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Review

Research progress of anthocyanins regulating intestinal microorganisms

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Abstract: Anthocyanins are a kind of glycoside derivatives with C_6-C_3-C_6 as the skeleton widely existing in various fruits and vegetables. In addition to giving food its bright color, anthocyanins have a variety of biological health effects on the human body. In this paper, the structure, distribution, and content of anthocyanins and the research progress of anthocyanins and their metabolites on intestinal microbiological regulation in recent years were reviewed in order to provide a theoretical basis for further development of nutritive and healthy food rich in anthocyanins.

Keywords: anthocyanin; intestinal microorganism

1. Introduction of anthocyanin

1.1. Structure and types of anthocyanin

Anthocyanins have a unique C_6-C_3-C_6 carbon skeleton structure of flavonoids and are formed by the condensation of anthocyanins and one or more sugar molecules through glycosidic bonds. Among them, the basic structure of anthocyanins is 2-phenylbenzopyran [1], and most anthocyanins have substituted hydroxyl groups at the 3-, 5-, and 7-carbon positions of their basic structures (as shown in **Figure 1**). Due to the different substituents (hydroxyl or methoxy) on the C-3' and C-5' positions of the B-ring, anthocyanins with different chemical properties and different colors are formed [2,3]. Nearly 50 kinds of anthocyanins have been identified, and more than 600 kinds have been distinguished in detail. Anthocyanins derivatives, such as cyanidin (Cy), delphinidin (Dp), pelargonidin (Pg), peony pigment peonidin (Pn), petunidin (Pt), and mallow pigment Malvidin (Mv), are distributed in a relatively high proportion in the edible parts of plants [4,5]. Their names and substituents at the corresponding positions are shown in **Table 1** [6].

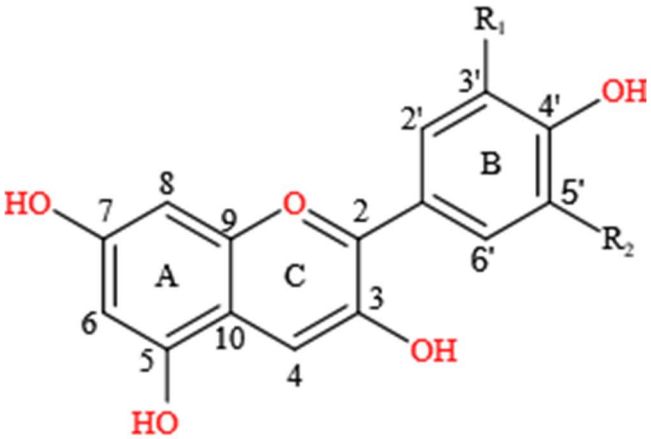

Figure 1. Structure of anthocyanin aglycone.

Table 1. Common anthocyanin species in nature.

Name of anthocyanins	R_1	R_2	Color
Cyanidin (Cy)	OH	H	Magenta
Delphinidin (Dp)	OH	OH	Magenta
Malvidin (Mv)	OCH_3	OCH_3	Red
Petunidin (Pt)	OH	OCH_3	Purple
Peonidin (Pn)	OCH_3	H	Purple
Pelargonidin (Pg)	H	H	Purple

Free anthocyanins are rare under natural conditions and often pass through one or more glucose (glu), rhamnose (rha), galactose (gal), arabinose (ara), xylose (xyl), etc. Glycosidic bonds link to form anthocyanins [7,8], of which 3-monoglycoside, 5-diglycoside, 3, 5-diglycoside, and 3, 7-diglycoside are the most common. Anthocyanins and their glycosides also exist in methoxylated forms, and most of the methoxylated positions are located at C-3' and C-5' [9]. At the same time, the acylated form also often exists in anthocyanins, usually formed at the C-3 or C-6 position through acyl bonds with coumaric acid, ferulic acid, caffeic acid, malonic acid, p-hydroxybenzoic acid, etc. [10].

1.2. Distribution and content of anthocyanins

Anthocyanins are widely distributed in different organs of plants from 27 families and 72 genera, such as fruits, flowers, stems, leaves, roots, etc. These anthocyanins are usually homogeneously dissolved in the vacuolar solution of epidermal cells, and in some species, anthocyanins are distributed in discrete regions of the cell vacuole, called anthocyanin protoplasts [11]. The distribution of anthocyanins in plants is mainly divided into the following five categories: in fruits, anthocyanins mainly exist in tissues such as peel, pulp, flowers, leaves, and bark; in vegetables, anthocyanins are mainly found in leaves, tubers, or epidermal tissues; in cereals and potatoes, anthocyanins mainly exist in tissues such as seed coat, leaves, whiskers, spikes, and tubers; in legumes, anthocyanins mainly exist in tissues such as seed coat, hypocotyls, cotyledons, pods, and tubers; and in other plants, anthocyanins are mainly found in leaves, stems, and flowers [12].

