



Influence of dietary polyphenols on greenhouse gas emissions, ruminant production and welfare: a review

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Abstract

*Intensification of global climate change and rising consumer demand for animal products necessitate the development of sustainable strategies to reduce livestock greenhouse gas (GHG) emissions while enhancing food security. This review assesses the impact of dietary polyphenols, specifically sugarcane-derived extracts such as Polygain™, on methane emissions, rumen fermentation, and animal performance in ruminants. It was observed that dietary supplementation of ruminants with 0.25–1% Polygain™ reduced methane emissions from enteric fermentation by 33–49% in lambs and 30–35% in dairy cows, while improving growth rates and milk yield. However, milk fat content tended to decrease. In contrast, the effects of polyphenols on methane emissions in beef heifers were not significant, highlighting the context-dependent factors of intake rates and other dietary constituents before and after supplementation. Polyphenols modulated the rumen microbiota, reducing the abundance of methanogens (e.g., *Methanobrevibacter*) and shifting the volatile fatty acid profile toward propionate production. Productive outcomes were species-dependent: dairy cows exhibited improved milk yield (7.4%) but lower milk fat content (6.7%), while lambs showed enhanced growth rates and feed conversion ratios. Antioxidant and anti-inflammatory effects were observed, including a reduction in somatic cell counts in dairy herds. However, responses depended on dosage, basal diet, and adaptation duration, with excessive intake potentially impairing nutrient absorption. Despite promising results, key gaps remain, including long-term safety, cost-effectiveness, and practical integration into farming systems, which require further investigation. Future research should refine dosing strategies, assess the economic viability, and explore interactions with alternative feed sources. Sugarcane polyphenols represent a multifunctional solution for sustainable livestock production; however, the broader environmental impact of polyphenol production and consumption, as well as the economic viability and practicality of implementing this solution within production systems, deserves further consideration.*

Keywords: Anti-methanogenic, Feed additive, Methane, Performance, Antioxidant, Greenhouse gases, Ruminant.

Introduction

To avert increasingly frequent extreme climatic events associated with global warming, urgent actions are needed to put deep and continuing reductions in greenhouse gas (GHG) emissions (Harrison, 2021; Harrison and Liu, 2024). Methane (CH₄), a potent GHG primarily generated by ruminant animals, is a key contributor to global warming (Taylor *et al.*, 2016; Gadzama, 2025). As such, identifying

effective and sustainable strategies to reduce emissions from ruminant livestock is crucial (Taylor *et al.*, 2016; Ahmadi *et al.*, 2023; Gadzama, 2024). Methane mitigation in ruminants can be achieved in many ways. Some of these include improving animal health and selling animals sooner (to avoid methane emissions), genetic improvements to reduce methane yield, adoption of anti-methanogenic pastures, improving diet quality (reducing fibre content),

concurrently reducing mortality and stocking rates, and combinations thereof (Taylor *et al.*, 2016; Meier *et al.*, 2020; Gadzama *et al.*, 2023; Bilotto *et al.*, 2023; Gadzama *et al.*, 2025).

A much-lauded route for inhibition of methanogens is via feed supplementation (Bilotto *et al.*, 2023; Bilotto *et al.*, 2024; Gadzama *et al.*, 2024). While ruminants have been valuable for testing methane inhibition strategies, many abatement options remain cost-prohibitive for farmers (Harrison *et al.*, 2021; Gadzama, 2025). Further research is thus necessary to support the adoption of these strategies, particularly the investigation of impacts on enteric methane and feed efficiency (Rawnsley *et al.*, 2018; Garnett and Eckard, 2024). Major challenges in mitigating CH₄ emissions from the livestock sector include the complexity and diversity of livestock production systems, increasing costs and demand for livestock products, and limited availability and adoption of emission reduction strategies (Harrison *et al.*, 2021; Harrison and Liu, 2024). Investigation of wider influencing factors, such as environmental co-impacts, economic viability, fit within the existing production system, peer-to-peer learning, and social licence to operate are also critical determinants of whether or not a particular intervention is sustainably adopted for the long-term (Phelan *et al.*, 2018; Shahpari *et al.*, 2021; Fleming *et al.*, 2022).

Plant-based supplements, especially herbal extracts, have shown promise as natural solutions for reducing enteric CH₄ emissions due to their chemical properties and ability to alter the microbiota to produce less CH₄, potentially by serving as an alternative hydrogen sink (McGivern *et al.*, 2024). Such supplements enhance nitrogen metabolism and could potentially replace antibiotics (Ahmed *et al.*, 2023), depending on dietary composition. A major class of

plant-derived chemicals implicated in methane reduction is polyphenols; secondary metabolites characterized by the presence of at least one hydroxyl group attached to an aromatic ring. Polyphenols play crucial roles in plant defence mechanisms against biotic and abiotic stressors, such as UV radiation, microbial infection, and herbivory (Huang *et al.*, 2025). Their structural diversity, ranging from simple phenolic acids to complex polymeric tannins, underpins their broad spectrum of biological activities, including antioxidant, anti-inflammatory and antimicrobial properties (Singh *et al.*, 2018; Rana *et al.*, 2022).

Sugarcane (*Saccharum officinarum*) is particularly rich in polyphenolic compounds, including phenolic acids, glycosides, flavonoids, fatty acids, policosanols, and steroids, making it a superior source of polyphenols in terms of feed additives (Singh *et al.*, 2015; Karunaratne *et al.*, 2025). Sugarcane is widely produced in many key livestock production countries, such as Australia, Brazil, India, Thailand, and China, and its by-products (e.g., bagasse, molasses, and polyphenols) are abundant, low-cost, and underutilized in feed systems. The combination of sugarcane's high polyphenol content, regional availability, and economic viability underscores its strategic relevance for sustainable livestock production compared to alternatives requiring specialized cultivation or long-distance sourcing. For example, Polygain™, a natural sugarcane extract containing simple polyphenols such as derivatives of gallic acid to more complex dimeric, oligomeric, or polymeric structures, has demonstrated positive effects on various animal species, such as improved liveweight gain, meat quality, and physiological parameters in heat-stressed broiler chickens (Zheng *et al.*, 2017; Shakeri *et al.*, 2020). Furthermore, Polygain™ has been linked to methane

reduction in ruminants (Prathap *et al.*, 2023; Ahmed *et al.*, 2023; Prathap *et al.*, 2024) and increased milk production in dairy cows (Ahmed *et al.*, 2023). Efficacy of Polygain™ as a feed supplement in mitigating methane (CH₄) from enteric fermentation has been demonstrated through various mechanisms, including direct effects on methanogenic archaea, disruption of protozoa membranes, and shifting rumen fermentation towards propionate production (Prathap *et al.*, 2024). Additionally, plant bioactives can increase the amount of protein and starch that resists rumen fermentation while maintaining whole-tract digestibility (Ahmadi *et al.*, 2023).

The purpose of this review was to comprehensively evaluate GHG mitigation, animal performance and health implications of sugarcane-derived polyphenols as sustainable feed additives in ruminant diets. We elucidate their efficacy in reducing enteric methane emissions, enhancing growth performance, and improving health outcomes in ruminants. We cover dose-dependent effects, dietary interactions and species-specific responses to identify optimal applications. Mechanistic insights into microbiota modulation, antioxidant activity, and metabolic regulation are critically examined to highlight advancements, inconsistencies, and research gaps. The review aims to guide future investment in eco-friendly animal nutrition, ensuring that purported innovations strike a balance between environmental stewardship, economic viability, farming system practicability, and social justice. While we focus on all sugarcane-derived polyphenols, we centre on PolyGain™, as this product tends to be more widely covered in the literature.

