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Anthocyanins as a Natural Feed Additive for Methane Mitigation in Ruminant Nutrition

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Abstract

Ruminant animal enteric methane emmissions contribute significantly to the accumulation of greenhouse gas and also represent a great loss of dietary energy. Natural feed additives that can reduce methane emissions without any negative effect on animal performance have been the focus of recent researches to enhance the sustainability of livestock production. Anthocyanins are naturally occuring flavonoid pigments richly available in purple corn, grape pomace, purple rice, black cane and other plants. They have antioxidant, antimicrobial, and rumen-modulating characteristics making them a potential option for enteric methane emissions mitigation. Anthocyanins have been shown to boost fermentation efficiency, decrease methanogenic archaea, interfere with microbial ecology of the rumen, and reroute hydrogen use toward propionate synthesis. This review examine the function of anthocyanins as a natural methane mitigation agents in ruminant nutrition. Their mode of action, efffects on rumen microbiota and fermentation characteristics, effects on animal performance, and potential contributions to sustainable ruminant animal production are all given a careful emphasis. Limitations and future research directions are also addressed.

Keywords: *Methane mitigation, anthocyanins, rumen fermentation, ruminants, methane emissions*

Introduction

The ruminant industry contributes significantly to global food security by transforming fibrous feed supplies unfit for human consumption in to quality meat and milk. However, ruminant production systems are the main generators of anthropogenic greenhouse gas emissions, especially methane which has a global warming potential roughly 28 times larger than carbon dioxide over a 100-year period (Legg, 2021). According to Moss et al. (2000), enteric methane produced during fermentation represents an energy loss of 2-12% of gross dietary energy intake and accounts for 30-40% of global agricultural methane emissions. Methane is produced in the rumen naturally from microbial fermentation. Rumen bacteria ferment carbohydrates during feed digestion to produce hydrogen (H_2), carbon dioxide (CO_2), and volatile fatty acids (VFAs). By using carbon dioxide and hydrogen to create methane, methanogenic archaea keep the partial pressure of hydrogen in the rumen low (Moss et al., 2000; Dijkstra et al,. 2005). This process lowers feed efficiency and significantly contributes to environmental contamination, yet being necessary for ruminal homeostasis. Methane emissions from livestock production have drawn a lot of attention because they generate approximately 14.5% of global anthropogenic greenhouse gas emissions, with enteric fermentation accounting for the highest share (Gerber et al., 2013). In addition to its negative effects on the environment, methane production is a major inefficiency in ruminant production systems since the energy wasted as a methane cannot be used for growth, lactation, or reproduction (Johnson & Johnson, 1995). As a result, all efforts towards lowering enteric methane emissions are now essential to sustainable agricultural and climate-smart ruminant production. Several methods of methane emission prevention have been evaluated which includes; nitrate feeding, ionophores, dietary lipid supplementation, probiotics, essential oils, and plant secondary metabolites (Beauchemin et al., 2008; Gerber et al., 2013; Vasta et al., 2019). Phytochemicals have drawn more attention among these strategies because they are naturally occuring substances that can both enhance animal performance and lessen environmental effects (Patra & Saxena, 2011). Anthocyanins are among the water-soluble flavonoid pigments, these pigments are responsible for the red, blue, and purple coloration in many vegetables, forage plants, fruits, and cereals (He & Giusti, 2010). Purple corn, purple rice, black cane, purple sweet potatoes, grape pomace and purple neem leaves are common feed sources that are rich in anthocyanins (Hosoda et al., 2009; Taethaisong et al., 2022). Anthocyanins have a strong antioxidant, antibacterial, anti-inflammatory and immunomodulatory functions in addition to their function as natural pigments (Han et al., 2006; Aboonabi & Singh, 2015). Recent findings showed that anthocynin rich feed have the ability to enhance rumen fermentation, modulate rumen microbiota, improve antioxidant status, enhance nutrient digestibility, and boost animal productivity (Tian et al., 2019; Tian et al., 2021; Suong et al., 2022). A study using a purple corn anthocyanin supplementation in goats reveal an altered ruminal fermentation functions and overall rumen microbial composition (Tian et al., 2021). Similar study by Taethaisong et al. (2022) reported an improvements in rumen fermentation efficiency, growth performance, and plasma antioxidant activity in goats supplemented with anthocyanin-rich purple neem foliage. In addition, polyphenol-rich feed resources containing anthocyanins, such as grape pomace, have been shown to reduce methane emissions in dairy cattle (Moate et al., 2014). Despite growing interest in anthocyanin-rich feed resources, most available studies have focused on their