The types of anthocyanins in plants vary from species to species, and differences between varieties will also affect the types of anthocyanins. The content of anthocyanins will vary depending on plant species, varieties, cultivation methods, seasons, growth environments, maturity, and storage conditions. The types and contents of anthocyanins in common plants are shown in **Table 2** [13–23].

Table 2. Species and content of anthocyanins in plants.

Source		Content (mg/100g FW)	Major anthocyanins
Fruits	*Pyrus arbutifolia* var. *melanocarpa*	506–1000	Cy-3-gal, Cy-3-ara
	Vaccinium microcarpum	300–500	Dp-3-gal, Cy-3-gal, Mv-3-gal
	Ribes nigrum	250	Cy-3-(2G-xylosylrutinoside), Cy-3-sam, Cy-3-glu, Cy-3-rut
Fruits	*Sambucus nigra*	200–1560	Cy-3-glu, Cy-3-sam, Cy-3-sam-5-glu, Cy-3-diglu
	Vaccinium vitis-idaea L	180–330	Cy-3-gal, Cy-3-ara, Cy-3-glu, Dp-3-ga, Dp-3-gul, Dp-3-ara, Mv-3-glu
	Rubus fruticosus	90–250	Cy-3-glu, Cy-3-rut
	Ribes rubrum L	80–810	Cy-3-glu, Dp-3-glu, Cy-3-rut, Dp-3-rut
	Rubus mesogaeus	76–428	Cy-3-rut, Cy-3-xyl-rut, Cy-3-glu, Cy-3-sam
	Semen Trigonellae	60–480	Mv-3-gal, Dp-3-gal, Dp-3-ara, Pt-3-gal, Pt-3-ara, Mv-3-ara
	Canarium album	42–228 (dry weight)	Cy-3-rut,Cy-3-glu,Cy-3-caffeoylrutinoside,Cy-3-(2G-glucosylrutinoside)
	Vitis vinifera L	33–751	Cy-3-glu, Dp-3-glu, Pn-3-glu, Pt-3-glu, Mv-3-glu, Mv-3-glu-acetate
	Oxycoccus Hill	20–360	Cy-3-gal, Cy-3-glu, Cy-3-ara, Pn-3-ara, Pn-3-gal
	Fragaria ananassa	12–36	Pg-3-glu, Cy-3-glu
	Malus pumila (peel)	10–2160	Cy-3-gal, Cy-3-ara, Cy-3-glu, Cy-3-xyl
	Rubus idaeus L	10–116	Cy-3-sop, Cy-3-glu, Cy-3-rut, Cy-3-glu-rut
	Pyrus	5–10 (peel)	Cy-3-glu, Cy-3-ara
	Cerasus pseudocerasus	4–450	Cy-3-glu, Cy-3-rut
	Ficus carica (peel)	3.2–9.7	Cy-3-rut, Cy-3-glu
	Ficus carica (pulp)	0.15–1.5	Cy-3-rut, Cy-3-glu
Vegetables	*Solanum melongena* L	750	Dp-3-glu, Dp-3-diglu-5-glu, Dp-5- glu-3-diglu-caffeic acid, Dp-3-rut
	Brassica oleracea	25–203.26	Cy-3-sop-5-glu acylated with p-coumaric, ferulic or sinapyl acids, Cy-3-sop-5-glu
	Solanum tuberosum L (red)	15–45	3-caffeylferulylsophoroside-5-glu of Cy and Pn
	Daucus carota	11–60	Pg-3-diglu-5-glu acylated with p-coumaric, ferulic or caffeic acids
	Allium cepa L	5–25	Cy-3-glu, Cy-3-lam
	Brassica oleracea	4.21	Cy-3-sop-5-glu acylated with p-coumaric or ferulic acids
Cereals and potatoes	*Zea mays* L	1779	Cy-3-glu, Cy-3-gal, Pg-3-glu, Pn-3-glu, Cy-3-(6'malonylglucoside)
	Solanum tuberosum	24.6–53.1	3-caffeylferulysophoroside-5-glu of Cy and Pn
	Oryza sativa L	10–493	Cy-3-glu, Pn-glu
	Triticum aestivum L	0.5–16	Cy-3-glu
Legumes	*Glycine max* (L.) merr	1248	Dp-3-glu，Cy-3-glu，Pt-3-glu，Pg-3-glu，Pn-3-glu
	Clitoria L	Not reported	Dp-3-rut-7,3-di(6-p-coumarylglucoside) and four similar Dp glycosides

Table 2. (*Continued*).

