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REVIEW ARTICLE

Anthocyanins from Vegetable By-Products: A Pharmacological Perspective on Recovery, Stabilization and Bioavailability

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Abstract

Vegetable processing produces significant amounts of by-products including peels, skins, and pomace, which serve as important sources of anthocyanins. These water-soluble flavonoid pigments impart red, purple, and blue coloration and thus exhibit antioxidant, anti-inflammatory, antidiabetic, cardiovascular, anticancer, neuroprotective, and antimicrobial properties. However, their practical application is restricted due to structural instability in the environment and processing conditions, sensitivity to pH, temperature, light, and enzymatic degradation, high gastrointestinal and metabolic transformation, and low systemic bioavailability. This review focuses on the valorization of anthocyanin-rich vegetable by-products, their recovery, stabilization, bioavailability, and pharmacological potential. The recovery of anthocyanins by conventional and green methods is critically compared to discuss anthocyanin recovery, selectivity, stability, and environmental sustainability. The advanced use of stabilization and delivery systems such as spray drying, freeze-drying, complex coacervation, cyclodextrin inclusion complexes, liposomes and polymeric nano-carriers is examined for their ability to preserve anthocyanin structure and enhance its gastrointestinal stability and bioavailability. Safety issues and toxicological concerns are also discussed. Overall, this review shows that vegetable by-products are sustainable sources of anthocyanins, and it is important to implement an integrated recovery, stabilization, and delivery strategy to transform these bioactive compounds into valuable ingredients for nutraceutical and pharmaceutical applications.

Key words: Anthocyanins, bioavailability, encapsulation, pharmacological activity, stability

INTRODUCTION

Vegetable supply chains generate large quantities of peels, pomace, and trimmings.[1] Approximately 1.3 billion tonnes of food are wasted or lost annually, with vegetables contributing approximately 45–50% globally.[2] Industrial processing produces significant amounts of peels, pomace, and outer leaves as by-products of washing, trimming, peeling, and juicing; these are underutilized sources of bioactive compounds rather than waste.[3,4] Anthocyanins are water-soluble flavonoid pigments that cause red, purple, and blue coloration in most vegetables. They exhibit red, purple, and blue hues in vegetables such as red cabbage, purple or black carrots, eggplant, purple sweet potato, and red onions.[5,6] The usual content of anthocyanins in red or purple vegetables ranges from a few mg to 200–300 mg/100 g fresh weight.[6] These pigments are repartitioned during processing; peels, pomace, and outer leaves often have significantly higher anthocyanin and total phenolic values than the edible flesh, as in onion peels and black carrot pomace. These compounds exhibit potent antioxidant, anti-inflammatory, hypoglycemic,

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antidiabetic, cardioprotective, and potential anticancer properties, making them promising functional ingredients in nutraceuticals.

Chronic low-grade inflammation and oxidative stress are linked to the development of numerous chronic non-communicable diseases, including cardiovascular conditions, type 2 diabetes mellitus, neurodegenerative illnesses, and a range of cancers, which add to the global health burden worldwide.[7] The antioxidant, immunomodulatory, and anti-inflammatory effects of plant-derived polyphenols have sustained pharmaceutical and nutraceutical interest for use as additional or preventive tools against these diseases.[8] Among these compounds, anthocyanins are of particular interest because of their broad spectrum of bioactivity and high prevalence in the human diet.

Anthocyanins are emerging as bioactive phytochemicals of pharmacological significance, in addition to their use as food colorants. Their antioxidant, anti-inflammatory, and enzyme-modulating actions have established their potential for use in nutraceutical and phytopharmaceutical formulations for managing oxidative stress-related chronic non-communicable diseases. However, *in vivo* clinical application is limited due to aqueous insolubility, chemical instability, and low oral bioavailability, leading to increased research on pharmaceutical delivery systems that can effectively protect and deliver anthocyanins *in vivo*.[9] Consequently, various strategies have been investigated to address these pharmacokinetic challenges related to the therapeutic application of anthocyanins, such as nanoencapsulation, liposomal trapping, polymeric nanoparticles, and hydrogel formulations.[9]

Traditionally, solvent extraction has been widely used for anthocyanin recovery; however, these methods often involve extended extraction times and high solvent usage. When these compounds are used in a pharmaceutical or nutraceutical application, the extraction method determines the purity, yield, and bioactivity of the resulting anthocyanin extract.[10] This review aims to assess anthocyanin-rich vegetable by-products with respect to their chemistry, extraction and stabilization methods, biological activities and applications in pharmaceutical and nutraceutical delivery systems.

