further improve extraction efficiency [188]. However, some disadvantages still restrict its scalability and industrial application, particularly the high cost of equipment and energy consumption.

4.2.4 EAE

To improve the recovery of bioactive compounds from plant materials, several hydrolytic enzymes, including pectinase, cellulase, hemicellulase, and β-glucanase, are used to degrade cell wall components such as pectin, cellulose, and hemicellulose. EAE is typically conducted under mild conditions, at moderate temperatures (30–50°C) and controlled pH, which preserve the structural integrity, color, and antioxidant capacity of ACNs and maintain the activity of the hydrolytic enzymes. Thus, EAE is an effective, eco-friendly, and safe method for improving ACN recovery from plant materials [196].

Studies on flowers such as butterfly pea, roselle, rose, and peony have shown that enzyme pretreatment significantly enhances ACN yield and extraction efficiency compared with CSE [197]. The addition of enzymes (cellulase, pectinase, and Viscozyme) significantly increased the TAC, TPC, and antioxidant activity of butterfly pea flower extracts. Specifically, treatment with 1% Viscozyme at pH 3.5 and 50°C for 30 min produced a 33.3% higher TAC than extraction without enzymes, which was supported by SEM images showing cell wall disruption [164]. Extraction of roselle using enzymes (cellulase, pectinase, and enzyme mixtures) resulted in significantly higher TAC, TPC, and antioxidant activities than CSE (hot water at 100°C for 5 min) [169].

EAE aligns with green processing principles by allowing the use of aqueous or low-ethanol solvents and enabling combination with technologies such as microwave [165] or ultrasound [179] for synergistic effects. Nevertheless, enzyme cost, specificity, and stability remain key limitations. Additionally, enzymatic hydrolysis must be carefully controlled, as excessive treatment can lead to pigment degradation or alteration of ACN structure, such as deglycosylation.

4.2.5 NADES-Based Extraction

DESs are eutectic mixtures formed by hydrogen bond donors and acceptors, exhibiting melting points significantly lower than those of their individual components [198]. NADES represent a specific subclass of DESs in which all components are naturally occurring primary metabolites, such as organic acids, sugars, amino acids, and choline. These solvents generally exhibit lower toxicity, higher biocompatibility, and improved environmental friendliness. In ACN extraction, NADES act as efficient green solvents through

multiple mechanisms, including strong hydrogen bonding, polarity compatibility, and pH stabilization. Furthermore, NADES can swell and partially disrupt plant cell walls, increasing membrane permeability and promoting the release of intracellular ACNs. Consequently, NADES have attracted increasing attention as green solvents for the extraction of ACNs from edible and medicinal plants, particularly in food and pharmaceutical applications [199].

Extraction efficiency of ACNs from ornamental plants is highly affected by the solvent composition, pH, polarity and viscosity of DES [198]. Among the three DES tested for the extraction of ACNs from roselle, choline chloride-citric acid showed the highest yield (187 mg/L), followed by choline chloride-ethylene glycol (131 mg/L) and choline chloride-glycerol (96 mg/L) [171]. Using a sodium acetate/formic acid-based NADES under ultrasound assistance, the molar ratio of the two components significantly affected ACN extraction from *Hibiscus sabdariffa* calyces. Moderate water addition significantly reduced the viscosity of NADES and markedly increased the yields of ACNs and polyphenols due to improved mass transfer in the extraction matrix. Moreover, this NADES extraction method yielded significantly higher TAC (+56.2%) from roselle flowers than that obtained using water or 70% ethanol in Table 5 [170]. Similarly, under ultrasound assistance, choline chloride/glycerol-based NADES enabled more efficient extraction of anthocyanins (+77.2%) from butterfly pea flowers than water in Table 4 [166]. For the combination of DES with microwave technology, the optimal conditions for extracting ACNs from peony petals were 57°C, 12 min, an LSR of 43 g/g, using betaine/1,2-propanediol as the DES. Low-viscosity betaine-based DES showed superior extraction performance, whereas temperatures above 60°C significantly reduced ACN content. Morphological analysis indicated greater tissue disruption with DES than with 60% ethanol, explaining the higher extraction yields. Hydrogen bonding interactions between DES and active compounds played a key role, with a maximum interaction energy of 361 kJ/mol [178].

In summary, NADES-based extraction is an ecofriendly, safe, green, and sustainable technique for ACN recovery, and its efficiency can be enhanced by ultrasound or microwave assistance. Nevertheless, difficulties in solvent removal and product purification remain major challenges for scalability and application in the food industry.

4.2.6 SFE

SFE usually using carbon dioxide as the supercritical solvent, offers an environmentally friendly and solvent-free alternative. However, since ACNs are polar molecules, carbon dioxide alone is inefficient for their extraction. To overcome this limitation, modifiers such as ethanol or water are often added to increase polarity. Under the optimal SFE conditions (160 atm, 50°C, and a co-solvent ethanol flow rate of 2.0 g/min), TAC and TPC from dried jamun fruit pulp powder reached 2.31 g/kg and 11.43 g GAE/kg, respectively [200]. Six ACNs from *Chaenomeles sinensis* petals were successfully isolated and analyzed within 300 min using SFE with a co-solvent mixture (n-butanol, acetonitrile, etc.) combined with high-speed countercurrent chromatography [201]. SFE is ideal for producing high-purity extracts, but it requires expensive equipment and precise control of pressure and temperature. Consequently, SFE is less commonly used for anthocyanins.

Due to the non-polar nature of carbon dioxide, SFE is an effective method for obtaining essential oils, oleoresins, and volatile compounds from edible flowers such as lavender, rose, peony, and jasmine, which are valuable for the perfume, cosmetic, and food industries [202–204]. It can also extract bioactive compounds, including linalool, eucalyptol, ursolic acid, sitosterol, and cannabinoids. When a co-solvent such as ethanol is used, SFE is also suitable for extracting polar bioactive compounds, such as phenolics and flavonoids [205].

In summary, the advantages of SFE include the absence of organic solvent residues, low-to-moderate temperature operation (35–60°C), prevention of oxidation, and the ability to be scaled up for industrial production. However, there have been no literature reports on the extraction of ACNs from ornamental flowers using this technique. Therefore, it is worthwhile to investigate the extraction of these flower ACNs by SFE with co-solvents such as ethanol or water.

4.2.7 CPAE

Cold plasma (CP), characterized as a partially ionized gas sustained at near-ambient temperature, is generated through the application of a high-voltage electric field to a working gas such as air, nitrogen, or argon. This process yields a non-equilibrium plasma rich in reactive oxygen and nitrogen species, ions, electrons, free radicals, and ultraviolet photons, while maintaining a low thermal footprint. CP can effectively disrupt cell wall structure via physical and chemical etchings, increase surface hydrophilicity of plant materials, and thus significantly improve the extraction efficiency of phytochemicals, particularly polyphenols and essential oils [206]. The principal advantages of CP technology include its non-thermal operational mode, which ensures the integrity of heat-labile compounds; high processing efficiency; and its alignment with green chemistry principles through the potential reduction of solvent and energy consumption. A concurrent benefit is its effective surface decontamination capability [207].

CPAE is a very new research field, and its current application in ACN extraction of flowers is still very limited. When aqueous samples of blue pea flower were treated with cold plasma at higher power or for longer times, it increased the levels of ACNs (by up to +92%) and phenolic compounds (by up to +32%). However, it degraded pigments in powdered samples due to greater radical exposure. This difference shows that the physical form of the plant matrix is critical [208]. Treating lotus flower powder with a low-pressure CP system at 2.5 kV for 5 min significantly increased TFC from 358 to 898 mg QE/kg. Meanwhile, TPC only appeared a slight increase, and antioxidant activity (mg ascorbic acid equivalent/kg) rose from 429 to 766 [209]. Using the CP (200 V for 5–10 min) plus EAE method to extract phenolic compounds (21 identified) from marigold petals resulted in a yield increase of 15% to 120% compared to conventional water-based CSE [210]. Compared to dielectric barrier discharge treatment, glow discharge cold plasma treatment resulted in higher levels of pelargonidin 3,5-diglucoside, greater antioxidant activity, and increased bioaccessibility of some phenolic compounds in rose flowers [211]. For *Berberis vulgaris* fruit, optimal bioactives extraction with vacuum-cold plasma (80 W, 5 min) produced ACN and polyphenol yields (256.32 and 433.71 mg/L) comparable to PEF extraction [189].

Cold plasma technology represents a promising, non-thermal, environmentally friendly, and sustainable processing method for the extraction of bioactive compounds from plant materials. By modulating operational parameters—such as gas composition, applied voltage, and exposure time—the extraction of various valuable phytochemicals from flowers can be effectively optimized. However, the practical application of this technique faces several challenges. These include its limited penetration depth into samples, high initial equipment costs, the risk of over-treatment leading to excessive oxidation of target compounds, and a still incomplete understanding of the chemical interactions between plasma species and complex plant matrices. Thus, further research on edible flowers is essential for advancing the scalability and industrial adoption of cold plasma-assisted extraction.

5 Applications in Food Industry

The use of ornamental flowers in food has a long history, dating back centuries across various cultures. Owing to their richness in ACNs, polyphenols, phenolic acids, flavones, essential oils and dietary fibers,

edible flowers and their extracts are increasingly incorporated into a wide range of food products, including beverages, baked goods, confectionery products, dairy products, and meat products, as shown in Table 11. Beyond their visual appeal, flowers contribute distinctive aromas, flavors, and textures, thereby enhancing the sensory quality of foods. Moreover, many flowers provide nutritional and bioactive compounds that offer potential health benefits, such as antioxidant, anti-inflammatory, and antimicrobial effects (Table 2), thus adding functional value to both culinary and processed food products.

Table 11: Applications of some edible ACN-rich flowers in food industry.

