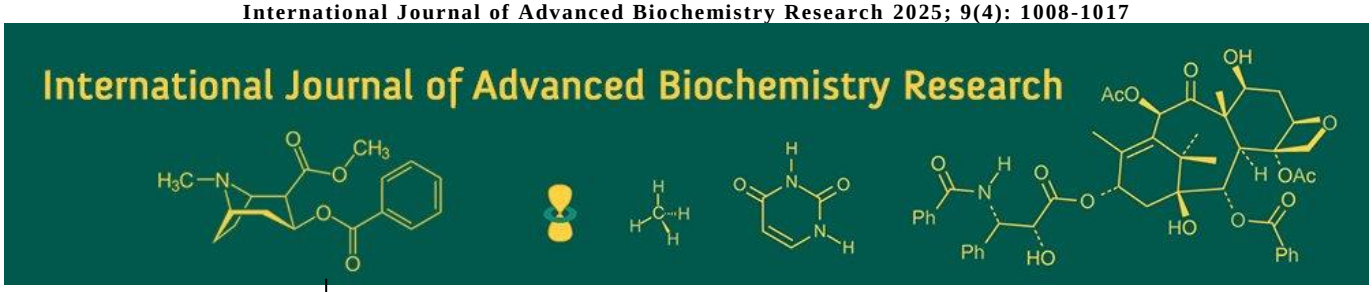

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating: 5.29
IJABR 2025; 9(4): 1008-1017
www.biochemjournal.com
Received: 15-01-2025
Accepted: 20-02-2025

Dr. Ashish Tyagi
School of Agricultural & Environmental Sciences, Shobhit Institute of Engineering & Technology, Meerut, Uttar Pradesh, India

Alpana Joshi
School of Agricultural & Environmental Sciences, Meerut, Uttar Pradesh, India

Neeshu Joshi
College of Agriculture, Agriculture University, Jodhpur, Rajasthan, India

Corresponding Author:
Alpana Joshi
School of Agricultural & Environmental Sciences, Meerut, Uttar Pradesh, India

Health-promoting effects of anthocyanin in whole grain cereals: Insights from a quantitative perspective

Ashish Tyagi, Alpana Joshi and Neeshu Joshi

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i4l.4219

Abstract
Anthocyanin, a group of plant-derived pigments, have gained significant attention due to their potential health benefits. Predominantly found in whole grain cereals such as black rice, purple corn, and purple wheat, anthocyanin offer a range of bioactive properties that make them valuable components in functional foods aimed at promoting health. This review examines the diverse sources, molecular mechanisms, and health-related effects of anthocyanin in whole grain cereals, while identifying current challenges and future opportunities for their application. Different whole grain varieties exhibit unique anthocyanin profiles; black rice, for instance, is rich in cyanidin-3-glucoside, while purple corn contains pelargonidin derivatives, and purple wheat is notably high in delphinidin compounds. These anthocyanin influence key molecular pathways, such as the Nrf2 and NF-κB pathways, modulating oxidative stress and inflammation. Additionally, anthocyanin show enhanced health benefits when combined with other bioactive compounds present in whole grains. Their antioxidant and anti-inflammatory properties have been linked to the prevention of chronic diseases like cardiovascular disease, diabetes, and neurodegenerative disorders. Anthocyanin also promote gut health by supporting beneficial microbiota. Furthermore, emerging evidence points to their anticancer potential. Despite their promising benefits, challenges such as variability in anthocyanin content, low bioavailability, and stability during processing remain. Advances in food technology, including microencapsulation and fermentation, present solutions to these challenges. Large-scale clinical trials are also needed to further establish the health benefits of anthocyanin. The future of anthocyanin lies in their integration into functional foods through sustainable practices.

Keywords: Anthocyanin, antioxidant activity, functional foods, health-promoting properties, whole grain cereals

Introduction
Whole grain cereals, a staple in the diets of many cultures, are renowned for their exceptional nutritional value and health benefits. When consumed in their minimally processed form, whole grains retain all three components—bran, germ, and endosperm—resulting in a nutrient-rich profile abundant in fiber, vitamins, and minerals. In recent years, colored whole grains such as black rice, purple corn, and red wheat have garnered particular interest due to their elevated anthocyanin content, which enhances their health-promoting potential. These grains have emerged as functional foods, combining nutritional benefits with bioactive compounds like anthocyanin that contribute to human health and disease prevention [1]. Their consumption aligns with global dietary trends favoring plant-based, nutrient-dense foods to combat rising rates of chronic diseases. Anthocyanin are naturally occurring, water-soluble pigments that belong to the flavonoid group of polyphenols. They are responsible for the vibrant red, purple, and blue colors found in a wide range of fruits, vegetables, and grains. These pigments are synthesized in plant tissues as part of secondary metabolism, playing a crucial role in attracting pollinators and providing protection against ultraviolet light and pathogens. Structurally, anthocyanin are glycosides derived from anthocyanidins; the bonding of sugar molecules enhances their solubility and stability. The major anthocyanin found in foods include cyanidin, delphinidin, malvidin, pelargonidin, peonidin, and petunidin, each contributing unique hues and health-promoting properties [2].
Anthocyanin levels and profiles exhibit considerable variation across different whole grains. For example, black rice is particularly abundant in cyanidin-3-glucoside, a potent antioxidant, while purple corn is rich in peonidin and pelargonidin derivatives.

These bioactive compounds provide more than aesthetic appeal, offering a broad spectrum of pharmacological benefits, including anti-inflammatory, anticancer, and neuroprotective effects. Their integration into daily diets through whole grains offers a sustainable and accessible means to enhance overall health [3]. Although anthocyanin in fruits and vegetables have been extensively studied, their presence and potential in whole grain cereals remain underexplored. This review addresses this gap by emphasizing the dual significance of anthocyanin-rich whole grains as both nutritional staples and sources of health-promoting bioactive. As whole grains are widely consumed across the globe, they serve as an effective medium for delivering anthocyanin to diverse populations. Their inclusion in staple diets holds significant promise for mitigating the global burden of chronic diseases, such as cardiovascular disorders, diabetes, and neurodegenerative conditions [4].

One distinct advantage of anthocyanin in whole grains lies in their relative stability compared to those in other food sources. While processing and storage conditions often degrade anthocyanin, the structural matrix and dense nutrient composition of cereals enhance retention. This stability not only facilitates their incorporation into food formulations but also improves their bioavailability during digestion [5]. Notably, several commercially relevant cereal grains, such as wheat, maize, sorghum, barley, rice, and millet, possess distinctly colored varieties due to the anthocyanin concentrated in the outer layers of their kernels. These anthocyanin-rich grains have emerged as promising ingredients for the development of whole grain functional foods. Anthocyanin are linked to various health benefits through their capacity to modulate oxidative stress, inflammation, and metabolic pathways. They act as antioxidants by scavenging free radicals and enhancing endogenous antioxidant enzyme activity. Additionally, they exhibit anti-inflammatory effects by suppressing pro-inflammatory cytokines and inhibiting key pathways such as NF-κB and MAPK. These mechanisms contribute to their cardio protective, antidiabetic, and anticancer properties, underscoring the importance of anthocyanin in nutritional science and functional food innovation [6]. This paper will review the structure and function of anthocyanin, with a specific focus on their antioxidant potential and the role of cereal anthocyanin in health and disease prevention.

