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Review Article

Sustainable Utilization of Plant By-Product Biomass as Alternative Feedstuff Resources for Livestock: A Comprehensive Review

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Abstract | Numerous agricultural by-products can be utilized as sustainable feed resources for livestock, provided that they meet key criteria related to quality, quantity, and palatability. One such resource is a by-product of cassava (*Manihot esculenta Crantz*) production in the form of cassava leaves. They contain high crude protein (20–33.4% dry matter), essential minerals, vitamins, and fermentable carbohydrates, but their utilization is limited by anti-nutritional factors, mainly hydrogen cyanide (HCN) and condensed tannins. Excessive intake of these compounds can reduce feed intake, nutrient digestibility, rumen microbial activity, animal performance, and may cause toxicity. This comprehensive review evaluates the potential of cassava leaf by-products as sustainable ruminant feed, focusing on nutritional composition, anti-nutritional constraints, processing strategies, and their effects on digestibility, rumen fermentation, animal performance, and milk production. This article presents a comprehensive review using peer-reviewed articles from Scopus, Google Scholar, Wiley Online Library, Taylor and Francis, and SpringerLink. This review confirms that appropriate processing methods such as wilting, sun-drying, boiling, fermentation, ensiling, and ammoniation are effective in reducing HCN and tannin concentrations to safe levels, thereby improving nutrient digestibility, rumen fermentation, feed intake, and animal performance. Overall, properly processed cassava leaves represent a promising alternative protein source that supports circular bioeconomy principles, reduces feed costs, and promotes sustainable ruminant production systems.

Keywords | By-product, Feed processing, Nutrition, Performance, Ruminant

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INTRODUCTION

Livestock production in tropical regions faces increasing pressure due to rising feed costs, land-use competition, and fluctuating availability of conventional feed resources. Feed commonly accounts for more than 60–70% of total production costs in ruminant systems (Begna and Masho, 2024). To address these challenges, the utilization of locally abundant agro-industrial by-products has been widely promoted as a strategic approach for sustainable livestock production (Gerlach *et al*., 2018; Wanapat and Kang, 2015).

Cassava (*Manihot esculenta* Crantz) is one of the most widely cultivated crops in tropical regions and generates substantial by-products, particularly cassava leaves, which remain underexploited despite their high nutritional potential (Morgan and Choct, 2016; Suryani, 2020). Cassava leaves contain 20–30% crude protein (CP), high levels of essential minerals (Ca, Mg, Fe, Zn), vitamins, and readily fermentable carbohydrates, positioning them as a promising alternative protein source for ruminants (Alamu *et al*., 2022; Oresegun *et al*., 2016; Wanapat, 2002). Their nutritional profile is comparable to high-quality legume forages and several commercial protein supplements, suggesting significant opportunities for substitution in ruminant diets (Menci *et al*., 2021; Min and Hart, 2003).

However, cassava leaves also contain substantial concentrations of antinutritional factors (ANFs), primarily cyanogenic glycosides (linamarin and lotaustralin) and condensed tannins, which can limit their safe inclusion in livestock diets (Huang *et al*., 2018; Luque-Almagro *et al*., 2011; Yuningsih, 2012). Hydrogen cyanide (HCN) released from cyanogenic glycosides can cause acute toxicity, respiratory failure, and mortality when consumed above tolerance thresholds (Robson, 2007; Soto-Blanco and Górniak, 2010). Tannins, on the other hand, may reduce feed intake, bind dietary proteins, impair rumen microbial activity, and lower nutrient digestibility when present at excessive levels (Chung *et al*., 1998; Min *et al*., 2012; Patra and Saxena, 2010). Nonetheless, at moderate concentrations, condensed tannins may exert beneficial effects, including protein protection in the rumen, antimicrobial activity, improved nitrogen utilization, and modulation of rumen lipid metabolism (Frutos *et al*., 2020; Goel *et al*., 2005; Sharma *et al*., 2021).