Source		Content (mg/100g FW)	Major anthocyanins
Other plants	*Malus spectabilis*	Not reported	Cy-3-(3-malonylglucoside),Cy-3-(2-xylosyl-6-caffeylglucoside)
	Consolida ajacis	Not reported	Pg-3-rut-7-(6-p-hydroxybenzoylglucoside)
	Platycodon grandiflorus	Not reported	Dp-3-rut-5-(6-p-coumarylglucoside)
	Pelargoniumdomesticum Bailey	Not reported	Dp-3,3-diglu-5-(6-p-coumarylglucoside)
			Dp-3-glu-5-(6-p-coumarylglucoside),Mv-3-(6-acetylglucoside)-5-glu
	Ipomoea nil	Not reported	Cy-3-glu-7,3-di-(6-sinapylglu),Pn-3-[6-(3-glucosylcaffeyl)glu]
	Eustoma grandiflorum	Not reported	Cy-3-glu-5,3-di(6-caffeylglucoside)Cy-3-glu-5-(6-p-coumarylglucoside), Dp-3,3 -diglu-5-(6-caffeylglucoside)
	Phalaenopsis aphrodite	Not reported	Cy-3-(6-malonylglucoside)-7,3-di-(6-sinapylglucoside)

Note: Cy: cyanidin; Pg: pelargonidin; Dp: delphinidin; Pn: paeoniflorin; Pt: petunidin; Mv: malvidin; glu: glucoside; gal: galactoside; xyl: xyloside; ara: arabinoside; diglu: diglucoside; sop: sophoroside; rut: rutinoside

1.3. Digestion, absorption, and metabolism of anthocyanins

Anthocyanins and their derivatives can be absorbed by the digestive system and widely transported to various tissues and organs [24]. During ingestion, anthocyanins are partially digested by bacteria in the mouth and by digestive enzymes secreted by epithelial cells before entering the stomach. During digestion, due to the very low pH of the stomach, anthocyanins' structure remains relatively stable, but approximately 20%–25% of anthocyanins are absorbed in the form of glycosides. The remaining anthocyanins that are not absorbed by the stomach enter the intestine and are rapidly metabolized. The absorbed anthocyanins enter the blood in the form of unchanged substances or metabolites, or are secreted into bile and urine [25], and are then transported throughout the body or excreted.

Additionally, studies have shown that anthocyanins are retained in tissues. Kalt et al. [24] fed pigs with blueberries-supplemented feed for 4 weeks and then had the pigs fasted for 18–21 h in order to detect the anthocyanin composition in pig tissues. Although no anthocyanins were detected in the plasma or urine of the fasted animals, 11 derivatives of anthocyanins were detected in the liver, eye, cortex, and cerebellum. This indicates that some anthocyanins are retained in tissues instead of entering the blood circulation to participate in body metabolism or to be eliminated from the body. However, the mechanism of this retention is not clear and may involve the localization of subcellular components. In another study, rats were fed a diet rich in blackberry anthocyanins for 15 days, and their stomachs were found to contain only natural blackberry anthocyanins (Cy-3-glc and Cy-3-pen), while other organs (jejunum, liver, and kidney) contained natural, methylated, and conjugated anthocyanins (Cy and Pn) [26]. The proportions of anthocyanin derivatives vary in different organs. The liver

presents the highest proportion of methylated forms, while the jejunum and plasma contain aglycone forms.

In recent years, research has also further studied the relationship between anthocyanin metabolites and physiological functions through in vitro simulated digestion. Studies have shown that in vitro simulated digestion has a significant impact on the active ingredients and antioxidant properties of *Lycium barbarum* [26]. Black rice anthocyanins can regulate the endoplasmic reticulum stress, as well as enhance the barrier function, of retinal pigment epithelium cells [27]. *Lycium barbarum* anthocyanins prevent and treat obesity through their effects on the intestinal flora and liver transcriptome of obese mice [28].

1.3.1. Digestion and absorption of anthocyanins in oral cavity

Factors affecting anthocyanin digestion and absorption in the oral cavity include saliva, oral epithelial tissue, and oral microflora. Research shows that during ingestion, anthocyanins are initially digested in the mouth. Salivary proteases and β-glucosidase secreted by oral microflora and oral epithelial cells are key enzymes for the degradation of anthocyanins in the oral cavity. They deglycosylate anthocyanins and thereby degrade them into anthocyanin products and other degradation products (**Figure 2**). Hydrolytic enzymes similar to those in the small intestine, such as guanosine diphosphate glucuronosyltransferase, which are secreted in oral epithelial tissues and terminal ducts of salivary glands, can also degrade anthocyanins [27]. Human studies have found that after the oral digestion of anthocyanins, residual anthocyanins, protocatechuic acid, cyanidin-3-glucoside, and glucuronidated anthocyanins can be detected in saliva [14].