SOURCES, CHEMISTRY, AND STABILITY OF ANTHOCYANINS

Major vegetable by-product sources

Table 1 summarizes the major anthocyanin-rich vegetable by-products and their pharmaceutical relevance.

Structure and major anthocyanin types

Anthocyanins possess a flavylium structure characterized by a C6-C3-C6 configuration (2-phenylbenzopyrylium) consisting of two aromatic rings (A, B) linked by a heterocyclic C ring that retains the positive charge.[23-25] They typically occur as glycosides, consisting of an anthocyanidin aglycone bonded to one or more sugars (commonly glucose, galactose, arabinose, rhamnose, xylose), usually attached at C3, and sometimes at C5 or C7, and are frequently acylated with either aromatic or aliphatic acids.[23-25] Cyanidin, delphinidin, pelargonidin, peonidin, petunidin, and malvidin represent the predominant dietary anthocyanin types, as shown in Figure 1.[6,14,26] Cyanidin is the predominant functional and structural unit of most anthocyanins derived from vegetables, which are primarily obtained from onion skins and crucifer by-products.[27] In addition, some anthocyanins (delphinidin, malvidin and petunidin) are more abundant, bluish and purple in color and are found in some blue- and purple-pigmented carrots and cabbages. Pelargonidin is the predominant form of orange shades and is typically present in red vegetables, as depicted in Figure 1.[26,27]

Glycosylation, acylation and substitution patterns

The levels of glycosylation, acylation and substitution patterns affect the stability, color and bioavailability of anthocyanins as shown in Table 2. Glycosylation increases water solubility and acylation can increase the stability of the pigment to heat and pH. The hydroxylation and methoxylation patterns have an effect on the antioxidant activity and susceptibility to oxidation of anthocyanins. The differences in anthocyanin stability and biological activity between vegetable by-products are due to these structural variations.

Factors affecting stability

pH

In a strongly acidic environment (pH <3), the red flavylium form is the predominant species and is fairly stable.[11,30] When the pH ranges from 4 to 5, a combination of flavylium, quinoidal base, carbinol, and chalcone emerges, resulting in a faint color as the colored forms are in the minority.[26] Near-neutral to basic pH, deprotonation and hydration give quinoidal anions (purple or blue), then degradation to brown oxidized products; anthocyanins are unstable at basic pH 9.[6,26]

Temperature

However, high temperatures accelerate the process of hydration and oxidative degradation, leading to fading and loss of bioactivity.[6,26]

Table 1: Major anthocyanin-rich vegetable by-products and their pharmaceutical potential