A growing body of evidence indicates that appropriate processing techniques such as wilting, sun-drying, boiling, fermentation, ensiling, ammoniation, and microbial bioactivation can effectively reduce HCN and tannin content to safe levels while improving palatability, rumen fermentation patterns, and nutrient availability (Haque and Bradbury, 2004; Rira *et al*., 2022; Zuhra *et al*., 2024). These processing methods enhance the nutritional value of cassava leaves by lowering ANFs, increasing protein digestibility, and promoting favorable rumen microbial adaptation (Getachew *et al*., 2000; McSweeney *et al*., 2001). Processed cassava leaves have been associated with improvements in dry matter intake, volatile fatty acid (VFA) production, microbial protein synthesis, and milk yield in ruminants (Ali *et al*., 2017; Arief and Pazla, 2023; Katongole and Yan, 2020).

The integration of cassava by-products into ruminant diets also aligns with circular bioeconomy principles by reducing agricultural waste, enhancing feed self-sufficiency, and minimizing environmental impacts associated with conventional feed production (Makkar, 2003). Given the substantial biomass generated by cassava cultivation, especially in Southeast Asia and Sub-Saharan Africa, optimizing the use of cassava leaves represents a strategic opportunity to support climate-resilient and cost-effective livestock systems (Andama and Oloya, 2017; Wanapat and Kang, 2015).

Although numerous studies have assessed the nutritional characteristics, anti-nutritional constraints, processing technologies, and physiological responses of animals fed cassava leaves, findings remain scattered across various species, processing methods, and experimental conditions. A comprehensive synthesis is therefore required to consolidate current knowledge, clarify inconsistencies, and provide practical and mechanistic insights into the sustainable utilization of cassava by-products in ruminant feeding.

This comprehensive review evaluates the potential of cassava leaf by-products as sustainable feed resources, focusing on their nutritional composition and variability; anti-nutritional factors and associated risks; effectiveness of processing techniques in reducing HCN and tannins; impacts on nutrient digestibility, rumen fermentation, and production performance; and underlying metabolic and physiological mechanisms governing their utilization. By integrating multidisciplinary evidence, this article aims to support the development of scientifically grounded feeding strategies that enhance livestock productivity while promoting sustainable use of local resources.

MATERIALS AND METHODS

Study design

This study was conducted as a comprehensive review to synthesize and critically evaluate existing literature on the utilization of cassava (*Manihot esculenta* Crantz) leaves as feed resources for ruminant livestock.

Data sources and search strategy

A comprehensive literature search was performed using Scopus, Google Scholar, Wiley Online Library, Taylor and Francis, and SpringerLink. The search focused on the utilization of cassava leaves as livestock feed, particularly regarding nutritional composition, antinutritional factors (HCN and tannins), processing methods, and effects on livestock performance. The articles used must be from at least the year 2020 and meet the requirements so that a greater number of methods can be compared.

Keywords

Search terms included cassava leaves, HCN, tannin, processing cassava leaves, nutritional quality, animal feed, ruminant performance, milk production, fermentation, and digestibility, combined using Boolean operators AND, OR, and NOT.

Inclusion and exclusion criteria

Studies were included if they used cassava leaves as livestock feed; reported data on HCN, tannins, nutritional composition, or processing outcomes; evaluated animal responses such as performance, digestibility (*In vitro, In vivo* and *In sacco*), rumen fermentation parameters (pH, NH_3, VFA), or milk yield and quality; were written in English or Indonesian, and provided full-text access.

Article selection and data extraction

Titles and abstracts were screened for relevance, followed by full-text assessment of eligible studies. Data extracted included nutritional and antinutritional composition; processing methods; dry matter intake; digestibility; rumen fermentation characteristics; HCN and tannin levels after processing; and milk production and quality.