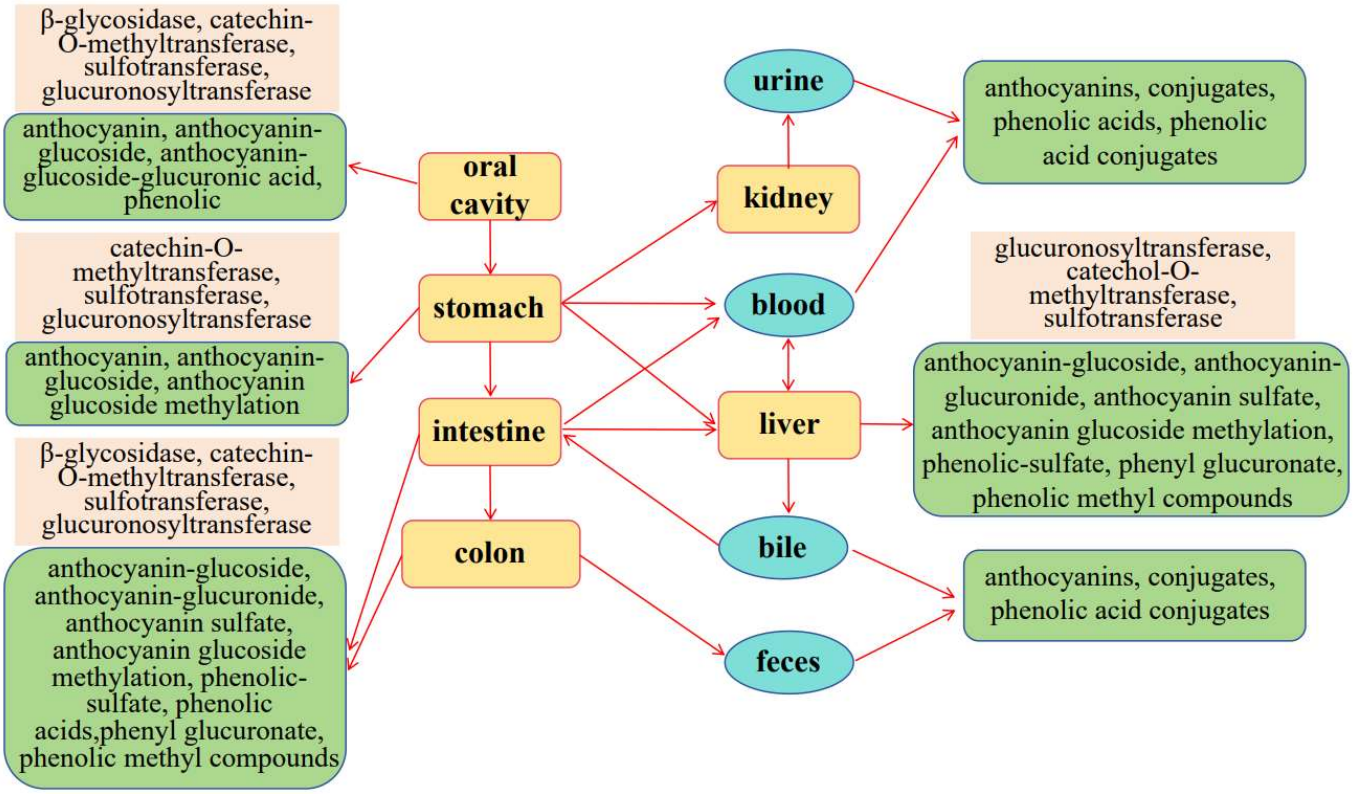

Figure 2. Absorption and metabolism of anthocyanins in vivo.

1.3.2. Digestion and absorption of anthocyanins in stomach

Anthocyanins that are not digested in the oral cavity are metabolically broken down by the low pH, mixed gases, and metabolic activity of the stomach [28]. Studies have shown that the low pH (1.5–4.0) in the gastric environment provides suitable conditions for anthocyanin metabolism. At pH ≤ 2, anthocyanins exist stably in the form of yellow salt ions. Anthocyanins can maintain their 2-phenylbenzopyran structure in the stomach, which is a stable structure of anthocyanins, and are able to pass through the gastric mucosa and rapidly absorbed by the stomach in the form of glycosides (about 20%–25%) [29]. The absorption of anthocyanins in the stomach has a saturation effect, indicating that the absorption of anthocyanins is an active absorption and requires the assistance of a transport system. However, the absorption and metabolism mechanism of anthocyanins in the stomach is still unclear. In vitro experiments show that this absorption depends on some transporters, such as glucose transporter 1 (GLUT1), organic anion transporter 2 (OAT2), Monocarboxylte transporters (MCTs), etc. [30].