Structure of Anthocyanin

Anthocyanin are water-soluble flavonoid compounds widely distributed in fruits, vegetables, and flowers, imparting vibrant colors such as red, blue, and purple. Common sources of anthocyanin-rich compounds include blueberries, sunflowers, grapes, dragon fruit, purple sweet potatoes, and purple cabbage. These compounds belong to an essential group of secondary metabolites in plants, fulfilling critical roles in pigmentation, defense mechanisms, and pollinator attraction. The core structure of anthocyanin is derived from the flavylium ion, characterized by a C6-C3-C6 carbon framework consisting of two aromatic rings (A and B) connected by a three-carbon chain forming a heterocyclic C ring. Due to their inherent instability in their free state, anthocyanin primarily exist as glycosides formed by glycosidic bonds with mono-, di-, or trisaccharides such as glucose, galactose, and rutinose, enhancing their solubility and stability for diverse biochemical and functional roles.

More than 700 types of anthocyanin with 30 different core structures have been identified, highlighting the remarkable diversity of Anthocynins. The six principal anthocyanin—delphinidin ($C_{15}H_{11}O_7$), cyanidin ($C_{15}H_{11}O_6$), pelargonidin ($C_{15}H_{11}O_5$), petunidin ($C_{16}H_{13}ClO_7$), malvidin ($C_{17}H_{15}O_7$), and peonidin ($C_{16}H_{13}O_6$) — each possess distinct structural configurations, contributing to their unique pigmentation profiles and functional properties [7] (Fig. 1; Table 1). Delphinidin, prevalent in blueberries and black currants, contains additional hydroxyl groups at the 3′ and 4′ positions on the B ring, contributing to its blue pigmentation. Cyanidin, the most widely distributed anthocyanin, is characterized by hydroxyl groups at the 3 and 5 positions of the B ring and is abundant in cherries, strawberries, and raspberries. Pelargonidin, commonly found in red fruits like strawberries and red apples, has fewer hydroxyl groups, which give it its bright red hue. Petunidin, present in eggplants and certain berries, includes a methoxy group at the 3′ position, resembling delphinidin in structure. Malvidin, notable for its role in red wine and grapes, has multiple methoxy groups that enhance its stability and color intensity. Peonidin, found in purple corn and specific berries, also features a methoxy group at the 3′ position, contributing to its color and stability [8].

Anthocyanin coloration and stability are significantly affected by environmental factors, particularly pH. Under acidic conditions, anthocyanin exist as flavylium cations (oxonium oxygen), exhibiting vibrant pigmentation. In neutral conditions, they predominantly transition to uncharged quinonoidal forms, while at basic pH, they become unstable and susceptible to degradation. Beyond their visual appeal, anthocyanin play essential roles in plant protection and human health, highlighting their ecological importance and wide-ranging applications.

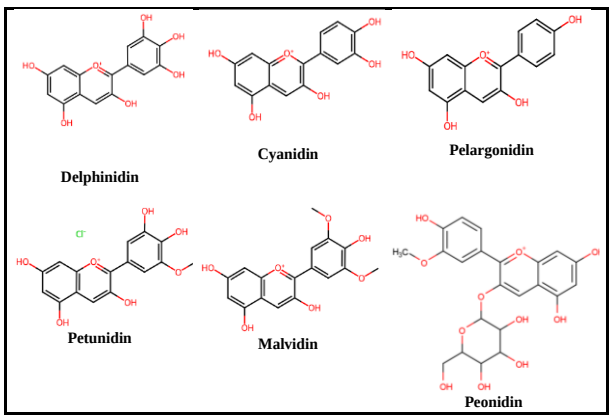

Fig 1: Molecular Structure of Common Found Anthocyanin.

Table 1: The structural differences among the six principal anthocyanin

Anthocyanin	R_3'	R_4'	R_5'	R_3	R_5	R_6	R_7
Cyanidin	-OH	-OH	-H	-OH	-OH	-H	-OH
Delphinidin	-OH	-OH	-OH	-OH	-OH	-H	-OH
Pelargonidin	-H	-OH	-H	-OH	-OH	-H	-OH
Malvidin	-OCH_3	-OH	-OCH_3	-OH	-OH	-H	-OH
Peonidin	-OCH_3	-OH	-H	-OH	-OH	-H	-OH
Petunidin	-OH	-OH	-OCH_3	-OH	-OH	-H	-OH

Biosynthesis of Anthocyanin and Mechanisms of Action

The biosynthesis of anthocyanin takes place through the phenylpropanoid pathway, which begins with the conversion of the amino acid phenylalanine into cinnamic acid. This pathway, occurring on the cytoplasmic face of the endoplasmic reticulum in plants, serves as the precursor for various phenolic compounds, including flavonoids like anthocyanin (Fig. 2). Key enzymes involved in this process include phenylalanine ammonia-lyase PAL), which converts phenylalanine into cinnamic acid, and chalcone synthase CHS), which catalyzes the condensation of p-coumaric acid into naringenin chalcone — the precursor for anthocyanin. The pathway is regulated by transcription factors such as the MYB-bHLH-WD40 MBW) complex, with MYB transcription factors playing a vital role in modulating the expression of structural genes involved in anthocyanin synthesis. Environmental factors, such as light and temperature, also influence anthocyanin accumulation. Exposure to light activates specific transcription factors that promote biosynthesis, while low temperatures encourage anthocyanin accumulation, while higher temperatures tend to inhibit the process. Additionally, plant hormones can modulate gene expression, further complicating regulatory control [8, 9].

The core pathway involves several steps after cinnamic acid is converted into p-coumaric acid, which enters the flavonoid biosynthetic pathway. The enzymes CHS and chalcone isomerase CHI) help in the formation of flavonoid precursors, which are then converted into anthocyanidins the aglycone forms of anthocyanin), including compounds like delphinidin, cyanidin, and pelargonidin. Subsequently, anthocyanidins are glycosylated to form anthocyanin, with enzymes such as flavonoid 3'-hydroxylase F3'H) and flavonoid 3', 5'-hydroxylase F3'5'H) contributing to the formation of distinct anthocyanidin varieties. The glycosylation process, wherein sugar molecules are attached, enhances the solubility and stability of anthocyanin, making them more effective in plants and beneficial for human consumption. In plants, the accumulation of anthocyanin in vacuoles serves several important functions, including attracting pollinators, deterring herbivores, and providing protection against ultraviolet radiation, oxidative stress, and pathogens [10, 11].