RESULTS AND DISCUSSION

Nutritional composition and variability

Sustainable feed must meet three aspects: quantity, quality, and palatability. One promising by-product is cassava by-products, particularly cassava leaves. The taxonomic classification of cassava is as follows: Kingdom: *Plantae*; Division: *Spermatophyta*; Subdivision: *Angiospermae*; Class: *Dicotyledoneae*; Order: *Euphorbiales*; Family: *Euphorbiaceae*; Genus: *Manihot*; Species: *Manihot esculenta* Crantz. Quantitatively, cassava leaves can be harvested every three months after planting and yield 11,786 kg dry matter (DM) ha^{-1} (Wanapat, 2002). Fresh cassava leaf production ranges from 10–40 tons ha^{-1} $year^{-1}$, or about 10–40% of the cassava plant biomassa (Hossain *et al*., 2025). This yield is considered competitive compared with other tropical forages, which generally produce only 5–8 tons DM ha^{-1} $year^{-1}$.

The equivalent to approximately 1.8–14 tons of crude protein ha^{-1} $year^{-1}$, depending on variety and harvest age (Alamu *et al*., 2022; Morgan and Choct, 2016; Oresegun *et al*., 2016). This amount is higher than that of most tropical grasses, which typically produce less than 10 tons of protein ha^{-1} $year^{-1}$. The essential amino acid profile is relatively good, particularly lysine and leucine, which contribute to rumen microbial protein synthesis and nitrogen utilization efficiency (Prachumchai *et al*., 2022). Cassava leaves contain vitamins A, B1, and C, calcium, phosphorus, magnesium, beta-carotene, carotene, and iron, all of which are important for livestock (Oresegun *et al*., 2016). In addition to serving as a protein source, cassava leaves also function as a natural anthelmintic in ruminants (Wanapat and Khampa, 2006), have potential as a source of lactic acid bacteria for use as probiotics in livestock (Samedi and Charles, 2019) and can inhibit the occurrence of mastitis in dairy animals (Cai *et al*., 2024).

Another quantitative advantage is the continuity of production throughout the year. Cassava plants allow periodic leaf harvesting through pruning at intervals of 2–4 months without disrupting root production. This staggered harvesting system enables relatively stable leaf availability year-round, particularly during the dry season when the availability of other forages declines (Lambebo and Deme, 2022). Processed cassava leaves can be included at levels of 10–30% of the ruminant diet DM, depending on livestock species and processing quality. At these inclusion levels, cassava leaf requirements range from 0.3–1.0 kg DM day^{-1} for small ruminants and are higher for large ruminants (Maciel *et al*., 2023; Nascimento *et al*., 2021).

Feed palatability can be assessed by increased feed intake. Cassava leaves processed using various methods have been shown to significantly improve palatability. Drying and wilting can reduce pungent odors and bitterness by lowering hydrogen cyanide (HCN) levels, thereby markedly increasing feed intake (Kennedy *et al*., 2021; Supapong *et al*., 2022; Yildiz *et al*., 2017). Fermentation and ensiling can further enhance palatability by producing an acidic aroma favored by ruminants and by improving feed texture (Sudarman *et al*., 2016; Syahniar *et al*., 2018). The use of fermented or ensiled cassava leaves can increase dry matter intake by 5–20% compared with fresh leaves (Dung *et al*., 2010; Grant and Ferraretto, 2018).

Overall, the high biomass and protein production of cassava leaves, combined with their continuous availability, make this material highly promising in terms of quantity and quality. Large-scale utilization of cassava leaves has the potential to reduce dependence on imported feeds, improve land-use efficiency, and support the integration of sustainable crop–livestock systems in tropical regions.

Anti-nutritional factors and associated risks

Hydrogen cyanide in cassava leaves is a carcinogenic compound mainly composed of linamarin (95%) and lotaustralin (5%) (Yuningsih, 2012). The maximum tolerable HCN concentration for livestock is approximately 2.0 mg kg^{-1} BW (Bahri and Tarmudji, 1984), less than 0.5 mg kg^{-1} BW (Simbolon *et al*., 2016) and 0.25 mg kg^{-1} BW (Nascimento *et al*., 2021). Robson (2007) and Yuningsih (2012) reported that excessive HCN intake in livestock causes bright red coagulated blood, darkened muscles, and hemorrhages in the trachea, lungs, and liver observed during post-mortem examination. Clinical signs typically appear within 15–20 minutes after ingestion, with death often occurring 2–3 minutes thereafter. Similarly, Soto-Blanco and Górniak (2010); Stephanie and Purwadaria (2014) reported that, fresh cassava leaves contain HCN in the latex and may induce poisoning, characterized by increased respiratory rate, convulsions, reddening of mucous glands, and death.