In some in vitro simulated gastric digestion experiments, results showed that blueberry anthocyanins were reduced to varying degrees after gastric digestion. For example, delphinidin-3-glucoside, cyanidin-3-galactoside and malvain-3-glucoside decreased by 13.21%, 12.59% and 27.29%, respectively. This suggests that digestive enzymes can cause the loss of most anthocyanins during gastric digestion [29].

1.3.3. Digestion and absorption of anthocyanins in small intestine

The small intestine is the main site where anthocyanins are absorbed in the body. Studies have shown that after in situ perfusion in the small intestine of rats, anthocyanins are rapidly and efficiently digested, absorbed, and metabolized [31]. As anthocyanins reach the near neutral or slightly alkaline (pH 7.5–8.0) region of the small intestine, their stability decreases. The anthocyanin B-ring structure undergoes methylation and sulfonation modification, and the glucose group undergoes glucuronidation modification. Anthocyanins also undergo cleavage of glycosidic bonds and ring-opening of anthocyanin heterocycles in the intestine, forming phenolic substances, such as anthocyanins, protocatechuic acid, syringic acid, vanillic acid, p-coumaric acid, and gallic acid. The metabolites of these anthocyanins are related to the intestinal physiological environment (pH and temperature), intestinal microorganisms, and intestinal epithelial transport metabolic proteins [32]. The small intestine is selective for the degradation of anthocyanins, and lactase phlorizin hydrolase (LPH) in the brush border of small intestinal epithelial cells and β-glucosidase (cytosolic β-glucosidase, CBG) may be the basis for the degradation of anthocyanins by hydrolyzing into free anthocyanins. The hydrolysis of glycosidic bonds is key to the digestion of anthocyanins because their aglycones are more readily absorbed than ingested glycosides. Studies have shown that sodium-dependent glucose transporter 1 (SGLT1) and glucose transporter 2 (GLUT2) are involved in anthocyanin cyanidin-3-glucoside (Cy-3-G) absorption in the small intestine [33].

In some in vitro simulated gastric digestion experiments, it was found that the stability of anthocyanins in the small intestine is closely related to their structure. The more hydroxyl groups on the glycosyl ligand are replaced by methoxy groups, the more stable it is, while the more hydroxyl groups on the glycosyl ligand are, the more

unstable it is. Since the weakly alkaline environment of the small intestine can cause the structure of anthocyanins to be destroyed, blueberry polyphenols are greatly lost during the digestion process in the small intestine, especially the content of total phenols and total anthocyanins is significantly reduced. At the same time, blueberry polyphenols can also form insoluble substances with digestive enzymes, resulting in some polyphenols not being absorbed by the body [29]. A large number of studies have shown that anthocyanins are rapidly metabolized in the small intestine and enter the blood circulation in the form of prototypes or metabolites (glucuronidation, sulfation and methylation derivatives) or are secreted into bile and urine.

1.3.4. Anthocyanin metabolism in colon

Anthocyanins that are not absorbed from the small intestine enter the colon, where they undergo substantial structural changes. Under complex physiological conditions or the action of microorganisms, they are further degraded and metabolized to form phenolic acids such as vanillic acid, protocatechuic acid, and hippuric acid [34]. Similar to the small intestine, the pH value in the colon is neutral, and anthocyanins are cleaved through the C-ring and degraded into the corresponding phenolic acids and aldehydes. At the same time, the colon is the main habitat of intestinal flora. The intestinal flora is regarded as another pathway for anthocyanin metabolism in the colon and plays an important role in the long-term metabolism and absorption of anthocyanins in the intestine. Anthocyanins are largely catabolized by bacteria into simpler chemical forms, which are rapidly deglycosylated and demethylated. Metabolites of anthocyanins subsequently metabolized in the colon function as intact glycosides as well as methylated forms and glucuronidated derivatives, which are absorbed into the blood circulation by colonic epithelial cells or secreted into the bile [32]. After anthocyanins enter the blood, they mostly exist in active forms such as prototype, methylation, or phenolic acid metabolites and exert their effects.

A large number of in vitro and in vivo experimental studies have shown that anthocyanins can directly or indirectly interfere with the development of colon cancer. Since the prototypical form of anthocyanins is poorly absorbed in the colon, it is mainly metabolized by microorganisms into various phenolic acids. Based on the interaction between anthocyanins and colonic flora, anthocyanins can affect the composition of intestinal flora, promote the proliferation of beneficial flora, and enhance the metabolic capacity of beneficial flora, thereby increasing the production of beneficial bacterial flora metabolites, such as short-chain fatty acids, and inhibiting the occurrence of intestinal inflammation. It has been speculated that anthocyanins interfere with the development of colon cancer through this pathway [30].

