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Review article

Anthocyanins in goat diets: A Review

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Abstract

Anthocyanins are common in fruits (especially berries), vegetables, grains and purple- or red-colored flowers. They have antioxidant properties and thus play a role in preventing or reducing the risk of chronic disorders such as cardiovascular disease, cancer and diabetes. Anthocyanin-containing plants included in the diet of goats increased the anthocyanin content of milk, which adds value by providing functional benefits for consumers' health. In addition, they improved growth performance and meat quality and prevented lipid oxidation by promoting the antioxidant status and elevating the proportions of polyunsaturated fatty acids in the muscle or superoxide dismutase activity. However, anthocyanin concentration is plant type-specific. Therefore, it is necessary to further investigate the nutritional values and anthocyanin levels of plant materials for application in the diets of ruminants, including goats, and anthocyanin persistence in the fresh and processed milk or meat.

Importance of the work: Anthocyanin-rich plants have considerable potential for use as natural antioxidants in meat or dairy goat diets.

Objectives: To gather insights into the role of anthocyanins in goat nutrition, contributing to future research and sustainable goat production.

Materials and Methods: A systematic approach was adopted, including defining the scope, searching appropriate databases and keywords, selecting reliable and up-to-date references, collecting and organizing data in a structured manner and synthesizing the collected data.

Results: Anthocyanin is a pigment present in the flavonoid compounds commonly found in plants, with antioxidant effects that are beneficial to ruminant animals and human health.
Anthocyanin-rich plants have considerable potential for use as natural antioxidants in meat or dairy goat diets, since they can: 1) improve the proportions of polyunsaturated fatty acids in muscle; 2) reduce oxidative stress; 3) reduce methanogenic bacteria and improve rumen fermentation; 4) enhance superoxide dismutase; and 5) enhance the anthocyanin composition in the milk.

Main finding: The use of anthocyanin-rich plants in goat diets can have a positive impact on goat health and increase production, enabling them to produce functional dairy products or meat that is beneficial for consumer health.

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Introduction

Goats, characterized by their small gastrointestinal tract, exhibit rapid production capabilities. Both their meat and milk offer considerable nutritional benefits comparable to cattle and buffalo products. The many benefits of raising these animals include the production of dairy products and meat as well as other byproducts such as manure, skin and hair. Their adjustable diet includes farm residues, enabling grazing or direct feeding, grass, bushes and weeds. They are highly resilient, thriving in a variety of environments, with high levels of reproduction and growth efficiency. These characteristics vary according to the breed, gender, age and production system (Zhang et al, 2022).

Diet formulation, necessitates considering the nutritional needs of goats for survival, body weight (BW) and productivity (Oliveira et al., 2014). Factors that influence animal feed requirements vary according to age, growth period and purpose; whether they are young, pregnant, suckling, or destined for meat production. For example, high-meat-producing goats, such as boar goats, require adequate nutrition, while weaned kids grow rapidly. Adequate nutrition is essential for the growth of the goat kids. A female goat that gives birth to twins or triplets produces more milk than a female goat that gives birth to a single kid. However, a single kid will grow faster and weigh more when weaned. Similarly, high-dairy-producing goats need an energy-rich diet for optimal milk production (Najera et al., 2021).

Anthocyanin, a plant-derived pigment or colored compound, has been of considerable interest due to its antioxidant properties and pH-indicating characteristics. It is used as a pH indicator because of color-changing properties over a broad range of pH, appearing red in acidic, purple in neutral and blue in alkaline conditions (Lopes et al., 2011). Various factors influence anthocyanin color and stability, including chemical structure, temperature, pH, ascorbic acid, sugars, pressure, light, oxygen and water activity (Zabetakis et al., 2000; Pang et al., 2001; Nikkhah et al., 2007; Rosso and Mercadante, 2007; Jimenez et al., 2012; Lopez et al., 2014; Charurungsipong et al., 2020; Azman et al., 2022). Forage crops rich in anthocyanins, such as purple Napier grass (Suong et al., 2022), purple yam (Zhang et al., 2022), mangosteen peel (Ban et al., 2022), red (blood) orange (Felice et al., 2021) and black cane (Suong et al., 2022), are ingredients in goat feed in various forms as roughage, concentrates and supplements (University of Arkansas, 2023). They offer antioxidant benefits against oxidative stress and inflammation, enhance meat quality and improve rumen health. Anthocyanins play a critical role in goat diets. Hence, it is beneficial to introduce anthocyanin-rich feeds that have the potential to enhance growth efficiency. This article aimed to gather insights into the role of anthocyanins in goat nutrition, contributing to future research and sustainable goat production.

Anthocyanins in plants

Anthocyanins are water-soluble but prone to decomposition upon exposure to heat, oxygen, pH fluctuations and light, resulting in varied colors. For example, in acidic conditions ($pH < 3$), anthocyanin appears red, turns purple in neutral pH (~6–7), blue at pH 7–8 and becomes colorless at $pH < 8$ (Charurungsipong et al., 2020). The chemical structure of anthocyanins follows a C6–C3–C6 pattern, representing glycosides of 2-phenyl benzopyrylium or flavylium cations. Among numerous structures, the common ones include pelargonidin, cyanidin, delphinidin, peonidin, petunidin and malvidin. Each anthocyanin varies based on factors such as the number of hydroxyl groups (OH), methylation degree of the hydroxyl groups, glycosylation nature, number and location, as well as the type and quantity of aromatic or aliphatic acids adjacent to the glycosyl residue. The presence of hydroxyl and methoxy (OCH_3) groups on the flavylium ring influences anthocyanin color; more OH groups result in a bluish hue, while increased OCH_3 groups lead to redness (Andersen and Markham, 2005).

In aqueous solutions, anthocyanin acts as a pH indicator, exhibiting a red color under acidic conditions, blue under neutral pH and becoming colorless at high pH levels, as four anthocyanin structures exist in equilibrium: the red flavylium cation (AH+), the blue quinonoidal base or the red quinonoidal base (A), the colorless carbinol pseudo base (B) and the colorless chalcone (C), as shown in Fig. 1. AH+ predominates at an acidic pH (<2); as the pH rises, AH+ depletes protons, forming A, which is the predominant structure. Hydration of AH+ produces B, whose abundance varies with pH changes. For example, 3-glycosides and 3,5-di glycosides form colorless B at pH >3. However, small amounts of A and C enhance the color at higher pH (4–6) (Lopes et al., (2021); Azman et al., 2011). Anthocyanin extract has nutraceutical properties, functioning as an antioxidant that helps mitigate cell degeneration. It aids in reducing the risk of heart disease and stroke by preventing blood clotting, slowing eye degeneration, inhibiting pathogenic microorganisms, such as *E. coli* in the gut, reducing inflammation, protecting blood vessels, lowering blood cholesterol, mitigating cancer risk and combating viruses. Its outstanding feature lies in its antioxidant efficiency, which is twofold that of vitamins C and E (Dini et al., 2019).

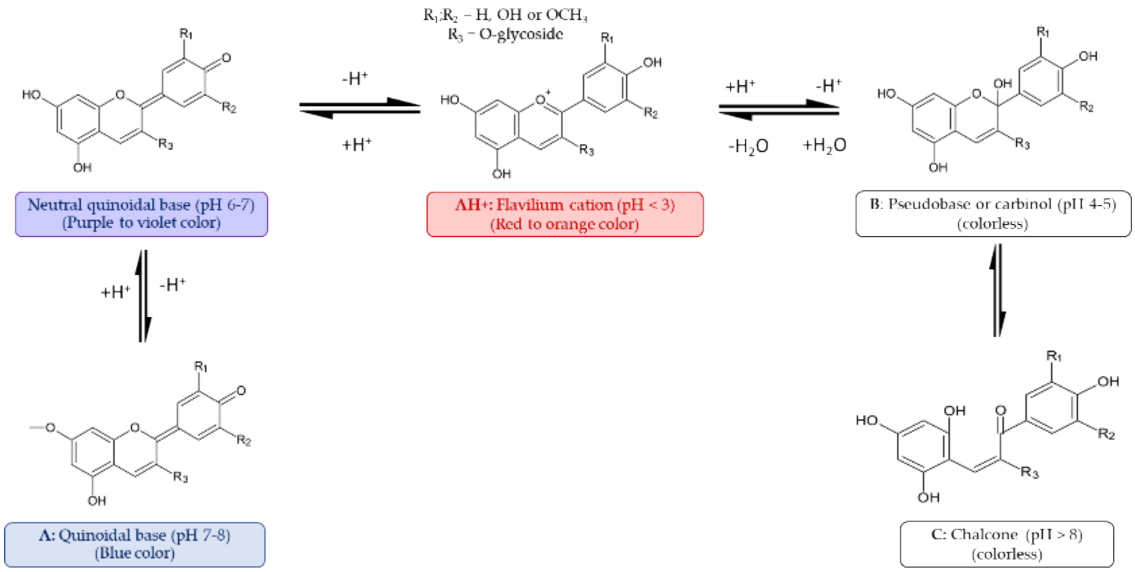

Fig. 1 Structural transformation of anthocyanin (modified from Azman et al., 2022)