antioxidant properties, animal health benefits, and product quality improvements (Tian & Lu, 2022). Comparatively fewer studies have comprehensively examined their role as methane mitigation agents and the specific mechanisms through which anthocyanins influence methanogenesis. Furthermore, available findings remain fragmented across different animal species, feed resources, and production systems. Therefore, there remains a need to synthesize current knowledge regarding the potential of anthocyanins as natural methane mitigation agents in ruminant nutrition. This paper reviews the sources, biological properties, and mechanisms through which anthocyanins influence rumen fermentation and methane production. Particular attention is given to their effects on rumen microbial ecology, hydrogen metabolism, animal performance, and environmental sustainability.

Anthocyanins: Sources and Biological Characteristics

Anthocyanins belong to the flavonoid family and are glycosylated derivatives of anthocyanidins. More than 600 anthocyanin compounds have been identified, with cyanidin, delphinidin, pelargonidin, peonidin, petunidin, and malvidin being the most common forms found in nature (He & Giusti, 2010). Anthocyanins are abundant in numerous feed resources used in ruminant production, including: Purple corn (Zea mays L.), Purple corn Stover silage, Purple rice silage, Black cane silage, Purple neem foliage, Grape seed and grape pomace, Berry by-products, Purple sweet potato. Hosoda et al. (2009) reported that anthocyanin-rich corn silage retained considerable anthocyanin stability during ensiling, suggesting its suitability as a practical feed resource. Likewise, Suong et al. (2022) demonstrated that anthocyanin-rich black cane silage can be successfully incorporated into goat diets while improving rumen fermentation and animal performance. Anthocyanins possess strong free radical scavenging capacity and are recognized as potent natural antioxidants (Brewer, 2011). According to Tian and Lu (2022), anthocyanins can enhance antioxidant defenses, improve immune responses, and reduce oxidative stress in ruminants. These biological properties may indirectly contribute to improved rumen function and methane mitigation.

Anthocyanin-Rich Feed Resources

Purple Corn: Purple corn is one of the most extensively studied anthocyanin-rich feed resources. Tian et al. (2019) reported that feeding anthocyanin-rich purple corn silage improved nutrient utilization, rumen fermentation, plasma antioxidant capacity, and mammary gland gene expression in dairy goats. Furthermore, Tian et al. (2019) observed improvements in productivity and blood superoxide dismutase concentrations in lactating cows receiving purple corn silage. Purple corn anthocyanins have also been shown to improve ruminal fermentation and modify rumen microbial populations in goats (Tian et al., 2021). **Black Cane Silage**: Black cane silage contains high concentrations of anthocyanins and has received increasing attention as a functional feed resource. Suong et al. (2022) demonstrated improvements in growth performance, blood biochemical indices, rumen bacterial communities, and carcass characteristics in goats fed anthocyanin-rich black cane silage. **Purple Neem Foliage:** Taethaisong et al. (2022) reported that consumption of purple neem foliage rich in anthocyanins improved rumen fermentation, growth performance, and plasma antioxidant activity in goats.