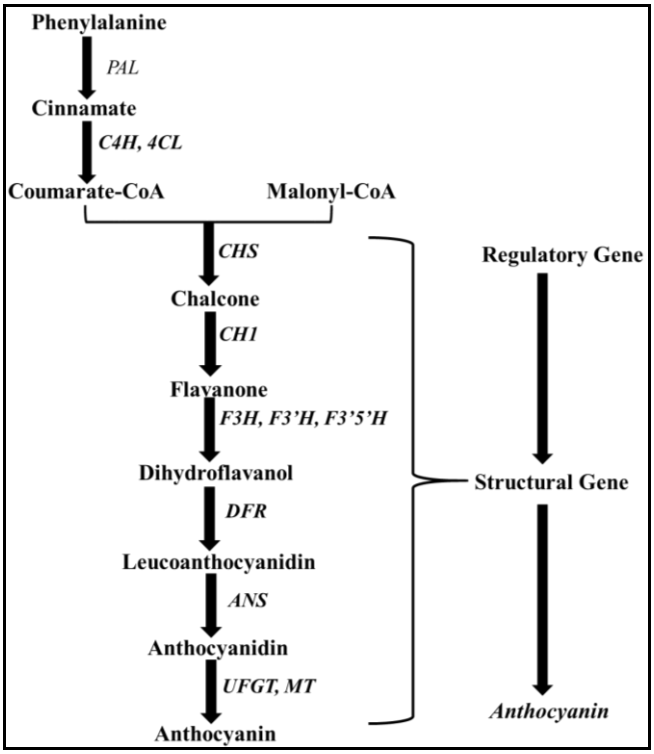

Fig 2: Anthocyanin Biosynthesis Pathway in Plants.
PAL: phenylalanine ammonia lyase gene; C4H: cinnamate-4-hydroxylase gene; 4CL: 4-coumarate: CoA ligase gene; CHS: chalcone synthase gene; CHI: chalcone isomerase gene; F3H: flavanone 3-hydroxylase gene; F3′H: flavonoid 3′-hydroxylase gene; F3′, 5′H: flavonoid 3′, 5′-hydroxylase gene; DFR: dihydroflavonol 4-reductase gene; ANS: anthocyanidin synthase gene; UFGT: UDP-glucose: flavonoid glucosyltransferase gene; MT: methyl transferase gene.

The health-promoting effects of anthocyanin are mediated through specific molecular mechanisms and their interactions with cellular pathways. These bioactive compounds influence various signaling pathways, contributing to their antioxidant, anti-inflammatory, and protective roles. Additionally, anthocyanin exhibit synergistic effects when combined with other bioactive compounds found in cereals, enhancing their overall health benefits. Anthocyanin exert their beneficial effects by

modulating critical signaling pathways involved in oxidative stress, inflammation, and cell survival. Two major pathways frequently influenced by anthocyanin are the nuclear factor erythroid 2-related factor 2 Nrf2 pathway and the nuclear factor kappa B NF-κB) pathway. Anthocyanin activate the Nrf2 signaling pathway, which plays a critical role in the cellular antioxidant response. By promoting the transcription of antioxidant enzymes, such as heme oxygenase-1 HO-1 and glutathione S-transferase GST, Nrf2 activation enhances the cell's capacity to neutralize reactive oxygen species (ROS). For instance, studies show that anthocyanin in black rice upregulate Nrf2, which leads to increased HO-1 activity and reduced oxidative damage both *in vitro* and *in vivo* [12]. The NF-κB pathway regulates inflammation, and its over activation is linked to chronic inflammation and related diseases. Anthocyanin inhibit NF-κB activation by preventing the phosphorylation of IκB-α, which in turn reduces the production of pro-inflammatory cytokines like TNF-α and IL-6. Research on purple corn anthocyanin has demonstrated that they suppress NF-κB activity in macrophages, leading to a significant reduction in inflammatory responses [13]. This pathway inhibition by anthocyanin helps to prevent cellular damage, reduce inflammation, and maintain cellular homeostasis. By interacting with these pathways, anthocyanin prevent cellular damage, reduce inflammation, and promote cellular homeostasis.

Synergistic Interactions of Anthocyanin in Whole Grains

The health benefits of anthocyanin in whole grain cereals are significantly enhanced when combined with other bioactive compounds such as polyphenols, dietary fibers, and vitamins. This synergy stems from the complementary mechanisms through which these compounds interact, amplifying the overall health-promoting effects [9-12]. When consumed together, anthocyanin and these compounds work synergistically to enhance antioxidant, anti-inflammatory, and gut-health-promoting properties. Whole grain cereals contain a wide variety of polyphenols, which interact synergistically with anthocyanin. For example, compounds like ferulic acid and quercetin, both commonly found in whole grains, enhance the antioxidant capacity of anthocyanin by stabilizing free radicals. Studies have shown that the combination of these polyphenols with anthocyanin provides superior protection against oxidative stress compared to anthocyanin alone[14]. The dietary fibers present in whole grains also contribute to their synergistic effects with anthocyanin. These fibers act as prebiotics, facilitating the fermentation of anthocyanin into bioactive metabolites in the colon. These metabolites further support a healthy gut microbiota, enhancing the gut-protective benefits of anthocyanin. A study on purple wheat demonstrated that the combination of anthocyanin and dietary fibers increased the abundance of beneficial gut bacteria like *Bifidobacterium*, promoting improved gut health [15, 16]. In addition to polyphenols and fibers, micronutrients such as zinc and selenium, which are commonly present in whole grains, play a key role in stabilizing anthocyanin. This stabilization enhances the bioavailability and effectiveness of anthocyanin during digestion. Research on fortified cereal formulations has shown that micronutrient interactions improve anthocyanin retention and bioactivity, further supporting the health benefits of these bioactive compounds [17]. The synergistic interactions between anthocyanin and other bioactive compounds in whole grains underscore the importance of consuming these nutrients within their natural food matrix. This not only maximizes their bioactivity but also amplifies their health-promoting potential, highlighting the significant role of whole grains in improving overall health [18].

The integration of anthocyanin-rich grains into daily diets presents a promising strategy for enhancing dietary quality and promoting better health. These grains can be incorporated into everyday meals by substituting them for traditional grains, thereby boosting nutritional value while maintaining aesthetic appeal. For instance, black rice can replace white rice in a variety of dishes, offering a rich color along with enhanced health benefits. Additionally, purple corn flour can be used in baking products like bread, muffins, and tortillas, offering both a vibrant color and health-promoting properties [19]. These practical applications not only improve the nutritional profile of foods but also have the potential to contribute significantly to public health nutrition.

Anthocyanin in Whole Grain Cereals

Anthocyanin are present in various whole grain cereals, with each exhibiting distinct profiles, concentrations, and associated bioactivities. Black rice is among the most anthocyanin-rich cereals, with cyanidin-3-glucoside making up a significant portion of its anthocyanin content, ranging from 200 to 400 mg/100 g depending on variety and processing conditions [20]. Purple corn, cultivated predominantly in South America, is another key source, with its anthocyanin content consisting mainly of cyanidin-3-glucoside and pelargonidin derivatives, and totaling around 160-350 mg/100 g. Although purple wheat contains fewer anthocyanin than black rice and purple corn, it is distinguished by a unique combination of delphinidin and malvidin derivatives, typically ranging from 100 to 200 mg/100g [20]. Factors such as genetic variability, environmental conditions, and post-harvest processing influence the composition and content of anthocyanin. For instance, milling and polishing can reduce anthocyanin content in black rice by up to 50%, while thermal processing may partially degrade anthocyanin in purple corn and wheat [21].

The health benefits of anthocyanin differ across cereals due to variations in their composition and bioavailability. Black rice, particularly rich in cyanidin-3-glucoside, is known for its potent antioxidant and anti-inflammatory properties, with studies highlighting its role in enhancing endothelial function, reducing oxidative stress, and modulating inflammatory pathways [22, 23]. Purple corn, on the other hand, has shown strong cholesterol-lowering effects and improved arterial stiffness, contributing to cardiovascular health [24, 25]. Anthocyanin in purple wheat, though present in lower quantities, appear to support gut health by promoting beneficial gut bacteria and reducing intestinal inflammation markers [26]. Bioavailability plays a crucial role in the health outcomes, as anthocyanin from black rice tend to be more stable during digestion, leading to higher plasma concentrations and enhanced systemic effects compared to anthocyanin from purple corn [27, 28].