Factors affecting anthocyanin color and stability

The degree of anthocyanin flexibility is determined by the arrangement of sugars near the flavilium ion and the glycosylic acid binding site (Remini et al., 2018). For example, 3-deoxyanthocyanin appears yellow without a hydroxyl group while the dihydroxylated anthocyanins are stabilized. Anthocyanins with aromatic acyl groups are more stable, which may be due to the rate of hydration. Adding a hydroxyl group increases light absorption and the anthocyanin changes color from orange to blue-red (Zhao et al., 2016; Fernandes et al., 2019), while the methoxy group has the opposite effect. Temperature and pH-based degradation greatly affect stability. Black rice bran color was optimally stable at lower temperatures and pH levels. Ascorbic acid derivatives can enhance stability, especially under irradiation. Adding sugar impacts stability; at a medium concentration it protects against other factors such as pressure, light, oxygen and water activity; it influences the retention of anthocyanins. High temperatures and pressure can lead to degradation and alter the activity of antioxidants. A study on the stability of wine under various treatments emphasized changes in the molecular composition (Corrales et al., 2008). As mentioned earlier, anthocyanins are unstable in high pH environments. The stability and color of anthocyanins in goat diets have been reported, with anthocyanins not destroyed in the rumen. However, anthocyanin pigments, powders, or plant extracts can be biodegraded by rumen fluid (Suong et al., 2022). A summary of these factors is presented in Table 1. The anthocyanin color is vital to its chemical structure and can be applied to control the quality of goat feed and the selection of raw materials containing anthocyanin.

Table 1 Factors affecting color and stability of anthocyanins extracted from plants

Factor	Plant extracted from	Effect on anthocyanin stability	Reference
Structure	Blackcurrant pomace	The anthocyanin solution’s half-life, color retention and antioxidant activity were successfully improved through intermolecular copigmentation, with cyanidin-3-O-glucoside (C-3-G) showing the greatest stability at pH 3 and pH 6.	(Azman et al., 2022)
Temperature and pH	Butterfly pea flower	The degradation rate of anthocyanin enhanced as the temperature increased. Anthocyanins became more stable at a lower pH.	(Charurungsipong et al., 2020)
Ascorbic acids	Acerola	The key factor for the low stability of acerola anthocyanins was the presence of high quantities of ascorbic acid which directly condenses on carbon 4 of the anthocyanin, resulting in frozen acerola pulp and processed juice losing their red color.	(Rosso and Mercadante, 2007)

Table 1 Continued

Factor	Plant extracted from	Effect on anthocyanin stability	Reference
Sugar	Berries	The primary concentration of sugars (sucrose) at 20% had a protective impact on anthocyanins, which diminished at higher concentrations.	(Nikkhah et al., 2007)
Pressure	Strawberry	The rate of degradation of pelargonidin 3-glucoside was only changed slightly by high-pressure treatment during storage at 20°C and 30°C. After being subjected to high-pressure treatments at 200 MPa and 800 MPa, pelargonidin 3-rutinoside was more stable.	(Zabetakis et al., 2000)
Light	Blackberry	Increasing the light intensity source caused the gradual loss of monomeric anthocyanins.	(Lopez et al., 2014)
Oxygen	Litchi pericarp	Anthocyanins were prone to destruction by active oxygen.	(Pang et al., 2001)
Water activity	Blackberry juice	The reduction in water activity negatively affected anthocyanin stability at high temperatures.	(Jimenez et al., 2012)

Anthocyanin plant sources for goat diets

Raw materials for animal diets, including goat feed, encompass a wide array of compounds, whether natural or synthetic, aimed at providing essential nutritional benefits to the animals. They include both nutrient-rich and non-nutrient components of the feed formula and can be categorized into three main groups based on their primary nutritional composition: 1) roughage, including fibrous feed with a fiber content >18% of dry matter (DM), typically derived from forage crops (University of Arkansas, 2023). Many agricultural byproducts, such as fresh pasture and green fodder, serve as roughage for goats with moisture contents in the range 70–85%, as well as dry silage with a moisture content <15%. Silage is prepared by cutting fresh roughage into small pieces, packing it tightly into a container and sealing it for ~21 days; it typically has a pH of 3.5–4.2 and a moisture content of 70–75%; 2) concentrated, as a nutrient-dense, low fiber, highly digestible feed; and 3) mineral and vitamin supplements (University of Arkansas, 2023).

Anthocyanins, which are a diverse group of phenolic compounds and flavonoids, help create magenta pigments and have antioxidant properties. As a subclass of flavonoids, anthocyanins are classified as bioflavonoids and further subdivided into anthocyanins and anthocyanidins (Bhowmik et al., 2010; Lao and Giusti, 2016; Promdang et al., 2018; Onjai-uea et al., 2024). They are common in several plants such as black glutinous rice, sweet potatoes, purple corn, purple cabbage, okra and red hibiscus. The nature of the anthocyanin varies among these plants. For example, purple corn is a more important source of antioxidants than yellow and white corn types because it has higher starch, lysine, protein and mineral contents (Lao and Giusti, 2016). Purple Napier grass (Fig. 2) is characterized by purple leaves and semi-dwarf stems ad provides a wide range of nutritional components in fresh formats at 45 d and 60 d, including protein, cellulose, hemicellulose, lignin, ash and anthocyanins (Onjai-uea et al., 2024). Purple yam is red or magenta, as the edible parts have varying chemical components. High-performance liquid chromatography analysis indicated the anthocyanin profiles of these species remained consistent with cyanidin-specified 3-O-glucoside and peonidin 3-O-glucodide (Promdang et al., 2018). Purple neem leaves have various levels of bioactive potential and medicinal benefits. Neem acts as a parasite killer and the presence of anthocyanins in purple neem leaves elevates their healing properties. Incorporating purple neem leaves into the ruminant diet enhances the benefits. It helps reduce severe malnutrition that is prevalent in the arid tropics during the dry season. In addition, it improves palatability, digestibility and productivity in animals.

Fig. 2 Examples of anthocyanin-containing plants: (A) black cane; (B) purple yam; (C) purple Napier grass; (D) purple corn; (E) mangosteen peel; (F) purple neem foliage.

Simultaneously, it exerts a potent antioxidant effect and reduces oxidative stress in ruminants (Bhowmik et al., 2010). Mangosteen peels contain various bioactive phenolic compounds, including xanthones, benzophenones, tannins, flavonoids and anthocyanins, thereby imparting medicinal properties. Notably, α- and γ-mangostin are prominent xanthones found in mangosteen, with α-mangostin being the primary compound. Additionally, mangosteen peels are high in anthocyanin and tannin contents, showcasing markedly higher phenolic levels and antioxidant activity than mangosteen flesh (Yuvanatemiya et al., 2022). Blood orange, characterized by its red flesh, owes its color to its anthocyanin content, making it a rich source of bioactive compounds. Black sugarcane, a by-product of sugar production, is a valuable source of nutrition in tropical ruminants, having elevated anthocyanin and flavonoid contents in its stems and leaves compared to other sugarcane varieties, benefiting goats reared for meat. These compounds, including petunidin 3-O-(6"-succinyl)-rhamnoside and cyanidin-3-O-glucoside, are found primarily on the surfaces of the stem and bark (Purba et al., 2022; Rittiron et al., 2022).

Effect of anthocyanins on the antioxidant activity of plants

Antioxidants are compounds that can inhibit or slow the oxidation reaction such as lipid oxidation that forms free radicals. They inhibit the formation of free radicals and help to stabilize fat samples. In general, antioxidants are classified into three types based on their inhibitory mechanism: 1) preventive antioxidants that help to arrest free radical formation; 2) scavenging antioxidants that destroy or inhibit the free radicals already present; and 3) chain-breaking antioxidants that interrupt the free radical generation chain (Tena et al., 2020). Each type has a different benefit, with the most potent being endogenous antioxidants, which can also be used to transform compounds into those needed by the body. The other types of antioxidants, also known as primary antioxidants, are considered shock absorbers, having a strength secondary to endogenous antioxidants. The last group of antioxidants includes vitamins, amino acids and coenzyme Q10 (Wang et al., 2010; Tena et al., 2020).