Materials and Methods

Literature Search

A comprehensive literature search was conducted using Google Scholar,

ScienceDirect, Scopus, PubMed, and Web of Science databases. The search aimed to identify studies evaluating the use of sugarcane-derived polyphenols as feed additives in animal diets. Only original research articles were considered to ensure scientific rigour, data accuracy, and peer-reviewed evidence for evaluating the efficacy of sugarcane-derived polyphenols in animal diets. Primary studies provide original experimental data on outcomes such as methane reduction, growth performance, and physiological effects, which are critical for validating claims about sugarcane-derived polyphenols. This approach also enabled a detailed scrutiny of study designs, including dosages, basal diets, and animal models, which are crucial for assessing reproducibility and relevance to real-world farming scenarios. Peer-reviewed conference papers were occasionally referenced for emerging insights; however, peer-reviewed original research articles formed the core of the synthesis to uphold scientific credibility and legitimacy.

Search Criteria

The search strategy employed the following keywords and phrases: “Polygain,” “Polygain in animal feeds,” “sugarcane-derived polyphenol as feed,” “sugarcane extract as feed supplement,” “sugarcane polyphenol as feed,” and “sugarcane polyphenol extract”. These terms were combined using Boolean operators (AND/OR) to maximize relevant results. Additional filters included studies on ruminants, poultry, aquaculture, swine, and rabbits to align with the scope. Reference lists of retrieved articles were manually screened to identify further relevant publications, which were then sourced from the aforementioned databases. No restrictions were applied to publication years to capture all available evidence, including foundational studies on polyphenol applications in animal nutrition. Preference was given to peer-reviewed journal articles

published in English, though conference proceedings were also included if they provided novel data. Non-academic sources, such as commercial websites or unverified reports, were excluded to maintain scientific rigour. Studies focusing on non-polyphenolic sugarcane components (e.g., fibre, sugars) or non-feed applications were omitted. This approach ensured a focused and high-quality synthesis of the role of sugarcane polyphenols in animal diets.

Nutrient Composition of Sugarcane and Its Derivatives

Sugarcane exhibits distinct nutrient profiles across its fresh juice, refined sugar, and non-centrifugal sugar (NCS) products (Table 1; Hewawansa *et al.*, 2024). Fresh sugarcane juice comprises approximately 82% water

and 17% carbohydrates, predominantly sugars, with minor contributions from proteins, lipids, and ash/minerals (each <1%) (Nur Sudraj *et al.*, 2020). In contrast, refined sugar is almost entirely sucrose (>99.9%), devoid of proteins, lipids, and micronutrients due to intensive processing (Payet *et al.*, 2006). NCS retains a more complex composition, including sucrose, glucose, and fructose (3.7%–10.5%), along with trace proteins (0.4%–1.7%), minimal lipids (<0.1%), and residual moisture (1.5–15.8 g) (Ebadi and Azlan, 2021). Micronutrient analyses reveal that NCS and molasses are rich in B vitamins (thiamine, riboflavin) and ascorbic acid, with food-grade molasses exhibiting the highest concentrations (Sangster and Righelato, 1989).

Table 1. Macronutrient Composition of Sugarcane*

Component	Fresh Sugarcane Juice	Refined Sugar	Non-Centrifugal Sugar (NCS)
Water	~82%	Negligible	1.5–15.8 g
Carbohydrates	~17% (mostly sugars)	>99.9% (sucrose)	Mixture of sucrose, glucose, fructose (3.7%–10.5%)
Proteins	<1%	Absent	0.4%–1.7%
Lipids (Fats)	<1%	Absent	<0.1%
Ash/Minerals	<1%	Absent	Present (varies)

*Adapted from Hewawansa *et al.* (2024)

Mineral content varies significantly: molasses contains elevated levels of potassium (K) and manganese (Mn), while juice provides sodium (Na), calcium (Ca), and iron (Fe) (de Souza *et al.*, 2015; Takahashi *et al.*, 2016). Additionally, sugarcane juice contains bioactive compounds such as amino acids (valine, alanine), organic acids (lactic, malic), and fatty acids (oleic, linoleic), although quantitative data remain limited (Ali *et al.*, 2019). These compositional differences accentuate the impact of processing on nutrient retention, with minimally processed products, such as NCS, preserving more micronutrients and phytochemicals

compared to refined sugar (Hewawansa *et al.*, 2024). The presence of these compounds, particularly in molasses and NCS, suggests potential health benefits and industrial applications, warranting further exploration of their bioavailability and functional properties (Hewawansa *et al.*, 2024).

Concentration of Phenolic Compounds in Sugarcane Juice

The study by Maurício Duarte-Almeida *et al.* (2006) identified and quantified key phenolic compounds derived from sugarcane extract, which contained flavonoids (apigenin, luteolin, triclin

derivatives) and phenolic acids (caffeic, sinapic, chlorogenic acids), highlighting their potential antioxidant properties and health benefits (Table 2). The study confirmed that sugarcane juice contains significant amounts of phenolic compounds, including hydroxycinnamic acids ($85.8 \pm 1.3 \text{ mmol}\cdot\text{L}^{-1}$), triclin derivatives ($35.7 \pm 1.1 \text{ mmol}\cdot\text{L}^{-1}$), apigenin derivatives ($27.8 \pm 0.8 \text{ mmol}\cdot\text{L}^{-1}$), sinapic acid ($25.4 \pm 0.2 \text{ mmol}\cdot\text{L}^{-1}$), luteolin derivatives ($9.2 \pm 0.8 \text{ mmol}\cdot\text{L}^{-1}$), and caffeic acid ($4.1 \pm 0.1 \text{ mmol}\cdot\text{L}^{-1}$). The total polyphenolic content was estimated to be 160 mg/L, indicating that sugarcane juice is a notable dietary source of antioxidants.

Assays with 2,2-Diphenyl-1-picrylhydrazyl (DPPH) scavenging and β -carotene bleaching confirmed that sugarcane phenolics act as effective antioxidants, which could be potentially valuable for food and therapeutic applications. These results

highlight sugarcane juice as a natural source of bioactive antioxidants, supporting its potential health benefits beyond its traditional use as a sweetener (Duarte-Almeida *et al.*, 2006).

Furthermore, Maurício Duarte-Almeida *et al.* (2006) reported that sugarcane juice has a higher polyphenolic content (160 mg/L) than commercial soy-based beverages (18–83 mg/L), making it a cost-effective alternative for dietary antioxidants. The flavonoids (apigenin, luteolin, triclin) and phenolic acids (caffeic, sinapic, hydroxycinnamic acids) in sugarcane juice may contribute to reducing oxidative stress, which is linked to chronic diseases like cancer and neurodegeneration. Additionally, these compounds have potential therapeutic applications in combating heavy metal toxicity and neurodegenerative conditions (Duarte-Almeida *et al.*, 2006).

Table 2. Concentration of phenolic compounds ($\text{mmol}\cdot\text{L}^{-1}$) in sugarcane juice*

Compound	Concentration ($\text{mmol}\cdot\text{L}^{-1}$)
Hydroxycinnamic acids	85.8 ± 1.3
Tricin	35.7 ± 1.1
Apigenin	27.8 ± 0.8
Sinapic acid	25.4 ± 0.2
Luteolin	9.2 ± 0.8
Caffeic acid	4.1 ± 0.1

* Values were reported as mean \pm standard deviation ($n = 3$). Adapted from Maurício Duarte-Almeida *et al.* (2006).

Nutrient and Phenolic Content in Sugarcane Extract (SCE)

Nutritional and phenolic composition of sugarcane extract (SCE) presented in Table 3 reveals a complex profile that may contribute to its beneficial effects in animal nutrition. SCE contains a substantial amount of crude protein (14%) and nitrogen-free extracts (60%), suggesting its potential as an energy and protein source in animal feed (Xia *et al.*, 2017; Wang *et al.*, 2023). Additionally, the high phenolic content (89.39 mg/g total phenols and 20.95 mg/g

flavones) highlights its antioxidant properties, which may play a role in mitigating oxidative stress in animals (Xia *et al.*, 2017; Prakash *et al.*, 2021; Wang *et al.*, 2023). The presence of bioactive compounds such as triclin, chlorogenic acid, gallic acid, and apigenin further supports SCE's potential as a phytogetic feed additive (PFA). These compounds have been linked to anti-inflammatory and immunomodulatory effects (Koorakula *et al.*, 2022).

