



REVIEW ARTICLE

Apple Pomace-Derived Fiber in Ruminant Nutrition: Processing, Biological Mechanisms, and Economic Implications

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Abstract

Apple pomace, a major by-product of fruit processing, has emerged as a promising source of dietary fiber for ruminant nutrition. This review explores its physicochemical characteristics, processing techniques for feed integration, and biological effects on rumen fermentation, nutrient digestibility, and animal performance. Comparative insights with conventional fiber sources highlight apple pomace's fermentability, antioxidant potential, and prebiotic properties. Furthermore, its utilization supports circular agriculture by reducing feed costs and valorizing agro-industrial waste. In addition to its high pectin content and moderate antioxidant activity, apple pomace provides fermentable carbohydrates that stimulate volatile fatty acid production, enhance microbial protein synthesis, and support immune modulation. Economic analyses indicate that partial replacement of conventional feed ingredients with dried apple pomace can lower ration costs by 5–12% in apple-producing regions. Despite its potential, challenges remain in standardizing composition, ensuring palatability, and optimizing inclusion rates. Future research should focus on long-term health outcomes, regional formulation strategies, and scalable processing technologies to fully realize its role in sustainable livestock production.

1. Introduction

The global livestock sector is increasingly challenged by feed resource limitations, environmental pressures, and the need for sustainable intensification. Conventional feed ingredients such as cereal grains and soybean meal are associated with high production costs, land-use competition, and ecological concerns (IFIF 2020). In response, agro-industrial by-products have gained attention as alternative feed resources that align with circular economy principles and sustainable agriculture (Vendruscolo *et al.*, 2008).

Apple pomace, the solid residue remaining after juice and cider extraction, represents a significant agro-industrial by-product with high nutritional potential. Rich in dietary fiber, pectin, polyphenols, and fermentable carbohydrates, it has attracted increasing attention as a sustainable feed ingredient for ruminants (Szymańska-Czerwińska *et al.*, 2024; Vendruscolo *et al.*, 2008). The valorization of apple pomace aligns with circular agriculture principles, offering both environmental and economic benefits by reducing feed costs and minimizing waste (Szymańska-Czerwińska *et al.*, 2024).

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Recent studies have demonstrated that apple pomace can positively influence rumen fermentation, microbial activity, and nutrient digestibility when properly processed and incorporated into ruminant diets (Tiwari, et al. 2008). Its antioxidant and prebiotic properties further enhance its functional value, contributing to improved animal health and productivity (Szymańska-Czerwińska *et al.*, 2024). However, variability in chemical composition, palatability concerns, and limitations in large-scale processing remain key challenges to its widespread adoption (Vendruscolo *et al.*, 2008).

This review aims to synthesize current knowledge on the physicochemical characteristics of apple pomace, evaluate processing techniques that enhance its feed value, and assess its biological effects on dairy and beef cattle. Additionally, the economic implications and future research directions for its integration into sustainable feeding systems are discussed.

2. Composition and Functional Properties of Apple Pomace Fiber

Apple pomace contains a complex matrix of dietary fiber and bioactive compounds that contribute to its nutritional and functional value in ruminant diets. The major fiber components include cellulose, hemicellulose, pectin, lignin, and polyphenols, each playing distinct roles in rumen physiology and microbial dynamics (Fidriyanto *et al.*, 2023; Murad and Azzaz, 2011).

Cellulose and hemicellulose are structural polysaccharides that stimulate chewing activity and saliva production, thereby enhancing rumen motility and buffering rumen pH (Fidriyanto *et al.*, 2023). Pectin, a soluble fiber, is rapidly fermented in the rumen, increasing the production of volatile fatty acids, particularly propionate, which serves as a key precursor for glucose. Lignin, although indigestible, contributes to rumen fill and satiety but can reduce overall diet digestibility when present at high levels. Polyphenols, found in moderate concentrations, possess antioxidant and anti-inflammatory properties that may help reduce oxidative stress and support immune function (Fidriyanto *et al.*, 2023; Murad and Azzaz, 2011; Schmid *et al.*, 2020; Szymańska-Czerwińska *et al.*, 2024). The typical composition of apple pomace (on a dry matter basis) includes crude fiber (15–25%), pectin (6–10%), crude protein (5–8%), total sugars (10–15%), and polyphenols (0.5–1.5%). These components and their functional roles are summarized in Table 1 (Fidriyanto *et al.*, 2023; Murad and Azzaz, 2011; Szymańska-Czerwińska *et al.*, 2024). While the protein content is relatively low and requires supplementation, the fermentable sugars and fiber fractions provide readily available energy and functional support for rumen microbes (Gadulrab *et al.*, 2023).

From a functional perspective, apple pomace fermentation yields VFAs such as acetate (linked to milk fat synthesis), propionate (gluconeogenesis), and butyrate (rumen epithelium health) (Gadulrab *et al.*, 2023). Pectin also promotes the growth of beneficial microbial populations including *Lactobacillus* and *Bifidobacterium*, contributing to improved gut health and immune modulation (Fidriyanto *et al.*, 2023). Additionally, polyphenols reduce oxidative stress, potentially improving reproductive performance and meat shelf life (Fidriyanto *et al.*, 2023; Kruczek *et al.*, 2017).