Sources	Major anthocyanin compounds and their content	Pharmaceutical relevance	Citation
Red cabbage (Outer trimming by-products)	Cyanidin-3-sophoroside-5-glucoside derivatives. (98.01 mg/100 g FW)	High DPPH/FRAP and cellular antioxidant capacity	[11]
Purple cauliflower (Florets and processing by-products)	Cyanidin-based anthocyanins such as p-coumaroyl and feruloyl esters of cyanidin-3-sophoroside-5-glucoside (8–201 mg C3G/100 g DW)	Rich antioxidant source; suitable for nutraceutical and pharmaceutical applications	[12]
Black carrot (Pomace, peel, trimming by-products)	Cyanidin 3-xylosylgalactosides acylated with sinapic acid, ferulic acid, and coumaric acid (13.84 mg/g DW)	Highly stable acylated anthocyanins and suitable for pharmaceutical formulations	[13,14]
Purple sweet potato (Peel, pulp and root by-products)	Dominant: Peonidin-3-caffeoyl-p-hydroxybenzoyl sophoroside-5-glucoside (16–266 mg/100g DW)	Rich source of stable anthocyanins with strong antioxidant activity; suitable for oral drug delivery systems	[15]
Purple yam (Peel and processing by-products)	Cyanidin- and peonidin-derived anthocyanins (13.04 mg Cy3G/100 g FW)	Rich source of acylated anthocyanins with antimicrobial activity	[16,17]
Eggplant (Peel and trimming by-products)	Delphinidin 3-O-rutinoside and glycosides (Yield 71.45%, TAC 578.66 mg C3G/100g)	Excellent source of nasunin with antioxidant and anticancer potential	[18,19]
Red onion (Outer dry skin and peel by-products)	Cyanidin 3-glucoside and cyanidin 3-laminaribioside (Maximum TAC 28.23mg/100g DW in dark red varieties)	Bioactive-rich processing by-product with strong antioxidant potential	[20,21]
Red radish (Peel, pomace and pulp by-products)	Pelargonidin-3-sophoroside-5-glucoside derivatives, acylated with hydroxycinnamic acids (63.77–160.74 mg/100 g FW)	Source of stable acylated anthocyanins with antioxidant activities.	[12,22]

FW: Fresh weight, DW: Dry weight, C3G: Cyanidin 3-glucoside, DPPH: 2,2-diphenyl-1-picrylhydrazyl, FRAP: Ferric reducing antioxidant power

Table 2: Impact of anthocyanin structure on stability and bioavailability across vegetable by-products

Structural feature	Impact on stability	Impact on bioavailability	Common vegetable sources	Citation
glycosylation Attachment of sugars (glucose, rhamnose) at the C3 or C5 position	High water solubility; protects against nucleophilic attack	Low intact; requires microbial metabolism for absorption	All anthocyanin-rich vegetables	[28]
acylation Esterification of organic acids to sugar	High; resists thermal and pH breakdown via intramolecular co-pigmentation	Delays absorption, allowing greater colon interaction	Black carrot, Purple sweet potato	[29]

Light

Promotes breakdown and loss of color, thus adds to overall instability.[6,26,31]

RECOVERY STRATEGIES FOR ANTHOCYANINS

Table 3 summarizes the conventional and green extraction methods, purification strategies, and characterization methods used to recover anthocyanins from vegetable by-products, as shown in Figure 2.

PHARMACOLOGICAL PROPERTIES OF ANTHOCYANINS

Antioxidant and anti-inflammatory activity

Anthocyanins are potent radical scavengers and contribute significantly to the antioxidant activity observed in many plant extracts and foods.[6] Anthocyanins isolated from purple sweet potato and purple cabbage have shown strong inhibition of protein glycation and a reduction in nitric oxide and tumor necrosis factor-alpha (TNF-α) levels in cell models, suggesting anti-glycation, antioxidant, and anti-inflammatory properties.[40] Furthermore, anthocyanins derived from black