Tannins are naturally occurring polyphenolic compounds with astringent properties that function in plant defense (Huang *et al*., 2018; Patra and Saxena, 2010). Tannins in cassava leaves are classified as condensed tannins, consisting of polymerized flavonoid units capable of binding proteins, which may exert beneficial biological effects at moderate levels but become toxic when excessive (Huang *et al*., 2018; Min *et al*., 2012; Min and Hart, 2003).Tannin intake is considered tolerable for livestock at levels below 50 g kg^{-1} DM (Mueller-Harvey, 2006) or 20–40 g kg^{-1} DM (Min *et al*., 2012). However, dietary tannin levels of approximately 4% have been reported to impair animal performance by reducing digestibility (Al-Kindi *et al*., 2016), while concentrations exceeding 50 g kg^{-1} DM negatively affect livestock productivity (Huang *et al*., 2018). Furthermore, Gerlach *et al*. (2018), reported that tannin levels of 30 g kg^{-1} DM begin to negatively affect milk production.

Tannins may exert either beneficial or detrimental effects on livestock depending on their concentration, type, chemical structure, and diet composition (Mueller-Harvey *et al*., 2019). At moderate levels, tannins can reduce ruminal protein degradation, enhance intestinal protein supply, improve gut microbial balance, and act as antiparasitic, antioxidant, antiviral, and anti-inflammatory agents, thereby improving productivity and milk quality (Huang *et al*., 2018; Mergeduš *et al*., 2020; Sharma *et al*., 2021). In contrast, excessive tannin intake decreases feed intake, digestibility, rumen microbial activity, and animal performance, and may induce antinutritional and toxic effects (Chung *et al*., 1998; Gerlach *et al*., 2018; Min and Hart, 2003; Yanza *et al*., 2021).

Effectiveness of processing techniques in reducing HCN, tannins and nutrient composition

The effects of different cassava leaves processing methods on HCN and tannin levels, nutrient composition, and digestibility are presented in Table 1.

Various processing methods for cassava leaves consistently reduce HCN and tannin concentrations to ranges considered safe for ruminants. Drying and boiling effectively reduce HCN levels, whereas fermentation, preservation, and further treatments such as the application of bamboo-derived activated charcoal result in more substantial reductions, accompanied by decreases in tannin content. These processing methods do not compromise nutritional quality; rather, they preserve high crude protein content and reduce fiber fractions, thereby increasing total digestible nutrients (TDN) and nutrient digestibility. Improvements in feed chemical composition positively influence rumen fermentation stability and animal performance, including feed intake, feed efficiency, and milk production, confirming the high potential of processed cassava leaves as a safe and nutritionally valuable alternative feed resource.

The selection of the most appropriate cassava leaf processing method can be tailored to specific feeding objectives, as different livestock species, growth stages, and production purposes require distinct nutritional standards. According to Utama *et al*. (2020), a desirable feed moisture content is below 14%. Jamarun *et al*. ((2020) reported that, forages with crude protein (CP) levels greater than 10% can be classified as high-protein forages, while the minimum crude fiber (CF) requirement in feed ingredients to meet livestock needs is 13%. Furthermore, Jamarun *et al*. ((2020), categorized forages into three classes based on CP and TDN contents: low quality forages (CP < 4%, TDN < 40%), medium quality forages (CP 5–10%, TDN 40–50%), and high quality forages (CP > 10%, TDN > 50%).

Effectiveness of processing techniques in reducing on livestock performance

The effects of different cassava leaves processing methods on ruminant animal performance are shown in Table 2.