The relationship between anthocyanins and free radicals under normal conditions is converted from superoxide (O_2^-) to hydrogen peroxide (H_2O_2), being catalyzed by superoxide dismutase (SOD). Then, it is converted to water by glutathione peroxidase (GPX) and catalase (CAT), as shown in Fig. 3. Thus, nicotinamide adenine dinucleotide phosphate (NADPH) oxidase activity is imbalanced, resulting in oxidative stress. Glucose metabolism is affected when free radicals are absent in the elimination system. This impacts the NADPH oxidase cycle, resulting in oxidative stress. It influences the NADPH-dependent and energy metabolism cycles, the functioning of the immune system, antioxidant capacity and calcium balance. Its main functions are: 1) neutralization of free radical scavengers via antioxidants; and (2) the reduction of oxidized molecules through the enzyme system.

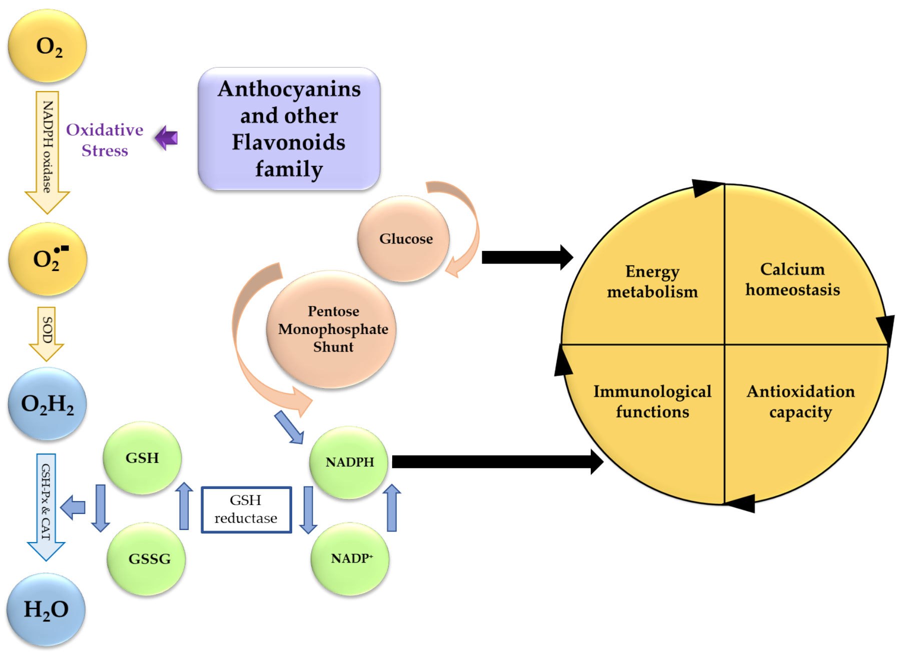

Fig. 3 Relationship between anthocyanins and free radicals, where CAT = catalase, GSH = glutathione; GSSG = glutathione disulfide; SOD = superoxide dismutase; GSH-Px = glutathione peroxidase; NADPH = nicotinamide adenine dinucleotide phosphate.

The anthocyanin-based free radical scavenging mechanism consists of a phenolic hydroxyl group that scavenges free oxygen radicals and activates the enzymes involved in it (Soobrattee et al., 2005; Sakano et al., 2005; Celi et al., 2014).

Oxidative stress is the main cause of many metabolic diseases, directly affecting growth and performance and causing debilitating health problems in ruminants, including goats. This effect may be due to oxidative stress causing an imbalance between oxidants and antioxidants, resulting in abnormally high levels of free radicals (Amiri et al., 2019), which may react with DNA, proteins and lipids, damaging cells and organs and resulting in various diseases. Antioxidants play a crucial role in alleviating oxidative stress in ruminants and their use in diets can help prevent the loss in productivity (Celi, 2010).

Anthocyanins are potent natural antioxidants and can inhibit oxidative stress and inflammation in ruminants by regulating peroxidation and scavenging free radicals. Apparently, purple corn anthocyanins have the potential to improve meat quality and prevent lipid oxidation. Anthocyanins enhance the antioxidant status and polyunsaturated fatty acid concentration in longissimus dorsi muscle of growing goats (Table 3). The effect has been reported of anthocyanins from purple corn on growth performance and the status of antioxidants and fatty acids in the muscles of growing goats. Anthocyanin is the primary factor affecting antioxidant activity, as it has a positive correlation with antioxidant activity (Tian et al., 2022). Furthermore, anthocyanin-rich purple corn stover silage is an excellent source of roughage in ruminant diets because it can improve SOD, while in plasma and milk, anthocyanins can enhance the antioxidant content in lactating dairy goats by transferring them to the milk (Tian et al., 2019b). The rearing of goats on enriched purple neem leaves is recommended (Taethaisong et al., 2022a; Taethaisong et al., 2022b). Anthocyanin in goat feed enhances plasma antioxidant capacity, improves rumen volatile fatty acids (VFAs) and alters the structure and abundance of rumen microbial communities (Taethaisong et al., 2022a; Taethaisong et al., 2022b).

Effect of anthocyanins on dry matter intake in goats

Although numerous studies have reported that plant anthocyanins do not affect dry matter intake (DMI), the use of high amounts of anthocyanin-rich plants in ruminant diets may affect feed palatability due to the bitter taste of phenolic compounds. In some cases, anthocyanin feeding, supplementing or inclusion of oils and anthocyanin-rich plants in goat diet enhanced feed intake (Taethaisong et al., 2022a; Taethaisong et al., 2022b). Higher feed and nutrient intake were reported in goats that received enhanced levels of anthocyanin from a 6% purple neem foliage (PNF) diet than with 3% PNF, as well as normal neem foliage (Taethaisong et al., 2022b). Similar findings were reported in a goat concentrate diet containing 6% PNF mixed with 3% sunflower oil (SFO) compared to 3% PNF mixed with 3% SFO or the control without either PNF or SFO (Taethaisong et al., 2022a). In addition, the feed and nutrient intake of goats increased when the diet was supplemented with neem leaves as a source of condensed tannin using 6% neem leaves + 15% polyethylene glycol in the concentrate (Taethaisong et al., 2023).

Anthocyanins are compounds of the flavonoid group that act similarly or demonstrate the properties of tannins, which are phenolic compounds. Anthocyanins belong to a group of phenolic compounds known as polyphenols (Yuvanatemiya et al., 2022). Bitter taste is a characteristic of plants that contain tannins and have polyphenols as constituents (Lhieochaiphant, 1988). Such chemical interactions are characterized by the pathway through which plants produce chemical constituents that produce a bitter taste. Bitterness can be sensed by most mammals, as well as some birds and reptiles. Plants that contain cardinoleids, alkaloids and tannins, may be referred to as those repelling herbivores. For vertebrates with highly developed olfactory and gustatory senses, it is possible to distinguish whether plants are palatable or unappetizing. Therefore, even if these chemicals are relatively low, humans may still resist eating such plants (Lhieochaiphant, 1988). Leucoanthocyanidins, which belong to the group of true flavonoid structures or typical flavonoids, are believed to be the precursors of condensed tannins and are more difficult to dissociate or decompose than hydrolyzable tannins. Condensed tannin structures are formed by the polymerization of phenolics, such as flavonoids (particularly leucoanthocyanidins and catechins). Leucoanthocyanidins are rarely found in their glycoside state (Lhieochaiphant, 1988). Anthocyanins can be found dissolved in the cell sap of plants, as crystals or amorphous particles (Kochhar, 1976). The biosynthesis of anthocyanins is determined by genetic factors and is aided by the buildup of sugars in plant tissues, as well as environmental conditions including strong light, low temperature, drought, low soil nitrogen content and oxygen availability (Kochhar, 1976). Additionally, the aforementioned astringent properties of anthocyanin may reduce the DMI, which would be detrimental to ruminant growth (Tayengwa and Mapiye, 2018).