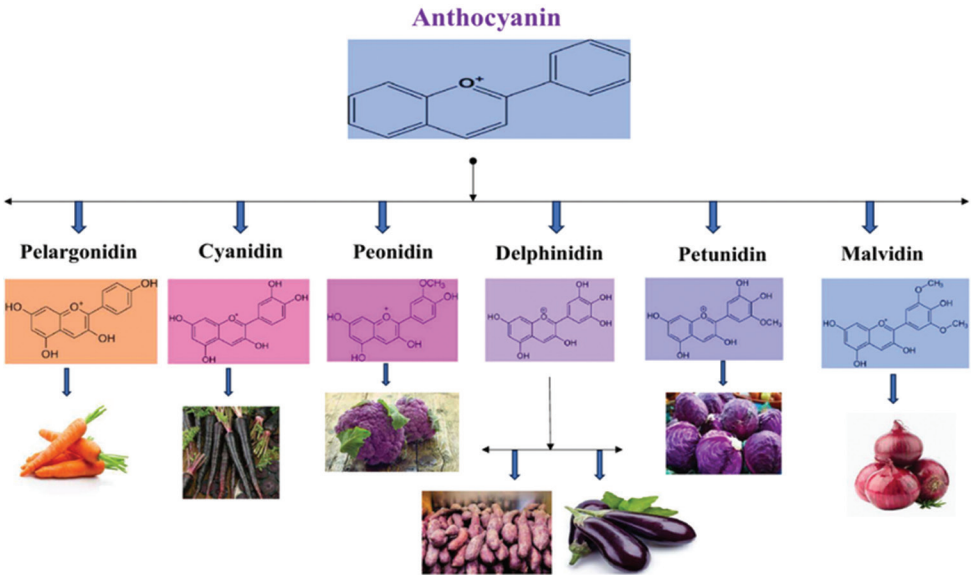


Figure 1: Anthocyanin chemical structure and its classification with vegetable source

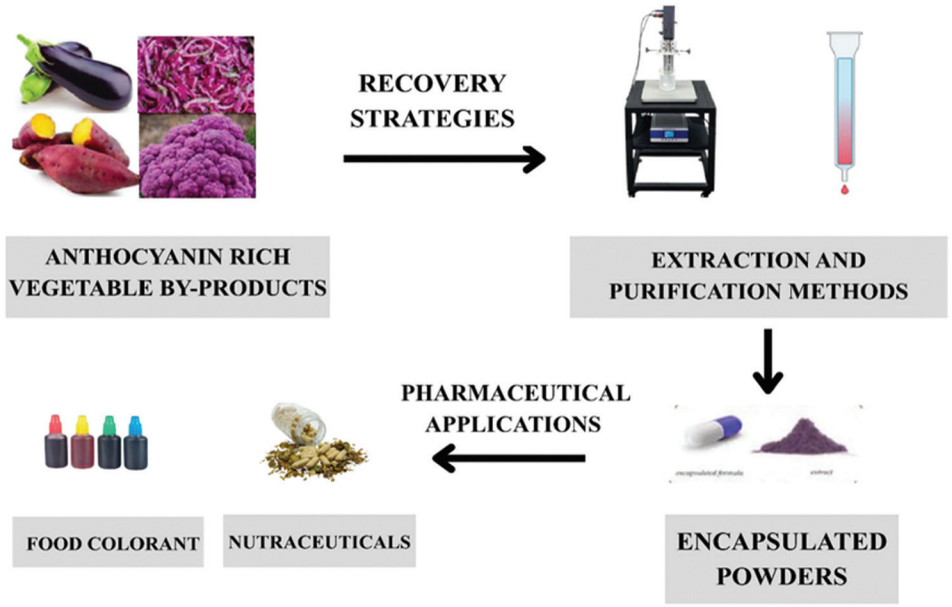


Figure 2: Overall valorization pathway of anthocyanins from vegetable by-products

carrot and other vegetable sources have been shown to reduce vascular cell adhesion molecule-1 (VCAM-1) and intercellular adhesion molecule-1 (ICAM-1), demonstrating anti-inflammatory effects on blood vessels that are critical for cardiovascular disease prevention.[41] *In vitro* studies showed that purified anthocyanin samples were isolated from vegetable sources such as anthocyanin-rich black carrot and sun black tomato (anthocyanin content between 4.9 and 38.5 mg/g dry weight). The antioxidant capacity of the extracts was assessed using the Trolox equivalent antioxidant capacity and oxygen radical absorbance capacity assays, respectively, and significant radical-scavenging activity was found to be directly linked to the chemical structure and concentration of anthocyanins.[42] The extracts significantly reduce the expression of pro-inflammatory cytokines (interleukin [IL]-1β, IL-6, IL-8, and TNF-α), and enhance the activities of endogenous antioxidant enzymes.[43]