Based on Table 2, most studies consistently indicate that the inclusion of processed cassava leaves does not impair rumen fermentation or animal performance and, in many cases, is associated with improvements in nutrient digestibility, feed intake, and productive responses. Across different processing methods and experimental conditions, ruminal pH generally remained within the optimal range, while NH_3 and VFA concentrations tended to increase, suggesting maintained or improved fermentation efficiency. Reported responses in body weight gain, feed efficiency, and milk production were either comparable to or higher than those observed with conventional feeding strategies. In addition, several studies reported ancillary functional effects, such as improved nitrogen utilization, reduced parasite load, or modulation of rumen microbial populations, although the magnitude of these effects varied among studies. Overall, the evidence summarized in Table 2 supports the conclusion that processed cassava leaves can be safely incorporated into ruminant diets, provided that appropriate processing methods and inclusion levels are applied.

Metabolic and physiological mechanisms HCN dan tannin ruminants

Ruminant livestock can consume feed materials containing hydrogen cyanide (HCN) without causing toxic effects. This is closely related to the integrated action between rumen microbial processes and detoxification mechanisms within the animal's body. Ruminants have a higher tolerance to cyanogenic compounds due to modulation

Table 1: The effects of different cassava leaves processing methods on HCN, tannin levels and nutrient composition.

Author	**Processing techniques**	**HCN**	**Tannin**	**Nutrient composition**										
				DM	**CP**	**CF**	**EE**	**Ash**	**NFE**	**TDN**	**ADF**	**NDF**	**Lignin**	**Cellulose**
(M. Wanapat *et al*., 2000)	Cassava leaf hay	35.00	25.70	86.30	23.60		-	8.90	-	-	30.00	44.30	5.80	-
(Khang and Wiktorsson, 2000)	Cassava leaf dried	-	-	-	22.54	-	7.57	-	-	-	18.85	25.60	-	-
(Wanapat *et al*., 2000)	Cassava leaf hay	35.00	25.70	87.80	24.50	-	-	10.20	-	-	27.30	35.40	3.90	-
(Wanapat, 2002)	Cassava leaf hay	38.00	39.00	86.30	25.00	-	6.20	12.50	48.00	65.00	30.30	44.30	5.80	-
	Cassava leaf dried	46.00	43.00	90.00	20-30		5.90	10.00	44.20	60.00	24.10	29.60	4.70	
(Kiyothong and Wanapat, 2004)	Hay sole cassava													
	- 1stharvest	-	34.00	-	21.60	-	-	7.50	-	-	37.40	48.90	15.30	-
	- 2ndharvest	-	35.00	-	21.90	-	-	6.60	-	-	35.40	50.30	13.80	-
	- 3rdharvest	-	39.00	-	21.90	-	-	6.30	-	-	31.10	44.70	13.50	-
	- 4thharvest	-	34.00	-	21.80	-	-	6.00	-	-	31.20	44.80	13.60	-
	Hay single cassava													
	- 1stharvest	-	36.00	-	21.50	-	-	6.80	-	-	32.50	47.50	14.90	-
	- 2ndharvest	-	38.00	-	20.90	-	-	6.10	-	-	34.80	45.50	14.00	-
	- 3rdharvest	-	37.00	-	25.50	-	-	5.90	-	-	32.70	45.50	15.30	-
	- 4thharvest	-	36.00	-	25.50	-	-	6.10	-	-	32.80	45.50	15.40	-
	Hay doble cassava													
	- 1stharvest	-	34.00	-	22.90	-	-	7.40	-	-	32.20	45.70	13.40	-
	- 2ndharvest	-	33.00	-	22.90	-	-	6.10	-	-	31.90	45.10	12.80	-
	- 3rdharvest	-	33.00	-	25.80	-	-	6.20	-	-	29.70	44.80	13.40	-
	- 4thharvest	-	34.00	-	25.70	-	-	6.20	-	-	29.50	44.70	13.60	-
	Hay triple cassava													
	- 1stharvest	-	32.00	-	21.30	-	-	7.70	-	-	30.90	47.20	14.20	-
	- 2ndharvest	-	30.00	-	20.70	-	-	6.30	-	-	33.80	45.30	13.50	-
	- 3rdharvest	-	32.00	-	25.60	-	-	5.30	-	-	27.90	44.90	13.60	-
	- 4thharvest	-	37.00	-	25.70	-	-	5.40	-	-	27.80	44.70	13.40	-
(Borin *et al*., 2005)	545 variety													
	Cassava leaf sun-dried	-	-	88.40	21.40	12.50	-	9.40	-	-	22.90	32.00	-	-
	Cassava leaf ensiled	-	-	-	20.80	14.40	-	10.60	-	-	24.10	34.90	-	-
	408 variety													
	Cassava leaf sun-dried	-	-	88.90	22.90	13.60	-	7.40	-	-	26.40	35.60	-	-
	Cassava leaf ensiled	-	-	-	20.70	14.70	-	5.70	-	-	23.50	35.30	-	-
(Dung *et al*., 2005)	Cassava leaf hay	-	23.00	92.40	18.90	-	9.80	10.70	-	-	29.70	39.50	-	-
(Granum *et al*., 2007)	Cassava leaf hay	-	40.00	91.40	18.50	-	-	5.70	-	-	47.90	63.80	11.90	-
(Marjuki *et al*., 2008)	Cassava leaf Silage	-	-	92.90	16.20	-	-	-	-	-	-	-	-	-