Table 3. Nutrient and phenolic content of sugarcane extract (SCE)*

Component	Content (%)
Moisture	6
Crude protein	14
Crude fat	3
Crude fiber	1
Ash	17
Nitrogen-free extracts	60
Phenolic Compounds	Content (mg/g)
Total phenol	89.390
Flavone	20.950
Chlorogenic acid	0.1070
Gallic acid	0.0812
Tricin	0.0731
Apigenin	0.0568
Sinapic acid	0.0116

*SCE was produced by Shin Mitsui Sugar Co., Ltd. in Tokyo. Adapted from Xia *et al.* (2017) and Wang *et al.* (2023)

Polyphenolic Composition of Sugarcane and Derivative Products

Sugarcane and derivatives thereof contain a diverse range of polyphenols, with their composition varying significantly across different plant parts and processing stages. The rind (Figure 1) is particularly rich in polyphenols such as gallic acid, p-coumaric acid, ferulic acid, catechin, resveratrol, and quercetin, with concentrations ranging widely from 0.004 to 125 mg/g dry weight (DW) (Table 4) (Feng *et al.*, 2015; Fang *et al.*, 2017; Zhao *et al.*, 2018; Kerdchan *et al.*, 2020). In contrast, sugarcane leaves contain chlorogenic acids, orientin, vitexin, and tricetin derivatives at lower concentrations (0.0001–43.1 mg/g DW) (Lee *et al.*, 2012; Abbas *et al.*, 2014; Castro-Moretti *et al.*, 2021). The culm and node (Figure 1) exhibit moderate polyphenol levels, with apigenin, luteolin, and catechin being the most prominent (Table 4; McGhie, 1993; Duarte-

Almeida *et al.*, 2011; Kerdchan *et al.*, 2020). Processed sugarcane products also retain varying polyphenol levels; for instance, sugarcane juice contains apigenin and luteolin derivatives (0.0001–14,084 mg/L), while non-centrifugal sugars like jaggery and panela are rich in gallic acid and chlorogenic acid (0.0001–2101 mg/g DW) (Takara *et al.*, 2002, 2003; Shang *et al.*, 2022). Molasses and bagasse (Figure 1), often considered waste products, contain appreciable amounts of ferulic acid, caffeic acid, and tricetin derivatives, suggesting their potential valorization for bioactive compound extraction (Payet *et al.*, 2006; Zheng *et al.*, 2017). The wide concentration ranges reported across studies (Table 4), highlight the influence of extraction methods, sugarcane varieties, and processing techniques on polyphenol yield (Hewawansa *et al.*, 2024).

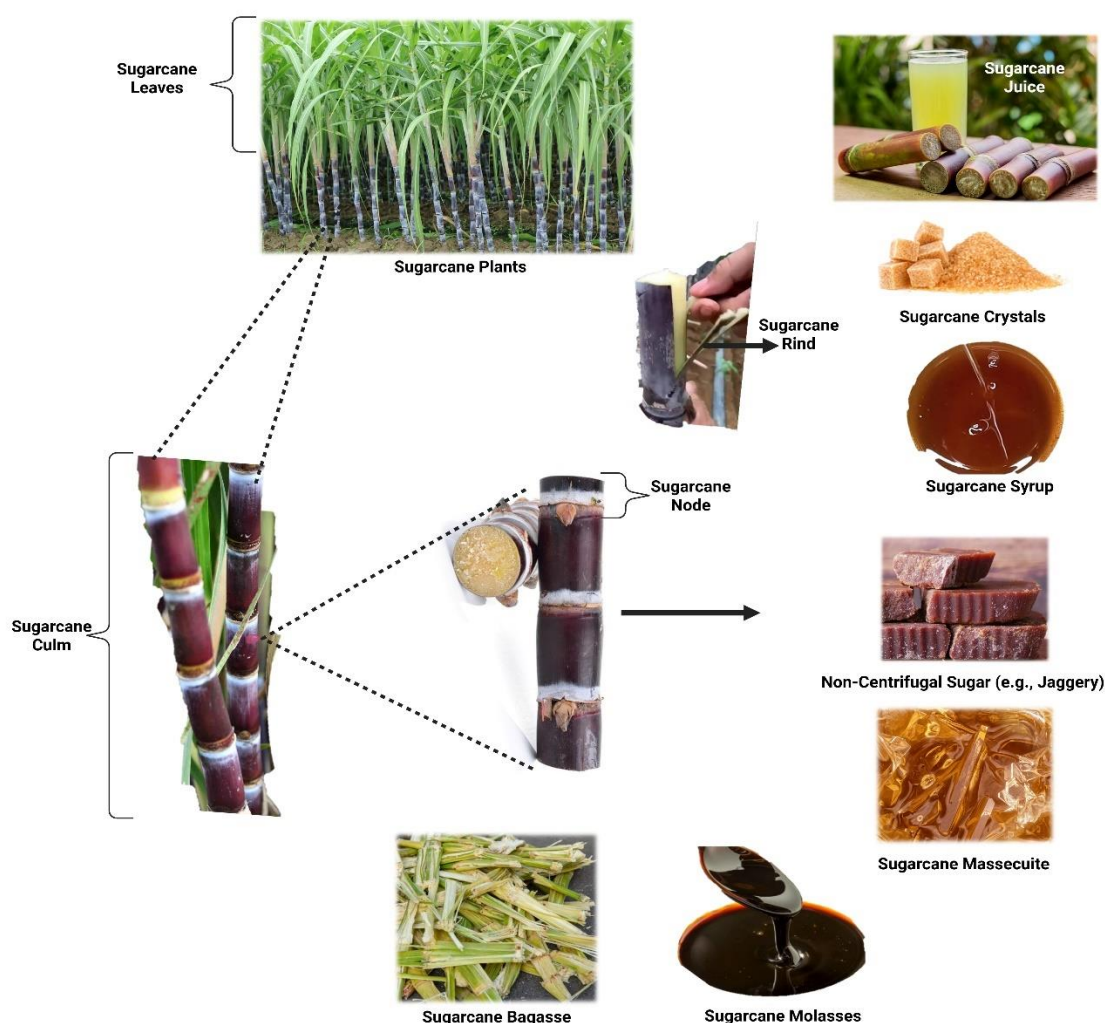


Figure 1. Key Products Derived from Sugarcane

Factors Influencing the Polyphenolic Composition of Sugarcane

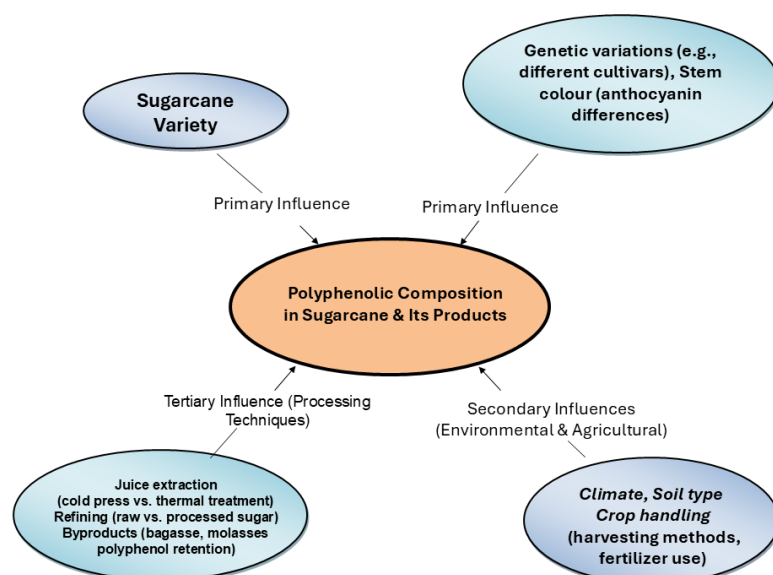
The polyphenolic composition of sugarcane and its products is highly variable, influenced by factors such as variety, climate, soil type, crop handling methods, and processing techniques (Azlan *et al.*, 2023). Among these, sugarcane variety plays the most significant role in determining polyphenol content, even under identical cultivation conditions. For example, the colour of the outer stem, dictated by

anthocyanin composition, varies across varieties, reflecting differences in phenolic profiles (Manohar *et al.*, 2014). Environmental factors, including rainfall and temperature, further modulate polyphenol levels, as demonstrated by variations observed in the same cultivar grown in different locations (Rodrigues *et al.*, 2021). These intrinsic and extrinsic factors contribute to the wide range of concentrations reported across studies (Figure 2).