1.3.5. Catabolism of anthocyanins by intestinal microorganisms

Anthocyanins are substrates for glycosidases in the small intestine, colon, and liver. Most intestinal bacteria, such as *Bifidobacterium* and *Lactobacillus*, can also produce β-glucosidase. Enzymes in the liver and kidneys convert anthocyanins into glucuronic acid, methylates, and sulfates, which can then be excreted in the bile into the jejunum and recycled through the enterohepatic circulation [35]. Intestinal microbiota can be regulated by anthocyanins in the food matrix. Intestinal microbiota (approximately 10^{13}–10^{14} microorganisms) is also involved in anthocyanin

metabolism, vitamin synthesis, carbohydrate decomposition, etc. In vitro studies have proven that bacterial metabolism involves the cleavage of glycosidic bonds and the decomposition of the anthocyanin heterocycle (C-ring) into phloroglucinol derivatives and benzoic acid. In addition, O-demethylation has also been observed [36].

The major human metabolites of Pg-3-*O*-glucoside, Cy-3-glucoside, Dp-3-*O*-glucoside, Pn-3-*O*-glucoside, and Mv-3-*O*-glucoside are 4-hydroxybenzoic acid, protocatechuic acid, gallic acid, vanillic acid, and butyric acid, respectively [28]. Other catabolites produced after the partial degradation of anthocyanins include catechol, pyrogallol, resorcinol, tyrosol, 3-(3'-hydroxyphenyl)propionic acid, and dihydrocaffeic acid [33]. Enzymatic glycosylation of Cy-3-*O*-glucoside can be catalyzed by intestinal bacteria *Mycobacterium*, *Eubacterium* and *Clostridium difficile*. Under specific conditions by intestinal microbes, cyanide can be degraded into dihydroxybenzoic acid, trimethoxybenzaldehyde, and several other products [37]. The degradation of Mv-3-*O*-glucoside may be related to specific bacterial-dependent metabolism, while the reduction of Dp-3-*O*-glucoside may be due to non-specific bacterial self-catabolism. Anthocyanins can also be metabolized to protocatechuic acid, ferulic acid, and hippuric acid. The metabolism of three anthocyanins (Cy-3-*O*-glucoside, Cy-3-*O*-rutin, and Dp-3-*O*-rutin) in mulberry trees produces aldehydes and phenolic acid metabolites (such as protocatechuic acid and vanillic acid) due to related enzyme-catalyzed or spontaneous cleavage [38]. Based on relevant research data, the hypothetical metabolism of anthocyanins by intestinal microbiota is summarized as shown in **Figure 3**.