Anthocyanins and Polyphenols in Ruminant Nutrition

Anthocyanins belong to the broader group of plant polyphenols, which have long been recognized for their biological activities in animal systems (Acosta-Estrada et al., 2014). Polyphenols can modulate rumen fermentation through direct interactions with microbial populations and indirect effects on nutrient metabolism (Vasta et al., 2019). Recent evidence suggests that anthocyanins may exert stronger antioxidant activities than vitamins C and E because of their unique molecular structure and high free radical scavenging capacity (Han et al., 2006). According to Brewer (2011), anthocyanins are among the most potent naturally occurring antioxidants identified in plant materials. In ruminants, anthocyanins have been associated with improved antioxidant status, reduced inflammatory responses, enhanced immune function, and improved production performance (Tian & Lu, 2022). These effects are particularly important during periods of metabolic stress such as early lactation, heat stress, and disease challenge (Xiao et al., 2021).

Methane Production in the Rumen

Methane production is a normal component of ruminal fermentation and is primarily carried out by methanogenic archaea. These microorganisms utilize hydrogen generated during carbohydrate fermentation to reduce carbon dioxide and produce methane (Moss et al., 2000). The primary methanogenesis reaction can be summarized as:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Methane production represents a loss of dietary energy and decreases feed conversion efficiency (Dijkstra et al., 2005). Factors influencing methane emissions include diet composition, rumen pH, forage-to-concentrate ratio, feed digestibility, microbial populations, and animal species (Moss et al., 2000; Vasta et al., 2019). Consequently, nutritional interventions capable of reducing hydrogen availability or suppressing methanogenic populations have become important research priorities.

Mechanisms through Which Anthocyanins Mitigate Methane Emissions

1. Modification of Rumen Fermentation Patterns: Anthocyanins influence rumen fermentation by altering microbial activity and fermentation end-products. Tian et al. (2021) observed significant changes in ruminal fermentation characteristics following supplementation with purple corn anthocyanins. According to Tian and Lu (2022), anthocyanins may promote propionate production while reducing acetate-to-propionate ratios. Because propionate formation consumes metabolic hydrogen, this pathway competes directly with methanogenesis. Increased propionate production therefore decreases hydrogen availability for methane-producing archaea, ultimately reducing methane emissions.

2. Suppression of Methanogenic Archaea: Plant polyphenols are known to possess antimicrobial activity against selected rumen microorganisms (Vasta et al., 2019). Anthocyanins appear capable of inhibiting methanogenic populations through disruption of microbial cell membranes and interference with enzymatic activity. Tian and Lu (2022) proposed that anthocyanins may decrease populations of methanogens while simultaneously promoting beneficial fermentative bacteria. Such microbial shifts reduce methane production without negatively affecting rumen function.

3. Alteration of Rumen Microbial Ecology: Recent advances in sequencing technologies have revealed significant effects of anthocyanins on rumen microbial communities. Tian et al. (2021) demonstrated that purple corn anthocyanin supplementation altered rumen microbiota composition and improved fermentation efficiency in goats. Similarly, Suong et al. (2022) reported changes in rumen bacterial communities in goats receiving anthocyanin-rich black cane silage. Vasta et al. (2019) emphasized that plant polyphenols can modify microbial populations responsible for fiber degradation, biohydrogenation, and methane production, thereby influencing overall fermentation efficiency.

4. Improvement of Antioxidant Status and Rumen Health: Anthocyanins possess strong antioxidant properties due to their ability to scavenge reactive oxygen species and activate antioxidant defense pathways (Han et al., 2006; Tian & Lu, 2022). Tian and Lu (2022) noted that anthocyanins activate Nrf2 signaling pathways and increase the activity of antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase. Improved antioxidant status may enhance microbial stability and rumen function, indirectly contributing to lower methane production.

5. Biohydrogenation process modulation: Apart from influencing methane production directly, anthocyanins may alter ruminal biohydrogenation processes. Vasta et al. (2019) reported that plant polyphenols can affect microbial species responsible for fatty acid biohydrogenation, leading to changes in ruminal lipid metabolism. Alterations in biohydrogenation pathways may influence hydrogen utilization patterns within the rumen. Because methanogenesis competes for available hydrogen, changes in hydrogen partitioning may contribute to reductions in methane production (Vasta et al., 2019).