Anti diabetic activity

Anthocyanins have been shown in multiple reviews to possess antidiabetic activity, improving hyperglycemia, improving insulin sensitivity, reducing dyslipidemia, and oxidative stress in animal and human studies.[26] Anthocyanins also demonstrate anti-glycation activity by binding to reactive carbonyls (such as methylglyoxal) and blocking the formation of advanced glycation end-products, as observed with extracts of purple cabbage and purple sweet potato.[40]

Table 3: Recovery and characterization of anthocyanins from vegetable by-products

Technique	Key parameters	Anthocyanin-rich vegetable by-product examples	Pharmaceutical relevance	Citation
Conventional extraction methods				
Solvent extraction	Acidified methanol or ethanol (0.1–1% HCl); 20% aqueous ethanol	Red cabbage leaves, purple sweet potato peels, eggplant peel by-products	Used to obtain crude anthocyanin extracts for antioxidant and anti-inflammatory studies	[20,32]
Soxhlet extraction	Reflux extraction with methanol/ethanol (4–8 h)	Black carrot pomace, purple yam peels, red radish by-products	Provides reference extracts; limited by heat-induced degradation	[20,32]
Maceration	Soaking at room temperature (12–72 h)	Red cabbage leaves, purple cauliflower, red onion skins by-products	Suitable for preserving heat-sensitive anthocyanins	[20,32]
Green extraction methods				
Ultrasound-assisted extraction	15–50°C; short extraction time	Red cabbage, black carrot pomace by-products	High extraction efficiency with good retention of bioactivity	[30,33]
Microwave-assisted extraction	Electromagnetic heating for a few minutes	Black carrot pomace, red cabbage by-products	Rapid extraction with high anthocyanin recovery	[33,34]
Enzyme-assisted extraction	Cell wall-degrading enzymes; pH 4–5.5, 30–50°C; 1–4 h incubation	Purple sweet potato peels, eggplant peels, red onion skins by-products	Solvent-free extracts suitable for pharmaceutical applications	[19,35]
Pressurized liquid extraction	High pressure; water or ethanol-water mixtures	Purple sweet potato, black carrot, purple yam by-products	Produces clean extracts suitable for encapsulation studies	[36]
Supercritical fluid extraction	Supercritical CO_2 with ethanol co-solvent	Black carrot pomace, eggplant peels, red cabbage by-products	Produces solvent-free, high-purity extracts	[37]
DES	Biodegradable DES with water	Red cabbage, purple sweet potato, red onion by-products	Improves anthocyanin stability and formulation	[20,38]
Purification and characterization				
High-performance liquid chromatography	C18 column with acidified mobile phase	All vegetable by-products	Quantifies individual anthocyanins for dose standardization	[39]
Liquid chromatography-tandem mass spectrometry	Electrospray ionization tandem mass spectrometry analysis	All vegetable by-products	Confirms anthocyanin structure and supports bioavailability studies	[39]
Ultraviolet-visible spectroscopy	pH differential method at 520 nm	Red cabbage; Black carrot; Purple sweet potato by-products	Determines TAC for quality assessment	[39]

DES: Deep eutectic solvents, TAC: Total anthocyanin content

Eggplant by-products (peel and calyx) were characterized for their phenolic composition and were tested for *in vitro* antidiabetic activity by inhibiting carbohydrate-hydrolyzing enzymes (α-amylase and α-glucosidase).[44] The findings of this study prove that eggplant by-products have the potential to be valorized as functional ingredients for the development of antidiabetic food products.

Anticancer activity

According to reviews, anthocyanins exert anti-cancer effects through anti-inflammatory and antioxidant mechanisms, inhibition of cell proliferation, cell cycle arrest, induction of apoptosis or autophagy, and reduction of invasion and metastasis.[31] In some animal studies and in a few human

trials, malvidin-type anthocyanins have shown anti-carcinogenic properties.[31] These anthocyanin structures are common in red or purple vegetables.[26] An *in vitro* study demonstrated that eggplant peel was used to extract anthocyanin compounds for a series of biological activities, including cytotoxic or antiproliferative activity. The study confirmed that eggplant peel has anticancer activity in addition to antioxidant and antimicrobial properties (mostly delphinidin-based nasunin).[45] The delphinidin anthocyanins are potent anticancer compounds that are present in the peel and calyx by-products of eggplant.