Table continues on next page.................

Author	Processing techniques	HCN	Tannin	Nutrient composition										
				DM	CP	CF	EE	Ash	NFE	TDN	ADF	NDF	Lignin	Cellulose
(Santoso and Aryani, 2007)														
Fermentation	A1 B1	-	-	86.36	24.98	29.94	3.48	6.25	26.11	-	-	-	-	-
A1: 0 ml EM4 $100g^{-1}$	A1 B2	-	-	83.37	25.11	29.74	4.35	6.98	28.76	-	-	-	-	-
A2: 2 ml EM4 $100g^{-1}$	A2 B1	-	-	86.66	22.01	25.35	4.39	6.97	33.85	-	-	-	-	-
A3: 4 ml EM4 $100g^{-1}$	A2 B2	-	-	86.76	26.43	31.24	4.46	7.73	22.49	-	-	-	-	-
B1: 0% rice bran	A3 B1	-	-	86.73	21.01	22.04	4.45	6.85	38.04	-	-	-	-	-
B2: 10% rice bran	A3 B2	-	-	86.99	28.45	32.74	4.58	7.35	18.58	-	-	-	-	-
(Antari and Umiyasih, 2009)	Cassava leaf hay	38.00	39.00	-	25.00	-	-	-	-	-	-	-	-	-
	Cassava leaf dried	36.00	43.00	-	-	-	-	-	-	-	-	-	-	-
(Khampa *et al*., 2009)	Cassava leaf hay	-	34.00	90.10	24.50	-	-	9.30	-	-	29.10	41.30	-	-
(Sirait and Simanihuruk, 2010)	Cassava leaf dried	-	-	-	20.00–30.00	-	-	-	44.20	60.00	24.10	29.96	-	-
	Cassava leaf hay [1]	-	-	90.00	25.00	-	-	-	48.00	60.00–	26.00–	43.00–	-	-
	Cassava leaf hay [2]	-	49.00-	86.30	20.79–28.65	-	-	5.20–7.70	-	65.00	38.00	56.00	-	-
	Cassava leaf meal	-	55.00-	87.60	24.80	21.80	5.90	8.60		-	-	-		
(Dung *et al*., 2010)	Cassava leaf hay	-	24.00	91.40	19.10	-	10.30	9.80	30.70	40.20	-	-	-	-
(Oni, Onwuka, *et al*., 2010)	Cassava leaf dried													
	Varieties													
	MS6	83.70	10.00	90.00	23.50	-	7.30	16.10	-	-	-	-	-	-
	TMS 30572	78.60	22.00	90.10	20.80	-	7.00	6.50	-	-	-	-	-	-
	TMS 30555	58.50	14.00	88.40	24.00	-	6.00	16.00	-	-	-	-	-	-
	Idileruwa	86.70	38.00	89.10	17.70	-	6.60	15.30	-	-	-	-	-	-
(Oni, Arigbede, *et al*., 2010)	Dried cassava leaves	78.60	21.60	90.10	20.80	-	6.97	-	51.50	-	48.00	61.30	25.40	13.30
(Régnier *et al*., 2012)	Cassava leaf meal	-	23.00	86.00	23.10	-	-	-	-	-	41.40	54.30	19.00	-
(Nguyen *et al*., 2012)	Cassava silage	-	-	92.00	24.20	14.30	7.00	-	-	-	-	-	-	-
	Cassava leaf dried	-	-	92.20	29.90	14.90	6.70	-	-	-	-	-	-	-
(Morgan and Choct, 2016)	Cassava leaf meal	-	-	92.06	23.79	17.70	6.83	8.07	40.58	-	-	-	-	-
(Phesatcha *et al*., 2016)	Cassava leaf hay	-	46.00	89.90	22.30	-	-	-	-	-	29.20	45.90	-	-
(Suharti *et al*., 2017)	Cassava leaf meal	-	-	86.78	19.80	32.80	6.43	10.06	30.91	45.48	-	-	-	-
(Sudarman *et al*., 2016)	Cassava leaf silage	71.00	27.00	24.80	21.10	-	-	4.20	-	77.10	-	-	-	-
(Syahniar *et al*., 2018)	Cassava leaf silage	-	30.00	30.30	33.40	-	5.76	7.30-7.80	-	-	21.70	38.90	-	-
(Hawashi *et al*., 2019)	24 hours	-	-	-	14.11	16.59	-	5.09	61.20	-	-	-	-	-
Fermentation using *Saccharomyces*	48 hours	-	-	-	14.87	16.80	3.36	5.29	59.68	-	-	-	-	-
cerevisiae.	72 hours	-	-	-	15.28	16.46	3.55	4.80	59.91	-	-	-	-	-
	96 hours	-	-	-	16.07	16.35	3.86	4.73	58.99	-	-	-	-	-