6. Influence on Fiber Degradation: Anthocyanins may also affect fiber digestion through interactions with cellulolytic microorganisms. Similar to other polyphenols, anthocyanins can bind to plant cell walls and microbial enzymes, altering degradation kinetics (Acosta-Estrada et al., 2014). Moderate reductions in fiber degradation may decrease hydrogen production and methane formation without negatively affecting overall animal performance. However, excessive inclusion rates may impair digestibility, emphasizing the need for optimal supplementation levels (Patra & Saxena, 2011).

Anthocyanins and Oxidative Stress Reduction

Oxidative stress is a major challenge in modern dairy production systems, particularly during transition periods and heat stress conditions (Sordillo & Aitken, 2009). Excessive production of reactive oxygen species (ROS) can impair immune function, reduce feed intake, and compromise productivity (Miller et al., 1993). Anthocyanins are capable of activating nuclear factor erythroid 2-related factor 2 (Nrf2), a key regulator of cellular antioxidant defense systems (Aboonabi & Singh, 2015). Activation of Nrf2 stimulates the expression of antioxidant enzymes including superoxide dismutase, glutathione peroxidase, catalase, and NAD(P)H quinone oxidoreductase (Tian & Lu, 2022). Simultaneously, anthocyanins inhibit activation of the nuclear factor-kappa B (NF-κB) signaling pathway, thereby reducing inflammatory responses and oxidative damage (Xiao, 2004; Kuntz et al., 2015). Such effects may contribute indirectly to improved rumen health and fermentation efficiency.

Heat Stress, Methane Emissions and Anthocyanins

Heat stress represents one of the most important environmental challenges affecting dairy cattle worldwide (Das et al., 2016). Elevated temperatures reduce feed intake, alter rumen fermentation patterns, impair immune responses, and decrease milk production. Anthocyanins may help alleviate heat stress through their antioxidant and anti-inflammatory properties. Tian et al. (2019) demonstrated that improved oxidative status during the postpartum period enhanced productivity and metabolic health in dairy cows. Because oxidative stress and methane production are both linked to rumen function, anthocyanin supplementation may offer dual benefits by reducing oxidative damage and improving fermentation efficiency.

Table 1. Effects of Anthocyanins in Ruminant Nutrition

Area of Effect	Observed Effects of Anthocyanins	Mechanism of Action	Animal Species/Studies	References
Antioxidant Status	Increased T-AOC, SOD, GSH-Px; reduced MDA	Scavenging free radicals; enhancing antioxidant enzymes	Dairy cows, sheep, goats	Tian et al. (2019)
Immune Function	Improved immune response; reduced TNF-α and IL-6	Modulation of NF-κB signaling and cytokine production	Dairy cows and lambs	Tsuda (2012);
Rumen Fermentation	Enhanced VFA production, especially propionate	Selective modulation of rumen microbial populations	Sheep and cattle	Makmur et al. (2022)
Methane Emission	Reduction in enteric methane production	Inhibition of methanogens and shift toward propionate	In vitro and in vivo ruminant studies	Patra et al. (2017); Makmur et al. (2022)
Nutrient Digestibility	Improved DM, OM and CP digestibility	Improved microbial efficiency and reduced oxidative stress	Sheep and dairy cattle	Tian et al. (2021)
Feed Intake and Palatability	Neutral to slightly positive effects on intake	Improved feed quality	Sheep and dairy cows	Tian et al. (2021)
Growth Performance	Increased ADG and feed efficiency	Better nutrient utilization and health status	Lambs and growing cattle	Tian et al. (2019)
Heat Stress Mitigation	Reduced oxidative stress during heat stress	Antioxidant and anti-inflammatory effects	Dairy cows and goats	Tian et al. (2021)
Gut Health and Microbiome	Improved beneficial microbial populations	Antimicrobial effects supporting beneficial microbes	Sheep and dairy cows	Makmur et al. (2022)
Blood Metabolites	Improved lipid profile and glucose regulation	Regulation of lipid metabolism and antioxidant pathways	Sheep, goats, dairy cows	Tsuda (2012); Tian et al. (2019)