Cardiovascular activity

Consumption of anthocyanin-rich foods and nutraceuticals has been associated with improvements in vascular function, lipid profiles, and oxidative and inflammatory markers in animal and human studies, supporting their potential role in cardiovascular disease prevention.[6,46] Anthocyanins have antiatherogenic, antihypertensive, antiglycation, and antithrombotic actions, in part through modulating endothelial nitric oxide synthase and reducing oxidative stress.[26] Anthocyanins from black carrot and other vegetables directly protected the vessels by reducing *VCAM-1* and *ICAM-1* gene expression.[41]

ENCAPSULATION TECHNOLOGIES FOR ANTHOCYANINS

Microencapsulation techniques

Spray drying

Microencapsulation involves enclosing anthocyanins within a protective coating that acts as a physical barrier against environmental elements such as heat, light, and oxygen.[32] Spray drying is a widely used technique that offers benefits such as high encapsulation efficiency, cost-effectiveness, scalability, and the production of free-flowing powders.[47] For example, the maltodextrin spray drying process of red cabbage anthocyanins has been reported to yield up to 96% encapsulation efficiency, which greatly enhances the thermal stability of the pigment at 70°C.[30] Likewise, spray drying maltodextrin-produced anthocyanins achieved an encapsulation efficiency of 86%, thus preventing degradation during simulated digestion and increasing bio accessibility by 20%.[48]

Freeze-drying

Another method of microencapsulation, known as freeze-drying or lyophilization that works under low-temperature and vacuum conditions and helps minimise thermal degradation and maintain the structure of anthocyanins.[47] This method produces low-moisture powders with high porosity that preserve antioxidant activity better than spray drying; however, higher production costs and longer production time.[30] Encapsulated freeze-dried red cabbage powders exhibited higher anthocyanin content and antioxidant activity than non-encapsulated powders, indicating that during drying the wall materials protect the antioxidants.[30]

Nano-carrier and inclusion complexes

Complex coacervation

Nanoencapsulation technologies such as nanoparticles, nanoemulsions, and nanoliposomes thus lower the size of the particles, which promotes cellular uptake and prevents degradation by gastric enzymes, enhancing their stability and solubility.[49] Anthocyanins have been successfully loaded into nanosized coacervation systems using the electrostatic interaction between oppositely charged polymers.[49] Whey protein isolate (WPI), for instance, was used for complex coacervation to encapsulate red cabbage anthocyanins in 380 nm nanoparticles that enhanced stability and potential for targeted delivery for pharmaceutical formulation.[50]

Cyclodextrin (CD) inclusion complexes

CDs are ring-shaped oligosaccharides featuring a hydrophobic inner cavity and a hydrophilic outer surface, capable of forming inclusion complexes with anthocyanins.[51] It has been reported that CD-anthocyanin complexes improve the solubility and bioavailability of these pigments, thereby enhancing their potential for use in the pharmaceutical sector. The relative size of the cavity of the CD must be the same as the structure of the anthocyanin, and beta-CD is employed for monomeric anthocyanins for optimum complexation.[51]

PHARMACEUTICAL APPLICATIONS OF ANTHOCYANINS

Oral drug delivery systems

The most common solid dosage forms are capsules, tablets and powders, as shown in Figure 2. Dried anthocyanin powders can be directly filled into hard gelatin or vegetarian capsules that have been coated with wall materials such as maltodextrin or gum arabic to protect them from moisture.[52] The spray-dried red cabbage microcapsules and red onion skin powders demonstrated high encapsulation efficiency (96.36% and 90.53%, respectively), indicating the potential of oral products in powder form.[20,30] For tablet formulations, the compression force and humidity need to be carefully controlled to prevent color loss, especially for purple sweet potato anthocyanin, which has high stability for coloring medical tablets.[33,48]