The low DMI is credited to the enhanced fiber content and reduced palatability caused by the ability of proanthocyanidins to bind with salivary proteins and impart an unpleasant astringent sense to the feed (Tayengwa and Mapiye, 2018). Unlike the bitter taste, the astringent taste produced by tannins contained in plant tissues is caused by the interaction between tannins and proteins contained in the saliva and the glycoproteins present in the mouth, due to which the lubricating properties of saliva are lost owing to the cross-linking of tannin polymers with proteins (Lhieochaiphant, 1988). Duncan and Gordon (1999) found that the factors that influence an animal's choice to eat forage plants depend on the secondary compounds present. However, their feed intake is contingent on increases in the fiber levels in the diet. Feed intake and productive performance of ruminant animals are reduced as a result of the fiber content that animals ingest in high amounts, which has the potential to suppress digestibility and impede the rate of passage of the feed (Stuart et al., 1990). Therefore, although plants are high in anthocyanin content, increased cutting age affected DM, fiber contents and digestibility.

An assessment primarily based on anthocyanin intake levels (Table 2), between 65.73 and 171.47 mg DM/day of anthocyanin-rich Napier grass silage without an additive and with an additive, respectively, has been reported not to affect DMI in goats (Soung et al., 2017). According to Table 2, an evaluation mainly based on total anthocyanin intake levels, with a wide range approximately 1.3–377 mg DM/day in the goat diet, showed no effect on DMI (Tian et al., 2019b; Tian et al., 2022; Soung et al., 2022). However, Taethaisong et al., (2022b) showed that DM and nutrient intake increased when the inclusion level of PNF was 3% and 6% in concentrate, or approximately 3,400 mg DM/d and 7,600 mg DM/d of the main total anthocyanin intake level. However, the optimum level of anthocyanin supplementation in goat diets affecting DMI depends on the anthocyanin source, the form of administration (pure extract or combined with forage) and the type of concentrate or roughage utilized. Although goats are more tolerant of phenolic compounds than cows (Waghorn and McNabb, 2003), the silage may have changed the roughage's palatability (Niderkorn and Jayanegara, 2021, cited by Ban et al., 2025). Further studies should be conducted on the maximum levels of anthocyanin-containing plants used as feed for ruminants that affect palatability for small ruminant animals, mechanism or maximum levels (or both) or the inclusion levels of feeding anthocyanin-rich plants, anthocyanin intake, including anthocyanin-rich plant silage, or anthocyanin extracts, in a ruminant diet in the long term on palatability.

Table 2 Amounts of compounds in each anthocyanin plant species

Anthocyanin plant (scientific name)	TA	AN	Pel	Peo	Cya	Mal	Pet	Del	C3G	P3G	M3G	P3-OG	PC	TT	NPC	CT	TF	TH	AS	CA	FE	RU	QU	CTE	CE3G	Reference
Purple corn (*Zea mays* L.)	2,619 ± 13.04 µg/g DM (2,619 ± 13.04 mg/kg DM)	-	45.3±1.9 µg/g DM	ND	1975 ± 8.4 µg/g DM	0.1 ± 0.01 µg/g DM	7.9 ± 0.1 µg/g DM	591 ± 11.9 µg/g DM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Tian et al., 2022)
Purple corn (*Zea mays* L.) silage	861.95± 33.37 mg/kg DM	-	118.80 ± 9.61 mg/kg DM	73.88 ± 3.85 mg/kg DM	125.42 ± 4.27 mg/kg DM	140.61 ± 10.97 mg/kg DM	-	101.43 ± 8.47 mg/ kg DM	100.78 ± 5.58 mg/kg DM	132.51 ± 11.85 mg/ kg DM	68.51 ± 1.32 mg/ kg DM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Tian et al., 2019b)
Napier grass silage (*Pennisetum purpureum)*	-	280.15 mg/kg DM*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Suong, 2017)
	-	300 mg/kg DM*	-	-	-	-	-	-	-	-	-	-	9.05 %DM	2.52 %DM	6.54 %DM	0.1 %DM	-	-	-	-	-	-	-	-	-	
	-	596.61 mg/kg DM**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	-	600 mg/kg DM**	-	-	-	-	-	-	-	-	-	-	10 %DM	2.81 %DM	7.19 %DM	0.1 %DM	-	-	-	-	-	-	-	-	-	
Purple yam (*Dioscorea alata* L.*)*	procyanidin B2 (1852.98 ng/mg), procyanidin B4 (475.24 ng/mg)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	352.08 ng/mg	-	-	212.96 ng/ mg	(Zhang et al., 2022)
Purple neem foliage (*Azadirachta indica* A.)	132.89 mg/g DM (132,890 mg/kg DM)	-	10.93 mg/g DM	9.492 mg/g DM	39.96 mg/g DM	19.67 mg/g DM	32.60 mg/g DM	26.12 mg/g DM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Taethaisong et al., 2022b)

Table 2 Continued

Anthocyanin plant (scientific name)	TA	AN	Pel	Peo	Cya	Mal	Pet	Del	C3G	P3G	M3G	P3-OG	PC	TT	NPC	CT	TF	TH	AS	CA	FE	RU	QU	CTE	CE3G	Reference
Mangosteen peel (*Garcinia mangostana* L.)	2.98 g/kg DM proanthocyanidins (2,980 mg/kg DM)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.21 g/kg DM	1.14 g/kg DM	2.90 g/kg DM	3.11 g/kg DM	3.23 g/kg DM	-	(Ban et al., 2022)
Red (Blood) orange (*Citrus sinensis* L.)	2.66% of total anthocyanins (as cyanidin 3-glucoside equivalents)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.91±0.01%	1.77±0.02%	2.40±0.01%	-	-	-	-	-	-	(Felice et al., 2021)
Black cane (*Saccharum sinensis* Robx.)	0.17 mg/g DM (170 mg/kg DM)	-	1.72% of TA	-	25.17 % of TA	13.79% of TA	-	16.90% of TA	4.83% of TA	7.24% of TA	14.14% of TA	16.21% of TA	-	-	-	-	-	-	-	-	-	-	-	-	-	(Suong et al., 2022)

DM = dry matter; TA = total anthocyanin; An = anthocyanin; Pel = pelargonidin; Peo = peonidin; Cya = cyanidin; Mal = malvidin; Pet = petunidin; Del = delphinidin; C3G = cyanidin-3-glucoside; P3G = pelargonidin-3-glucoside; M3G = malvidin-3-O-glucoside; P3-OG = peonidin-3-O-glucoside; PC = phenolic compound; TT = total tannin; NPC = non phenolic compound; CT = condensed tannin; TF = total flavanones; TH = total hydroxycinnamic acids; AS = ascorbic acid; CA = caffeic acid; FE = ferulic acid; RU = rutin; QU = quercetin; CTE = catechin; CE3G = centaurin3-galactoside; * = anthocyanin rich Napier grass silage without additive (additive = 4% molasses and 0.03% Iron (II) sulfate or ferrous sulfate ($FeSO_4$); ** = anthocyanin rich Napier grass silage with additive (additive = 4% molasses and 0.03% Iron (II) sulfate or ferrous sulfate ($FeSO_4$).

Effect of anthocyanins on antioxidant activity in goat

The effects have been studied of plant-derived anthocyanins in experimental animals, including the *in vivo* antioxidant activity (Seeram et al., 2006; Cimino et al., 2007). A 30% maize diet was used daily in place of *Dioscorea alata* L. powder with roughage (fresh King grass DM = 1:1). A treated mixed diet consisting primarily of corn, bran and soybean meal was fed at 500 g per day DM (Zhang et al., 2022). *D. alata*, which is rich in anthocyanins, may provide a pre-protective role in perinatal Hainan black goats by controlling the Nrf2 and MAPK/JNK pathways in the goat mammary epithelial cells, which would enhance antioxidase activity and remove reactive oxygen species (Zhang et al., 2022). Purple Napier grass silage production using 4% molasses and iron (II) sulfate or ferrous sulfate ($FeSO_4$) reduced anthocyanin loss in silage, which resulted in more anthocyanins compared to the control group (Suong et al., 2022). In experiments, crossbred Thai native × Anglo-Nubian male goats received either a standard total mixed ration (TMR) diet containing a 50% Napier grass silage-based diet, or containing isocaloric and isonitrogenous diets with a relative abundance of *Ruminococcus albus* to obtain the anthocyanin-rich black cane silage-based diet daily for 90 d; it promoted the total antioxidant capacity (TAC), SOD, CAT, glutathione peroxidase (GSH-Px) and glutathione reductase (GSH-Rx) levels in the plasma and resulted in 28% higher intramuscular fat and promoted the tenderness of meat (Suong et al., 2022). The supplementation of a basal diet with purple corn pigment at 1 g/d elevated the glutathione and 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity in the longissimus thoracis et lumborum (LTL) muscle but reduced the peroxidase activity (Tian et al., 2022).