Flowers	Forms	Optimal Amount (%)	Food Products	Results	References
Banana bract	ACN-rich dietary fiber powder	2%	Bread	Bread added the powder showed the best overall quality, with better volume, texture, color, sensory acceptability, and higher ACN content, while also reducing starch digestibility.	[212]
Butterfly pea	Petal powder	6%	Cookie	Fortified cookie with higher TPC, and antioxidative activities in ABTS and DPPH, but lower hydroperoxide.	[213]
Butterfly pea	Aqueous extract	20–30%	Noodle	Produce blue noodles with high TAC, TPC, antioxidant activities, and desirable sensory qualities.	[107]
Butterfly pea	Aqueous extract	5%	Baked bread	The addition of CTE decreased bread starch digestibility through inhibition of pancreatic α-amylase.	[214]
Butterfly pea	Aqueous extract	20–30%	Steamed bread	Produce blue Chinese steamed bread with high TAC, TPC, antioxidant activities, and acceptable sensory quality.	[215]
Butterfly pea	Aqueous extract	The mixture (CT extract, alginate, and sugar) was dropped and gelled using 1.5% $CaCl_2$	Flavored sweet water spheres	Edible spheres prepared exhibit good elasticity and texture, retained high antioxidant activity, and maintain acceptable appearance and structural integrity for up to 7 days at 5°C.	[216]
Butterfly pea	Aqueous extract	10%	Ice cream	Lemon juice lowered the pH (6–4), shifting the ice cream color from blue to purple and significantly improving consumer acceptance of butterfly pea ice cream.	[217]
Butterfly pea	Vacuum-dried anthocyanin extract	2% (W/V)	Yoghurt & fermented milk	The TAC of yoghurt with 2% extract remained stable during cold storage, whereas that of fermented milk decreased significantly. Both ACN-enriched products showed higher antioxidant activity than controls.	[114]

Table 11: *Cont.*

Flowers	Forms	Optimal Amount (%)	Food Products	Results	References
Lavender	Aqueous extract	10 mL	Bagel	Bagel with lavender extracts had significantly higher TPC and DPPH scavenging ability. Experimental subjects who ate bagels enriched with lavender had significantly lower anxiety scores.	[218]
Lotus	Flower powder	5–10%	Muffin	The enriched muffins exhibited higher redness, yellowness, and hardness, dietary fiber, and ash, while maintaining similar overall consumer sensory scores.	[219]
Lotus	Aqueous extract (10 mL/g of LSR)	7.81%	Yoghurt	Addition of lotus petal extract could enhance yogurt quality by promoting lactic acid production and probiotic growth, while improving water-holding capacity and textural properties.	[220]
Rose	Dried petals	1–2%	Tea	Rose teas prepared by hot-water infusion from 12 rose cultivars showed TPC values ranging from 50.7 to 119.5 mg GAE/g DB. These rose teas were rich in free gallic acid. Their $ABTS^{+}$ radical scavenging antioxidant activity was comparable to that of green tea.	[221]
Rose	Petals	15–25%	Jam	Apple jam enriched with rose petals showed high TPC and antioxidant activity, along with acceptable sensory attributes.	[222]
Rose	Petal powder	5%	Biscuit	Biscuits with the rose petals had significantly higher TAC, TPC and DPPH scavenging ability.	[223]
Rose	Encapsulated anthocyanins		Juice	β-Cyclodextrin encapsulation significantly enhanced the retention of ACNs in rose juice during 70 days of storage under high-temperature, light, and strong oxidative conditions with increases of 9.24%, 9.21%, and 2.57%, respectively.	[110]
Chinese hibiscus	Flower extract	1–2%	yogurt	Incorporation of Chinese hibiscus flower extract improved the antioxidant capacity and mineral (calcium and iron) content of yogurt while maintaining acceptable sensory properties.	[224]

Table 11: *Cont.*

Flowers	Forms	Optimal Amount (%)	Food Products	Results	References
Chinese hibiscus	Encapsulated powder: Using maltodextrin	0.6–1.375%	Juice, curd and butter cream	Acidic foods formulated with encapsulated ACNs showed good sensory acceptance.	[135]
Roselle	Fresh roselle	50%	Jam	The use of natural roselle flowers markedly enhances the jam's physicochemical properties, TPC, and antioxidant activity, while also improving its sensory profile by boosting aroma, flavor, texture, and overall acceptability.	[225]
Roselle	Encapsulated powder: Using maltodextrin and gum Arabic	5%	Marshmallow	Candy samples containing 5% encapsulated powder showed high appearance acceptability and purchase intention.	[137]
Roselle	Calyx powder	10–20%	Pasta	The enriched pasta exhibited increased levels of dietary fiber, minerals, vitamin C, and phenolic compounds, primarily gallic acid and ACNs.	[226]
Roselle	Encapsulated powder: Using starch and alginate	0.5 g powder/3 g soybean oil	Cooking oil	Incorporation of the ACN-rich spray-dried powder significantly improved the oxidative stability of soybean oil.	[136]
Roselle	Freeze-dried extract	0.63%	Beef patties	Addition of the roselle extract can minimize the formation of heterocyclic amines in beef patties without affecting their sensory properties.	[227]
Roselle	Aqueous extract	5%	Ice cream	Ice cream containing 5% roselle extract exhibited higher overrun and total solids, lower meltdown, and desirable viscosity and color intensity.	[228]
Sesban flower	Aqueous extract	5%	Jelly	Jelly containing 5% flower extract showed the highest phenolics, flavonoids, and antioxidant activity, and inhibited microbial growth over 30 days of cold storage	[229]

5.1 Colorants and Functional Ingredients

ACNs, the water-soluble pigments responsible for red, purple, and blue hues in many flowers, have attracted considerable attention as natural food colorants and functional ingredients. The global ACN market is forecast to grow from USD 415 million in 2025 to over USD 690 million by 2035, at an annual growth rate of 5.2% [230]. ACNs derived from edible flowers and/or their extracts can impart vibrant colors to foods and beverages while simultaneously providing antioxidant and health-promoting properties, thereby contributing to the development of functional foods.

Herbal teas prepared from edible flowers, including rose, roselle, lavender, butterfly pea, lotus, chrysanthemum, and jasmine, are widely consumed due to their appealing aroma, vibrant color, and

health-promoting properties. For example, rose petals have been used to produce antioxidant-rich, caffeine-free herbal teas [221]. Moreover, a composite herbal tea containing butterfly pea flower, rose petals, lemongrass, and mint showed that the blue pea–lemongrass formulation achieved the highest acceptability, strong antioxidant activity, and dose-dependent α-amylase inhibition, indicating its potential as a functional beverage for diabetes management [231]. Similarly, juices [216] and confectionery products such as jam [222,225], jelly [229] and candy [137] have been developed using rose petals, roselle calyces, blue pea flowers, *Sesbania javanica* flowers, or their ACN-rich extracts. These products exhibit high pharmaceuticals, strong antioxidant activities, and, in some cases, antimicrobial properties, while maintaining good sensory quality. Overall, the use of edible flowers and their ACN extracts supports the development of clean-label, functional beverage and confectionery products.

Dairy products, such as yogurt, fermented milk, and ice cream are particularly suitable matrices for the incorporation of ACNs, as their mildly acidic environment and ACN–protein copigmentation interactions contribute to improved ACN stability. The addition of edible flowers or their ACN-rich extracts can effectively enhance product color while providing bioactive compounds and antioxidant activity, thereby improving the nutritional quality and sensory properties of these dairy products. For instance, lotus petal and Chinese hibiscus flower extracts enhanced yogurt quality by promoting lactic acid production, probiotic growth, and improved texture and antioxidant activity [220,224]. Ice cream containing 5% roselle extract shows increased overrun and color intensity with reduced meltdown [228], while *Clitoria ternatea* ACNs enable naturally colored dairy products with high antioxidant activity and consumer acceptance [114,217]. Overall, ACNs from edible flowers facilitate the development of healthy, nutritious, and safe dairy products.

The addition of edible flowers or their extracts to wheat-based products—such as bread [218], muffins [219], cookies [213], steamed buns [215], and noodles [107]—can generally and significantly increase ACN content, total phenolics, and antioxidant capacity, while also altering the visual color of the products. When added at appropriate levels, these extracts can positively contribute to product quality. butterfly pea extract reduced bread starch digestibility by inhibiting pancreatic α-amylase, indicating its potential to lower the glycemic index of flour-based products [214]. However, the high-temperature processes involved in baking, steaming, and cooking can cause thermal degradation or loss of heat-sensitive anthocyanins, leading to color changes or fading [215]. Another important challenge is that wheat-based products are rich in wheat proteins and typically have a neutral to slightly acidic pH, which is unfavorable for most ACNs, as they require acidic conditions to exhibit stable red coloration.

Incorporation of ACN-rich roselle extract can enhance oxidative stability of cooking oil [136] and reduce the formation of heterocyclic amines in beef patties [227]. Essential oils are complex mixtures of volatile terpenes, terpenoids, and other aromatic compounds. Edible flowers, such as rose, lavender, roselle, jasmine, and *Paeonia lactiflora*, represent important sources of essential oils [30,37,204,232]. For example, the essential oil of lavender is characterized by high levels of linalyl acetate, linalool, and β-caryophyllene [30]. These essential oils are increasingly incorporated into food systems as natural preservatives and functional ingredients because of their antimicrobial, antioxidant, and flavor-enhancing properties [42,233].

In the food industry, ACNs from edible flowers are still far less utilized than those from fruits, vegetables, and cereals. Although many edible flowers exist, only a few have been explored for development. Further research is needed to find flowers with high, stable ACN content and to improve ACN stability during food processing.

5.2 Packaging Film

ACNs have gained considerable attention for applications in active edible films and intelligent food packaging. The key principle of using ACNs in packaging materials is their high sensitivity to environmental pH changes. Due to reversible structural transformations, ACNs exhibit distinct color variations under different pH conditions, typically appearing red in acidic environments and shifting to purple, blue, yellow, or green in neutral to alkaline conditions. This color responsiveness enables ACNs to function as natural indicators for monitoring food freshness. ACNs from some edible ornamental flowers have been used to develop intelligent and active packaging films, as summarized in Table 12.

Table 12: Applications of some edible ACN-rich flowers in packaging films.

Flowers	Forms	Optimal Amount (%)	Films	Results	References
Butterfly pea	Aqueous extract	(1) 500 mL extract per 100 g durian albedo. (2) Gelatin film with 15% CT extract was prepared.	Smart edible film	The film functioned as a pH-responsive indicator in fresh milk and fish, exhibiting a distinct color change during milk spoilage. Incorporation of the flower extract decreased the tensile strength of the film while enhancing its elongation at break.	[162,234]
Roselle	Extract	1%	Red pectin film	The active film containing roselle extract exhibited antioxidant activity and inhibited the growth of *Listeria monocytogenes* and *Staphylococcus aureus*.	[235]
Roselle	Aqueous extract	10% extract, 3% gluten 1.5% CMC.	Intelligent packaging film	The film exhibited the highest thermal stability and showed significant color changes in fish fillets, which aligned with variations in total volatile basic nitrogen.	[236]
Roselle	NADES extract	The ACN extract was incorporated into polyvinyl alcohol-carboxymethyl cellulose composite films.	Intelligent packaging film	The pH-responsive smart films exhibited superior mechanical performance, antimicrobial effectiveness, and UV-shielding capacity.	[171]

In edible and biodegradable packaging systems, ACNs are commonly incorporated into biopolymer matrices such as starch, chitosan, alginate, pectin, cellulose derivatives, and protein-based materials [171]. These biopolymers provide mechanical strength and barrier properties while acting as carriers that stabilize ACNs and facilitate their interaction with volatile compounds released during food spoilage. As microbial growth and protein degradation often produce alkaline metabolites such as ammonia and amines, ACN-containing films can visually indicate freshness changes through observable color shifts [236].

In addition to their indicator function, anthocyanins also exhibit antioxidant activity, which can help retard lipid oxidation and the growth of pathogens, as well as quality deterioration in packaged foods [235]. Their natural origin, biodegradability, and low toxicity make ACNs attractive alternatives to synthetic dyes in intelligent packaging applications. ACN-based films have been successfully applied to monitor the freshness of milk, meat, fish, and other perishable foods, showing good correlations with microbial counts and chemical spoilage indices [234,236]. Despite these advantages, the stability of ACNs against light, heat, and oxygen remains a challenge, and current research focuses on improving their stability through polymer

interactions and encapsulation strategies. Overall, ACN-incorporated edible and intelligent films represent a promising approach for sustainable and consumer-friendly food packaging.