Liposomal delivery system

Liposomes, composed of phospholipid bilayers, can contain hydrophilic anthocyanins in their water phase, protecting

them from digestive enzymes and gastric acid. The particle size of phosphatidylcholine nanoliposomes loaded with red cabbage extract was 37.12–56.1 nm, the encapsulation efficiency was 74% ± 3.5%, and their storage stability was good at 4°C for 30 days.[53] Red onion peel nanophytosomes showed 78.63% entrapment efficiency and twice the release in intestinal medium, highlighting the potential of liposomal systems to improve the therapeutic benefits of vegetable by-product anthocyanins.[54]

Nanoparticle-based delivery systems

The direct approach to these problems of instability and low bioavailability is improved through cellular uptake in nanoparticulate systems. The study showed that the nanoparticles WPI-pectin loaded with red cabbage extract were found to be around 380 nm, which is ideal for sustainable delivery.[30] Solid lipid nanoparticles loaded with red cabbage extract showed higher stability at gastric pH[3] as compared to intestinal pH,[5] and niosomes loaded with black carrot extract showed a 10-h release profile.[30,33]

Functional efficacy in pharmaceutical systems

The anthocyanins found in vegetable by-products can be used in the food sector for natural coloring, as natural antioxidants and as preservatives and in the pharmaceutical sector as functional ingredients in active and intelligent packaging.[10,55] The functional efficacy of anthocyanin-rich vegetables was represented in Figure 3. Red cabbage extracts have been added to starch-based edible films, resulting in pH-sensitive active packaging that shows enhanced mechanical and antioxidant properties, as depicted in Figure 3.[56] Natural colorants in eggplant peel have been stabilized through encapsulation, as shown in Figure 3.[10] These peels show excellent antioxidant activity and therefore require stabilization methods such as co-pigmentation or coating. These offer opportunities for application as meat preservatives and natural red colorants.

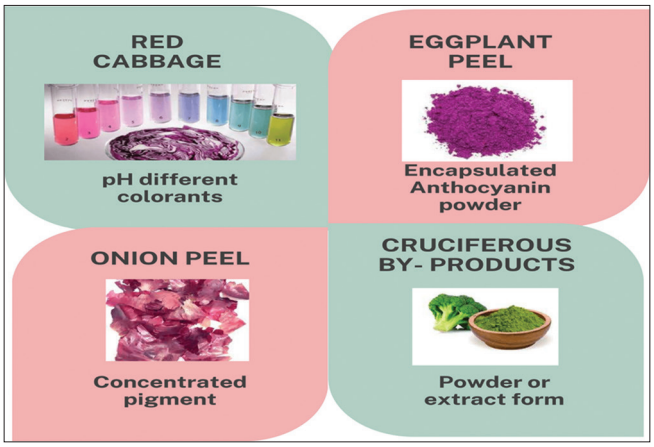


Figure 3: Functional efficacy of anthocyanin-rich vegetable by-products in pharmaceutical systems

BIOAVAILABILITY AND PHARMACOKINETICS OF ANTHOCYANINS

Bio accessibility, absorption, and bioavailability

Bioaccessibility is the proportion of anthocyanins that is released from the food or extract matrix and available for intestinal absorption. Physical and chemical interactions in the delivery system, including encapsulation matrices or co-pigmented complexes, are important factors to consider in this stage.[57] Absorption is the term used to describe the passage of these bioaccessible molecules across the intestinal epithelium into the portal circulation.[58] Bioavailability is the percentage of the administered dose that is absorbed into the systemic circulation either intact or metabolized and has physiological activity.[59]