Table 4. Polyphenols in Sugarcane and Its Products (mg/g DW) unless otherwise stated

Plant Part / Product	Polyphenols Identified	Concentration	Reference
Rind	Gallic acid, p-Coumaric acid, Ferulic acid, Catechin, Resveratrol, Quercetin	0.004–125	Feng <i>et al.</i> (2015), Fang <i>et al.</i> (2017), Zhao <i>et al.</i> (2018), Kerdchan <i>et al.</i> (2020)
Leaves	Chlorogenic acids, Orientin, Iso-orientin, Vitexin, Tricin derivatives, Caffeic acid	0.0001–43.1	Lee <i>et al.</i> (2012), Abbas <i>et al.</i> (2014), Castro-Moretti <i>et al.</i> (2021)
Culm	Apigenin, Luteolin, Tricin, Caffeic acid, Chlorogenic acid	0.0014–0.132	McGhie (1993), Duarte-Almeida <i>et al.</i> (2011)
Node	Catechin, Quercetin, Resveratrol, Ferulic acid	0.140–21.4	Kerdchan <i>et al.</i> (2020)
Sugarcane Juice	Apigenin derivatives, Luteolin derivatives, Tricin, p-Coumaric acid, Ferulic acid	0.0001–14084*	Payet <i>et al.</i> (2006), Ali <i>et al.</i> (2019), Rodrigues <i>et al.</i> (2021),
Sugarcane Syrup	p-Coumaric acid, Ferulic acid, Caffeic acid, Chlorogenic acid	0.0105–0.141	Payet <i>et al.</i> (2006), Duarte-Almeida <i>et al.</i> (2011)
Massecuite	p-Coumaric acid, Ferulic acid, Caffeic acid, p-Hydroxybenzoic acid	0.0021–0.144	Payet <i>et al.</i> (2006)
Sugar Crystals	Syringic acid, Vanillic acid, Vanillin, p-Coumaric acid, Ferulic acid	0.0000–0.0199	Payet <i>et al.</i> (2005), Azlan <i>et al.</i> (2020)
Non-Centrifugal Sugar	Gallic acid, Syringic acid, Vanillic acid, Chlorogenic acid, p-Coumaric acid	0.0001–2101*	Takara <i>et al.</i> (2002, 2003), Shang <i>et al.</i> (2022)
Bagasse	p-Coumaric acid, Ferulic acid, Gallic acid, Protocatechuic acid, Tricin derivatives	0.0081–12.6	Zheng <i>et al.</i> (2017), Juttuporn <i>et al.</i> (2018)
Molasses	Apigenin, Gentisic acid, Luteolin, Caffeic acid, Ferulic acid, Chlorogenic acid	0.0000–11.6	Payet <i>et al.</i> (2006), Ali <i>et al.</i> (2019)

*(mg/L: milligrams per litre); DW: Dry Weight (measured per gram of dried sample); Non-Centrifugal Sugar (unrefined sugar like jaggery, panela, kokuto); Massecuite (a thick blend of mill syrup and molasses); Adapted from Hewawansa *et al.* (2024)

**Figure 2. Factors influencing the variability in polyphenolic composition of sugarcane and its products**

Chemical structures of the most abundant polyphenols in sugarcane are illustrated in Figure 3, highlighting the predominance of flavonoids (e.g., apigenin, luteolin, and triclin derivatives) and phenolic acids (e.g.,

chlorogenic, ferulic, caffeic, and gallic acids) across the plant and its processed products (Hewawansa *et al.*, 2024). These compounds are consistently identified throughout sugarcane processing, from raw

juice to byproducts such as molasses and bagasse, with C-glycosylated flavonoids exhibiting notable stability due to their resistance to enzymatic hydrolysis (Hewawansa *et al.*, 2024). Comparative analyses reveal that processing stages influence polyphenol profiles; for instance, alkaline hydrolysis releases bound phenolic acids, such as ferulic and p-coumaric acids, which are abundant in molasses but minimal in refined sugar (Payet *et al.*, 2006). However, quantitative discrepancies arise

due to methodological variations, such as extraction techniques (e.g., resin-based methods yield higher recoveries) and analytical approaches (LC/MS/NMR vs. HPLC/DAD). Sugarcane byproducts, particularly molasses and bagasse, represent underutilized sources of bioactive polyphenols for nutraceutical and industrial applications (e.g., anti-inflammatory, antidiabetic, or food preservatives); and standardization of methodologies is critical to assess polyphenol bioavailability and health potential accurately.

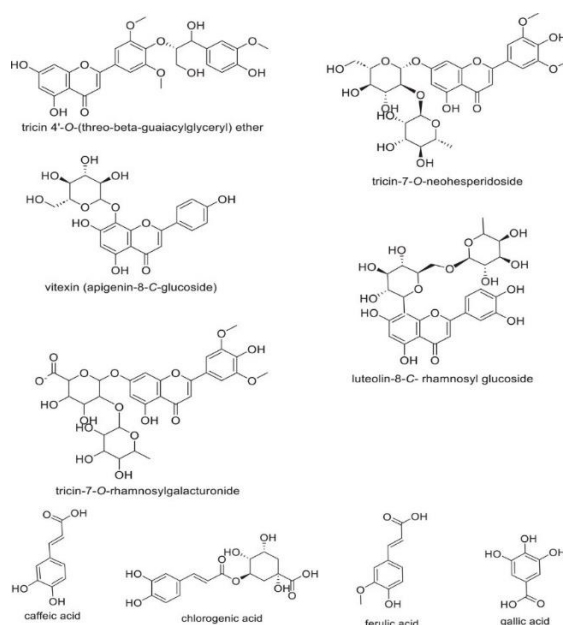


Figure 3. Chemical structures of the most abundant polyphenols in sugarcane (adapted from Hewawansa *et al.*, 2024).

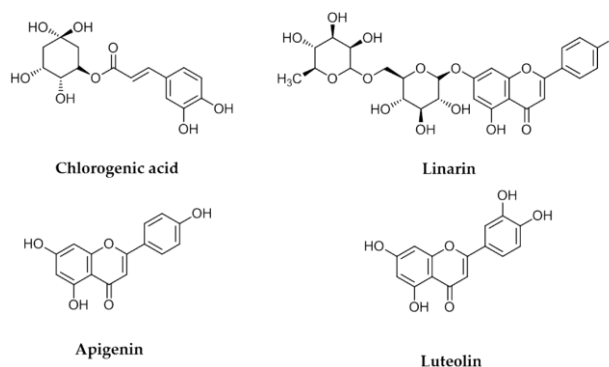


Figure 4. Chemical structures of chlorogenic acid, linarin, apigenin, and luteolin (adapted from Hwang *et al.*, 2016).

The study by Hwang *et al.* (2016) quantified four bioactive flavonoids, chlorogenic acid, linarin, apigenin, and luteolin, in different parts of Compositae in sugarcane species. This finding supports further research into structure-activity relationships of these flavonoids, given their known anti-inflammatory and anticancer properties (Figure 4).