6 Conclusions and Future Prospects

Consumers are increasingly seeking natural pigments that are safe and provide nutritional and health benefits. Edible flowers are rich sources of bioactive compounds, particularly ACNs, and can impart attractive colors as well as health-promoting effects, including antioxidant, anti-inflammatory, antidiabetic, anticancer, and cardioprotective activities. Among the 11 different types of edible flowers, the four with the highest TAC (expressed as grams of C3G per kilogram DB) are rose (33.3), saffron (10.2), roselle (10.0), and butterfly pea flower (3.5), making them good sources of red to blue ACNs for industrial scale-up exploration. A deeper understanding of the biosynthesis and its regulatory mechanisms in these flowers will be crucial for future breeding and cultivation efforts aimed at enhancing ACN yield and diversity. The article introduces eight extraction methods and compares their advantages and disadvantages. Considering factors such as extraction efficiency, cost, and energy consumption, the UAE and CSE methods are currently the most suitable for industrial extraction of edible flower ACNs, followed by the MAE and EAE methods. For PEF, CP, and SFE extraction techniques, there are currently very few or no reports on their application in the extraction of ACNs from edible ornamental flowers. Regarding ACN stability, low temperature, acidic pH, low water activity, and protection from light are favorable conditions. In addition, selecting inherently stable (poly-)acylated ACNs, together with stabilization strategies such as copigmentation with proteins, polysaccharides, and organic acids, as well as microencapsulation, can effectively enhance ACN stability and bioavailability, thereby promoting the application of edible flower ACNs in functional foods. However, a large number of edible ornamental flowers remain largely unexplored and underutilized. This review highlights the need for more in-depth investigations into diverse edible flowers, with an emphasis on developing more efficient ACN extraction methods and improved stabilization strategies, thereby enabling more effective incorporation of edible flower ACNs into foods and nutraceuticals to promote human health.

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Abbreviations

Abbreviations	Full Terms	Abbreviations	Full Terms
4CL	4-coumarate-CoA ligase	F3′5′H	Flavonoid 3′,5′-hydroxylase
ABC	ATP-binding cassette	F3H	Flavanone 3-hydroxylase

ACNs	Anthocyanins	F3′H	Flavonoid 3′-hydroxylase
ANS	Anthocyanidin synthase	GAE	Gallic acid equivalent
AOMT	Anthocyanin O-methyltransferase	GST	Glutathione S-transferase
AT	Anthocyanin acyltransferase	LSR	Liquid-to-solid ratio
BTL	Bilitranslocase	MAE	Microwave-assisted extraction
C3G	Cyanidin-3-glucoside	MATE	multidrug and toxic compound extrusion
C4H	Cinnamate 4-hydroxylase	MRP	Multidrug resistance-associated protein
CHI	Chalcone isomerase	NADES	Natural deep eutectic solvent
CHS	Chalcone synthase	PAL	Phenylalanine ammonia-lyase
CP	Cold plasma	PEF	Pulsed Electric Field
CPAE	Cold plasma-assisted extraction	QE	Quercetin equivalent
CSE	Conventional solvent extraction	SFE	Supercritical Fluid Extraction
D3G	Delphinidin-3-glucose	TAC	Total anthocyanin content
D3S	Delphinidin-3-sambubioside	TE	Trolox equivalent
DB	Dry weight basis	TFC	Total flavonoid content
DES	Deep eutectic solvent	TPC	Total phenolic content
DFR	Dihydroflavonol 4-reductas	UAE	Ultrasound-assisted extraction
DPPH	2,2-diphenyl-1-picrylhydrazyl	UFGT	UDP-glucose-flavonoid 3-O-glycosyltransferase
EAE	Enzyme-assisted extraction	WB	Wet weight basis

References

1. Pires TCSP, Barros L, Santos-Buelga C, Ferreira ICFR. Edible flowers: Emerging components in the diet. Trends Food Sci Technol. 2019;93:244–58. [CrossRef].
2. Tao Y, Zhang X, Li Z, Tian S, Li L, Zhou X. Comprehensive analysis of 50 edible flowers from Yunnan Province: Active components, antioxidant capacity, tyrosinase inhibition, and antimicrobial activity. Food Sci Nutr. 2025;13(7):e70666. [CrossRef].
3. Pasere IC, Roman GM, Bunea CI, Bunea A, Nicolescu A, Pintea A. Separation and identification of individual anthocyanins from the petals of some rose cultivars. Not Bot Horti Agrobo. 2024;52(3):13772. [CrossRef].
4. Yu Y, Shiau S, Pan W, Yang Y. Extraction of bioactive phenolics from various anthocyanin-rich plant materials and comparison of their heat stability. Molecules. 2024;29(22):5256. [CrossRef].
5. Janarny G, Ranaweera KKDS, Gunathilake KDPP. Optimization of ethanol based extraction of phenolics from *Ocimum sanctum* flowers by response surface methodology. Biocatal Agric Biotechnol. 2022;45:102493. [CrossRef].
6. Sumera S, Chitra R, Ganga M, Ramalakshmi A, Meenakshi P, Geetha P. Edible floral pigments: Exploring flowers as natural biocolourants for food applications. Plant Sci Today. 2025;12(2). [CrossRef].
7. Liu F, Qu J, Li Y, Fan J, Cui Y, Wu J, et al. Transcriptomic analysis reveals the formation mechanism of anthocyanins light-independent synthesis in chrysanthemum. Phyton. 2024;93(7):1599–621. [CrossRef].
8. Althobaiti F, Darwish H, Alruqayb R, Alotaibi SS, Alharthi FE, Jafri I, et al. Analyzing the cytotoxic and genetic impact of *Datura stramonium* extract on MCF7 and HT29 cancer cells: A metabolite and gene expression study. Phyton. 2025;94(1):181–98. [CrossRef].
9. Liu J, Nakamura S, Zhen Y, Yoshikawa M, Hussein GME, Matsuo K, et al. Medicinal Flowers. XXXX. Structures of dihydroisocoumarin glycosides and inhibitory effects on aldose reducatase from the flowers of *Hydrangea macrophylla var. thunbergia*. Chem Pharm Bull. 2013;61(6):655–61. [CrossRef].
10. Zhao Y, Afzal SF, Chen Z, Kamal KA, Fei Y, Meng X, et al. Systematic identification of *Acer rubrum* bZIP transcription factors and their potential role in anthocyanin accumulation under low temperature with light. Phyton. 2024;93(11):3109–30. [CrossRef].
11. Teixeira M, Tao W, Fernandes A, Faria A, Ferreira IMPLVO, He J, et al. Anthocyanin-rich edible flowers, current understanding of a potential new trend in dietary patterns. Trends Food Sci Technol. 2023;138:708–25. [CrossRef].
12. Jokioja J, Yang B, Linderborg KM. Acylated anthocyanins: A review on their bioavailability and effects on postprandial carbohydrate metabolism and inflammation. Compr Rev Food Sci Food Saf. 2021;20(6):5570–615. [CrossRef].
13. Wallace TC, Giusti MM. Anthocyanins-nature's bold, beautiful, and health-promoting colors. Foods. 2019;8(11):550. [CrossRef].

14. Yeung AWK, Solka M, Jóźwik A, Ksepka N, Matin M, Wang D, et al. Anthocyanins—Dietary natural products with a variety of bioactivities for the promotion of human and animal health. Anim Sci Pap Rep. 2024;42(1):5–34. [CrossRef].
15. Gonçalves AC, Nunes AR, Falcão A, Alves G, Silva LR. Dietary effects of anthocyanins in human health: A comprehensive review. Pharmaceuticals. 2021;14(7):690. [CrossRef].
16. Amini AM, Zhou R, Austermann K, Králová D, Serra G, Ibrahim IS, et al. Acute effects of an anthocyanin-rich blackcurrant beverage on markers of cardiovascular disease risk in healthy adults: A randomized, double-blind, placebo-controlled, crossover trial. J Nutr. 2025;155(7):2275–89. [CrossRef].
17. Książkiewicz M, Karczewska M, Nawrot F, Grabowska K, Szymański M, Cielecka-Piontek J, et al. Edible flowers as bioactive food ingredients with antidiabetic potential: A study on *Paeonia officinalis* L., *Forsythia* × *intermedia*, *Gomphrena globosa* L., and *Clitoria ternatea* L. Plants. 2025;14(16):2603. [CrossRef].
18. Liu X, Ge K, Shi H, Yao Z, Zhang Z. Effects of anthocyanins on human health: An umbrella review of systematic reviews and meta-analyses. Food Funct. 2025;16(19):7531–44. [CrossRef].
19. Maaz M, Sultan MT, Noman AM, Zafar S, Tariq N, Hussain M, et al. Anthocyanins: From natural colorants to potent anticancer agents. Food Sci Nutr. 2025;13(5):e70232. [CrossRef].
20. Qin X, Guo H, Luo Q, Gao Q. *Lycium ruthenium anthocyanins* attenuate acrylamide-induced neuroinflammation via gut microbiota-mediated NLRP3 inflammasome. Food Biosci. 2025;68:106516. [CrossRef].
21. Escher GB, Wen M, Zhang L, Rosso ND, Granato D. Phenolic composition by UHPLC-Q-TOF-MS/MS and stability of anthocyanins from *Clitoria ternatea* L. (butterfly pea) blue petals. Food Chem. 2020;331:127341. [CrossRef].
22. Nair V, Bang WY, Schreckinger E, Andarwulan N, Cisneros-Zevallos L. Protective role of ternatin anthocyanins and quercetin glycosides from butterfly pea (*Clitoria ternatea* Leguminosae) blue flower petals against lipopolysaccharide (LPS)-induced inflammation in macrophage cells. J Agric Food Chem. 2015;63(28):6355–65. [CrossRef].
23. Li C, Tang W, Chen S, He J, Li X, Zhu X, et al. Phytochemical properties and *in vitro* biological activities of phenolic compounds from flower of *Clitoria ternatea* L. Molecules. 2022;27(19):6336. [CrossRef].
24. Satpathy B, Sa N, Behera A, Sahu PK. Dose-dependent attenuation of the efficacy of *Clitoria ternatea* by cobalt oxide nanoparticles against diabetes-induced cognitive impairment. Mol Neurobiol. 2025;62(2):2601–16. [CrossRef].
25. Brozdowski J, Waliszewska B, Gacnik S, Hudina M, Veberic R, Mikulic-Petkovsek M. Phenolic composition of leaf and flower extracts of black cherry (*Prunus serotina* Ehrh.). Ann For Sci. 2021;78(3):66. [CrossRef].
26. Lee BB, Cha MR, Kim SY, Park E, Park HR, Lee SC. Antioxidative and anticancer activity of extracts of cherry (*Prunus serrulata* var. spontanea) blossoms. Plant Foods Hum Nutr. 2007;62(2):79–84. [CrossRef].
27. Wei Q, Liu RJ, Liu D, Wei CC. Compositions and their α-glycosidase inhibition activity of cerasua serrulata flowers. J Jinggangshan Univ Nat Sci. 2021;42(4):48–52. (In Chinese).
28. Khan SU, Hamza B, Mir RH, Fatima K, Malik F. Lavender plant: Farming and health benefits. Curr Mol Med. 2024;24(6):702–11. [CrossRef].
29. Caser M, Falla NM, Demasi S, Scariot V. From fresh to dried lavender flower: Changes in phytochemical profile according to drying method. Horticulturae. 2023;9(6):700. [CrossRef].
30. Dobreva A, Petkova N, Todorova M, Gerdzhikova M, Zherkova Z, Grozeva N. Organic vs. conventional farming of lavender: Effect on yield, phytochemicals and essential oil composition. Agronomy. 2024;14(1):32. [CrossRef].
31. Deng J, Chen S, Yin X, Wang K, Liu Y, Li S, et al. Systematic qualitative and quantitative assessment of anthocyanins, flavones and flavonols in the petals of 108 lotus (*Nelumbo nucifera*) cultivars. Food Chem. 2013;139(1–4):307–12. [CrossRef].
32. Choo JH, Lee SY, Min K, Kang NG. Chemical composition and bioactivity of *Nelumbo nucifera* gaertn. flower extract fractions: *In vitro* antioxidant and anti-inflammatory properties. Curr Issues Mol Biol. 2025;47(12):1065. [CrossRef].
33. Huang J, He G, Wu L, Ma P, Xu L, Sun L, et al. The edible lotus (*Nelumbo nucifera* Gaertn.) and its byproducts as valuable source of natural antioxidants: A review of phytochemicals, health benefits, safety and food applications. Future Foods. 2025;11:100603. [CrossRef].