Table continues on next page.................

Author	Processing techniques	HCN	Tannin	Nutrient composition										
				DM	CP	CF	EE	Ash	NFE	TDN	ADF	NDF	Lignin	Cellulose
(Artanti *et al*., 2019)	Cassava leaf hay	31.00		93.00	23.56	19.90	7.06	5.74	51.21	71.34	-	-	-	-
	Cassava leaf silage	73.00		87.00	24.67	20.66	6.30	9.50	46.39	71.52				
(Bakare *et al*., 2020)	Cassava leaf meal	-	-	89.90	17.00	15.00	6.80	7.00	54.20	-	-	-	-	-
(Suharti *et al*., 2021)	Bitter Cassava leaf	50.10	-	-	18.50	21.00	-	10.00	34.10	61.00	-	-	-	-
(Siska *et al*., 2025) A: Activated charcoal														
A1: 2%	A1 B	39.00	57.00	93.32	32.89	13.92	4.85	4.16	44.19	77.03	18.89	21.05	7.52	11.55
A2: 4%	A2 B	36.00	53.00	93.33	31.81	17.14	4.88	4.32	42.86	73.26	25.88	42.68	11.42	14.03
A3: 6%	A3 B	28.00	52.00	93.42	31.21	18.17	4.76	4.99	40.88	70.74	26.30	43.02	14.38	16.62
B: Soaking time														

Note: HCN = Hydrogen cyanide (mg kg^{-1}); Tannin (g kg^{-1}); DM = Dry matter (%); CP = Crude protein (% DM); CF = Crude fiber (% DM); EE = Ether extract (% DM); NFE = Nitrogen-Free extract (% DM); TDN = Total digestible nutrient (% DM); ADF = Acid detergent fiber (% DM); NDF = Neutral Detergent Fiber (% DM); Lignin (% DM); Cellulose (% DM); Hemicellulose (% DM).

at the rumen level prior to absorption, as well as efficient post-absorptive detoxification pathways (Lumbantobing *et al*., 2020; Maciel *et al*., 2023). In the rumen, cyanogenic glycosides are hydrolyzed by microbial β-glucosidase enzymes, releasing free hydrogen cyanide (HCN) (Zuhra *et al*., 2024). Although this process increases cyanide availability, the large rumen volume and continuous digesta flow can reduce the risk of acute toxicity by slowing the rate of absorption. Rumen microorganisms are able to adapt to cyanogenic substrates, allowing fermentation efficiency to be maintained under moderate HCN exposure (Bahri and Tarmudji, 1984; Robson, 2007; Andama dan Oloya, 2017).