The total anthocyanin content (TAC) and antioxidant potential of various colored rice, barley, maize, and wheat varieties vary significantly. For instance, purple rice varieties such as GPNO 20,175 and Hung Tsan exhibit TAC

levels between 68-199 mg/kg, with antioxidant potential ranging from 98 to 174 µmol TE/g bran, measured through ORAC (Oxygen Radical Antioxidant Capacity. In contrast, red rice varieties like SB7 show no measurable TAC and a moderate antioxidant potential (75 µmol TE/g). Black rice, such as Asamurasaki and Okunomurasaki, reveals diverse TAC levels, with Asamurasaki displaying a high antioxidant potential of 65 mmol TE/g DW, as determined by ORAC. Barley varieties like CI-1248 and Peru-35 also vary in TAC, with CI-1248 showing a TAC of 573 mg/kg and an antioxidant potential of 3937 µmol TE/100 g by ORAC (Table 2). Maize and wheat varieties exhibit a broad range of results, including varying TAC values, and their antioxidant potentials are measured through a range of assays like ORAC (oxygen radical antioxidant capacity), DPPH (2,2-diphenyl-1-picrylhydrazyl), and ABTS (2,2-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (Table 2). Furthermore, anthocyanin' structural features, such as hydroxylation and methoxylation patterns, influence their stability, bioactivity, and color, which are crucial to their role in reducing oxidative stress and inflammation. Overall, anthocyanin in whole grain cereals, with their varying concentrations and bioactivities, offer significant health benefits, from cardiovascular to gut health, largely depending on the grain type, its anthocyanin composition, and its bioavailability.

Table 2: Variation in Antioxidant Potential among Colored Grains

Plant	Variety	TAC (mg/kg Seed Weight)	Method Used for TAC	Antioxidant Potential	Antioxidant Assay(s)
Purple Rice	GPNO 20,175	68±29	Spectrophotometer	98 µmol TE/g bran	ORAC
Purple Rice	Hung Hsien Ju PI 16,097	151±25	Spectrophotometer	174 µmol TE/g bran	ORAC
Purple Rice	Hung Tsan	199±36	Spectrophotometer	147 µmol TE/g bran	ORAC
Purple Rice	IAC600	4700	Spectrophotometer	101 µmol TE/g	ORAC
Red Rice	SB7	-	pH Differential	75 µmol TE/g	ORAC
Red Rice	Red	94±1	Spectrophotometer	n.d.	n.d.
Black Rice	Asamurasaki	1400±41	HPLC	n.d.	n.d.
Black Rice	Asamurasaki	474	HPLC	65 mmol TE/g DW	ORAC
Black Rice	Okunomurasaki	80	HPLC	55 mmol TE/g DW	ORAC
Black Rice	Longjin 01	5101±79	pH Differential	1138 mmol TE/g DW	ORAC
Purple Barley	CI-1248	573±26	HPLC	3937 µmol TE/100 g	ORAC
Purple Barley	Yu 5904-088	679±19	Spectrophotometer	78%	DPPH
Blue Barley	Kompolti korai 1	84±3	Spectrophotometer	n.d.	-
Blue Barley	Ubamer	77±2	Spectrophotometer	35%	DPPH
Blue Barley	Tankard	345±1	Spectrophotometer	n.d.	-
Black Barley	Peru-35	0	HPLC	5430 µmol TE/100 g	ORAC
Black Barley	Black	8±1	Spectrophotometer	29%	DPPH
Purple Maize	KKU-WX211003	89±1	pH Differential	14 µmol TE/g DW	DPPH
Purple Maize	AREQ516540TL	850±6	Spectrophotometer	92%	ABTS
Purple-black Maize	KKU-WX111031	1439±8	pH Differential	22 µmol TE/g DW	DPPH
Purple-yellow Maize	KKU-WX211004	27±1	pH Differential	12 µmol TE/g DW	DPPH
Red-yellow Maize	ZPL-5	3±0	HPLC	23 mmol TE/kg	TEAC
Dark red Maize	ZPP-1 selfed	696±3	HPLC	27 mmol TE/kg	TEAC
Light blue Maize	ZPP-2 selfed	379±5	HPLC	36 mmol TE/kg	TEAC
Blue Maize	Blue	100±2	Spectrophotometer	63%	ABTS
Black Maize	Black	77±2	Spectrophotometer	60%	ABTS
Black Maize	Negro normal OLI 04 PV	120±2	Spectrophotometer	85%	ABTS
Purple Wheat	Laval	96±5	Spectrophotometer	n.d.	-
Purple Wheat	Laval 19	10	pH Differential	n.d.	-
Purple Wheat	Charcoal	305	pH Differential	n.d.	-
Purple Wheat	Indigo	72±1	Spectrophotometer	3959 µmol TE/100 g	ORAC
Blue Wheat	Purendo	212±3	Spectrophotometer	n.d.	-
Blue Wheat	BVAL-214025	74±2	Spectrophotometer	5 mmol Fe2 + equiv/100 g	FRAP
Black Wheat	BW/2 PBW621-F5	198±9	Spectrophotometer	n.d.	-
Black Wheat	Black Wheat	186±17	Spectrophotometer	n.d.	-
Black Wheat	UC 66049/Konini	56	pH Differential	n.d.	-

ABTS: 2,2-azinobis(3-ethylbenzothiazoline-6-sulfonic acid, DM: dry matter, DPPH: 2,2-diphenyl-1-picrylhydrazyl, DW: dry weight, FRAP: ferric reducing antioxidant power, GAE: Gallic acid equivalents; HPLC: High-performance liquid chromatography, ORAC: oxygen radical antioxidant capacity, TAC: total anthocyanin content, and TEAC: Trolox equivalent antioxidant capacity, n.d.: Not detected[24-28].

Bioavailability of Anthocyanin

The bioavailability of anthocyanin is significantly influenced by food processing, which affects both the content and accessibility of these compounds. Key factors such as the food matrix, the presence of additional components e.g., alcohol and fat), and the molecular structure of anthocyanin contribute to their bio accessibility. Acylation, for example, enhances anthocyanin stability but may reduce their bioavailability [29]. The structural characteristics of anthocyanidins also play a vital role, with anthocyanins derived from pelargonidin being more readily absorbed than those with more complex B-ring substituents. In addition, plant species and the composition of the food matrix affect anthocyanin content and bioavailability. The food's pH and temperature during processing can also modify these factors. Moreover, food-processing methods can create new compounds that either bind, solubilize, or stabilze anthocyanin, influencing their absorption [30].

Thermal processing has a unique effect on anthocyanin. While it reduces their content, it increases their bio accessibility and bioavailability. Thermal treatments disrupt cell walls, releasing cytoplasmic contents and making anthocyanin more accessible for absorption. However, much is still unknown about the precise effects of different processing methods on anthocyanin bioavailability. Once ingested, anthocyanin face additional challenges related to their instability during digestion and rapid metabolism. In the acidic stomach environment, they degrade, and only a small portion is absorbed in the small intestine. Absorbed anthocyanin are metabolized in the liver into phase II conjugates, such as glucuronides and sulfates, which may influence their bioactivity. A large proportion of anthocyanin reaches the colon, where gut microbiota metabolize them into smaller phenolic acids, which contribute to the health benefits of these compounds. The food matrix, co-ingested nutrients, and individual gut microbiota composition all influence the bioavailability of anthocyanin, indicating the importance of the dietary context in optimizing their health-promoting effects [31-34].