Nevertheless, increased antioxidant activity was found in the milk of anthocyanin-fed goats (Tian et al., 2019a), which had a beneficial outcome on consumer health. The activity of antioxidant enzymes in the plasma of goats fed with 100% purple Napier grass silage rich in anthocyanin, notably enhanced the TAC and suppressed plasma SOD activity and malondialdehyde (MDA) contents; nonetheless, CAT, glutathione reductase (GR), glutathione S-transferases (GST) and cholesterol were not affected. Anthocyanins affect the activities and levels of antioxidant enzymes and compounds, including SOD, CAT, GR, GST, TAC, MDA and cholesterol (Onjai-uea et al., 2024). Anthocyanins have been studied from purple maize silage included in the diets of other ruminants. For example, feeding sheep with corn silage containing high anthocyanin levels enhanced plasma antioxidant activity, which can help minimize oxidative stress (Hosoda et al., 2012a). When purple corn silage was fed to dairy cows, it enhanced the plasma concentration of SOD, which also elevated their efficiency without influencing milk yield, composition, or rumen fermentation (Hosoda et al., 2012b). Since they are antioxidants, anthocyanins may have a role in improving the health of ruminants. Improvements in TAC and SOD were observed when diets were supplemented with anthocyanin-containing plants, due to these bioactive compounds having antioxidant activity, which consequently helped reduce the risk of coronary artery disease and cancer (Tsuda et al., 2003; Hosoda et al., 2012a; Hosoda et al., 2012b; Hosoda et al., 2012c).

Goats fed an anthocyanin-rich TMR diet containing 50% black cane silage treated with 4% molasses and 0.030% commercial iron sulfate elevated the plasma TAC concentrations, SOD, CAT, GSH-Px and GSH-Rx activities and reduced the concentration of thiobarbituric acid-reactive substances (Purba et al., 2023), similar to the use of 50% anthocyanin-rich black cane silage treated with ferrous sulfate heptahydrate (iron sulfate) (Purba et al., 2022). The relationship between anthocyanins and free radicals, such as O_2^-, was investigated, which are normally transformed to H_2O_2 by SOD and finally to water by GPX and CAT (Onjai-uea et al., 2024). In contrast, under conditions of high metabolism, nutritional imbalances enhance NADPH oxidase activity, leading to oxidative stress. The elimination system is affected by glucose metabolism when free radicals are absent. It influences the NADPH-dependent and energy metabolism cycles, the functionality of the immune system, the ability to neutralize free radicals and calcium balance. The two primary roles they play are: 1) neutralization of free radical scavengers by antioxidants; in addition to preventing oxidation by donating protons or electrons to free radicals, anthocyanins increase the activity of antioxidant enzymes, enhancing the antioxidant capacity (Kruger et al., 2014); and 2) reduction of oxidized molecules through the action of enzymes; the free radical scavenging mechanism of anthocyanins includes: 1) phenolic hydroxyl groups, whose function is to remove oxygen from free radicals; and 2) improvement of the free radical scavenging capacity of enzymes (Sakano et al., 2005; Soobrattee et al., 2005).

Effect of anthocyanins on rumen fermentation

The anthocyanin degradation rate rose as the pH increased (Reyes and Cisneros-Zevallos, 2007), indicating the instability of anthocyanins in high pH environments (Brouillard and Cheminat, 1988). However, anthocyanins may be stable in an acidic aqueous solution (Passamonti et al., 2003). The proton transfer process of anthocyanin from AH+ to A or the anthocyanin ionization from AH+ to A- or A2- occurs when pH is >7. Since A- and A2- are structurally less stable than AH+, they are more likely to degrade into other products (Brouillard and Cheminat, 1988; Tian and Lu, 2022). The rumen-pH did not vary with the diet having a rich anthocyanin content (Soung et al., 2022; Purba et al., 2022; Purba et al., 2023). According to these results, microbial rumen appears to be highly adaptable to the anthocyanin treatment, consistent with Ban et al. (2022), who reported no change in the ruminal pH of meat goats fed the peel powder of mangosteen (*Garcinia mangostana* L.) rich in condensed tannins, flavonoids and cinnamic acid.

Anthocyanins, which are flavonoid phytochemicals, play an important role in improving the ruminal microbial population of goats, especially cellulolytic bacteria. Goats fed purple neem foliage, which is rich in total anthocyanins, had greater levels of total bacteria, *Ruminococcus albus*, *R. flavefaciens*, *Fibrobacter succinogenes*, *Streptococcus bovis* and *Butyrivibrio fibrisolvens* (Taethaisong et al., 2022b), with a similar result in purple neem foliage combined with sunflower oil (Taethaisong et al., 2022a). The results showed that anthocyanins stimulated the growth of cellulolytic bacteria, which substantially increased the efficiency of fiber digestion. The expansion of this cellulolytic bacteria group was related to the increase in C_2 concentration (Tien et al., 2021; Taethaisong et al., 2022a; b) and total volatile fatty acids (TVFA) contents (Taethaisong et al., 2022a; b) used as the main energy source of the goats. This finding was consistent with Suong et al. (2022) and Purba et al. (2023), who reported that anthocyanins regulated the expansion of bacterial populations in the rumen, as evidenced by the increased relative abundance of *R. albus*. Three types of bacteria, namely *Ruminococcus albus*, *R. flavefaciens*, *Fibrobacter* (formerly *Bacteriodes*) *succinogenes*, are cellulolytic bacteria that play a crucial role in cellulose digestion (Weimer, 1996) and are found mostly in the rumen. Normally, bacteria that are capable of digesting cellulose can also digest hemicellulose. *Butyrivibrio fibrisolvens* is a hemicellulose-digesting bacteria that can digest fiber and produce C_4 as an end-product (Bryant and Small, 1956) and can also utilize starch (Hungate, 1966). These bacteria can digest feed to produce C_2, C_3, C_4, succinic acid and lactic acid, with succinic acid being able to be converted to C_3 (Hungate, 1966). *Streptococcus bovis* is an amylolytic bacteria that can digest starch.

One interpretation is that anthocyanins can improve ruminal cellulolytic bacteria activities, which influences the rumen microbiota by modulating the proportion of rumen bacteria and expanding the diversity of rumen microbes (Tian et al., 2021b). Rumen microbiota can be enhanced by anthocyanins' strong antioxidant attributes, which can shield the organism from peroxidation damage. Consequently, anthocyanins alter the rumen microbiome, possibly encouraging the growth of anaerobic bacteria as a gut modulator (Taethaisong et al., 2022b). The microbial population, rumen environment and fermentation substrate all play a major role in identifying the kind of rumen microbial community (Taethaisong et al., 2022a; b). In addition to promoting beneficial bacteria, anthocyanins reduce the number of protozoa and methanogens in the rumen, which reduces energy loss to methane, increases energy efficiency in animals and reduces the environmental impact of methane emissions (Taethaisong et al., 2022a). In terms of the microbiome balancing and diversity dimension, anthocyanins could modulate the microbial community structure by reducing pathogens and supporting the growth of beneficial bacteria (Igwe et al., 2019), resulting in improved microbiome diversity and stability, which is important for maintaining a rumen environment that is suitable for the functioning of digestive enzymes (Tian et al., 2021b).

Here has been little reported regarding the putative anthocyanin metabolism, digestibility and absorption pathways in ruminants, especially in meat and dairy goats. Although the function of anthocyanins is not entirely clear (Kochhar et al., 1976), they play a role in providing phenolic characteristics to forage. Anthocyanins are water-soluble pigments (Kochhar et al., 1976) that belong to a group of phenolic compounds, known as polyphenols, which have tannin-like properties. Tannins are phenolic compounds, having antibacterial properties and may bind to nutrients, preventing them from being digested by enzymes (Scalbert, 1991; Kamalak et al., 2005). The degraded anthocyanins in the rumen can bind with proteins, bypassing the rumen (Tian et al., 2021a) and increasing nitrogen utilization (Cordreddu et al., 2020). Anthocyanins from maize are not digested in the rumen (Hosoda et al., 2009). This was consistent with the findings of Song et al. (2012), who discovered that anthocyanin was not digested *in vitro* by rumen microbes. The ruminal pH, which ranges between 5.5 and 7.0, presents the conditions for anthocyanin bypass from the rumen and so could be absorbed effectively in the small intestine. Anthocyanin absorption may begin in the stomach and appear rapidly in the bloodstream within a few minutes (6–20 min) after ingestion and reach peak levels at 15–60 min (Ichiyanagi et al., 2004). However, anthocyanin absorption is influenced by various factors, including the nature of the feed, chemical structure, processing methods and preparation, interaction with other macro and micro phytonutrients and individual pathophysiological, nutritional and genetic factors (Riaz et al., 2016).