34. On-nom N, Thangsiri S, Inthachat W, Temviriyanukul P, Sahasakul Y, Chupeerach C, et al. Seasonal effects on phenolic contents and *in vitro* health-promoting bioactivities of sacred lotus (*Nelumbo nucifera*). Plants. 2023;12(7):1441. [CrossRef].
35. Villa C, Russo E, Schito AM, Robustelli della Cuna FS, Sottani C, Barabino M, et al. Multifunctional NADES-based extracts from *Paeonia lactiflora* pall. flowers for potential cosmetic and pharmaceutical applications. Molecules. 2026;31(1):97. [CrossRef].
36. Liu L, Yuan Y, Zuo J, Tao J. Composition and antioxidant activity of *Paeonia lactiflora* petal flavonoid extract and underlying mechanisms of the protective effect on H_2O_2-induced oxidative damage in BRL3A cells. Hortic Plant J. 2023;9(2):335–44. [CrossRef].
37. Chen M, Niu T, Gao K, Tan Z, Zhao Y, Hou X, et al. Floral volatiles in natural populations of *Paeonia lactiflora*: Key components and cultivar differential analysis. Phyton. 2025;94(6):1921–40. [CrossRef].
38. Zhou H, Li T, Li B, Sun S. Skin health properties of *Paeonia lactiflora* flower extracts and tyrosinase inhibitors and free radical scavengers identified by HPLC post-column bioactivity assays. Heliyon. 2023;9(8):e18569. [CrossRef].
39. Zhai YM, Li YY, Liu LX, Liu YG. Extraction methods, physiological activities, and applications of rose residue and its bioactive components: A comprehensive review. J Food Meas Charact. 2025;19(8):5183–96. [CrossRef].
40. Prata GGB, de Souza KO, Lopes MMA, Oliveira LS, Aragao FAS, Alves RE, et al. Nutritional characterization, bioactive compounds and antioxidant activity of Brazilian roses (*Rosa* spp). J Agric Sci Technol. 2017;19(4):929–41.
41. Kumar S, Gautam S, Sharma A. Identification of antimutagenic properties of anthocyanins and other polyphenols from rose (*Rosa centifolia*) petals and tea. J Food Sci. 2013;78(6):H948–54. [CrossRef].
42. Zhao X, Jiang Y, Qiao M, Lin F, Miao B. Recent advances in bioactive compounds, health functions, and utilization of rose (*Rosa* spp.). Molecules. 2025;30(19):3869. [CrossRef].
43. Jabeur I, Pereira E, Barros L, Calhelha RC, Soković M, Oliveira MBPP, et al. *Hibiscus sabdariffa* L. as a source of nutrients, bioactive compounds and colouring agents. Food Res Int. 2017;100:717–23. [CrossRef].
44. Da-Costa-Rocha I, Bonnlaender B, Sievers H, Pischel I, Heinrich M. *Hibiscus sabdariffa* L.—A phytochemical and pharmacological review. Food Chem. 2014;165:424–43. [CrossRef].
45. Peredo Pozos GI, Ruiz-López MA, Zamora Nátera JF, Álvarez Moya C, Barrientos Ramírez L, Reynoso Silva M, et al. Antioxidant capacity and antigenotoxic effect of *Hibiscus sabdariffa* L. extracts obtained with ultrasound-assisted extraction process. Appl Sci. 2020;10(2):560. [CrossRef].
46. Mannino G, Gentile C, Ertani A, Serio G, Bertea CM. Anthocyanins: Biosynthesis, distribution, ecological role, and use of biostimulants to increase their content in plant foods—A review. Agriculture. 2021;11(3):212. [CrossRef].
47. Zheng J, Sun R, Wu D, Chen P, Zheng P. Engineered *Zea mays* phenylalanine ammonia-lyase for improve the catalytic efficiency of biosynthesis trans-cinnamic acid and p-coumaric acid. Enzyme Microb Technol. 2024;176:110423. [CrossRef].
48. Lavhale SG, Kalunke RM, Giri AP. Structural, functional and evolutionary diversity of 4-coumarate-CoA ligase in plants. Planta. 2018;248(5):1063–78. [CrossRef].
49. Khatri P, Chen L, Rajcan I, Dhaubhadel S. Functional characterization of Cinnamate 4-hydroxylase gene family in soybean (*Glycine max*). PLoS One. 2023;18(5):e0285698. [CrossRef].
50. Furumura S, Ozaki T, Sugawara A, Morishita Y, Tsukada K, Ikuta T, et al. Identification and functional characterization of fungal chalcone synthase and chalcone isomerase. J Nat Prod. 2023;86(2):398–405. [CrossRef].
51. Ma G, Zhang L, Yamamoto R, Kojima N, Yahata M, Kato M. Molecular characterization of a flavanone 3-hydroxylase gene from citrus fruit reveals its crucial roles in anthocyanin accumulation. BMC Plant Biol. 2023;23(1):233. [CrossRef].
52. Guo X, Hu J, Yang S, Wang D, Wang J. Genome-wide analysis of the F3′5′H gene family in blueberry (*Vaccinium corymbosum* L.) provides insights into the regulation of anthocyanin biosynthesis. Phyton. 2023;92(9):2683–97. [CrossRef].
53. Szewczuk NA, Duchowicz PR, Pomilio AB, Lobayan RM. Resonance structure contributions, flexibility, and frontier molecular orbitals (HOMO–LUMO) of pelargonidin, cyanidin, and delphinidin throughout the conformational space: Application to antioxidant and antimutagenic activities. J Mol Model. 2022;29(1):2. [CrossRef].

54. Cappellini F, Marinelli A, Toccaceli M, Tonelli C, Petroni K. Anthocyanins: From mechanisms of regulation in plants to health benefits in foods. Front Plant Sci. 2021;12:748049. [CrossRef].
55. Zhang L, Fan WJ, Zheng ZY, Yang J, Kang L, Wang HX. Research progress of anthocyanin glycosylation, methylation and acylation modification in plants. Mol Plant Breed. 2023;21(7):2378–87. (In Chinese). [CrossRef].
56. Wang Y, Julian McClements D, Chen L, Peng X, Xu Z, Meng M, et al. Progress on molecular modification and functional applications of anthocyanins. Crit Rev Food Sci Nutr. 2024;64(31):11409–27. [CrossRef].
57. Sunil L, Shetty NP. Biosynthesis and regulation of anthocyanin pathway genes. Appl Microbiol Biotechnol. 2022;106(5):1783–98. [CrossRef].
58. Zhao J. Flavonoid transport mechanisms: How to go, and with whom. Trends Plant Sci. 2015;20(9):576–85. [CrossRef].
59. Kaur S, Sharma N, Kapoor P, Chunduri V, Pandey AK, Garg M. Spotlight on the overlapping routes and partners for anthocyanin transport in plants. Physiol Plant. 2021;171(4):868–81. [CrossRef].
60. Winkel-Shirley B. Flavonoid biosynthesis. a colorful model for genetics, biochemistry, cell biology, and biotechnology. Plant Physiol. 2001;126(2):485–93. [CrossRef].
61. Manzoor MA, Ali Sabir I, Shah IH, Riaz MW, Rehman S, Song C, et al. Flavonoids: A review on biosynthesis and transportation mechanism in plants. Funct Integr Genom. 2023;23(3):212. [CrossRef].
62. Li C, Yu W, Xu J, Lu X, Liu Y. Anthocyanin biosynthesis induced by MYB transcription factors in plants. Int J Mol Sci. 2022;23(19):11701. [CrossRef].
63. Liu JJ, Wang SW, Yang XR, Chang KX, Zhang HL. The regulatory role of bHLH transcription factors in plant anthocyanin biosynthesis. J Plant Genet Resour. 2025;26(5):844–53. (In Chinese). [CrossRef].
64. Liu XF, Xiang LL, Yin XR, Grierson D, Li F, Chen KS. The identification of a MYB transcription factor controlling anthocyanin biosynthesis regulation in *Chrysanthemum* flowers. Sci Hortic. 2015;194:278–85. [CrossRef].
65. Lim SH, Kim DH, Jung JA, Lee JY. Alternative splicing of the basic helix–loop–helix transcription factor gene *CmbHLH2* affects anthocyanin biosynthesis in ray florets of chrysanthemum (*Chrysanthemum morifolium*). Front Plant Sci. 2021;12:669315. [CrossRef].
66. Wang Y, Zhou LJ, Wang Y, Geng Z, Liu S, Chen C, et al. CmMYB9a activates floral coloration by positively regulating anthocyanin biosynthesis in chrysanthemum. Plant Mol Biol. 2022;108(1):51–63. [CrossRef].
67. Zhou LJ, Geng Z, Wang Y, Wang Y, Liu S, Chen C, et al. A novel transcription factor CmMYB012 inhibits flavone and anthocyanin biosynthesis in response to high temperatures in chrysanthemum. Hortic Res. 2021;8:248. [CrossRef].
68. Wang Y, Zhou LJ, Wang Y, Geng Z, Ding B, Jiang J, et al. An R2R3-MYB transcription factor CmMYB21 represses anthocyanin biosynthesis in color fading petals of chrysanthemum. Sci Hortic. 2022;293:110674. [CrossRef].
69. Hong Y, Li M, Dai S. Ectopic expression of multiple chrysanthemum (*Chrysanthemum* × *morifolium*) R2R3-MYB transcription factor genes regulates anthocyanin accumulation in tobacco. Genes. 2019;10(10):777. [CrossRef].
70. Fu X, Liu P, Zheng H, Liu H, Hu X, Li S, et al. DcbHLH1 interacts with DcMYB1 and DcMYB2 to dynamically regulate petal pigmentation in *Dianthus caryophyllus*. Ind Crops Prod. 2024;207:117606. [CrossRef].
71. Fu X, Li S, Zhang Y, Zheng H, Liu H, Liu P, et al. DcWRKY15 positively regulates anthocyanin biosynthesis during petal coloration in *Dianthus caryophyllus*. Plant Physiol Biochem. 2025;219:109358. [CrossRef].
72. An W, Sun Y, Gao Z, Liu X, Guo Q, Sun S, et al. *LvbHLH13* regulates anthocyanin biosynthesis by activating the *LvMYB5* promoter in lily (*Lilium* 'viviana'). Horticulturae. 2024;10(9):926. [CrossRef].
73. Yamagishi M, Toda S, Tasaki K. The novel allele of the *LhMYB12* gene is involved in splatter-type spot formation on the flower tepals of Asiatic hybrid lilies (*Lilium* spp.). New Phytol. 2014;201(3):1009–20. [CrossRef].
74. Yamagishi M. Involvement of a LhMYB18 transcription factor in large anthocyanin spot formation on the flower tepals of the Asiatic hybrid lily (*Lilium* spp.) cultivar "Grand Cru". Mol Breed. 2018;38(5):60. [CrossRef].
75. Cao Y, Bi M, Yang P, Song M, He G, Wang J, et al. Construction of yeast one-hybrid library and screening of transcription factors regulating LhMYBSPLATTER expression in Asiatic hybrid lilies (*Lilium* spp.). BMC Plant Biol. 2021;21(1):563. [CrossRef].
76. Bi M, Liang R, Wang J, Qu Y, Liu X, Cao Y, et al. Multifaceted roles of LhWRKY44 in promoting anthocyanin accumulation in Asiatic hybrid lilies (*Lilium* spp.). Hortic Res. 2023;10(9):uhad167. [CrossRef].