Polyphenols for Livestock Feed

The increasing global demand for livestock products has led to intensified farming practices, often resulting in health challenges for animals and reduced product quality (Formato *et al.*, 2022). Historically, antibiotic growth promoters (AGPs) were widely used to enhance productivity; however, their overuse contributed to the development of antibiotic-resistant bacteria, prompting regulatory bans in the European Union since 2006 (Castanon, 2007). Consequently, alternative feed additives, such as enzymes, probiotics, prebiotics, and plant-derived bioactive compounds, have gained attention (Cheng *et al.*, 2014). Among these, polyphenols, a diverse group of plant secondary metabolites, have emerged as promising candidates due to their antioxidant, anti-inflammatory, and antimicrobial properties (Vasta *et al.*, 2019).

Plant Polyphenols: Health Benefits and Applications in Animal Nutrition

Plant polyphenols are a diverse group of bioactive compounds found abundantly in tea, fruits, vegetables, and other plant-based foods such as sugarcane (Figure 5). Polyphenols are classified into flavonoids, tannins (condensed and hydrolysable), phenolic acids, and lignans, which are derived from biosynthetic pathways such as the shikimate and acetate pathways (Dewick, 2009). These compounds are known for their potent antioxidant, anti-inflammatory, and antimicrobial properties (Wang *et al.*, 2024). Polyphenols play a crucial role in mitigating oxidative stress, a key factor in chronic diseases and ageing, by scavenging free radicals and enhancing endogenous antioxidant defences (Yan *et al.*, 2020). Their ability to modulate cellular signalling pathways also makes them promising candidates for therapeutic applications, particularly in metabolic and neurodegenerative disorders (Hong *et al.*, 2022).

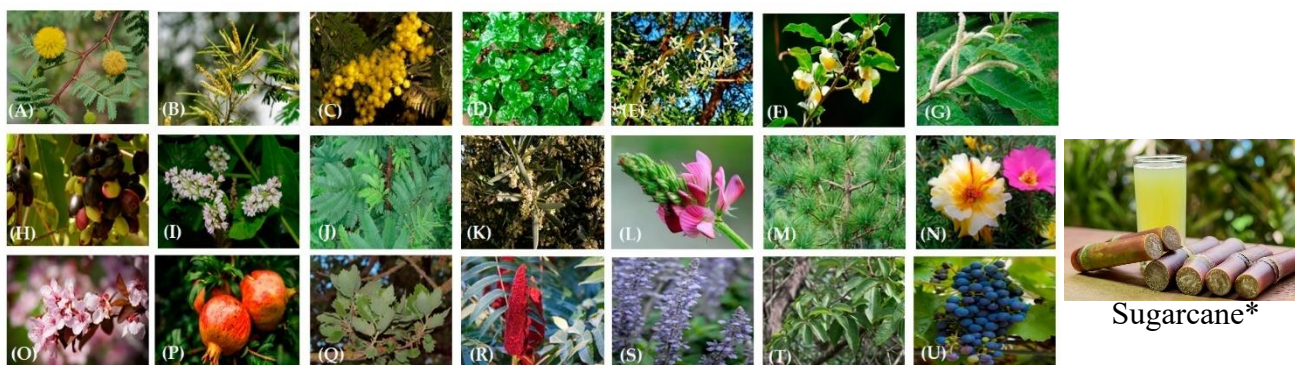


Figure 5. Common plant sources of polyphenolic extracts of interest for their impact on rumen fermentation. These plants include *Acacia arabica* (A), *Acacia catechu* (B), *Acacia dealbata* (C), *Alternanthera sissoo* (D), *Azadirachta indica* (E), *Camellia sinensis* (F), *Castanea mollissima* (G), *Eugenia jambolana* (H), *Fagopyrum esculentum* (I), *Mimosa tenuiflora* (J), *Olea europaea* (K), *Onobrychis viciifolia* (L), *Pinus radiata* (M), *Portulaca oleracea* (N), *Prunus cerasifera* (O), *Punica granatum* (P), *Quercus ithaburensis* subsp. *macrolepis* (Q), *Rhus typhina* (R), *Salvia officinalis* (S), *Schinopsis balansae* (T), and *Vitis vinifera* (U). Adapted from Formato *et al.* (2022).

*Source: <https://pixabay.com/photos/sugarcane-sugarcane-juice-natural-5388628/>

Rumen Gas Composition

The rumen is a complex anaerobic ecosystem where microbial fermentation breaks down plant material, producing gases as metabolic byproducts. The table 5 below presents the typical composition of rumen gases in cattle, with carbon dioxide (CO₂) being the most abundant (45–75%),

followed by methane (CH₄) at 20–30%, nitrogen (N₂) at 7.0%, and trace amounts of oxygen (O₂), hydrogen (H₂), nitrous oxide (N₂O), and hydrogen sulfide (H₂S). These gases are byproducts of microbial fermentation in the rumen, a crucial process in ruminant digestion (Min *et al.*, 2022).

Table 5. Typical Composition of Rumen Gases*

Gas	Average Percentage (%)	Notes
Carbon dioxide (CO ₂)	45–75	Primary fermentation byproduct
Methane (CH ₄)	20–30	Major greenhouse gas from ruminants
Nitrogen (N ₂)	7.0	Inert gas, mostly from swallowed air
Oxygen (O ₂)	0.5	Low due to anaerobic conditions
Hydrogen (H ₂)	0.2	Intermediate in microbial fermentation
Nitrous oxide (N ₂ O)	Trace (minor)	Minor, but potent GHG
Hydrogen sulfide (H ₂ S)	Trace (minor)	Toxic at high levels

*Gases are ranked from most to least abundant. Adapted from Min *et al.* (2022)

The high concentration of CO₂ (45–75%) reflects its role as a primary end product of carbohydrate fermentation. Methane, a potent greenhouse gas, is produced by methanogenic archaea that utilize H₂ and CO₂ in a process called methanogenesis. The presence of nitrogen (N₂, 7.0%) is largely due to swallowed air, while the low oxygen (O₂, 0.5%) levels result from the anaerobic conditions required for microbial fermentation (Min *et al.*, 2022). Hydrogen (H₂, 0.2%) is an intermediate in microbial fermentation and serves as a key substrate for methane production. Trace amounts of N₂O and H₂S are also present, though their concentrations are minor. N₂O is a byproduct of microbial nitrogen metabolism, while H₂S arises from sulfate-reducing bacteria (Min *et al.*, 2022). The composition of rumen gases reflects the dynamic interplay between microbial activity, diet, and host physiology. Understanding these relationships allows for targeted strategies to mitigate methane emissions without compromising animal productivity.

Rumen Microbial Fermentation and Methane Emissions

The rumen microbial fermentation process, also referred to as enteric fermentation, produces various gases, including carbon dioxide (CO₂) and methane (CH₄) as byproducts, which are exhaled or eructated by ruminants (Min *et al.*, 2022). The eructation of gases via belching is important for bloat prevention and serves as the primary route for CH₄ emission to the atmosphere (Clarke and Reid, 1974). Estimates of gas production rates in cattle range from less than 0.2 L/min in fasted animals to 2.0 L/min after feeding (Johnson and Johnson, 1995). Generally, lower feed quality and higher feed intake lead to increased CH₄ emissions (Knapp *et al.*, 2014). While feed intake is positively correlated with animal size, growth rate, activity level, and production factors like milk yield or pregnancy (USEPA, 2021), it also varies among animal types and management practices such as feedlot versus grassland grazing.

From an energy perspective, enteric CH₄ emissions associated with rumen fermentation result in the loss of 6–12% of gross energy intake (GEI) or 8–14% of digestible energy intake (DEI) in ruminants (Johnson and Johnson, 1995). This energy could otherwise be utilized for animal growth or milk production. Reducing enteric CH₄ emissions from cattle would therefore benefit both the environment and improve the efficiency and economic profitability of meat and milk production (Min *et al.*, 2022).