Anthocyanins can enhance the ammonia-N (NH_3-N) concentration of the ruminal fluid, facilitating dietary amino acid assimilation by ruminants (Francisco et al., 2018). They may also be digested and absorbed in the small intestines. The small intestine absorbs anthocyanins from the blood, which subsequently transfers to the liver. Only a small amount is absorbed in the colon and reabsorbed back into the liver. Some anthocyanins circulate in the liver and are excreted with bile salts to the small intestine. Anthocyanins can be absorbed into tissues, metabolized and excreted by the kidneys and urine. The unused portion is excreted with feces (Gonthier et al., 2003). The NH_3-N in the rumen is a vital nitrogen source for the growth of fibrolytic bacteria (Jeronimo et al., 2016). Approximately 60% of the structural carbohydrates digested within the rumen, including cellulose and hemicellulose, yield C_2 and butyric acid (C_4), respectively (Hungate, 1966). The TVFAs in the ruminal fluid were also improved by adding the diet with sources rich in anthocyanin containing plants (Suong et al., 2022); however, lower VFA levels may be caused by reduced microbial activity and substrate degradation (Murphy et al., 1982). By changing the acetate-to-propionate ratio, the quantities of VFAs and the kinetics of gas production, anthocyanins can modify the ruminal microbiota synergistically (Correddu, 2013). The consumption anthocyanin-rich plants results in an improvement in ruminal fluid VFAs and an alteration in the structure and relative abundance of ruminal microbiota (Tian et al., 2021a). This could explain their ability to elevate the microbial proteins passing through the small intestine, nitrogen and amino acid utilization and enhanced uptake. This ability can be attributed to polyphenols, bioactive substances that enhance the efficiency of turning dietary proteins into animal protein, which in turn improves ruminant growth performance (Jerónimo et al., 2016).

However, Suong et al. (2022) and Purba et al. (2022) reported that the NH_3-N in the rumen decreased in goats fed anthocyanin-rich black cane silage or anthocyanin-rich black cane silage treated with ferrous sulfate heptahydrate and molasses in the diet, consistent with Purba et al. (2023), possibly due to the presence of fermentable carbohydrates that convert rumen-degradable crude protein (CP) to microbial proteins (Vorlaphim et al., 2021; Yousefi et al., 2022).

Additionally, increased consumption of anthocyanins may have reduced the solubility of dietary proteins in the rumen, hence lowering the amounts of rumen NH_3-N (Tian et al., 2021a). Despite this, there is insufficient research data to consider anthocyanins as a direct indicator of rumen ammonia-N reduction. Purba et al. (2023) stated that their current study did not offer evidence to support the reduction in protein solubility caused by anthocyanins. Therefore, further investigation was required into this intriguing topic. One explanation could be that consuming more anthocyanins may reduce the solubility of dietary proteins in the rumen, resulting in lower amounts of ammonia-N. Bioactive compounds may impact rumen ammonia concentrations, potentially reducing protozoal population, a key factor in ruminal feed protein degradation (Bodas et al., 2012). A steady supply of enough ammonia for microbial growth in the rumen can be produced by polyphenols binding NH_3-N from microbial protein breakdown in a balanced chemical reaction controlled by the ammonia concentration (Patra and Saxena, 2011, cited by Tayengwa and Mapiye, 2018).

The total anthocyanins content from feeding anthocyanin-rich plants silage decreased the relative abundance of the methanogens in the rumen fluid of goats (Soung et al., 2002, Purba et al., 2023), respectively, suggesting that there can be decreases in methane production. However, the results of these studies were not in line with the observed increase in the rumen C_2-to-C_3 ratio, since TVFAs were elevated (in terms of acetic acid [C_2] and the proportion of acetic acid-to-propionic acid [C_2/C_3]), and in spite of having more *R. albus* and fewer methanogenic microorganisms present (Soung et al., 2022; Purba et al., 2023). Propionic acid fermentation utilizes hydrogen to reduce methane production and accelerate energy utilization. Generally, more hydrogen indicates that the ruminant had more methane (Lu et al., 2022). It is widely acknowledged that the synthesis of acetate, instead of propionate, uses hydrogen as a source (Purba et al., 2020). This can be explained by acetogenic bacteria synthesizing acetate using hydrogen. Notably, acetogenic bacteria can directly produce acetate from hydrogen and carbon dioxide (Katsyv and Müller, 2020).

Protozoa numbers and methanogen levels were lowered in goats fed 6% purple neem foliage, indicating that the anthocyanin content inhibited rumen microorganisms (Taethaisong et al., 2022b). Patra et al. (2010) reported that the plant's total phenols demonstrated inhibitory effects on methanogenesis by reducing the numbers of protozoa. Polyphenolic compounds added to ruminant diets can reduce the production of methane by inhibiting the growth and activity of methanogens, which are responsible for methanogenesis and include Methanobrevibacter and Methanomicrobium (Moate et al., 2014; Tayengwa and Mapiye, 2018). This was supported by Lu et al. (2022), who studied bioactive substances, which are abundant in total phenols and total anthocyanins presented in red distiller's grain, and reported lower levels of methane production (%) and high levels of C_3, which might promote the fermentation of C_3 in goat ruminal fluid, preventing methane emissions. Polyphenols (including total phenol and anthocyanin) can enhance microbial protein flow, reduce methane production in the gastrointestinal tract and combine protein nutrients to form complex nutrients in the rumen, as well as being digested and absorbed through the rumen to the small intestine, enhancing feed utilization efficiency and reducing methane emissions (Lu et al., 2022). From these research data, there appears potential for anthocyanins to decrease methane production, perhaps due to their competition for H_2, as the generation of CH_4 and propionate is negatively correlated (Moss et al., 2000). Thus, when hydrogen is consumed by C_3 in rumen fermentation, the methane production may decrease in the rumen when C_3 concentrations are high, producing a rise in the utilization of energy. Ruminal microbes and the main polyphenols interact; a decrease in hydrogen ions due to the reduced feed degradability and reduced fiber digestibility in the rumen results in lower methane production (Correddu et al., 2020).

Effect of anthocyanin on growth performance in goats

Feeding an anthocyanin-rich diet to goats had no negative effect on their growth performance, being rather more likely to promote growth performance. Since anthocyanins can bind to dietary proteins in the rumen, their digestibility is reduced, enhancing nitrogen utilization, resulting in protein bypass through the abomasum, which leads to more digestion and absorption through the small intestine, elevating protein intake and improving the absorption and utilization of amino acids. Furthermore, anthocyanins boost beneficial fatty acids (polyunsaturated fatty acids). This effect on the fatty acid profile may help increase the biohydrogenation process, which is the microbial conversion of unsaturated fatty acids to saturated fatty acids. This process can improve the quality of goat meat and milk because fatty acids provide benefits to the animal and the health of consumers. A few of the studies relating to the effects of anthocyanin on growth and other production parameters in goats are summarized in Table 3.