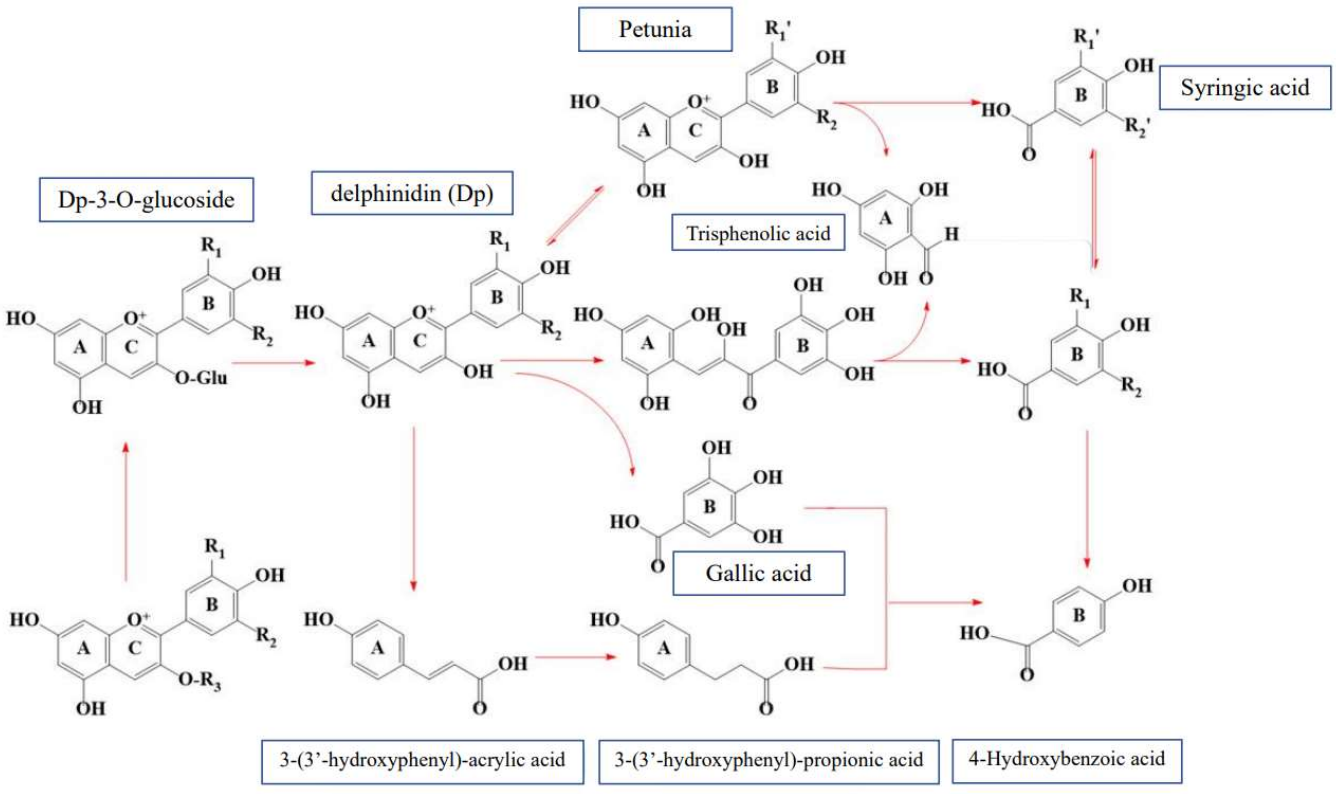

Figure 3. Hypothesized metabolism of anthocyanins by intestinal microbiota [39].

Note: R1, R2 = H, OH or OCH_3; the Chinese names of the chemical formulas in the figure are R_1, R_2 = OH, R_1', R_2' = OCH_3.

2. Regulation of intestinal microorganisms by anthocyanins and their metabolites

2.1. Regulatory effects of anthocyanins on intestinal microorganisms

At present, with in-depth research on intestinal microorganisms, there is sufficient evidence that the composition of human intestinal microbiota is closely related to human health. In addition, intestinal health depends to a large extent on the interaction between the host and intestinal microbiota [40]. There are multiple studies showing that polyphenol monomers can have a significant impact on intestinal microorganisms. Polyphenols can directly inhibit the activity of some intestinal microbial enzymes. Studies have found that the anthocyanin metabolite catechin can bind to the ATP-binding site of the gyrase B (GryB) subunit to inhibit the activity of *E. coli* DNA gyrase [41]. Polyphenols change the number of microbial metabolic enzymes by regulating the type and quantity of intestinal microorganisms, ultimately affecting the metabolic reactions in which the enzymes participate.

In addition, some studies have found that when a variety of polyphenols are mixed together, they have a more significant regulatory effect on the type and quantity of intestinal microorganisms. In in vitro fermentation experiments of malvac-3-glucoside mixed with other anthocyanins, the growth of beneficial bacteria increased compared with that of malvac-3-glucoside alone [42]. Studies have shown that polyphenols can affect the activity of intestinal flora, that is, they can reshape the intestinal microbial community and also enhance the interaction between the host and microorganisms [35]. Research results on the impact of high-purity blueberry anthocyanidins on intestinal microbiota show that they can significantly regulate the composition and abundance of intestinal microorganisms. Chen et al.'s experiments showed that freeze-dried black raspberry (*rubus occidentalis*) anthocyanins can act as effective prebiotics by maintaining the growth of beneficial microorganisms and regulating the composition and symbiosis of intestinal microbiota [43].

2.2. Inhibitory effects of anthocyanins on harmful bacteria

Anthocyanins can inhibit intestinal pathogenic bacteria. Animal experiments have shown that low-dose purple corn anthocyanins significantly inhibit the growth of *Escherichia coli*, and purple potato anthocyanins have good inhibitory effects on *Salmonella* Typhi (Salmonella) and *Shigella* Castellani [44]. "Bitter Rose" anthocyanins inhibit *Staphylococcus aureus* [45]. The total anthocyanins in blackberries have varying degrees of inhibitory effects on *Escherichia coli* and *Staphylococcus aureus*, with the inhibitory effect on *Escherichia coli* stronger than that on *Staphylococcus aureus* [46]. Anthocyanins in black rice also have the same effect [47]. Indigo anthocyanins can inhibit the enzyme activity of bacteria and affect their metabolism, thereby inhibiting the growth of *Escherichia coli* and *Staphylococcus aureus* [48]. Cactus fruit anthocyanin intervention can change the diversity and composition of intestinal microbiota at the phylum level, mainly reducing the Proteobacteria phylum; at the genus level, the relative abundance of harmful intestinal bacteria of the genera *Escherichia coli* and *Desulfovibrio* was reduced [31]. The inhibitory effect of black rice anthocyanins on *Escherichia coli* was

found to be stronger than that on *Staphylococcus aureus*. The minimum inhibitory concentrations of the two were 1.5 mg/mL and 6 mg/mL, respectively, and the antibacterial effect increased with the increase in anthocyanin concentration [33].