Livestock production systems face increasing challenges from rising food demand and environmental concerns (Christie *et al.* 2014; Fleming *et al.* 2022). When animal productivity is improved through nutrition, feeding management, reproduction, or genetics, CH₄ production per unit of meat or milk is reduced (Beauchemin and McGinn, 2020). For instance, Beauchemin and McGinn (2020) estimated that a 20% reduction in CH₄ production could allow growing cattle to gain an additional 75 g/d of body weight and increase milk yield by 1 L/d in dairy cows. Although total CH₄ emissions in cattle fed total mixed rations (TMR) increase with higher concentrate feed levels (Aguerre *et al.*, 2011; Schils *et al.*, 2006), emissions per unit of milk produced or per kg of average daily gain (ADG) generally decrease (Arndt *et al.*, 2020). However, there is limited evidence concerning the effects of dry matter intake (DMI), feed efficiency, rumen fermentation profiles, and microbiome changes on enteric CH₄ emissions per unit of ADG or milk yield (CH₄ intensity) in dairy and beef cattle (Beauchemin *et al.*, 2008).

Plant Polyphenols and Their Effects on Rumen Function

Plant polyphenols, including their bioactive compounds, significantly influence rumen function (Vasta *et al.*, 2019). These compounds interact with rumen microbiota, altering key metabolic processes such as

fatty acid biohydrogenation (BH), fiber digestion, and methane production (Henderson *et al.*, 2016). They also lower methane emissions by 10–65% through direct inhibition of methanogens (e.g., *Methanobrevibacter* spp.) and by reducing protozoa, which host methane-producing microbes (Goel and Makkar, 2012). Flavonoids, such as quercetin, further curb methane by acting as hydrogen sinks (Becker *et al.*, 2014).

Effects of Plant Polyphenols on Rumen Microbiota, Fatty Acid Biohydrogenation, and Methane Production

Plant polyphenols (PP), including tannins and flavonoids, significantly influence rumen microbial communities, altering key metabolic processes such as fatty acid biohydrogenation (BH), fiber digestion, and methane production. These compounds, naturally present in forage legumes, agro-industrial byproducts, and tannin-rich shrubs, interact with rumen microbiota, leading to shifts in microbial populations and fermentation patterns (Vasta *et al.*, 2019). Recent advances in molecular techniques, such as next-generation sequencing (NGS), have provided more profound insights into these interactions, revealing how PP modulate rumen function (Henderson *et al.*, 2016).

Effects on Fiber Digestion and Volatile Fatty Acid (VFA) Production

Polyphenols generally suppress fiber-digesting microbes, particularly gram-positive bacteria like *Fibrobacter succinogenes* and *Ruminococcus* spp., leading to reduced acetate production (Jayanegara *et al.*, 2015). This shift in fermentation patterns is attributed to differential microbial responses; gram-negative bacteria (e.g., *Prevotella*) are less affected by plant polyphenols than gram-positive species (Costa *et al.*, 2018). Protozoa, which contribute to fiber

degradation and methanogen activity, are also suppressed by PP, further altering rumen fermentation (Oskoueian *et al.*, 2013).

Relationship of Plant Polyphenols to Methane Emissions and Animal Performance

The review by Min *et al.* (2022) highlights strategies to mitigate enteric methane emissions by altering rumen fermentation. The researchers reported that methane production is closely linked to dry matter intake (DMI), feed efficiency, and rumen microbial activity. Unwell ruminants tend to exhibit higher methane emissions, although DMI may also be reduced (Chang-Fung Martel *et al.*, 2021). Dietary interventions, such as increasing concentrate feed or adding methane inhibitors (e.g., plant polyphenols), can reduce methane emissions while maintaining animal productivity (Ahmed *et al.*, 2023). For example, methane emissions per unit of milk production ($\text{CH}_4/\text{kg ECM}$) decrease with improved feed efficiency, demonstrating that optimizing rumen fermentation can enhance environmental sustainability and livestock performance (Min *et al.*, 2022). Additionally, shifts in volatile fatty acid (VFA) profiles, particularly a lower acetate-to-propionate (A/P) ratio, are associated with reduced methane production, as propionate formation consumes H_2 that would otherwise be used for methanogenesis (Min *et al.*, 2022).

Effects of Sugarcane-Derived Polyphenols on Ruminant Performance, Health, and Methane Emissions

The global demand for red meat and dairy is projected to rise by 76% and 63%, respectively, by 2050 (Alexandratos and Bruinsma, 2012; Harrison and Liu, 2024). However, ruminant agriculture significantly contributes to anthropogenic methane emissions through enteric fermentation and manure management (Saunois *et al.*, 2020).

Mitigating these emissions while maintaining productivity remains a challenge, prompting research into feed additives such as sugarcane-derived polyphenols (e.g., Polygain™). Recent studies demonstrate their potential to reduce methane emissions while improving animal performance, although efficacy varies across species, diets, and dosages (Prathap *et al.*, 2023; Bai *et al.*, 2025).

Sugarcane-derived polyphenols exhibit significant methane-suppressing potential, but their efficacy depends on dosage, duration, and basal diet composition (Table 6). In dairy cows, Bai *et al.* (2025) reported a 24% reduction in methane production (from 495 to 377 g/animal/day) and a 31% decrease in methane intensity (g $\text{CH}_4/\text{kg milk}$) with 0.25% Polygain™ supplementation over five weeks. Similarly, Ahmed *et al.* (2023) observed a 30–35% methane reduction in dairy cows fed 0.25% sugarcane extract for three weeks. These findings align with studies in lambs, where 0.25–1% Polygain™ reduced methane emissions by 33–49% (Prathap *et al.*, 2023, 2024). Lower doses (0.25%) often yielded greater reductions than higher doses (1%), possibly due to microbial adaptation or inhibitory thresholds (Prathap *et al.*, 2024).

Conversely, Williams *et al.* (2025) found no significant methane reduction in beef heifers fed 0.3–1.2% Polygain™ in a high-forage (78% corn silage) diet. This discrepancy suggests that starch-rich diets (e.g., grain-fed lambs and dairy cows) may enhance polyphenol-methanogen interactions compared to fiber-dominant beef diets. Additionally, dairy calves supplemented with 10 g/day Polygain™ exhibited a 24% reduction in methane production (Osei-Amponsah *et al.*, 2025), reinforcing the potential for early-life microbiome modulation.

While methane mitigation is critical, polyphenols must not compromise animal productivity. In dairy cows, Bai *et al.* (2025) and Ahmed *et al.* (2023) reported no adverse effects on milk yield or feed intake, though Ahmed *et al.* (2023) noted a 6.7% decline in milk fat, a trade-off requiring further investigation. In contrast, Polygain™ improved feed conversion ratio (FCR) and average daily gain (ADG) in lambs (Prathap *et al.*, 2023, 2024), suggesting productivity benefits in small ruminants. Health benefits were also evident, particularly in dairy systems (Table 6). Ahmed *et al.* (2023) observed a 47% reduction in somatic cell counts, indicating improved udder health, likely due to polyphenols' anti-inflammatory properties. However, beef heifer studies

lacked health assessments (Williams *et al.*, 2025), highlighting a research gap.

Rumen Fermentation and Microbial Shifts

Polyphenols likely suppress methanogens (e.g., *Methanobrevibacter*) and fiber-degrading bacteria (e.g., *Ruminococcaceae*), altering rumen fermentation (Figure 6). Dairy calves showed methane reductions without microbiome analysis (Osei-Amponsah *et al.*, 2025), whereas lamb studies confirmed microbial shifts (Prathap *et al.*, 2024). The lack of methane reduction in beef heifers (Williams *et al.*, 2025) suggests dietary fiber may buffer polyphenol effects, emphasizing the need for diet-specific formulations.