Table 3 Examples of plant anthocyanin sources supplemented in goat diets

Anthocyanin plant (scientific name)	Goat type (number of goats)	Diet formula	Total anthocyanins and % CP content in the diet	Potential of anthocyanin	Reference
Purple corn *(Zea mays* L.)	Qianbei-pockmarked wether goats (18)	Supplemented basal diet with purple corn pigment at 0.5 g/d and 1 g/d levels	2,619 ± 13.04 µg/g DM, 13.8% CP of basal diet	No effect on DMI, BW change, ADG, feed conversion ratio; reduced shear force; increased unsaturated fatty acids (C18:1n9 *trans*, C20:3n6, C22:5n3) in the LTL muscle	(Tian et al., 2022)
Purple corn (*Zea mays* L.)	Multiparous lactating Saanen dairy goats (16)	TMR consisting of 50% purple corn silage	861.95 mg/kg DM, 15.10% CP	No effect on DMI; increased lactose, peonidin, malvidin-3-O-glucoside and SOD in milk; increased SOD in plasma	(Tian et al., 2019b)
Napier grass silage (*Pennisetum purpureum)*	Crossbred Thai native x Anglo-Nubian goats (18)	Napier grass silage treated with 4% molasses and 0.03% $FeSO_4$ (additive) *ad libitum* with concentrate 1.5% BW	596.61mg/kg DM Anthocyanin, 8.97% CP	Improved productivity by increasing CP, ADF, anthocyanin intake, weight change, ADG, C_3 proportion, TVFAs, nitrogen digestibility	(Suong, 2017)
			600 mg/kg DM Anthocyanin, 8.41% CP	Reduced stress in goats naturally infected with *H. contortus* by enhancing the activities of catalase, glutathione and glutathione-s-transferase antioxidant enzymes.	
Purple yam (*Dioscorea alata* L.*)*	Nonpregnant Hainan black goats (28)	500 g concentrate mixed with a 30% corn diet was substituted for *D. alata* L. powder daily:roughage (fresh King grass) = 1:1 (DM),	15.33% CP of concentrate mixed diet	No effect on C_2 concentration in the rumen; improved the antioxidant capacity in blood and milk and their kids during the perinatal period and increased their resistance to oxidative stress	(Zhang et al., 2022)
Purple neem foliage (*Azadirachta indica* A.)	Anglo-Nubian Thai native male goats (25)	6% PNF in concentrate	132.89 mg/g DM, 16.62% CP of diet	High FI, NI, nutrient digestion, final weight, weight change, ADG, NH_3-N, BUN, C_2, C_3, C_2/C_3 ratio, TVFA, total bacteria TAC, SOD, GPX, DPPH, CAT at 2 and 4 h after feeding with no effect on pH but low protozoa and MDA	(Taethaisong et al., 2022b)
Purple neem foliage (*Azadirachta indica* A.)	Boar male goats (18)	6% PNF + 3% SFO in concentrate	16.29% CP of diet	Increased feed consumption, NI (OM, CP and EE), nutrient apparent digestion, NH_3-N, BUN, C_2, C_3, C_4, TVFA and total bacteria, TAC, SOD, GPX, DPPH, CAT at 2 and 4 h after feeding and fatty acid profile in meat but low protozoa, methanogen levels and MDA in plasma	(Taethaisong et al., 2022a)
Mangosteen peel (*Garcinia mangostana* L.)	Crossbred Thai native × Anglo-Nubian male goats (12)	TMR consisting of 4.125% mangosteen peel powder	2.98 g/kg DM proanthocyanidins with caffeic acid, ferulic acid, rutin, quercetin and catechin, 10.2	Increased BW and OM digestibility. Total VFAs, with a higher proportion of C_2. Lesser CH_4 production with increased plasma glutathione peroxidase concentration and 2,2-diphenyl-1-picrylhydrazyl scavenging activity boosted plasma total protein and albumin.	(Ban et al., 2022)
Red (Blood) orange (*Citrus sinensis* L.)	Kids of Saanen bred (60)	100 g hay and 150 g kid starter + 90 mg/kg of red-orange and lemon extract (Cream was created by combining red-orange and lemon extract with water)	2.66% of total anthocyanins (as cyanidin 3-glucoside equivalents)	NPY immunoreactive cells considerably increased in the pancreatic islets and abomasal epithelium.	(Felice et al., 2021)

Table 3 Continued

Anthocyanin plant (scientific name)	Goat type (number of goats)	Diet formula	Total anthocyanins and % CP content in the diet	Potential of anthocyanin	Reference
Black cane (*Saccharum sinensis* Robx.)	Crossbred Thai native Anglo-Nubian goats (36)	TMR diet containing anthocyanin-rich black cane silage-based diet containing 50% Napier grass silage	0.17 mg/g DM and 11.6 % CP	Reduced oxidative stress and promoted the production of tender meat without affecting animal performance.	(Suong et al., 2022)

CP = crude protein; DM = dry matter; DMI = dry matter intake; BW =body weight; ADG = average daily gain; LTL = *longissimus thoracis et lumborum*; TMR = total mixed ration; SOD = superoxide dismutase; $FeSo_4$ = Iron (II) sulfate or ferrous sulfate; ADF = acid detergent fiber; C_3 = propionic acid; TVFAs = total volatile fatty acids; *H. contortus* = *Haemonchus contortus*; *D. alata* L. = *Dioscorea alata* L.; C_2 = acetic acid; FI = feed intake; PNF = purple neem foliage; NI = nutrient intake; NH_3-N = ammonia nitrogen; BUN = blood urea nitrogen; C_2/C_3 ratio = acetic acid/ propionic acid ratio; TAC = total antioxidant capacity; GPX = glutathione peroxidase; DPPH = 2, 2-diphenyl-1- picrylhydrazyl; CAT = catalase; MDA = malondialdehyde; OM = organic matter; EE = ether extract; C_4 = butyric acid; SFO = sunflower oil; CH_4 = methane; NPY = neuropeptide Y;.

In the first of a two-stage study, Thai native × Anglo-Nubian crossbred goats (average BW 14.42 ± 0.6 kg) were fed *ad libitum* with a concentrate equivalent to 1.5% of their BW and Napier grass silage treated with 4% molasses and 0.03% $FeSO_4$ as an additive (8.97 mg/kg DM of anthocyanin, 8.97% CP). This regimen enhanced productivity, including increased CP and anthocyanin intake, improved DM and nutrient digestibility, weight gain, C_3 proportion, TVFAs, nitrogen digestibility, nitrogen retention and number of *Streptococcus bovis* at 2 hr and 4 hr in the rumen fluid, as well as TAC in the plasma (Suong et al., 2022).

Male Thai native × Anglo-Nubian crossbred goats fed a TMR diet containing 4.125% mangosteen peel powder (2.98 g/kg DM proanthocyanidins) had enhanced levels of BW change and organic matter (OM) digestibility, as well as TVFAs with a greater proportion of C_2 (Ban et al., 2022). These changes led to increased plasma GPX levels and higher DPPH scavenging activity, as well as improved plasma total protein and albumin levels (Ban et al., 2022). In another study, 60 Saanen kids were allocated into two groups: one receiving a standard diet (100 g hay and 150 g kid starter) and the other receiving the standard diet + 90 mg/kg of red-orange and lemon extract for 40 d (Felice et al., 2021). The extract contained total anthocyanins (measured as cyanidin 3-glucoside equivalents), total flavanones, total hydroxycinnamic acids and ascorbic acid at 2.66%, 15.91%, 1.77% and 2.40%, respectively. The group receiving the extract had a marked increase in neuropeptide Y immunoreactive cells in the abomasal epithelium and pancreatic islets (Felice et al., 2021). Qianbei-pockmarked wether goats were fed with a basal diet supplemented with purple corn pigment at 0.5 g/d or 1 g/d level, that included concentrate, premix and roughage in the TMR (total anthocyanin at 2,619 ± 13.04 g/g DM, 13.8% CP) for 74 d, which resulted in no effect on DMI, BW change, average daily gain (ADG), feed conversion ratio or reduced shear force (Tian et al., 2022). However, this diet, which also included a concentrate diet, enhanced unsaturated fatty acids (C18:1n9 trans, C20:3n6 and C22:5n3) in the LTL goat muscle compared to the basal diet (Tian et al., 2022). PNF is rich in flavonoids, polyphenolics and secondary plant compounds (Taethaisong et al., 2022a), which may exert antimicrobial activity and alter digestion and rumen fermentation by interacting with the fibers and proteins. It has been reported that PNF contains anthocyanins. This could be interpreted as the anthocyanins contributing to optimizing the microbial population, increasing fiber-degrading bacteria, reducing pathogens and methanogens, protecting microorganisms from oxidative stress and increasing nitrogen utilization efficiency, all of which support the digestive performance, increase the growth rate and overall health of meat goats (Taethaisong et al., 2022a).

In a study, 40 Thai native × Anglo-Nubian crossbred male goats fed on a TMR diet incorporating 50% anthocyanin-rich black cane silage treated with ferrous sulfate heptahydrate (iron sulfate) were compared to a control group fed with 50% anthocyanin-rich black cane silage without iron sulfate; there were no statistically significant differences in final BW, ADG, or the ADG-to-DMI ratio between the two groups (Purba et al., 2022). In another study, two TMR isocaloric and isonitrogenous diets were fed to Thai native × Anglo-Nubian crossbred male goats for over 90 d and compared; Group 1 received a diet containing 50% anthocyanin-rich black cane silage, while Group 2 received the same silage treated with 4% molasses and 0.030% commercial iron sulfate (Purba et al., 2023). Despite the reported astringency and bitter taste of anthocyanin (Tian et al., 2021a; Tian and Lu, 2022), there were no significant differences in DMI between the two groups. This finding aligned with other research (Purba et al., 2022), which showed that the addition of iron sulfate and molasses to anthocyanin-rich black cane silage

(Group 2) resulted in comparable ADGs (36.5 g/d versus 43.6 g/d, respectively). The lack of any notable effects on DMI and ADG in Group 2 may be attributed to the lower inclusion of anthocyanin-rich plants, as cited by other studies (Tian et al., 2022; Tian and Lu, 2022). Notably, the total anthocyanin levels in the TMR diets for Groups 1 and 2 were 0.17 mg/g and 0.75 mg/g, respectively (Purba et al., 2022).