Table 1
Chemical composition and functional roles of apple pomace fiber components (DM basis)

Component	Range (% DM)	Functional role
Crude fiber	15-25	Stimulates rumen motility
Pectin	6-10	Enhances microbial fermentat
Crude protein	5-8	Requires supplementation
Total sugars	10-15	Provides fermentable energy
Polyphenols	0.5-1.5	Antioxidant and anti-inflammatory effects

3. Processing Techniques for Feed Application

Apple pomace requires appropriate processing to ensure its stability, digestibility, and suitability for ruminant feed. Drying reduces the moisture content of fresh apple pomace (typically 70–80%) to below 10%, significantly improving shelf life, microbial stability, and transportability. Techniques include solar drying, which is cost-effective but weather-dependent; hot-air drying, offering controlled and scalable conditions; and drum drying, suitable for industrial-scale operations with consistent output and low energy loss. Drying also affects grinding efficiency and powder morphology, which are critical for feed uniformity and digestibility (Shalini and Gupta, 2010; Tulej and Głowacki, 2022).

Mechanical processing such as grinding and pelleting improves particle size uniformity, feed texture, and overall palatability in mixed rations. Grinding reduces particle size and enhances mixing efficiency, while pelleting increases bulk density, improves intake, and reduces feed sorting. Biological fermentation with lactic acid bacteria or yeast improves digestibility, reduces anti-nutritional factors such as tannins, and enhances probiotic effects. Mixed silage containing dried apple pomace and brewers' spent grains has been shown to improve lactic acid production, protein digestibility, and metabolizable energy in ruminants (Dai *et al.*, 2022).

Table 2 compares the nutritional and functional attributes of apple pomace with conventional fiber

sources such as wheat bran, beet pulp, and alfalfa hay. It highlights apple pomace's higher pectin content, moderate antioxidant activity, and strong prebiotic potential, which distinguish it from other fiber sources.

References: Kalia & Gupta (2005) and Szymańska-Czerwińska *et al.* (2024).

Apple pomace stands out for its high pectin content, moderate antioxidant activity, and strong prebiotic potential, making it a valuable addition to ruminant diets when processed appropriately (Fidriyanto, *et al.* 2023).

4. Biological Mechanisms and Performance Effects of Apple Pomace in Ruminant Nutrition

Apple pomace fibre stimulates microbial fermentation in the rumen, increasing the production of acetate and butyrate, which are key volatile fatty acids (VFAs) involved in milk fat synthesis and epithelial health. Pectin, a rapidly fermentable fibre, promotes the growth of cellulolytic bacteria such as *Fibrobacter succinogenes* and *Ruminococcus albus*, thereby enhancing fibre degradation and energy yield (Fidriyanto *et al.*, 2023; Gadulrab *et al.*, 2023). The high fibre content of apple pomace also increases chewing time, which in turn enhances saliva flow and buffers rumen pH. This buffering action is critical for preventing subacute ruminal acidosis (SARA), particularly in high-concentrate diets (Zebeli *et al.*, 2012).

Fermentable carbohydrates in apple pomace support microbial growth, contributing to microbial protein synthesis and improved nitrogen utilisation. This mechanism is especially beneficial in diets with low crude protein, where microbial synthesis can compensate for protein deficits (Dai, *et al.* 2022). In addition, polyphenols such as quercetin and chlorogenic acid present in apple pomace may reduce oxidative stress and inflammation, particularly in high-producing dairy cows under metabolic strain. These compounds enhance immune function and may improve reproductive efficiency (Boyer and Liu, 2004; Fidriyanto *et al.*, 2023). Table 3 summarises the main biological mechanisms and contributions of apple pomace in ruminant nutrition.

5. Effects on Dairy and Beef Cattle

In dairy cattle, inclusion of dried apple pomace at levels up to 15% of dry matter (DM) in total mixed rations (TMR) has been shown to maintain or slightly improve milk yield and fat content in lactating cows. This effect is attributed to increased acetate production from fibre fermentation, which supports milk fat synthesis, and propionate production from pectin, which enhances glucose availability for lactose synthesis (Gadulrab, *et al.* 2023). Rumen health is positively influenced by the high fibre and low starch content of apple pomace, which promotes chewing activity and saliva flow, thereby stabilising rumen pH and reducing the risk of subacute ruminal acidosis (SARA) (Zebeli *et al.*, 2012; Allen, 1997).