Environmental Benefits

Anthocyanins contribute to environmentally sustainable ruminant production systems primarily through their potential to reduce enteric methane emissions, a greenhouse gas with approximately 28 times higher global warming potential than CO_2 over a 100-year horizon (Legg, 2021). By modifying rumen fermentation pathways and decreasing methanogenesis, anthocyanin supplementation helps lower the overall carbon footprint of livestock production systems (Vasta et al., 2019). In addition to direct methane mitigation, anthocyanin-rich feed resources enhance the utilization of agricultural by-products such as grape pomace, black cane, and berry residues, thereby promoting circular bioeconomy approaches in livestock feeding systems (Tayengwa & Mapiye, 2018). Furthermore, since enteric methane production represents a loss of 2–12% of gross dietary energy (Moss et al., 2000), reducing methane emissions also improves feed energy efficiency, indirectly enhancing productivity and reducing environmental pressure per unit of animal product.

Challenges and Limitations

Despite their promising potential, several limitations hinder the widespread application of anthocyanins in ruminant nutrition. One of the major constraints is the variability in anthocyanin composition and concentration, which depends on plant species, environmental conditions, maturity stage, and post-harvest processing methods (Tian & Lu, 2022). This variability makes standardization of dietary supplementation difficult. Another significant limitation is the low bioavailability of anthocyanins, as these compounds are often extensively metabolized or degraded in the digestive tract before reaching systemic circulation or exerting maximal ruminal effects (Fang, 2014). Additionally, inconsistencies in experimental outcomes have been reported across studies due to differences in animal species, diet composition, dosage levels, and anthocyanin sources. These inconsistencies make it challenging to develop universally applicable feeding recommendations. Finally, most existing studies are short-term and conducted under controlled experimental conditions, limiting the understanding of long-term productivity, adaptation, and sustainability outcomes under field conditions.

Research Gaps and Future Perspectives

Future research on anthocyanins in ruminant nutrition should focus on optimizing their application under practical feeding systems. Determining optimal dietary inclusion levels for different animal species and production stages remains a key priority. Advanced metagenomic and metabolomic approaches should be used to better characterize shifts in rumen microbial populations and functional pathways associated with anthocyanin supplementation (Vasta et al., 2019). Long-term in vivo studies under commercial farming conditions are also required to evaluate sustained effects on productivity, methane emissions, and animal health. Furthermore, exploring synergistic interactions between anthocyanins and other plant secondary metabolites such as tannins, essential oils, and saponins may provide enhanced methane mitigation strategies. From a sustainability perspective, life cycle assessment (LCA) approaches should be integrated into future studies to quantify the full environmental benefits of anthocyanin-based feeding strategies. In addition, improving extraction, preservation, and feed formulation technologies will be essential for increasing the stability and cost-effectiveness of anthocyanin-rich feed additives.

Conclusion

Anthocyanins represent a promising class of natural plant secondary metabolites with significant potential to mitigate enteric methane emissions in ruminant livestock systems. Through modulation of rumen microbial populations, enhancement of propionate synthesis, suppression of methanogenic archaea, and improvement of fermentation efficiency, anthocyanins contribute to both reduced greenhouse gas emissions and improved nutrient utilization. Their incorporation into ruminant diets through anthocyanin-rich feed resources such as purple corn, grape pomace, and black cane offers a sustainable strategy for improving livestock productivity while reducing environmental impact. However, challenges such as variability in compound composition, limited bioavailability, and insufficient long-term field validation must be addressed before large-scale implementation. Overall, anthocyanins hold strong promise as part of integrated climate-smart livestock production strategies aimed at improving efficiency and reducing the environmental footprint of ruminant agriculture.

Author Contribution Statement

Abdulhamid Muhammad GARBA: Data collection, and writing the original draft
Sema YAMAN FIRINCIOĞLU: review and editing

Conflict of Interest

The authors declare no conflict of interest.

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