Wang et al. [49] and Wang et al. [50] reported that the mechanism of inhibition of microbial growth is as follows: the inhibitor reacts with the proteins on a bacterium's cell membrane, deforms the cell membrane, and destroys its DNA structure as well as enzyme activity, which makes the metabolic disorders of the pathogenic bacterium imbalanced and finally leads to the loss of bacterial growth and reproduction, destroying part of the microbial cell wall and causing it to die.

2.3. Promoting effects of anthocyanins on beneficial bacteria

Anthocyanins can change the composition of intestinal microorganisms, increase the diversity of intestinal flora, and make beneficial bacteria, such as bifidobacterial, dominant. Therefore, anthocyanins can intervene in colon cancer by changing the composition of intestinal microorganisms, enhancing the metabolism of beneficial bacteria, and increasing the production of beneficial metabolites, such as short-chain fatty acids and acetate. Anthocyanins in wine can promote the growth of probiotic bacteria, such as *Lactobacillus* and *Fusobacterium*, and have a promoting effect on the growth of the *Fusobacterium* and *Parabacterium* genera [51]. Purple sweet potato acylated anthocyanins also have similar effects. Research has found that wolfberry anthocyanins can affect the abundance of intestinal flora [52]. Experiments have confirmed that anthocyanins can increase the abundance of *Bifidobacterium*, *Lactobacillus*, and *Desulfovibrio* in the intestine. Therefore, it can be seen that anthocyanins can be metabolized to form short-chain fatty acids to function and promote the abundance of beneficial microorganisms, such as *Lactobacillus* and *Bifidobacterium*. At the same time, anthocyanins can also be hydrolyzed by intestinal probiotics, and the hydrolyzate and intestinal probiotics promote each other to have a more stable and efficient antioxidant effect [53]. Test results have proven that the concentration effect of wine anthocyanins and dimethyldelphinidin-3-O-glucoside on intestinal flora. The higher the concentration, the longer the effect on intestinal flora and the more obvious the effect [32].

Overall, anthocyanins are able to balance intestinal microflora by acting on the enzymes of intestinal microorganisms to promote a decrease in the population of harmful bacterial (**Figure 4**) and an increase in the number and diversity of beneficial bacteria, thus maintaining intestinal microbial homeostasis and contributing to intestinal health.

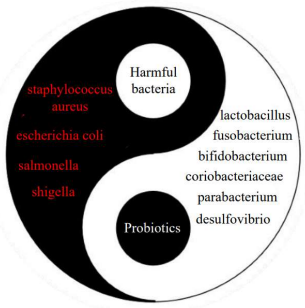

Figure 4. Anthocyanin-regulated intestinal microorganisms.

3. Conclusion and outlook

Anthocyanins are a class of flavonoids' active ingredients widely present in a variety of plant-derived foods. China has an abundance of resources rich in anthocyanins, such as grapes, cranberries, lychees, mustard greens, mulberries, cherries, blood oranges, perilla, purple sweet potatoes, eggplant peels, black (red) rice, and other plants, and some purple cereals and their by-products are rich in anthocyanins. Epidemiological studies indicate that metabolites produced by the consumption of anthocyanin-rich foods may contribute to health. Anthocyanins are mainly absorbed through the upper gastrointestinal tract and directly metabolized by endogenous enzymes. The metabolites of anthocyanins metabolized in the colon are absorbed by colon epithelial cells into the blood circulation or secreted into bile and urine. The bioavailability of anthocyanins in the intestine is the key to evaluating their bioactivity in vivo. Eating plant foods rich in anthocyanins helps balance intestinal microflora, thereby helping to prevent and improve gastrointestinal-related diseases and enhance host health. In addition, anthocyanin phytochemicals help improve various biomarker pathological indicators, such as oxidative stress and chronic inflammation related to cardiovascular diseases (CVDs), inhibiting the formation of atherosclerotic plaques and delaying the progression of CVDs. People can increase their anthocyanin intake by consuming dark-colored plant foods to promote their cardiovascular system health and prevent the occurrence of CVDs. Overall, research on anthocyanin bioavailability will be of great significance in promoting human dietary guidelines and epidemiology.

However, existing research results show that the bioavailability of anthocyanins is still low, which affects their functional activity to a certain extent. Therefore, how to improve their bioavailability is an important research direction in the future. According to research, the stability of anthocyanins' own structure and properties affects the sensory, nutritional, and functional properties of their products. Therefore, the bioavailability of anthocyanins can be improved by improving its stability. Anthocyanins have a significant impact on intestinal microorganisms and can affect human health by regulating the structure of intestinal flora. However, there are currently relatively few studies on the impact of anthocyanins on health, especially on their effects on intestinal flora. Later studies can focus on the mechanism of action to gain a deeper understanding of the metabolism of anthocyanins. The potential mechanism of action of anthocyanin products and bacterial flora composition in protecting cardiovascular health can enable anthocyanins to be more effectively applied in the prevention and auxiliary treatment of CVDs.

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