77. Sun Y, Zhang X, Zhang H, Zhang M, Sun S, Han W, et al. *LvWRKY75* enhances the transcription of*LvMYB5* and promotes anthocyanin biosynthesis in lily petals during the blooming phase. Physiol Plant. 2025;177(2):e70143. [CrossRef].
78. Gao Z, Sun Y, Zhu Z, Ni N, Sun S, Nie M, et al. Transcription factors LvBBX24 and LvbZIP44 coordinated anthocyanin accumulation in response to light in lily petals. Hortic Res. 2024;11(10):uhae211. [CrossRef].
79. Bi M, Xu L, Wang J, Liu X, Yang P, Bai J, et al. Three transcription factors form an activation–inhibition module to regulate anthocyanin accumulation in Asiatic hybrid lilies. Plant Physiol. 2025;198(2):kiaf203. [CrossRef].
80. Guo P, Huang Z, Zhao W, Lin N, Wang Y, Shang F. Mechanisms for leaf color changes in *Osmanthus fragrans* 'Ziyan Gongzhu' using physiology, transcriptomics and metabolomics. BMC Plant Biol. 2023;23(1):453. [CrossRef].
81. Qian Y, Shan L, Zhao R, Tang J, Zhang C, Chen M, et al. Recent advances in flower color and fragrance of *Osmanthus fragrans*. Forests. 2023;14(7):1403. [CrossRef].
82. Wang X. Preliminary construction of coloration mechanism and genetic transformation system of Jasmine [master's thesis]. Yangzhou, China: Yangzhou University; 2025. [CrossRef].
83. Chen Y. Cloning of lavender MYB transcription factors and their functional study in anthocyanin synthesis [master's thesis]. Ürümqi, China: Xinjiang Agricultural University; 2025. [CrossRef].
84. Ye Q, Liu F, Feng K, Fu T, Li W, Zhang C, et al. Integrated metabolomics and transcriptome analysis of anthocyanin biosynthetic pathway in *Prunus serrulata*. Plants. 2025;14(1):114. [CrossRef].
85. He G, Zhang R, Jiang S, Wang H, Ming F. The MYB transcription factor RcMYB1 plays a central role in rose anthocyanin biosynthesis. Hortic Res. 2023;10(6):uhad080. [CrossRef].
86. Shen Y, Sun T, Pan Q, Anupol N, Chen H, Shi J, et al. RrMYB5- and RrMYB10-regulated flavonoid biosynthesis plays a pivotal role in feedback loop responding to wounding and oxidation in *Rosa rugosa*. Plant Biotechnol J. 2019;17(11):2078–95. [CrossRef].
87. Wang Y, Li S, Zhu Z, Xu Z, Qi S, Xing S, et al. Transcriptome and chemical analyses revealed the mechanism of flower color formation in *Rosa rugosa*. Front Plant Sci. 2022;13:1021521. [CrossRef].
88. Xu XL, Li J, Xu HX, Zhou Y, Zhao Y, Peng T, et al. Cloning and functional analysis of the promoter of VwF3H gene in pansy (*Viola* × *wittrockiana* Gams). J South Agric. 2025;56(2):368–77. (In Chinese). [CrossRef].
89. Wang T. Study on the coloration mechanism of black flowers in pansy (*Viola* × *wittrockiana*) [dissertation]. Haikou, China: Hainan University; 2023. [CrossRef].
90. Fan Z, Zhai Y, Wang Y, Zhang L, Song M, Flaishman MA, et al. Genome-wide analysis of anthocyanin biosynthesis regulatory WD40 gene FcTTG1 and related family in *Ficus carica* L. Front Plant Sci. 2022;13:948084. [CrossRef].
91. Park S, Lee H, Song J, Kim EH, Lim CJ, Oh J, et al. Redirecting flavonoid flux in purple Chinese cabbage via Cas9-mediated BrDFR knockout. Plant Physiol Biochem. 2025;229(Pt B):110534. [CrossRef].
92. Khusnutdinov E, Sukhareva A, Panfilova M, Mikhaylova E. Anthocyanin biosynthesis genes as model genes for genome editing in plants. Int J Mol Sci. 2021;22(16):8752. [CrossRef].
93. Zhu Q, Yu S, Zeng D, Liu H, Wang H, Yang Z, et al. Development of "purple endosperm rice" by engineering anthocyanin biosynthesis in the endosperm with a high-efficiency transgene stacking system. Mol Plant. 2017;10(7):918–29. [CrossRef].
94. Ni J, Zhao Y, Tao R, Yin L, Gao L, Strid Å, et al. Ethylene mediates the branching of the jasmonate-induced flavonoid biosynthesis pathway by suppressing anthocyanin biosynthesis in red Chinese pear fruits. Plant Biotechnol J. 2020;18(5):1223–40. [CrossRef].
95. Yao T, Feng K, Xie M, Barros J, Tschaplinski TJ, Tuskan GA, et al. Phylogenetic occurrence of the phenylpropanoid pathway and lignin biosynthesis in plants. Front Plant Sci. 2021;12:704697. [CrossRef].
96. Mao Y, Luo J, Cai Z. Biosynthesis and regulatory mechanisms of plant flavonoids: A review. Plants. 2025;14(12):1847. [CrossRef].
97. Enaru B, Dreţcanu G, Pop TD, Stănilă A, Diaconeasa Z. Anthocyanins: Factors affecting their stability and degradation. Antioxidants. 2021;10(12):1967. [CrossRef].
98. Vidana Gamage GC, Lim YY, Choo WS. Anthocyanins from *Clitoria ternatea* flower: Biosynthesis, extraction, stability, antioxidant activity, and applications. Front Plant Sci. 2021;12:792303. [CrossRef].
99. Levy R, Okun Z, Shpigelman A. The influence of chemical structure and the presence of ascorbic acid on anthocyanins stability and spectral properties in purified model systems. Foods. 2019;8(6):207. [CrossRef].

100. Zhao CL, Chen ZJ, Bai XS, Ding C, Long TJ, Wei FG, et al. Structure-activity relationships of anthocyanidin glycosylation. Mol Divers. 2014;18(3):687–700. [CrossRef].
101. Oliveira J, Coimbra JTS, Freitas V, Yang P, Basílio N, Pina F. Achieving a dramatic blue colour stability in anthocyanins bearing acylated sugars in position 3′,5′. Chem Commun. 2025;61(65):12187–90. [CrossRef].
102. Fu X, Wu Q, Wang J, Chen Y, Zhu G, Zhu Z. Spectral characteristic, storage stability and antioxidant properties of anthocyanin extracts from flowers of butterfly pea (*Clitoria ternatea* L.). Molecules. 2021;26(22):7000. [CrossRef].
103. Zhang B, Jiang X, Huang G, Xin X, Attaribo T, Zhang Y, et al. Enhancement of stability and antioxidant activity of mulberry anthocyanins through succinic acid acylation. Food Technol Biotechnol. 2022;60(3):321–9. [CrossRef].
104. Jolly E, Goupy P, Claisse-Gainvors A, Dangles O, Garcia-Bernet D, Dufour C, et al. A two-step biocatalytic process to extract and to acylate anthocyanins: A sustainable approach for red grape pomace biorefining. Appl Food Res. 2025;5(2):101431. [CrossRef].
105. Patras A, Brunton NP, O'Donnell C, Tiwari BK. Effect of thermal processing on anthocyanin stability in foods; mechanisms and kinetics of degradation. Trends Food Sci Technol. 2010;21(1):3–11. [CrossRef].
106. Garzón GA, Wrolstad RE. The stability of pelargonidin-based anthocyanins at varying water activity. Food Chem. 2001;75(2):185–96. [CrossRef].
107. Shiau SY, Yu Y, Li J, Huang W, Feng H. Phytochemical-rich colored noodles fortified with an aqueous extract of *Clitoria ternatea* flowers. Foods. 2023;12(8):1686. [CrossRef].
108. Eliášová M, Kotíková Z, Lachman J, Orsák M, Martinek P. Influence of baking on anthocyanin content in coloured-grain wheat bread. Plant Soil Environ. 2020;66(8):381–6. [CrossRef].
109. Bal A, Shilpa HN, Debnath S, Rastogi NK. Extraction of anthocyanin from *Hibiscus rosa*-sinensis and concentration by forward osmosis membrane process. Innov Food Sci Emerg Technol. 2024;96:103782. [CrossRef].
110. Xiong Y, Chang M, Shi ZW, Li YY, An SY, Ren DF. Encapsulation of rose anthocyanins with β-cyclodextrin for enhanced stability: Preparation, characterization, and its application in rose juice. Food Biosci. 2025;64:105875. [CrossRef].
111. Wu HY, Yang KM, Chiang PY. Roselle anthocyanins: Antioxidant properties and stability to heat and pH. Molecules. 2018;23(6):1357. [CrossRef].
112. Shiau SY, Ni S, Yu Y, Cai S, Huang W. Phytochemicals, antioxidation, and heat stability of aqueous extracts from cherry (*Prunus serrulata*) petals. Phyton. 2025;94(10):3047–60. [CrossRef].
113. Chen L, Chen N, He Q, Sun Q, Zeng WC. Effects of casein on the stability, antioxidant activity, and bioavailability of lotus anthocyanins. J Food Biochem. 2022;46(10):e14288. [CrossRef].
114. Vidana Gamage GC, Goh JK, Choo WS. Application of anthocyanins from blue pea flower in yoghurt and fermented milk: An alternate natural blue colour to spirulina. Int J Gastron Food Sci. 2024;37:100957. [CrossRef].
115. Jiménez N, Bassama J, Bohuon P. Estimation of the kinetic parameters of anthocyanins degradation at different water activities during treatments at high temperature (100–140°C) using an unsteady-state 3D model. J Food Eng. 2020;279:109951. [CrossRef].
116. Nadarajan S, Kumar V, Ovadia R, Kumari A, Doron-Faigenboim A, Singh B, et al. Active anthocyanin degradation in *Solanum macranthum* flowers involves both peroxidase and β-glucosidase enzymes. Physiol Plant. 2025;177(6):e70603. [CrossRef].
117. Luo H, Deng S, Fu W, Zhang X, Zhang X, Zhang Z, et al. Characterization of active anthocyanin degradation in the petals of *Rosa chinensis* and *Brunfelsia calycina* reveals the effect of gallated catechins on pigment maintenance. Int J Mol Sci. 2017;18(4):699. [CrossRef].
118. Ziabakhsh Deylami M, Abdul Rahman R, Tan CP, Bakar J, Olusegun L. Effect of blanching on enzyme activity, color changes, anthocyanin stability and extractability of mangosteen pericarp: A kinetic study. J Food Eng. 2016;178:12–9. [CrossRef].
119. Ijod G, Nawawi NIM, Sulaiman R, Khalid NI, Anwar F, Adzahan NM, et al. Inactivation of polyphenol oxidase and peroxidase activity in mangosteen pericarp via blanching: Correlation between anthocyanins and enzyme activities. Int J Food Sci Technol. 2025;60:vvae010. [CrossRef].
120. Estupiñan DC, Schwartz SJ, Garzón GA. Antioxidant activity, total phenolics content, anthocyanin, and color stability of isotonic model beverages colored with *Andes* Berry (*Rubus glaucus* Benth) anthocyanin powder. J Food Sci. 2011;76(1):S26–34. [CrossRef].