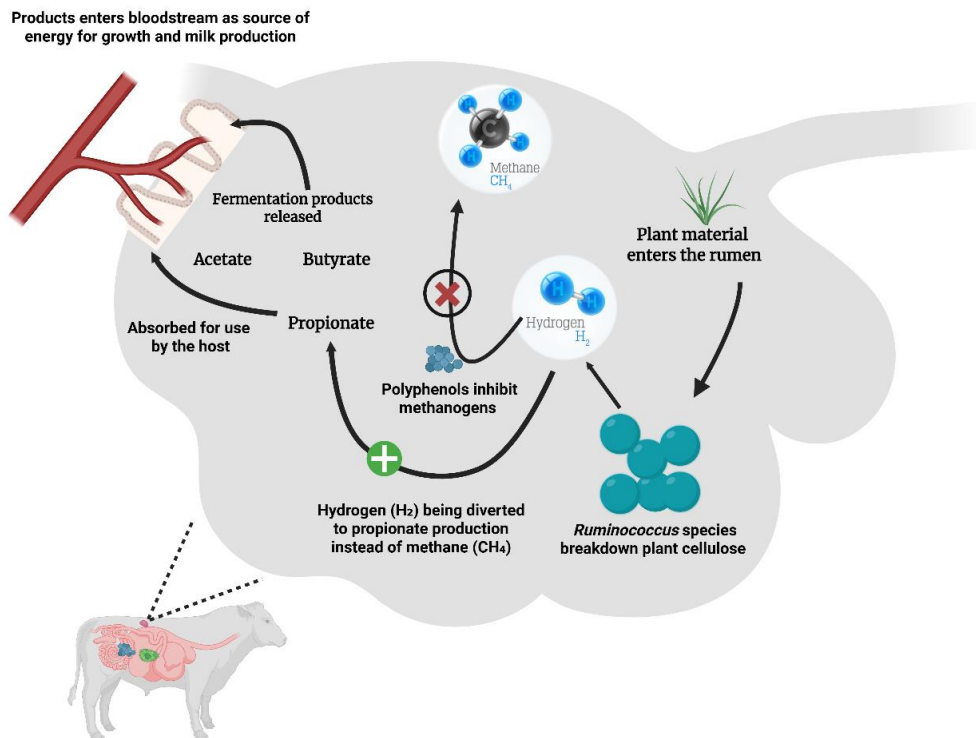


Figure 6. The impact of polyphenols on rumen microbes and their influence on enteric methane production.

Gadzama and Harrison 2025

Table 6. Impact of polyphenol supplements on ruminant performance, health and methane emissions

Species/Breed	Test Ingredient	Dosage (Duration)	Basal Diet	Performance	Health/Product Quality	Environmental Impact	Reference
Holstein Friesian dairy cows (2–5 years old, average body weight: 663 kg)	Polygain™ (polyphenol-rich sugarcane feed material)	0.25% of dry matter intake (DMI) for 5 weeks (3-week adaptation + 2-week measurement)	Concentrate pellets (16% crude protein) + rye-grass pasture forage	↔ feed intake (9.4 kg/day concentrate consumed in both groups) ↔ in body weight or milk production	Polyphenols inhibit methanogen activity and alter microbial populations	Control: 495 ± 12 g CH ₄ /animal/day Treatment: 377 ± 12 g CH ₄ /animal/day (24% reduction in methane production) Methane yield: Control: 24.84 g CH ₄ /kg DMI Treatment: 18.96 g CH ₄ /kg DMI Control: 17.04 g CH ₄ /kg milk/day Treatment: 13.01 g CH ₄ /kg milk/day (31% reduction in methane intensity)	Bai <i>et al.</i> (2025)
Holstein Friesian weaned calves	Polygain™ (sugarcane-derived polyphenolic extract)	10 g/calf/day (3-month study, including a 2-week adaptation period)	Annual rye-grass pasture + supplementary pellets (Barastoc calf-rearer cubes) fed at 200 g/calf/day	↔ in initial/final body weight or average daily gain (ADG) between control (1.09 kg/day) and treatment (0.97 kg/day) groups	No adverse effects on calf health or development.	Significant reduction in methane: 26.66 g/day (treatment) vs. 35.28 g/day (control) ~24% reduction in daily emissions.	Osei-Amponsah <i>et al.</i> (2025)
Poll Dorset Lambs	Polygain™ (Polyphenol)	0.25% and 1% (16 days)	25% cracked wheat grain, 25% cracked barley grain, 25% oaten chaff, 25% lucerne chaff	↑ DMI (1%) ↑ ADG Improved FCR (1%) Altered rumen microbiome	↓ Abundance of methane-producing archaea (<i>Methanobrevibacter</i> , <i>Methanosphaera</i>) ↓ <i>Ruminococcaceae</i> , <i>Lachnospiraceae</i> , <i>Christensenellaceae</i> in rumen microbiota	↓ Total CH ₄ production, yield, and intensity Greater reduction at 0.25% vs. 1% ↓ Methane production by 33–49%	Prathap <i>et al.</i> (2024)
Poll Dorset × Merino Lambs	Polygain™ (Sugarcane-based polyphenol)	0.25–1% (16 days +15-day acclimatization)	25% barley, 25% wheat, 25% oaten/lucerne	Linear ↑ liveweight ↔ Feed intake	NR	↓ Methane emissions by 33.5–49.2% ↓ Methane yield by 37.1–51.5%	Prathap <i>et al.</i> (2023)
Holstein × Friesian Cows	Sugarcane extract	0.25% of DMI (3 weeks)	Partial mixed ration + concentrate	↑ Milk yield (7.4%)	↓ Fat content (6.7%) ↔ Protein ↓ Somatic cell counts ↑ Mastitis resistance	↓ Methane (~30–35%)	Ahmed <i>et al.</i> (2023)

Table 6. Impact of polyphenol supplements on ruminant performance, health and methane emissions

Species/Breed	Test Ingredient	Dosage (Duration)	Basal Diet	Performance	Health/Product Quality	Environmental Impact	Reference
Holstein Friesian dairy cows (2–5 years old, average body weight: 663 kg)	Polygain™ (polyphenol-rich sugarcane feed material)	0.25% of dry matter intake (DMI) for 5 weeks (3-week adaptation + 2-week measurement)	Concentrate pellets (16% crude protein) + rye-grass pasture forage	↔ feed intake (9.4 kg/day concentrate consumed in both groups) ↔ in body weight or milk production	Polyphenols inhibit methanogen activity and alter microbial populations	Control: 495 ± 12 g CH ₄ /animal/day Treatment: 377 ± 12 g CH ₄ /animal/day (24% reduction in methane production) Methane yield: Control: 24.84 g CH ₄ /kg DMI Treatment: 18.96 g CH ₄ /kg DMI Control: 17.04 g CH ₄ /kg milk/day Treatment: 13.01 g CH ₄ /kg milk/day (31% reduction in methane intensity)	Bai <i>et al.</i> (2025)
Holstein Friesian weaned calves	Polygain™ (sugarcane-derived polyphenolic extract)	10 g/calf/day (3-month study, including a 2-week adaptation period)	Annual rye-grass pasture + supplementary pellets (Barastoc calf-rearer cubes) fed at 200 g/calf/day	↔ in initial/final body weight or average daily gain (ADG) between control (1.09 kg/day) and treatment (0.97 kg/day) groups	No adverse effects on calf health or development.	Significant reduction in methane: 26.66 g/day (treatment) vs. 35.28 g/day (control) ~24% reduction in daily emissions.	Osei-Amponsah <i>et al.</i> (2025)
Angus Cross Heifers	Polygain™ (Polyphenol extract)	0%, 0.3%, 0.6%, 1.2% DM (35 days)	78% corn silage, 15% barley straw, 6% supplement	↔ DMI/LW	NR	↑ Rumen pH (0.6%) ↔ Methane emissions	Williams <i>et al.</i> (2025)

↑ = increased/improved; ↔ = no significant change in; ↓ = decreased/reduction in; NR = Not reported; ADG = Average Daily Gain; LW = Liveweight; DMI = Dry Matter Intake; DM = Dry Matter; FCR = Feed Conversion Ratio; CH₄ = methane; SCFA = Short-Chain Fatty Acids; DDGS = Dried Distillers Grains with Solubles; SCC = Somatic Cell Count; % = percentage; days = experimental duration.