Table 2

Comparative analysis of apple pomace and conventional fiber sources (DM basis)

Parameter	Apple pomace	Wheat bran	Beet pulp	Alfalfa hay
Dry Matter (%)	~20 (fresh) / >90 (dried)	~88	~90	~85
Crude fiber (% DM)	15–25	10–12	16–20	25–30
Pectin content (% DM)	6–10	<2	15–20	<1
Lignin (% DM)	5–8	3–5	2–4	8–10
Fermentability	Moderate–high	Moderate	High	Moderate
Energy density	Low–moderate	Moderate	High	Moderate
Protein (% DM)	5–8	14–16	8–10	17–20
Antioxidant content	Moderate	Low	Low	Low
Cost (per ton)	Low (by-product)	Moderate	Moderate–high	High
Prebiotic potential	High	Low	Moderate	Low

Table 3

Summary of biological mechanisms and apple pomace contributions.

Mechanism	Apple pomace contribution	Impact on cattle
VFA Production	High propionate and acetate from pectin/cellulose	Milk fat, energy metabolism
Rumen pH buffering	Increased chewing → more saliva → stable pH	Prevents acidosis
Microbial protein synthesis	Fermentable sugars support microbial growth	Milk protein, growth
Antioxidant modulation	Polyphenols reduce oxidative stress	Immunity, meat quality
Prebiotic effects	Pectin fosters beneficial microbes	Gut health, nutrient absorption

Additionally, polyphenolic compounds such as quercetin and chlorogenic acid may contribute to improved reproductive efficiency and immune modulation by reducing oxidative stress in high-producing dairy cows (Boyer and Liu, 2004; Fidriyanto *et al.*, 2023).

In beef cattle, inclusion of apple pomace up to 10% DM supports average daily gain (ADG) and feed conversion ratio (FCR), particularly when diets are balanced with energy-rich components such as cereal grains (Dai *et al.*, 2022; Tiwari *et al.*, 2008). The antioxidant properties of polyphenols enhance oxidative stability of muscle tissue, reducing lipid peroxidation and improving shelf life and sensory quality of beef (Fidriyanto *et al.*, 2023). Importantly, no adverse effects have been reported on dressing percentage or muscle-to-fat ratio at moderate inclusion levels. Balanced energy intake ensures optimal lean tissue deposition without excessive fat accumulation, making apple pomace a viable component in finishing rations (Gadulrab *et al.*, 2023).

Apple pomace also contains polyphenolic compounds such as quercetin, chlorogenic acid, and ursolic acid, which exhibit strong antioxidant and anti-inflammatory properties. These bioactives may reduce oxidative stress in high-producing dairy cows, particularly during early lactation when metabolic strain is elevated. By mitigating oxidative damage, these compounds support immune modulation and may enhance reproductive efficiency through improved ovarian function and reduced inflammatory cytokine activity (Boyer and Liu, 2004; Kruczek *et al.*, 2017; Ma *et al.*, 2022; Vendruscolo *et al.*, 2008). Recent studies have demonstrated that methanol and fermented alcohol extracts of dried apple pomace show high radical scavenging activity (DPPH and ABTS assays), with antioxidant capacity exceeding that of ascorbic acid in some cases. These findings suggest that apple pomace-derived antioxidants may play a supportive role in maintaining reproductive and metabolic health in dairy cattle under physiological stress (Boyer and Liu, 2004; Kruczek *et al.*, 2017; Ma *et al.*, 2022).

6. Economic Analysis

Apple pomace is often available at low or zero cost from juice processors, making it an economically attractive feed ingredient. Drying and processing costs typically range from 30 to 70 USD per ton, depending on the scale of operation and the technology used (Schmid *et al.*, 2020). Replacing 10–15% of conventional feed ingredients with apple pomace can reduce total feed costs by approximately 5–12%, particularly in regions with abundant apple production (Pascoalino *et al.*, 2025).

Beyond direct cost savings, apple pomace offers opportunities for local entrepreneurship in drying and pelletising operations. Its utilisation also reduces envi-

ronmental disposal costs for juice producers and enhances feed self-sufficiency in apple-growing regions. These benefits align with circular economy principles and agro-industrial waste valorisation strategies (Pascoalino *et al.*, 2025).

Despite these advantages, several risks must be managed. Seasonal availability and variability in composition require flexible formulation strategies. Quality control measures, including mycotoxin monitoring and microbial safety checks, are essential to ensure feed safety. Furthermore, logistics and storage infrastructure must be optimised to handle dried pomace efficiently, preventing spoilage and maintaining nutritional quality (Piñeiro, 2008; Shalini and Gupta, 2010; Tulej and Głowacki, 2022).

7. Conclusions and Recommendations

Apple pomace-derived fibre is a nutritionally viable and economically sustainable feed ingredient for ruminants. Its inclusion in dairy and beef cattle diets supports rumen health, productivity, and meat quality while contributing to the valorisation of agro-industrial residues. To maximise its potential, future research should focus on standardising processing protocols to ensure consistent quality, evaluating long-term health and reproductive outcomes, and developing region-specific feeding guidelines based on pomace composition. Integrating apple pomace into certified organic feed systems and conducting life-cycle assessments will further strengthen its role in sustainable livestock production.

By addressing variability in composition, improving processing efficiency, and ensuring robust quality control, apple pomace can be transformed from a waste product into a strategic resource for sustainable ruminant nutrition.

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