121. Berké B, Chèze C, Vercauteren J, Deffieux G. Bisulfite addition to anthocyanins: Revisited structures of colourless adducts. Tetrahedron Lett. 1998;39(32):5771–4. [CrossRef].
122. Guldiken B, Gibis M, Boyacioglu D, Capanoglu E, Weiss J. Ascorbic acid-induced degradation of liposome-encapsulated acylated and non-acylated anthocyanins of black carrot extract. J Sci Food Agric. 2021;101(13):5707–14. [CrossRef].
123. Li J, Bao Y, Jiang Q, Wen B, Wang L, He Y, et al. Indicator-enhanced starch-based intelligent film for nondestructive monitoring of beef freshness: Different structural phenolic acids copigment anthocyanin. J Food Eng. 2024;383:112241. [CrossRef].
124. Hsu WY, Shipman PD, Thompson S. Molecular transformations and self-association in anthocyanin pigment patterns. J Biosci. 2023;49(1):4. [CrossRef].
125. Goto T, Kondo T. Structure and molecular stacking of anthocyanins—Flower color variation. Angew Chem Int Ed. 1991;30(1):17–33. [CrossRef].
126. Bahreini Z, Abedi M, Ashori A, Parach A. Extraction and characterization of anthocyanin pigments from Iris flowers and metal complex formation. Heliyon. 2024;10(11):e31795. [CrossRef].
127. Dangles O, Saito N, Brouillard R. Anthocyanin intramolecular copigment effect. Phytochemistry. 1993;34(1):119–24. [CrossRef].
128. Mizuno T, Uehara A, Mizuta D, Yabuya T, Iwashina T. Contribution of anthocyanin–flavone copigmentation to grayed violet flower color of Dutch iris cultivar 'Tiger's Eye' under the presence of carotenoids. Sci Hortic. 2015;186:201–6. [CrossRef].
129. Liu H, Wang X, Li A, Zhang L, Mo Q, Zhang S. Organic acids copigmentation with *Hibiscus syriacus* flower (*Hibiscus syriacus* L.) anthocyanins: Thermal stability, characterization, and copigmentation mechanisms. J Food Sci. 2025;90(7):e70371. [CrossRef].
130. Li J, Lin J, Ramaswamy H, Duan H, Bai W, Wang C. The effect of high hydrostatic pressure on anthocyanin stability via pectin interaction: A multifaceted study on thermal, digestive, and environmental stress in food systems. J Agric Food Res. 2025;24:102382. [CrossRef].
131. Wang Y, Wang S, Zhang X, Wu W, Bai W, Tian L. Non-covalent interactions of roselle anthocyanins with milk proteins and egg white protein. Food Hydrocoll. 2024;154:110125. [CrossRef].
132. Mohammadalinejhad S, Kurek MA. Microencapsulation of anthocyanins—Critical review of techniques and wall materials. Appl Sci. 2021;11(9):3936. [CrossRef].
133. Sharif N, Khoshnoudi-Nia S, Jafari SM. Nano/microencapsulation of anthocyanins; a systematic review and meta-analysis. Food Res Int. 2020;132:109077. [CrossRef].
134. Baeza R, Chirife J. Anthocyanin content and storage stability of spray/freeze drying microencapsulated anthocyanins from berries: A review. Int J Food Eng. 2021;17(12):927–44. [CrossRef].
135. Ramya A, Thamaraiselvi SP, Karthikeyan S, Ganga M, Mirunalini SP, Visalakshi M. Physico-chemical properties of spray dried anthocyanin extract from hibiscus flowers (*Hibiscus rosasinensis* L.) as food colourant. Plant Sci Today. 2025;12(2). [CrossRef].
136. Vargas DA, Vargas N, Osorio-Doblado AM, Ruano-Ortiz JA, de Medeiros FGM, Hoskin RT, et al. Valorization of hibiscus flower (*Hibiscus sabdariffa* L.) anthocyanins to produce sustainable spray-dried ingredients. Sustainability. 2024;16(13):5523. [CrossRef].
137. Hoang NTN, Nguyen NNK, Nguyen LTK, Le ATH, Dong DTA. Research on optimization of spray drying conditions, characteristics of anthocyanins extracted from *Hibiscus sabdariffa* L. flower, and application to marshmallows. Food Sci Nutr. 2024;12(3):2003–15. [CrossRef].
138. Karasu S, Sagdic O, Arici M, Kayacan S. Optimization of microencapsulation conditions of tulip petal anthocyanin: Storage stability test. Lat Am Appl Res Int J. 2020;50(3):221–6. [CrossRef].
139. Gull A, Masoodi FA, Gani A. Valorization of saffron petal waste anthocyanin extract, microencapsulation storage kinetic stability, and *in vitro* release behavior of anthocyanin microcapsules. Biomass Convers Biorefin. 2025;15(4):5481–92. [CrossRef].
140. Mahdavee Khazaei K, Jafari SM, Ghorbani M, Hemmati Kakhki A. Application of maltodextrin and gum Arabic in microencapsulation of saffron petal's anthocyanins and evaluating their storage stability and color. Carbohydr Polym. 2014;105:57–62. [CrossRef].

141. Jafari SM, Mahdavi-Khazaei K, Hemmati-Kakhki A. Microencapsulation of saffron petal anthocyanins with cress seed gum compared with Arabic gum through freeze drying. Carbohydr Polym. 2016;140:20–5. [CrossRef].
142. Yu Y, Lv Y. Degradation kinetic of anthocyanins from rose (*Rosa rugosa*) as prepared by microencapsulation in freeze-drying and spray-drying. Int J Food Prop. 2019;22(1):2009–21. [CrossRef].
143. Pashazadeh H, Ali Redha A, Johnson JB, Koca I. Extraction optimization and microencapsulation of anthocyanins from okra flowers: Utilizing plant waste as a source of bioactive compounds. Food Biosci. 2025;63:105710. [CrossRef].
144. Tavlasoglu M, Ozkan G, Capanoglu E. Entrapment of black carrot anthocyanins by ionic gelation: Preparation, characterization, and application as a natural colorant in yoghurt. ACS Omega. 2022;7(36):32481–8. [CrossRef].
145. Silva NC, Chevigny C, Domenek S, Almeida G, Assis OBG, Martelli-Tosi M. Nanoencapsulation of active compounds in chitosan by ionic gelation: Physicochemical, active properties and application in packaging. Food Chem. 2025;463:141129. [CrossRef].
146. de Moura SCSR, Berling CL, Germer SPM, Alvim ID, Hubinger MD. Encapsulating anthocyanins from *Hibiscus sabdariffa* L. calyces by ionic gelation: Pigment stability during storage of microparticles. Food Chem. 2018;241:317–27. [CrossRef].
147. de Moura SCSR, Berling CL, Garcia AO, Queiroz MB, Alvim ID, Hubinger MD. Release of anthocyanins from the hibiscus extract encapsulated by ionic gelation and application of microparticles in jelly candy. Food Res Int. 2019;121:542–52. [CrossRef].
148. da Silva Carvalho AG, da Costa Machado MT, de Freitas Queiroz Barros HD, Cazarin CBB, Maróstica MR Jr, Hubinger MD. Anthocyanins from jussara (*Euterpe edulis* Martius) extract carried by calcium alginate beads pre-prepared using ionic gelation. Powder Technol. 2019;345:283–91. [CrossRef].
149. da Silva VG, Nogueira GF, Soares CT, de Oliveira RA. Anthocyanin-rich jamun (*Syzygium cumini* L.) pulp transported on protein-coated ionic gelation microparticles of calcium alginate: Production and morphological characteristics. Polysaccharides. 2023;4(1):33–50. [CrossRef].
150. Javadi B, Farahmand A, Soltani-Gorde-Faramarzi S, Ali Hesarinejad M. Chitosan-coated nanoliposome: An approach for simultaneous encapsulation of caffeine and roselle-anthocyanin in beverages. Int J Biol Macromol. 2024;275:133469. [CrossRef].
151. Zhao L, Temelli F. Preparation of anthocyanin-loaded liposomes using an improved supercritical carbon dioxide method. Innov Food Sci Emerg Technol. 2017;39:119–28. [CrossRef].
152. Camilleri D, Attard K, Lia F. Formulation and evaluation of liposome-encapsulated phenolic compounds from olive mill waste: Insights into encapsulation efficiency, antioxidant, and cytotoxic activities. Molecules. 2025;30(11):2351. [CrossRef].
153. Ardestani SB, Sahari MA, Barzegar M. Encapsulation of barberry fruit extracts by spray drying and liposome entrapment. Acta Aliment. 2020;49(2):125–34. [CrossRef].
154. Hwang JM, Kuo HC, Lin CT, Kao ES. Inhibitory effect of liposome-encapsulated anthocyanin on melanogenesis in human melanocytes. Pharm Biol. 2013;51(8):941–7. [CrossRef].
155. Cheng Z, Wang J, Bian Y, Tan M, Chen Y, Wang Y, et al. Oral polysaccharide-coated liposome-modified double-layered nanoparticles containing anthocyanins: Preparation, characterization, biocompatibility and evaluation of lipid-lowering activity *in vitro*. Food Chem. 2024;439:138166. [CrossRef].
156. Zhang L, Aniya, Xing S, Li J, Liu Y, Li C, et al. Preparation, physicochemical properties and stability of anthocyanin nanoliposomes before and after double-layer modification using synanthrin and pea protein isolate. Molecules. 2025;30(14):2892. [CrossRef].
157. Wang N, Li XJ, Wang L, Li B, Tian JL. Design of a liposome casein hydrogel as an efficient front-end homeostatic anthocyanin loading system. Int J Biol Macromol. 2024;278:134928. [CrossRef].
158. Suo K, Feng Y, Zhang Y, Yang Z, Zhou C, Chen W, et al. Comparative evaluation of quality attributes of the dried cherry blossom subjected to different drying techniques. Foods. 2024;13(1):104. [CrossRef].
159. Sánchez-Feria C, Salinas Moreno Y, Ybarra-Moncada MC, González-Hernández VA, Machuca-Sánchez ML. Effect of the dehydration method of *Hibiscus sabdariffa* L. calyces on the quality of their aqueous extracts. Emir J Food Agric. 2021;32(2):159–70. [CrossRef].
160. Shiau SY, Wang Y, Yu Y, Cai S, Liu Q. Phytochemical, antioxidant activity, and thermal stability of *Clitoria ternatea* flower extracts. Czech J Food Sci. 2024;42(4):284–94. [CrossRef].