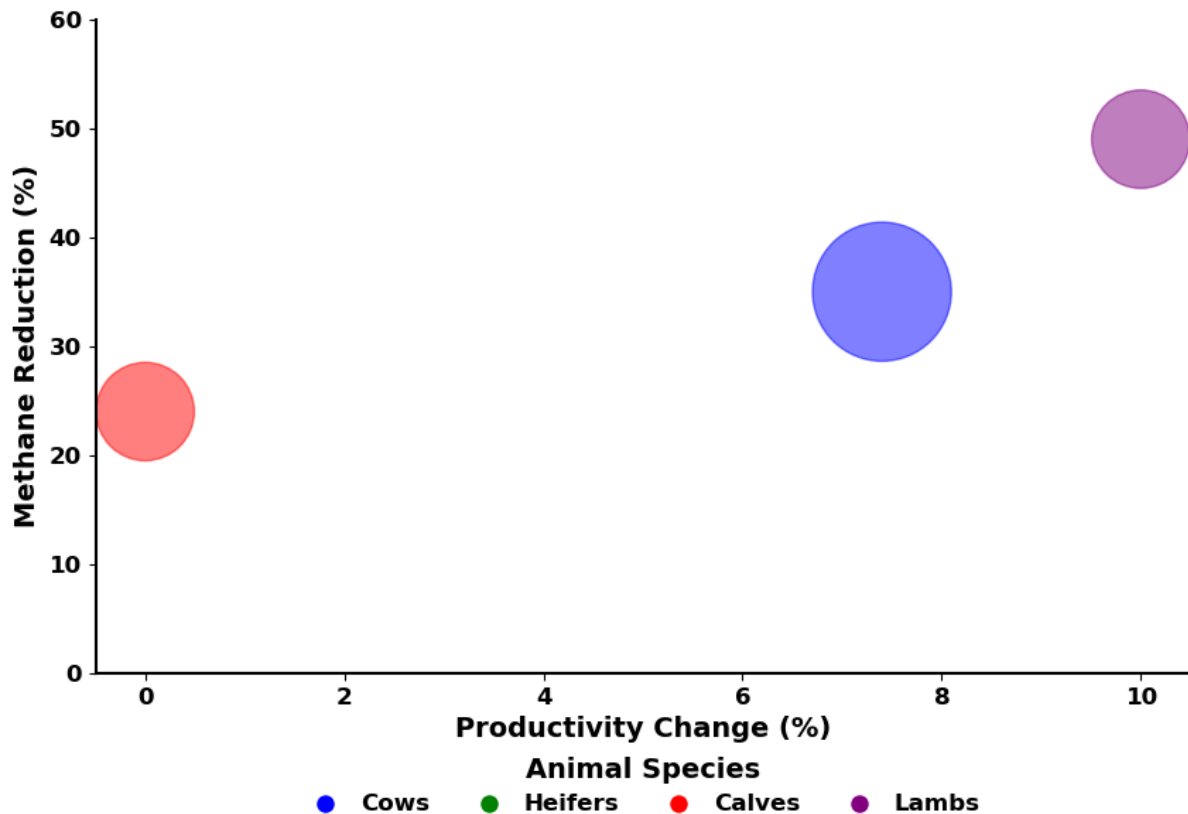


Figure 7. Summary of how polyphenol supplementation reduces methane emissions without negatively affecting productivity and may improve specific health parameters (Cows = 2; Heifers = 1; Calves = 1; Lambs = 2).

Polygain™ offers a plant-based alternative to synthetic additives like 3-NOP, which raises safety concerns (Hristov, 2024). Extrapolating Bai *et al.* (2025)'s findings, widespread adoption could reduce Australia's agricultural methane emissions by 2.63%. However, sustainable sugarcane sourcing and long-term efficacy studies are necessary (Ahmed *et al.*, 2023).

Figure 7 illustrates that for ruminants, polyphenol supplementation can result in a reduction in methane emissions, with varying effects on productivity. Importantly, some studies, like the one on Holstein × Friesian cows, suggest a potential synergy where productivity (milk yield) increases by 7.4% while methane emissions decrease by 35%, accompanied by improvements in health (Ahmed *et al.*, 2023; Bai *et al.*, 2025). This suggests that polyphenol supplements are highly effective in improving both productivity and environmental sustainability for cows. In

contrast, heifers show no change in productivity or methane emissions, and their health impact score remains at zero, indicating that the supplements have no significant effect on this group (Williams *et al.*, 2025).

Calves exhibit a methane reduction of 24% with no change in productivity or health (Osei-Amponsah *et al.*, 2025). Lambs exhibit the most significant improvements, with a 10% increase in productivity, a 49% reduction in methane emissions, and a 1% improvement in feed conversion ratio (Prathap *et al.*, 2024). These results highlight the potential of polyphenol supplements to enhance productivity and reduce environmental impact, particularly in lambs. Animals with higher liveweight gain often exhibit lower GHG emissions per unit of production, suggesting that practices for improving production efficiency may be conducive to lower emissions intensity (Cottle *et al.* 2016).

Conclusion

Sugarcane-derived polyphenols exhibit considerable potential as sustainable feed additives for mitigating enteric methane emissions in ruminants while enhancing productivity. Supplementation with polyphenol-rich extracts, such as Polygain™, has been shown to reduce methane emissions by 30–49% in lambs and dairy cows, primarily through modulation of the rumen microbiota, suppression of methanogenic archaea, and redirection of hydrogen toward propionate production. However, efficacy varies with diet composition, as evidenced by negligible effects in beef heifers fed high-forage rations, emphasizing the importance of diet. Beyond methane abatement, polyphenols enhance animal performance, with dairy cows exhibiting increased milk yield (up to 7.4%) and lambs demonstrating improved growth rates and feed efficiency. Health benefits, including reduced somatic cell counts in dairy cattle, further highlight their multifunctional role. Nevertheless, trade-offs such as decreased milk fat content warrant further investigation to optimize inclusion levels. The variability in responses across ruminant species and diets emphasizes the need for tailored supplementation strategies.

To advance the application of sugarcane-derived polyphenols in animal nutrition, future research should focus on several key areas. First, studies should elucidate the

precise mechanisms by which polyphenols influence immune, metabolic, and rumen microbial pathways, particularly their effects on methanogens in different diets (high-forage vs. high-concentrate). Additionally, researchers should investigate why methane reduction efficacy varies among livestock species (e.g., sheep, dairy vs. beef cattle) and assess the role of microbial community dynamics. Another priority is establishing species-specific optimal doses to balance methane mitigation, growth performance, and health outcomes while evaluating long-term safety and nutrient absorption effects, especially at higher inclusion rates. Further research should examine the interactions between polyphenols and dietary components (e.g., plant proteins, starch-rich vs. fiber-rich diets) to optimize feed formulations for methane reduction and efficiency. Conflicting prior results on sugarcane polyphenol extracts (SPE) in high-forage beef and dairy diets warrant clarification. Agricultural sustainability efforts must enhance sugarcane yield and processing techniques to improve polyphenol availability for large-scale livestock production. Ultimately, interdisciplinary studies should align environmental benefits (e.g., methane reduction) with economic feasibility to ensure the practical adoption of these benefits across diverse farming systems. Addressing these research gaps will foster innovation in sustainable animal nutrition while balancing productivity, ecological resilience, and industry viability.

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