Clinical studies indicate that only about 1% of the anthocyanin consumed are detected in plasma as glucuronides and sulfates, suggesting significant metabolic processing before they reach systemic circulation. *in vitro* studies show that approximately 50% of anthocyanin degrade in the stomach, while 40% reach the colon for microbial metabolism. Furthermore, the presence of lipids during consumption improves anthocyanin stability and absorption in the small intestine by about 20%, suggesting a potential role of dietary fats in enhancing their bioavailability[35]. The interaction of anthocyanin with protein-bound matrices during simulated digestion further supports the importance of the food matrix, as protein binding significantly reduces degradation and maintains up to 70% of anthocyanin stability [35, 36]. Additionally, individual variations in gut microbiota composition influence the conversion of anthocyanin to bioactive phenolic acids, complicating their metabolic profiles[34]. Studies on anthocyanin stability show that they are highly stable at pH levels between 4 and 6 but rapidly degrade under highly acidic conditions pH < 2) such as those found in the stomach[35]. Urinary excretion studies show that anthocyanin metabolites include glucuronides and phenolic acids, reflecting partial absorption and metabolism. Moreover, co-digestion with polyphenol-rich compounds enhances anthocyanin recovery by about 15%, suggesting potential synergistic effects that could further optimize their health benefits [32-36].

Health-Promoting Properties of Anthocyanin

Anthocyanin are widely studied for their diverse health-promoting properties. As potent bioactive compounds, they combat oxidative stress, reduce inflammation, and offer therapeutic potential for cardiovascular diseases, cancer, neurodegenerative disorders, and gut health (Fig. 3).

Antioxidant Activity

One of the most recognized functions of anthocyanin is their ability to combat oxidative stress, which is implicated in various chronic diseases. Anthocyanin act as scavengers of reactive oxygen species ROS) and reactive nitrogen species RNS), preventing cellular damage. Their antioxidant capacity is attributed to their chemical structure, particularly the hydroxyl groups on the B-ring that donate hydrogen atoms to neutralize free radicals [37]. *in vitro* studies have demonstrated that anthocyanin-rich extracts from black rice and purple corn exhibit significant free radical-scavenging activity, reducing lipid peroxidation and DNA damage. *in vivo* studies have further confirmed these effects; anthocyanin supplementation in rodents increased the activity of endogenous antioxidant enzymes such as superoxide dismutase (SOD) and catalase, thereby enhancing oxidative defense mechanisms [38].

Anti-Inflammatory Effects

Anthocyanin reduce inflammation by inhibiting pro-inflammatory signaling pathways and modulating cytokine levels. These compounds interact with nuclear factor-kappa B (NF-κB) and mitogen-activated protein kinase MAPK) pathways, which are critical mediators of inflammation. By suppressing these pathways, anthocyanin prevent the release of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) [39]. In a clinical study, supplementation with anthocyanin-rich black rice significantly reduced C-reactive protein (CRP) levels, a key inflammatory biomarker. Similarly, *in vivo* studies in mice showed that purple wheat anthocyanin reduced inflammation in induced colitis models, confirming their role in inflammation control [40, 41]. A randomized controlled trial on elderly individuals found that consuming a blueberry anthocyanin supplement decreased plasma IL-6 and CRP levels, displaying potential applications in age-related inflammatory conditions [30, 41]. Another animal study using a model of atherosclerosis revealed that anthocyanin-rich black soybean significantly reduced systemic inflammatory markers, including CRP and TNF-α, while improving endothelial function[21]. Additionally, a double-blind, placebo-controlled study demonstrated that tart cherry juice, a rich source of anthocyanin, decreased serum markers of muscle damage and inflammation, including CRP, in endurance athletes. Another *in vitro* investigation observed that anthocyanin extracted from elderberries suppressed lipopolysaccharide (LPS)-induced expression of pro-inflammatory cytokines in macrophages through NF-κB pathway inhibition.

Cardiovascular Activities

Anthocyanin contribute to cardiovascular health by improving lipid profiles, reducing blood pressure, and decreasing the risk of atherosclerosis. They exert these effects by enhancing endothelial function, reducing oxidative stress, and inhibiting low-density lipoprotein (LDL) oxidation [42]. Several human studies have highlighted the positive effects of anthocyanin on lipid metabolism. For instance, a randomized controlled trial found that participants consuming anthocyanin-rich black rice experienced reductions in total cholesterol and triglycerides. Furthermore, anthocyanin have been shown to improve arterial stiffness and reduce systolic blood pressure, which are critical factors in cardiovascular disease management [43]. A meta-analysis of randomized controlled trials confirmed that anthocyanin supplementation significantly reduces LDL cholesterol and increases high-density lipoprotein HDL) cholesterol levels, contributing to improved lipid profiles [41]. Another study demonstrated that anthocyanin derived from bilberries significantly reduced both systolic and diastolic blood pressure in patients with

hypertension, suggesting potential therapeutic applications [42].

In addition, a prospective cohort study found that individuals with higher dietary intake of anthocyanin-rich foods, such as berries, had a lower risk of myocardial infarction, particularly in young and middle-aged women [2]. Experimental studies have also shown that anthocyanin from purple corn inhibit the progression of atherosclerotic plaques by modulating oxidative stress and improving endothelial function in animal models. Clinical research on anthocyanin-rich tart cherries revealed improvements in vascular function and reductions in biomarkers of inflammation, such as C-reactive protein (CRP), which are linked to cardiovascular health. Furthermore, anthocyanin supplementation has been found to enhance nitric oxide bioavailability, promoting vasodilation and improved blood flow [6].

Anticancer and Neuroprotective Activities

Anthocyanin possess anticancer properties, with mechanisms involving the inhibition of cell proliferation, induction of apoptosis, and modulation of cancer-related pathways. Their anticancer effects are largely mediated through the regulation of the PI3K/Akt and MAPK pathways, as well as the activation of tumor suppressor genes [44]. In colorectal cancer models, anthocyanin extracted from black rice demonstrated significant inhibition of tumor growth. Similarly, purple corn anthocyanin were shown to reduce metastasis in breast cancer models by modulating the expression of matrix metallo-proteinases (MMPs) [45].

Emerging evidence suggests that anthocyanin may protect against neurodegenerative diseases such as Alzheimer's and Parkinson's. Their neuroprotective effects stem from their antioxidant and anti-inflammatory properties, as well as their ability to cross the blood-brain barrier and modulate neural pathways. In a study on aged rats, supplementation with anthocyanin-rich purple corn improved memory and learning performance. Human studies have also reported enhanced cognitive function in older adults consuming anthocyanin-rich whole grains [46].

Gut Health and Microbiota Modulation

Anthocyanin play a significant role in promoting gut health by modulating gut microbiota composition. They stimulate the growth of beneficial bacteria such as *Lactobacillus*, while also reducing the abundance of pathogenic bacteria, thus improving gut barrier function and reducing inflammation [47]. Several studies have demonstrated the potential of anthocyanin to positively impact gut health. For example, a study on black rice revealed that it promoted the growth of *Lactobacillus*, a beneficial gut bacterium, suggesting that anthocyanin in black rice could help foster a healthy gut microbiome [48].

In addition, purple wheat has been shown to reduce markers of gut inflammation in an animal model, highlighting its anti-inflammatory effects on gut health [47]. Similarly, purple corn has been associated with improved gut barrier function in a human trial, further supporting the potential of anthocyanin-rich grains in enhancing intestinal health [45].