161. Janarny G, Ranaweera KKDS, Gunathilake KDPP. Modeling and optimization of polyphenol extraction from the petals of *Clitorea ternatea* using response surface methodology. JSFA Rep. 2022;2(8):376–84. [CrossRef].
162. Salacheep S, Kasemsiri P, Pongsa U, Okhawilai M, Chindaprasirt P, Hiziroglu S. Optimization of ultrasound-assisted extraction of anthocyanins and bioactive compounds from butterfly pea petals using Taguchi method and Grey relational analysis. J Food Sci Technol. 2020;57(10):3720–30. [CrossRef].
163. Netravati, Gomez S, Pathrose B, Mini Raj N, Meagle Joseph P, Kuruvila B. Comparative evaluation of anthocyanin pigment yield and its attributes from Butterfly pea (*Clitorea ternatea* L.) flowers as prospective food colorant using different extraction methods. Future Foods. 2022;6:100199. [CrossRef].
164. Nguyen KD, Le QK, Tran TTT, Dong TAD. Improvement of phenolic and anthocyanin compound recovery efficiency of *Clitoria ternatea* L. extract by enzyme-assisted hydrolysis extraction method and anthocyanin determination by LC-HRMS. J Food Biochem. 2025;2025:8439891. [CrossRef].
165. Nguyen KD, Nguyen NAT, Dong TAD. Optimization of extraction conditions for anthocyanin and phenolic compounds from *Clitoria ternatea* L. assisted by microwave and enzyme hydrolysis. J Food Biochem. 2025;2025:1101732. [CrossRef].
166. Almeida Maia NM, Andressa I, Cunha JS, de Almeida Costa N, Borges LLR, Fontes EAF, et al. Optimization of ultrasound-assisted obtention of bluish anthocyanin extracts from butterfly pea (*Clitoria ternatea*) petal powders using natural deep eutectic solvents. Plants. 2025;14(7):1042. [CrossRef].
167. Boukerche H, Malki F, Saidji N, Ghaliaoui N, Bensalem A, Mokrane H. Combination of ultrasound, microwave and conventional extraction techniques for roselle (*Hibiscus Sabdariffa*. L.) total anthocyanins and phenolics recovery: Effect on antioxidant and structural properties. Biomass Convers Biorefin. 2024;14(15):18051–63. [CrossRef].
168. Larasati ID, Carrera C, Lioe HN, Estiasih T, Yuliana ND, Manikharda, et al. Anthocyanin extraction from roselle (*Hibiscus sabdariffa* L.) calyces: A microwave-assisted approach using Box-Behnken design. J Agric Food Res. 2024;18:101480. [CrossRef].
169. Cira-Chávez LA, Gassós-Ortega LE, Nuñez-Vega J, Camelo-Méndez GA, Cañedo-Urias R, Blanco-Rios AK, et al. Green extraction or roselle (*Hibiscus sabdariffa* L) calyces: An enzymatic assisted extraction to increase bioactive compounds and antioxidant capacity. Appl Food Res. 2025;5(2):101149. [CrossRef].
170. Zannou O, Koca I, Aldawoud TMS, Galanakis CM. Recovery and stabilization of anthocyanins and phenolic antioxidants of roselle (*Hibiscus sabdariffa* L.) with hydrophilic deep eutectic solvents. Molecules. 2020;25(16):3715. [CrossRef].
171. Giribabu D, Kumari A, Singh S, Yadav S, Bhavanam A, Bansal A. Deep-eutectic solvent assisted extraction of *Hibiscus sabdariffa* anthocyanin for the synthesis of polyvinyl alcohol/carboxy methyl cellulose composite smart films. Int J Biol Macromol. 2026;339:149846. [CrossRef].
172. Cendrowski A, Ścibisz I, Mitek M, Kieliszek M, Kolniak-Ostek J. Profile of the phenolic compounds of *Rosa rugosa* petals. J Food Qual. 2017;2017:7941347. [CrossRef].
173. Özgür MÜ, Çimen E. Ultrasound-assisted extraction of anthocyanins from red rose petals and new spectrophotometric methods for the determination of total monomeric anthocyanins. J AOAC Int. 2018;101(4):967–80. [CrossRef].
174. Blažeković B, Vladimir-Knežević S, Brantner A, Štefan MB. Evaluation of antioxidant potential of *Lavandula* × *intermedia* emeric ex loisel. 'budrovka': A comparative study with *L. angustifolia* mill. Molecules. 2010;15(9):5971–87. [CrossRef].
175. Falla NM, Caser M, Demasi S, Scariot V. Heat pump drying of lavender flowers leads to decoctions richer in bioactive compounds. Agronomy. 2022;12(12):3162. [CrossRef].
176. Nurzynska-Wierdak R, Zawislak G. Chemical composition and antioxidant activity of lavender (*Lavandula angustifolia* Mill.) aboveground parts. Acta Sci Pol Hortorum Cultus. 2016;15(5):225–41.
177. Ecem Bayram N, Yenigün B, Gerçek YC. Extraction of phenolic compounds from lavender (*Lavandula angustifolia* L.) plant by natural deep eutectic solvent and greenness assessment of analytical method with modified green analytical procedure index. Chem Biodivers. 2025;22(9):e202500194. [CrossRef].
178. Wang S, Wei J, Ge H, Yan Z, Jiang M, Lu J, et al. Molecular simulation and machine learning assisted in exploring betaine-based deep eutectic solvent extraction of active compounds from peony petals. Sep Purif Technol. 2025;361:131550. [CrossRef].

179. Oancea S, Perju M, Olosutean H. Influence of enzyme-aided extraction and ultrasonication on the phenolics content and antioxidant activity of *Paeonia officinalis* L. petals. J Serb Chem Soc. 2020;85(7):845–56. [CrossRef].
180. Álvarez A, Terreros S, Cocero MJ, Mato RB. Microwave pretreatment for the extraction of anthocyanins from saffron flowers: Assessment of product quality. Antioxidants. 2021;10(7):1054. [CrossRef].
181. Jafari SM, Mahdavee Khazaei K, Assadpour E. Production of a natural color through microwave-assisted extraction of saffron tepal's anthocyanins. Food Sci Nutr. 2019;7(4):1438–45. [CrossRef].
182. Schmitzer V, Veberic R, Osterc G, Stampar F. Color and phenolic content changes during flower development in groundcover rose. J Am Soc Hortic Sci. 2010;135(3):195–202. [CrossRef].
183. Ludin NA, Al-Alwani MAM, Mohamad AB, Kadhum AAH, Hamid NH, Ibrahim MA, et al. Utilization of natural dyes from *Zingiber officinale* leaves and *Clitoria ternatea* flowers to prepare new photosensitisers for dye-sensitised solar cells. Int J Electrochem Sci. 2018;13(8):7451–65. [CrossRef].
184. Mehmood A, Ishaq M, Zhao L, Yaqoob S, Safdar B, Nadeem M, et al. Impact of ultrasound and conventional extraction techniques on bioactive compounds and biological activities of blue butterfly pea flower (*Clitoria ternatea* L.). Ultrason Sonochem. 2019;51:12–9. [CrossRef].
185. Płotka-Wasylka J. A new tool for the evaluation of the analytical procedure: Green Analytical Procedure Index. Talanta. 2018;181:204–9. [CrossRef].
186. Lefebvre T, Destandau E, Lesellier E. Selective extraction of bioactive compounds from plants using recent extraction techniques: A review. J Chromatogr A. 2021;1635:461770. [CrossRef].
187. Santos LG, Martins VG. Optimization of the green extraction of polyphenols from the edible flower *Clitoria ternatea* by high-power ultrasound: A comparative study with conventional extraction techniques. J Appl Res Med Aromat Plants. 2023;34:100458. [CrossRef].
188. Ferraz LP, Silva EK. Pulsed electric fields and ultrasound for enhanced mass transfer: A review of extraction and drying in food processing. ACS Food Sci Technol. 2025;5(9):3229–53. [CrossRef].
189. Dara A, Feizy J, Naji-Tabasi S, Fooladi E, Rafe A. Intensified extraction of anthocyanins from *Berberis vulgaris* L. by pulsed electric field, vacuum-cold plasma, and enzymatic pretreatments: Modeling and optimization. Chem Biol Technol Agric. 2023;10(1):93. [CrossRef].
190. Pataro G, Bobinaitė R, Bobinas Č, Šatkauskas S, Raudonis R, Visockis M, et al. Improving the extraction of juice and anthocyanins from blueberry fruits and their by-products by application of pulsed electric fields. Food Bioprocess Technol. 2017;10(9):1595–605. [CrossRef].
191. Leong SY, Burritt DJ, Oey I. Evaluation of the anthocyanin release and health-promoting properties of Pinot Noir grape juices after pulsed electric fields. Food Chem. 2016;196:833–41. [CrossRef].
192. Puértolas E, Cregenzán O, Luengo E, Álvarez I, Raso J. Pulsed-electric-field-assisted extraction of anthocyanins from purple-fleshed potato. Food Chem. 2013;136(3–4):1330–6. [CrossRef].
193. Gachovska T, Cassada D, Subbiah J, Hanna M, Thippareddi H, Snow D. Enhanced anthocyanin extraction from red cabbage using pulsed electric field processing. J Food Sci. 2010;75(6):E323–9. [CrossRef].
194. Leong SY, Treadwell M, Liu T, Hochberg M, Sack M, Mueller G, et al. Influence of Pulsed Electric Fields processing at high-intensity electric field strength on the relationship between anthocyanins composition and colour intensity of Merlot (*Vitis vinifera* L.) musts during cold maceration. Innov Food Sci Emerg Technol. 2020;59:102243. [CrossRef].
195. Fincan M. Impact of pulsed electric field frequency on the disintegration of model petal tissue. J Food Process Eng. 2025;48(6):e70171. [CrossRef].
196. Gligor O, Mocan A, Moldovan C, Locatelli M, Crișan G, Ferreira ICFR. Enzyme-assisted extractions of polyphenols—A comprehensive review. Trends Food Sci Technol. 2019;88:302–15. [CrossRef].
197. Ribeiro BD, de Moraes Ferreira R, Coelho LAB, Barreto DW. Production of anthocyanin-rich red rose petal extract by enzymatic maceration. Biomass. 2024;4(2):429–41. [CrossRef].
198. Osamede Airouyuwa J, Sivapragasam N, Ali Redha A, Maqsood S. Sustainable green extraction of anthocyanins and carotenoids using deep eutectic solvents (DES): A review of recent developments. Food Chem. 2024;448:139061. [CrossRef].
199. Pires IV, da Silva LHM, da Cruz Rodrigues AM, Saldaña MDA. Natural deep eutectic solvents for anthocyanin extraction from agricultural sources: Process parameters, economic and environmental analysis, and industrial challenges. Compr Rev Food Sci Food Saf. 2024;23(6):e70057. [CrossRef].