Enzymatic deglycosylation and structural transformation

Anthocyanins rapidly change their structure during digestion, mostly through enzymatic deglycosylation. Anthocyanins are mainly present as glycosides, with sugar groups linked to the anthocyanidin aglycone.[60] Enzymes, including the small-intestinal enzymes lactase, phlorizin hydrolase, and microbial beta-glucosidases, break down these glycosidic bonds, converting anthocyanins into anthocyanidins.[58] Moreover, the structural change in the intestine is pH-dependent, with the stable flavylium cation in acidic media being converted to quinoidal bases, carbinol pseudobases and chalcones. As pH increases, many of these are colorless and less stable.[61]

Poor gastrointestinal absorption

Anthocyanin molecules are especially challenged in the gastrointestinal tract. In the oral cavity, anthocyanins are partially hydrolyzed to anthocyanosides by microbiota and then glucuronidated by glucuronidase.[62] Anthocyanins enter the stomach by specific transporters, such as sodium-dependent glucose co-transporter 1 and facilitative glucose transporters 1, and in the small intestine mainly as aglycones.[62] The absorption and bioavailability of these compounds decrease during digestion because they are molecularly unstable.[63]

SAFETY, TOXICOLOGY AND STANDARDIZATION CONSIDERATIONS

Anthocyanins extracted from vegetable by-products are considered Generally Recognized as Safe (GRAS), with no significant toxicological issues found in human studies at dietary levels.[64] But translating these extracts to pharmaceutical applications will need rigorous standardization for consistent efficacy and safety. Biological

effects of anthocyanins may vary depending on the source of the plants, the extraction process, and storage conditions.[55] Standardization processes should consider different anthocyanin profiles, total phenolic content, and stability indicators to ensure product quality.[65] In addition, while anthocyanins are considered safe, the solvents and processes used to isolate anthocyanins from other components in by-products, including deep eutectic solvents, should be assessed for potential residual toxicity and regulatory requirements for pharmaceutical formulations.[59]

CONCLUSION

The processing of vegetables can produce an enormous number of by-products with high anthocyanin contents, which can serve as a valuable and sustainable source of natural pigments with health benefits. These by-products can be used to recover anthocyanins and also offer a cost-effective method to obtain bioactive compounds for pharmaceutical and food industries. Although anthocyanins are highly beneficial, they have significant drawbacks, resulting in poor stability and low bioavailability. Moreover, anthocyanins have low bioavailability in the gastrointestinal tract after ingestion and are rapidly metabolized in the human body, which reduces their therapeutic potential. Several extraction and protection strategies have been developed to overcome these challenges. Furthermore, green extraction methods such as ultrasound-assisted extraction, pressurized liquid extraction, and enzyme-assisted extraction boost anthocyanin recovery while reducing solvent use and maintaining natural structures. There are several methods of anthocyanin encapsulation, including microencapsulation, spray drying, freeze-drying, nanoencapsulation, and CD inclusion complexes. Furthermore, delivery systems such as liposomes or nanoparticles help anthocyanins reach the targeted area more efficiently, without being digested.

The pharmacological evidence, which includes antioxidant, anti-inflammatory, antidiabetic, anticancer, cardiovascular, neuroprotective, and antimicrobial properties, strongly indicates the potential therapeutic value of anthocyanins. However, several obstacles exist between laboratory discoveries and actual pharmaceutical products. There is a lack of standardized extraction and quality control procedures, safety and toxicological information is insufficient, human bioavailability studies are scarce, and no anthocyanin-based product has yet passed the clinical validation necessary for regulatory approval. Future research should concentrate on enhancing green recovery methods, standardizing anthocyanin-rich extracts to ensure consistent composition, producing robust clinical evidence regarding efficacy and safety, and creating cost-effective delivery systems. The continuous improvement of these technologies will make it possible to use anthocyanins as effective, stable, and bioavailable additives for pharmaceutical applications.

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AUTHOR(S) CONTRIBUTIONS

Conceptualization: K. M. Anusri, G. Ashokkumar; Writing- Original draft: K. M. Anusri; Writing- review and editing: K. M. Anusri, G. Ashokkumar, C. Indu Rani; Supervision - G. Amuthaselvi, K. Gurusamy, S.T. Bini Sundar

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