Anthocyanin undergo microbial metabolism in the colon, leading to the production of bioactive phenolic acids that exert systemic health effects. A clinical study found that anthocyanin-rich black rice improved gut microbial diversity and reduced markers of gut inflammation in individuals with irritable bowel syndrome (IBS) [46-48]. Collectively, these findings underscore the beneficial impact of anthocyanin on gut microbiota and overall gut health.

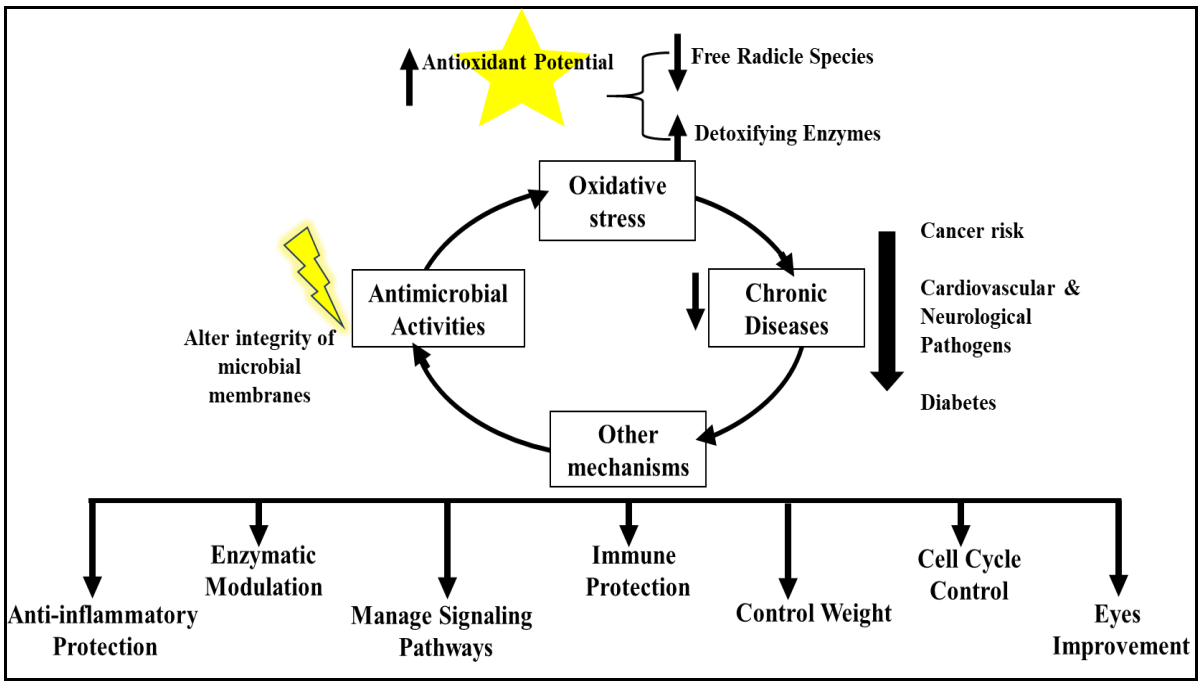

Fig 3: Health Benefits of Anthocyanin

Challenges in Developing Anthocyanin-Rich Functional Foods

The development of functional foods incorporating anthocyanin-rich grains represents a growing area of interest within the food industry. These foods are specifically designed to provide health benefits that extend beyond basic nutrition, potentially reducing the risk of disease and promoting overall health. Anthocyanin-rich grains offer a unique opportunity to create products that appeal to health-conscious consumers seeking natural, nutrient-dense options

[49]. The creation of cereal-based health-promoting products is one promising avenue, including nutraceuticals derived from grain extracts for use in supplements, fortified foods like anthocyanin-enriched pasta or noodles, functional beverages containing anthocyanin, and natural food colorants that replace synthetic dyes with added health benefits [50]. Advances in food technology are enabling the preservation of anthocyanin throughout the production process. Techniques such as microencapsulation protect anthocyanin from degradation, ensuring their stability and bioactivity in functional foods. Fermentation processes can also enhance anthocyanin bioavailability by breaking down complex compounds into more absorbable forms, increasing the bioactive potential of cereal-based products. In response to growing consumer interest in natural, health-promoting foods, the market for anthocyanin-rich products is expanding. Vibrant colors, coupled with health claims, make these products especially appealing, and greater education on the health benefits and culinary versatility of these grains can further enhance their acceptance and incorporation into daily diets [47, 49].

However, despite the promise of anthocyanin in whole grain cereals as functional food components, several challenges hinder their widespread application. Addressing these barriers will require rigorous research and innovation. One significant issue is the variability in anthocyanin content, which is affected by environmental conditions, cultivation practices, and post-harvest handling. This variation complicates the standardization of anthocyanin-rich products and presents challenges in drawing consistent conclusions across studies [34, 36]. Furthermore, bioavailability remains a crucial concern, as anthocyanin degrade rapidly in the stomach's acidic environment and are extensively metabolized in the liver, limiting their bioactive efficacy. The food matrix and co-ingested nutrients also influence their absorption, making effective delivery through diet alone challenging[33]. Another obstacle is the limited clinical evidence regarding the long-term benefits of anthocyanin. While preclinical studies have demonstrated significant health benefits, clinical trials in humans remain limited, with most studies being small-scale and short-term. This lack of robust clinical evidence hampers the generalizability and long-term applicability of the findings [51, 52]. Additionally, food-processing methods, such as milling, thermal treatment, and storage, often degrade anthocyanin, reducing their health-promoting potential. Developing effective preservation techniques is essential for maintaining anthocyanin efficacy in functional foods over time. To overcome these challenges, future research should focus on enhancing anthocyanin bioavailability, optimizing processing techniques, and conducting large-scale clinical trials to substantiate the health benefits of anthocyanin. Additionally, investigating the synergistic effects of anthocyanin with other bioactive compounds can unlock further therapeutic potentials, making anthocyanin-rich grains an integral part of functional foods designed to promote long-term health and mitigate disease risks.

Conclusions

Anthocyanin in whole grain cereals represent a unique confluence of nutrition and bioactivity, offering significant potential to address modern dietary and health challenges. This review underscores the role of anthocyanin-rich grains such as black rice, purple corn, and purple wheat as valuable sources of bioactive compounds like cyanidin-3-glucoside and pelargonidin derivatives, which contribute to antioxidant, anti-inflammatory, and overall health-promoting effects. These benefits are mediated through molecular pathways, including Nrf2 activation and NF-κB suppression, thereby aiding in the management of chronic diseases such as cardiovascular disorders, cancer, and neurodegenerative conditions. Additionally, the positive influence of anthocyanin on gut microbiota further highlights their holistic health potential. Despite their promise, anthocyanin face challenges related to bioavailability due to instability during digestion, emphasizing the need for innovative delivery systems and formulations to enhance their efficacy. Incorporating anthocyanin-rich grains into functional foods like cereals, baked goods, and beverages provides a practical means to deliver these health benefits to diverse populations. Future efforts must address critical gaps in research and development. Priorities include sustainable cultivation practices, advanced processing technologies, and comprehensive clinical trials to validate the health effects of anthocyanin in human populations. Innovations such as microencapsulation and nanoemulsion systems can significantly improve bioavailability. Moreover, developing standardized protocols for anthocyanin quantification and investigating their synergistic effects with other bioactive compounds in cereals could open new avenues for therapeutic applications. By integrating sustainable practices and harnessing technological advancements, the potential of anthocyanin in whole grain cereals can be fully unlocked, contributing to improved public health and more diverse dietary options. These initiatives will establish anthocyanin-rich whole grains as vital components of functional foods and preventive healthcare strategies.