200. Maran JP, Priya B, Manikandan S. Modeling and optimization of supercritical fluid extraction of anthocyanin and phenolic compounds from *Syzygium cumini* fruit pulp. J Food Sci Technol. 2014;51(9):1938–46. [CrossRef].
201. Li S, Guo L, Liu C, Fu Z, Zhang Y. Combination of supercritical fluid extraction with counter-current chromatography to isolate anthocyanidins from the petals of *Chaenomeles sinensis* based on mathematical calculations. J Sep Sci. 2013;36(21–22):3517–26. [CrossRef].
202. Darvishi Nooshabadi MA, Sabet JK, Zahirifar J, Dastbaz A. Supercritical fluid extraction of damask rose: Optimization, simulation, and economic estimation of process. Korean J Chem Eng. 2024;41(6):1775–90. [CrossRef].
203. Adaşoğlu N, Dinçer S, Bolat E. Supercritical-fluid extraction of essential oil from Turkish lavender flowers. J Supercrit Fluids. 1994;7(2):93–9. [CrossRef].
204. Santos Martinez AJ, Añonuevo AM, Cruz L, Manayaga D, Tayo L. Influence of drying methods and parameters on the quality of *Jasminum sambac* (L.) flower extracts obtained via supercritical fluid extraction. Processes. 2025;13(10):3369. [CrossRef].
205. López-Hortas L, Rodríguez P, Díaz-Reinoso B, Gaspar MC, de Sousa HC, Braga MEM, et al. Supercritical fluid extraction as a suitable technology to recover bioactive compounds from flowers. J Supercrit Fluids. 2022;188:105652. [CrossRef].
206. Heydari M, Carbone K, Gervasi F, Parandi E, Rouhi M, Rostami O, et al. Cold plasma-assisted extraction of phytochemicals: A review. Foods. 2023;12(17):3181. [CrossRef].
207. Xi J, Wang Y, Zhou X, Wei S, Zhang D. Cold plasma pretreatment technology for enhancing the extraction of bioactive ingredients from plant materials: A review. Ind Crops Prod. 2024;209:117963. [CrossRef].
208. Jan KC, Gavahian M. Cold plasma at various voltage, gas flow rate, and time assisted extraction of blue pea flower: Quantitative UPLC-ESI/MS/MS analysis of bioactive compounds, phenolics, and anthocyanin content. Innov Food Sci Emerg Technol. 2024;98:103837. [CrossRef].
209. Dakshayani R, Paul A, Mahendran R. Cold plasma-induced effects on bioactive constituents and antioxidant potential of lotus petal powder. IEEE Trans Plasma Sci. 2021;49(2):507–12. [CrossRef].
210. Shelar AN, Kahar SP, Suryawanshi N, Annapure US. A novel enzyme-assisted pin-to-plate atmospheric cold plasma extraction of bioactive compounds from marigold (*Tagetes erecta*) petals. Food Bioprocess Technol. 2025;18(7):6228–46. [CrossRef].
211. Santos de Morais J, Cabral L, Fonteles TV, Silva FA, Sant'Ana AS, dos Santos Lima M, et al. Effects of different cold plasma treatments on chemical composition, phenolics bioaccessibility and microbiota of edible red mini-roses. Food Chem. 2024;460:140522. [CrossRef].
212. Begum YA, Baishya P, Das MJ, Chakraborty S, Deka SC. Novel approach for the development of dietary fibre-anthocyanin enriched functional bread from culinary banana bract. Int J Food Sci Technol. 2020;55(11):3455–62. [CrossRef].
213. Multisona RR, Myszka K, Kulczyński B, Arnold M, Brzozowska A, Gramza-Michałowska A. Cookies fortified with *Clitoria ternatea* butterfly pea flower petals: Antioxidant capacity, nutritional composition, and sensory profile. Foods. 2024;13(18):2924. [CrossRef].
214. Chusak C, Henry CJ, Chantarasinlapin P, Techasukthavorn V, Adisakwattana S. Influence of *Clitoria ternatea* flower extract on the *in vitro* enzymatic digestibility of starch and its application in bread. Foods. 2018;7(7):102. [CrossRef].
215. Shiau SY, Yu YL, Pan WC, Li GH. Colorful and health improving Chinese steamed bread fortified by anthocyanin-rich extract of butterfly pea flower. J Food Process Preserv. 2022;46(10):e16925. [CrossRef].
216. Pornsuksawat P, Chysirichote T, Pongtong P, Piriyaphattarakit A, Pinkaew P. Edible blue flowers (butterfly pea): Extraction methods and application in flavored sweet water spheres by basic spherification technique. Int J Gastron Food Sci. 2025;42:101284. [CrossRef].
217. Mat Rashid NF, Zulkifli NA, Rois Anwar NZ, Mat Gani HS, Che Ku Jusoh TFI. Physicochemical properties, antioxidant activities and sensory evaluation of butterfly pea (*Clitoria ternatea* L.) ice cream flavoured with citrus juice. Biosci Res. 2022;19:73–81. [CrossRef].
218. Manzoor S, Rakha A, Rasheed H, Munir S, Abdi G, Bhat ZF, et al. Development and evaluation of anxiolytic potential of bagels incorporated with banana peel flour and lavender. J Agric Food Res. 2024;15:101029. [CrossRef].

219. Ashoka S, Revanna ML, Shamshad Begum S, Raju CA, Mounika P, Babu Rajaram Mohan R, et al. Development of muffins fortified with *Nelumbo nucifera* dried flower flour as a source of dietary fibre: Analysis of quality, nutritional value, and consumer acceptability. Sustain Food Technol. 2025;3(5):1505–16. [CrossRef].
220. Chen L, Li ZY, He Q, Gao MR, Sun Q, Zeng WC. Effect of lotus (*Nelumbo nucifera*) petals extract on the quality of yogurt and its action mechanism. J Food Process Preserv. 2021;45(5):e15396. [CrossRef].
221. Vinokur Y, Rodov V, Reznick N, Goldman G, Horev B, Umiel N, et al. Rose petal tea as an antioxidant-rich beverage: Cultivar effects. J Food Sci. 2006;71(1):S42–7. [CrossRef].
222. Moreira MCND, de Almeida GL, Carvalho EEN, Garcia JAD, Nachtigall AM, Vilas Boas BM. Quality parameters, antioxidant activity, and sensory acceptability of mixed jams of rose petals and apple. J Food Process Preserv. 2019;43(12):e14272. [CrossRef].
223. Sik B, Ajtony Z, Lakatos E, Gál LH, Székelyhidi R. Evaluation of the physical, antioxidant, and organoleptic properties of biscuits fortified with edible flower powders. Food Sci Nutr. 2024;12(5):3265–72. [CrossRef].
224. Ali A, Radha K, Sathian CT, Gleeja VL. Anti-oxidant activity of functional yoghurt incorporated with *Hibiscus rosasinensis* flower extract. Indian J Dairy Sci. 2023;76(4):343–7. [CrossRef].
225. Guerrero Veliz AE, Arguello Cedeño JA, Revilla Escobar KY, Aldas Morejon JP. Development of Jamaica flower (*Hibiscus sabdariffa*) jam in different states (natural and dehydrated). Nutr Clin Dietet Hosp. 2025;45(1):219–26. [CrossRef].
226. Baigts-Allende DK, Pérez-Alva A, Metri-Ojeda JC, Estrada-Beristain C, Ramírez-Rodrigues MA, Arroyo-Silva A, et al. Use of *Hibiscus sabdariffa* by-product to enhance the nutritional quality of pasta. Waste Biomass Valorization. 2023;14(4):1267–79. [CrossRef].
227. Pérez-Báez AJ, Valenzuela-Melendres M, Camou JP, González-Aguilar G, Tortoledo-Ortiz O, González-Ríos H, et al. Modelling the effects of roselle extract, potato peel flour, and beef fat on the sensory properties and heterocyclic amines formation of beef patties studied by using response surface methodology. Foods. 2021;10(6):1184. [CrossRef].
228. Singo T, Beswa D. Effect of roselle extracts on the selected quality characteristics of ice cream. Int J Food Prop. 2019;22(1):42–53. [CrossRef].
229. Chheng S, Jafari S, Mishra D, Assatarakul K. Sesban flower extract as a natural functional ingredient: Effects on texture, antioxidant activity, and shelf-life stability of jelly formulation. Sustain Food Technol. 2025;3(6):1865–79. [CrossRef].
230. Fact.MR. Anthocyanin Market: Global Industry Analysis and Forecast, 2025–2035. Rockville (MD): Fact.MR; 2025 [cited 2026 Feb 3]. Available from: https://www.factmr.com/report/2467/anthocyanin-market
231. Ramesh S, Rajkumar M, Silambuselvi K, Velraja S. Exploring *Clitoria ternatea* (Blue pea) herbal tea: A potent beverage with antioxidant and α-amylase inhibitory activity. Indian J Nat Prod Resour. 2025;16(2):271–8. [CrossRef].
232. Hegde AS, Gupta S, Sharma S, Srivatsan V, Kumari P. Edible rose flowers: A doorway to gastronomic and nutraceutical research. Food Res Int. 2022;162:111977. [CrossRef].
233. Milea ŞA, Dima CV, Enachi E, Dumitraşcu L, Barbu V, Bahrim GE, et al. Combination of freeze drying and molecular inclusion techniques improves the bioaccessibility of microencapsulated anthocyanins from black rice (*Oryza sativa* L.) and lavender (*Lavandula angustifolia* L.) essential oils in a model food system. Int J Food Sci Technol. 2020;55(12):3585–94. [CrossRef].
234. Jati IRAP, Utomo AR, Setijawaty E, Yoshari RM, Budianta TDW, Suseno TIP, et al. Durian albedo and eggshell-based smart edible film with infused butterfly pea flower extract as active agent. Discov Food. 2025;5(1):146. [CrossRef].
235. Szymański M, Długaszewska J, Pawlik M, Dobrucka R. Development of innovative environmental safety: Bioactives against pathogenic bacteria red pectin films from *Hibiscus sabdariffa* flos Extract for circular economy. Coatings. 2024;14(12):1500. [CrossRef].
236. Fallah N, Aarabi A, Zaki Dizaji H, Ghashang M. Optimization and characterization of colorimetric composite film based on biodegradable polymers (Gluten and Carboxymethyl Cellulose) and Roselle (*Hibiscus Sabdariffa*) anthocyanins as a TVN-B indicator in fish fillet. J Food Meas Charact. 2025;19(8):5829–47. [CrossRef].