Overall, growth performance was not adversely affected by anthocyanins, with the anthocyanins tending to improve the growth efficiency of goats due to anthocyanins being flavonoids, which are absorbed through the digestive tract of ruminants and flow from the rumen to the small intestine (Dijkstra et al., 2005). When the proper quantity of anthocyanin is fed to goats, they receive greater amounts of amino acids and protein, due to the anthocyanin binding to proteins. The digestibility of such proteins in the rumen decreases; consequently, more proteins flow via the abomasum and lead to digestion and absorption in the small intestine (Gonthier et al., 2003).

Effect on milk production

Limited research is available on the effects of anthocyanins on dairy goats, though purple Napier grass is found in some regions of Thailand. Multiparous lactating Saanen dairy goats were fed for 8 wk with a TMR consisting of a 50% anthocyanin-rich purple corn silage instead of sticky corn silage, which had total anthocyanin contents of 861.95 mg/kg DM and 15.10% CP (Tian et al., 2019b). TMR consisting of 50% purple corn silage did not affect the DMI but elevated the lactose, peonidin, malvidin-3-O-glucoside and SOD levels in the milk and SOD in the plasma. Numerous antioxidant enzymes and the anthocyanin content of milk had stronger positive correlations—TAC and pelargonidin; SOD and peonidin; as well as SOD and malvidin-3-O-glucoside (Tian et al., 2019b). Positive effects of anthocyanins have been reported regarding milk antioxidative capacity during the storage period (Ban et al., 2025). By preserving the capacity to scavenge free radicals, the use of anthocyanin-rich black sugarcane (*Saccharum sinensis* Robx.) (AS) as roughage in the diet of lactating dairy cows extended the shelf life of the milk by moderating lipid peroxidation, without altering milk yield or milk composition. Lactating dairy cows fed the AS diet had higher SOD inhibition in the plasma and DPPH scavenging capacities in the milk than with Napier grass, demonstrating that anthocyanins are accessible and able to enter the bloodstream, where they strengthen antioxidant defense through providing electrons to O_2-•. The AS could also prevent lipid peroxidation by maintaining free radical scavenging, thereby preserving the flavor and shelf life of the milk, which is consistent with consumer expectations for food produced naturally. The quality and flavor of milk are impacted by lipid peroxidation (Tian et al., 2022), which is stimulated by the many free radicals (FR) produced by lipid oxidation. Anthocyanins in AS aid in lipid oxidation by acting as hydrogen donors, transforming lipid FRs into stable forms, scavenging peroxyl radicals, preventing chain reactions and inhibiting peroxide formation (Narayan et al., 1999). Anthocyanins can terminate oxidation and improve antioxidant-related enzyme activity, enhancing the body's antioxidant capacity (Kruger et al., 2014). Dairy goats fed anthocyanins-rich purple corn silage had higher SOD activity, suggesting antioxidant potential. Superoxide dismutase, a defense against prooxidants, is involved in reducing mitochondrial hydrogen peroxide (H_2O_2), which has high toxicity. This may alleviate OS status by converting O2 −• into H_2O_2 (Tian et al., 2019).

Goats have high metabolic demands for maintenance and production that can lead to oxidative stress, causing health issues including mastitis, reproductive issues and decreased milk production (Celi, 2010). This finding is consistent with the oxidative status of the transition-phase cows reportedly varying somewhat depending on their metabolic status (Bernabucci et al., 2005). The capacity for producing milk will decrease if there is excessive stress from free radicals. Anthocyanins have powerful antioxidant properties and dietary antioxidants can lower oxidative stress by preserving redox equilibrium, enhancing defenses and possibly raising milk production (Tian et al., 2022). Notably, ruminant diets that contain anthocyanin-rich pigments or plants do not have a deleterious impact on milk components (Tian et al., 2019b) or production (Tian and Lu, 2022). For example, Tian et al. (2019b) reported that feeding with anthocyanin-rich purple corn stover silage in the diet did not adversely affect the milk yield of lactating dairy goats, plasma and milk levels of SOD were increased. Thereby, anthocyanin-rich purple corn stover silage can increase the quantity of antioxidants in lactating dairy goats by transferring anthocyanins to milk. Onjai-uea et al. (2024) demonstrated that antioxidant enzyme levels in milk and plasma, as well as milk lactose, could increase in lactating dairy goats fed anthocyanin-rich purple Napier grass silage.

Tian et al. (2019b) found that the lactose in milk was high in lactating dairy goats fed anthocyanin-rich purple corn stover silage. The milk lactose content is initiated by C_3; thus, it is possible that the anthocyanin-rich purple corn silage was able to influence rumen fermentation, particularly by inhibiting C_2 and increasing the proportion of C_3 in the rumen (Tian et al., 2018). Furthermore, the sugars in anthocyanins may be metabolized in the digestive tract and contribute to the synthesis of lactose (Tian et al., 2019b). These discrepancies might result from the various ways that the plant secondary metabolites influence bacteria that produce VFAs, particularly cellulose and hemicellulose bacteria, which control the formation of VFAs from soluble sugars (Hassan et al., 2020). However, the inhibition of C_2 may not directly result from anthocyanins. Normally, the proportion of C_2 and C_3 is heavily influenced by management of the roughage-to-concentrate ratio. Digestibility is reduced when ruminant animals are fed a diet with a high percentage of fiber content; consequently, C_2 is reduced. There is another possibility that forage material containing anthocyanins may be bitter, which could affect animal uptake by reducing roughage intake and consequently reducing C_2. The bitter taste that anthocyanins as phenolic chemicals contribute, decrease plant palatability and feed intake, according to Jöbstl et al. (2004).

Because of their size and hydrophilicity, anthocyanin molecules are not absorbed via passive transport, but rather by an active transport system. Prior to absorption, the anthocyanin macromolecules are hydrolyzed to glycosides (Riaz et al., 2016) which form a serosal fluid before transport or entering the systemic circulation as aglycone. Additionally, the co-transport of sodium and glucose (Williamson et al., 2000) or extracellular glycoside hydrolysis (Gee et al., 2000; Onjai-uea et al., 2024) is another potential mechanism for anthocyanin absorption. The key element affecting the transfer of polyphenolic components to milk was reportedly molecular weight (Jordan et al., 2010), with anthocyanins most likely absorbed into the milk via entry into the circulation in an intact form (Tian et al., 2019b). Anthocyanin absorption was meager due to its limited intestinal absorption and susceptibility to intestinal microbial destruction (Tian et al., 2019b). Despite their wide variety, anthocyanins all have the same fundamental structural elements, known as anthocyanidins. The most common anthocyanidins in plants are pelargonidin (18%), cyanidin (30%), delphinidin (22%), malvidin (20%), peonidin and petunidin (Anderson and Markham, 2005). The two main types of anthocyanins found in milk are cyanidin and pelargonidin, with molecular weights <300 g/mol. After ruminant metabolism, other anthocyanins with molecular weights >300 g/mol are not absorbed into milk and have very low stability in milk (Tian et al., 2019b). Although some have indicated that anthocyanins have a positive effect on milk production in goats, further studies are needed to obtain clearer and more comprehensive data and mechanisms because many factors may affect the efficacy of anthocyanins such as the type of anthocyanin, the level of feeding and the breed of goat.

Conclusion

This article gathered insights into the role of anthocyanins in goat nutrition, contributing to future research and sustainable goat production. The research review confirmed that anthocyanins play an important role in goat diets. Hence, it is beneficial to introduce feeds rich in anthocyanins, such as purple Napier grass and purple corn stalks, as roughage for meat or dairy goats. Anthocyanins have the potential to enhance growth efficiency and both unsaturated and saturated fatty acids in goat meat and milk, improve meat quality and promote antioxidant capacity. Consequently, functional milk or meat products can be produced to benefit consumer health, which may lead to enhanced productivity and farmer incomes in line with sustainable development goals. However, further investigation of anthocyanin in meat and dairy goats is required to ascertain the physiological importance from regional roughage or other edible plants at low and high concentrations, as well as to identify the mechanism(s) driving this effect. Furthermore, the quality and feed preferences of the animals should be considered for maximum benefit.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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