Acknowledgement

The author would like to School of Agricultural and Environmental Sciences at Shobhit Institute of Engineering and Technology Deemed-to-be University), Meerut, India, for their support.

Funding

The author(s) received no financial support for the research and publication of this article.

Conflicts of Interest

All authors declare no conflict of interest.

References

1. Francavilla A, Joye IJ. Anthocyanins in whole grain cereals and their potential effect on health. Nutrients. 2020 Sep 24;12(10):2922. https://doi.org/10.3390/nu12102922.
2. Rees A, Dodd GF, Spencer JP. The effects of flavonoids on cardiovascular health: A review of human intervention trials and implications for cerebrovascular function. Nutrients. 2018 Dec 1;10(12):1852. https://doi.org/10.3390/nu10121852.
3. Cappellini F, Marinelli A, Toccaceli M, Tonelli C, Petroni K. Anthocyanins: from mechanisms of regulation in plants to health benefits in foods. Frontiers in Plant Science. 2021 Oct 28;12:748049. https://doi.org/10.3389/fpls.2021.748049.

4. Heo H, Lee H, Park J, Kim KH, Jeong HS, Lee J. Antioxidant and cytoprotective capacities of various wheat (*Triticum aestivum* L.) cultivars in Korea. Foods. 2022 Aug 5;11(15):2338. https://doi.org/10.3390/foods11152338.
5. Custodio-Mendoza JA, Aktaş H, Zalewska M, Wyrwisz J, Kurek MA. A Review of Quantitative and Topical Analysis of Anthocyanins in Food. Molecules. 2024 Apr 11;29(8):1735. https://doi.org/10.3390/molecules29081735.
6. Chen Z, Zhang SL. The role of flavonoids in the prevention and management of cardiovascular complications: a narrative review. Annals of Palliative Medicine. 2021 Jul;10(7):8254263-8263. https://doi.org/10.21037/apm-21-1343.
7. Gowd V, Jia Z, Chen W. Anthocyanins as promising molecules and dietary bioactive components against diabetes-A review of recent advances. Trends in Food Science & Technology. 2017 Oct 1;68:1-3. https://doi.org/10.1016/j.tifs.2017.07.015.
8. Lin Y, Li C, Shi L, Wang L. Anthocyanins: modified new technologies and challenges. Foods. 2023 Mar 23;12(7):1368. https://doi.org/10.3390/foods12071368.
9. Ma Y, Ma X, Gao X, Wu W, Zhou B. Light induced regulation pathway of anthocyanin biosynthesis in plants. International Journal of Molecular Sciences. 2021 Oct 15;22(20):11116. https://doi.org/10.3390/ijms222011116.
10. Serna L, Martin C. Trichomes: different regulatory networks lead to convergent structures. Trends in Plant Science. 2006 Jun 1;11(6):274-80. https://doi.org/10.1016/j.tplants.2006.04.008.
11. Winkel-Shirley B. Flavonoid biosynthesis. A colorful model for genetics, biochemistry, cell biology, and biotechnology. Plant Physiology. 2001 Jun 1;126(2):485-93. https://doi.org/10.1104/pp.126.2.485.
12. Tu W, Wang H, Li S, Liu Q, Sha H. The anti-inflammatory and anti-oxidant mechanisms of the Keap1/Nrf2/ARE signaling pathway in chronic diseases. Aging and Disease. 2019 Jun 1;10(3):637. https://doi.org/10.14336/AD.2018.0513.
13. Ma Z, Du B, Li J, Yang Y, Zhu F. An insight into anti-inflammatory activities and inflammation related diseases of anthocyanins: A review of both *in vivo* and *in vitro* investigations. International Journal of Molecular Sciences. 2021 Oct 14;22(20):11076. https://doi.org/10.3390/ijms222011076.
14. Kumkum R, Aston-Mourney K, McNeill BA, Hernández D, Rivera LR. Bioavailability of anthocyanins: whole foods versus extracts. Nutrients. 2024 May 7;16(10):1403. https://doi.org/10.3390/nu16101403.
15. Gamel TH, Saeed SM, Ali R, Abdel-Aal ES. Purple wheat: food development, anthocyanin stability, and potential health benefits. Foods. 2023 Mar 23;12(7):1358. https://doi.org/10.3390/foods12071358.
16. Shen Y, Zhang N, Tian J, Xin G, Liu L, Sun X, Li B. Advanced approaches for improving bioavailability and controlled release of anthocyanins. Journal of Controlled Release. 2022 Jan 1;341:285-99. https://doi.org/10.1016/j.jconrel.2021.11.031.
17. Blesso CN. Dietary anthocyanins and human health. Nutrients. 2019 Sep;11(9):2107. https://doi.org/10.3390/nu11092107.
18. Arruda HS, Silva EK, Peixoto Araujo NM, Pereira GA, Pastore GM, Marostica Junior MR. Anthocyanins recovered from agri-food by-products using innovative processes: Trends, challenges, and perspectives for their application in food systems. Molecules. 2021 Apr 30;26(9):2632. https://doi.org/10.3390/molecules26092632.
19. Leonarski E, Kuasnei M, Cesca K, Oliveira DD, Zielinski AA. Black rice and its by-products: Anthocyanin-rich extracts and their biological potential. Critical Reviews in Food Science and Nutrition. 2024 Oct 2;64(25):9261-9279. https://doi.org/10.1080/10408398.2023.2211169.
20. Paulsmeyer MN, Vermillion KE, Juvik JA. Assessing the diversity of anthocyanin composition in various tissues of purple corn (*Zea mays* L.). Phytochemistry. 2022 Sep 1;201:113263. https://doi.org/10.1016/j.phytochem.2022.113263.
21. Francavilla A, Joye IJ. Anthocyanin content of crackers and bread made with purple and blue wheat varieties. Molecules. 2022 Oct 24;27(21):7180. https://doi.org/10.3390/molecules27217180.
22. Dykes L, Rooney LW. Phenolic compounds in cereal grains and their health benefits. Cereal Foods World. 2007 Jun 27;52(3):105-11.
23. Kozłowska A, Dzierżanowski T. Targeting inflammation by anthocyanins as the novel therapeutic potential for chronic diseases: An update. Molecules. 2021 Jul 20;26(14):4380. https://doi.org/10.3390/molecules26144380.
24. Chuntakaruk H, Kongtawelert P, Pothacharoen P. Chondroprotective effects of purple corn anthocyanins on advanced glycation end products induction through suppression of NF-κB and MAPK signaling. Scientific Reports. 2021 Jan 21;11(1):1895. https://doi.org/10.1038/s41598-021-81384-4.
25. Nthimole CT, Kaseke T, Fawole OA. Exploring the Extraction and Application of Anthocyanins in Food Systems. Processes. 2024 Nov;12(11):2444. https://doi.org/10.3390/pr12112444.
26. Tian L, Tan Y, Chen G, Wang G, Sun J, Ou S, Chen W, Bai W. Metabolism of anthocyanins and consequent effects on the gut microbiota. Critical Reviews in Food Science and Nutrition. 2019 Mar 26;59(6):982-91. https://doi.org/10.1080/10408398.2018.1533517.
27. Lila MA, Burton-Freeman B, Grace M, Kalt W. Unraveling anthocyanin bioavailability for human health. Annual Review of Food Science and Technology. 2016 Feb 28;7(1):375-93. https://doi.org/10.1146/annurev-food-041715-033346.
28. Cappellini F, Marinelli A, Toccaceli M, Tonelli C, Petroni K. Anthocyanins: from mechanisms of regulation in plants to health benefits in foods. Frontiers in Plant Science. 2021 Oct 28;12:748049. https://doi.org/10.3389/fpls.2021.748049.
29. Sharma S, Chunduri V, Kumar A, Kumar R, Khare P, Kondepudi KK, Bishnoi M, Garg M. Anthocyanin bio-fortified colored wheat: Nutritional and functional characterization. PloS One. 2018 Apr 4;13(4):e0194367. https://doi.org/10.1371/journal.pone.0194367.
30. Sadowska-Bartosz I, Bartosz G. Antioxidant activity of anthocyanins and anthocyanidins: a critical review. International Journal of Molecular Sciences. 2024 Nov

8;25(22):12001. https://doi.org/10.3390/ijms252212001.
31. Cheng H, Zhang D, Wu J, Liu J, Zhou Y, Tan Y, Feng W, Peng C. Interactions between gut microbiota and polyphenols: A mechanistic and metabolomic review. Phytomedicine. 2023 Oct 1;119:154979. https://doi.org/10.1016/j.phymed.2023.154979.
32. Netzel G, Wright O, Sultanbawa Y, Netzel M. Understanding the metabolic fate and bioactivity of dietary anthocyanins. InProceedings 2020 Jan 19 (Vol. 36, No. 1, p. 64). MDPI. https://doi.org/10.3390/proceedings2019036064.
33. Kraithong S, Liu Y, Suwanangul S, Sangsawad P, Theppawong A, Bunyameen N. A comprehensive review of the impact of anthocyanins from purple/black rice on starch and protein digestibility, gut microbiota modulation, and their applications in food products. Food Chemistry. 2025 Jan 22:143007. https://doi.org/10.1016/j.foodchem.2025.143007.
34. Li D, Wang P, Luo Y, Zhao M, Chen F. Health benefits of anthocyanins and molecular mechanisms: Update from recent decade. Critical Reviews in Food Science and Nutrition. 2017 May 24;57(8):1729-41. http://dx.doi.org/10.1080/10408398.2015.1030064.
35. Xue H, Zhao J, Wang Y, Shi Z, Xie K, Liao X, Tan J. Factors affecting the stability of anthocyanins and strategies for improving their stability: A review. Food Chemistry: X. 2024 Oct 5:101883. https://doi.org/10.1016/j.fochx.2024.101883.
36. Spinardi A, Cola G, Gardana CS, Mignani I. Variation of anthocyanin content and profile throughout fruit development and ripening of highbush blueberry cultivars grown at two different altitudes. Frontiers in Plant Science. 2019 Sep 4;10:1045. https://doi.org/10.3389/fpls.2019.01045.
37. Liu J, Zhou H, Song L, Yang Z, Qiu M, Wang J, Shi S. Anthocyanins: Promising natural products with diverse pharmacological activities. Molecules. 2021 Jun 22;26(13):3807. https://doi.org/10.3390/molecules26133807.
38. Van Hung P. Phenolic compounds of cereals and their antioxidant capacity. Critical Reviews in Food Science and Nutrition. 2016 Jan 2;56(1):25-35. https://doi.org/10.1080/10408398.2012.708909.
39. Mohammadi N, Farrell M, O'Sullivan L, Langan A, Franchin M, Azevedo L, Granato D. Effectiveness of anthocyanin-containing foods and nutraceuticals in mitigating oxidative stress, inflammation, and cardiovascular health-related biomarkers: A systematic review of animal and human interventions. Food & Function. 2024;15(7):3274-99. https://doi.org/10.1039/d3fo04579j.
40. Li S, Wu B, Fu W, Reddivari L. The anti-inflammatory effects of dietary anthocyanins against ulcerative colitis. International Journal of Molecular Sciences. 2019 May 27;20(10):2588. https://doi.org/10.3390/ijms20102588.
41. Bendokas V, Stanys V, Mažeikienė I, Trumbeckaite S, Baniene R, Liobikas J. Anthocyanins: From the field to the antioxidants in the body. Antioxidants. 2020 Sep 9;9(9):819. https://doi.org/10.3390/antiox9090819.
42. Panchal SK, John OD, Mathai ML, Brown L. Anthocyanins in chronic diseases: The power of purple. Nutrients. 2022 May 23;14(10):2161. https://doi.org/10.3390/nu14102161.
43. Xu L, Tian Z, Chen H, Zhao Y, Yang Y. Anthocyanins, anthocyanin-rich berries, and cardiovascular risks: Systematic review and meta-analysis of 44 randomized controlled trials and 15 prospective cohort studies. Frontiers in Nutrition. 2021 Dec 15;8:747884. https://doi.org/10.3389/fnut.2021.747884.
44. Wang LS, Stoner GD. Anthocyanins and their role in cancer prevention. Cancer Letters. 2008 Oct 8;269(2):281-90. https://doi.org/10.1016/j.canlet.2008.05.020.
45. Chen XY, Zhou J, Luo LP, Han B, Li F, Chen JY, Zhu YF, Chen W, Yu XP. Black rice anthocyanins suppress metastasis of breast cancer cells by targeting RAS/RAF/MAPK pathway. BioMed Research International. 2015;2015(1):414250. https://doi.org/10.1155/2015/414250.
46. Feng RC, Dong YH, Hong XL, Su Y, Wu XV. Effects of anthocyanin-rich supplementation on cognition of the cognitively healthy middle-aged and older adults: A systematic review and meta-analysis of randomized controlled trials. Nutrition Reviews. 2023 Mar 1;81(3):287-303. https://doi.org/10.1093/nutrit/nuac055.
47. Verediano TA, Stampini Duarte Martino H, Dias Paes MC, Tako E. Effects of anthocyanin on intestinal health: A systematic review. Nutrients. 2021 Apr 17;13(4):1331. https://doi.org/10.3390/nu13041331.
48. Kapoor P, Tiwari A, Sharma S, Tiwari V, Sheoran B, Ali U, Garg M. Effect of anthocyanins on gut health markers, Firmicutes-Bacteroidetes ratio and short-chain fatty acids: A systematic review via meta-analysis. Scientific Reports. 2023 Jan 31;13(1):1729. https://doi.org/10.1038/s41598-023-28764-0.
49. Abdel-Aal ES, Hucl P, Rabalski I. Compositional and antioxidant properties of anthocyanin-rich products prepared from purple wheat. Food Chemistry. 2018 Jul 15;254:13-9. https://doi.org/10.1016/j.foodchem.2018.01.170.
50. He J, Giusti MM. Anthocyanins: Natural colorants with health-promoting properties. Annual Review of Food Science and Technology. 2010 Apr 10;1(1):163-87. https://doi.org/10.1146/annurev.food.080708.100754.
51. Kowalczyk T, Muskała M, Merecz-Sadowska A, Sikora J, Picot L, Sitarek P. Anti-inflammatory and anticancer effects of anthocyanins in *in vitro* and *in vivo* studies. Antioxidants. 2024 Sep 22;13(9):1143. https://doi.org/10.3390/antiox13091143.
52. Shi N, Chen X, Chen T. Anthocyanins in colorectal cancer prevention review. Antioxidants. 2021 Oct 12;10(10):1600. https://doi.org/10.3390/antiox10101600.