After absorption, the main detoxification pathway involves the enzymatic conversion of cyanide to thiocyanate (SCN^-), mediated by the enzyme rhodanese (*Thiosulfate sulfurtransferase*) (Oresegun *et al*., 2016). Increased SCN^- concentrations in blood and/or milk directly reflect the activation of the cyanide detoxification pathway via rhodanese (Bhalla *et al*., 2017; Robson, 2007). A positive relationship exists between SCN^- levels and sulfur status, which acts as a limiting factor in this process, as sulfur serves as an essential donor in the conversion of cyanide to thiocyanate (Prachumchai *et al*., 2022). Thus, adequate dietary sulfur not only enhances cyanide detoxification capacity but also contributes to the stability of blood metabolites by preventing the accumulation of toxic cyanide. The primary defense mechanism against cyanide toxicity in ruminants is associated with high rhodanese activity, which has been reported mainly in liver and kidney tissues (Kennedy *et al*., 2021). Toxicokinetic studies in ruminants also indicate rapid clearance of cyanide from circulation, supporting the role of efficient metabolic detoxification (Soto-Blanco and Górniak, 2010).

Sulfur is therefore a key factor modulating cyanide detoxification efficiency, as it functions as an essential donor in rhodanese-catalyzed reactions. Sulfur supplementation can increase tolerance to cyanogenic feeds and reduce biomarkers of cyanide stress in ruminants (Prachumchai *et al*., 2022). Thiocyanate, as the final product of cyanide detoxification, is primarily excreted via urine, while smaller amounts can be detected in milk and saliva. Thiocyanate concentration in milk can serve as an indicator of chronic cyanogenic exposure without posing health risks at physiological levels (Cherdthong *et al*., 2018; Robson, 2007). In addition, thiocyanate plays a role in the lactoperoxidase system, thereby enhancing the natural antimicrobial defense of milk and indicating an additional functional role of cyanide detoxification products (Supapong and Cherdthong, 2020). Although ruminants possess considerable adaptive capacity, these detoxification mechanisms are not unlimited. Acute consumption of feeds with high HCN levels can exceed the buffering capacity of the rumen and the detoxification ability of the liver, triggering severe respiratory and neurological disorders (Soto-Blanco and Górniak, 2010). The risk of toxicity is mainly related to intake rate and lack of dietary adaptation rather than the mere presence of cyanogenic feedstuffs (Cherdthong *et al*., 2018; Supapong *et al*., 2022).

Table 2: Effects of processed cassava leaves on ruminant animal performance.

Author	Treatment	Research findings
(Khang and Wiktorsson, 2000)	In sacco degradability of diets containing 30% cassava leaf silage	Improved digestibility (DMD and OMD). Stable ruminal pH with efficient NH_3 and VFA profiles.
(Borin *et al*., 2005)	Cassava leaf silage is provided at a rate of 20 g DM.	Reduces HCN levels to a greater extent than drying, making it safer as feed. Increases the total digestibility (CTTAD) of DM, CP, OM, and fiber fractions (NDF, ADF, CF). Increases nitrogen utilization efficiency, as indicated by higher N retention and N utilization.
(Dung *et al*., 2005)	Cassava hay can replace concentrates at a rate of 750 g kg^{-1}	Resulting in comparable BW gain and feed conversion rates to concentrate-based rations, as well as lower feed costs. Cassava hay reduces the number of nematode eggs and coccidia oocysts in feces.
(Granum *et al*., 2007)	Supplementation of cassava hay at 1 kg DM	Increased consumption and digestibility of DM, CP, and energy. Increased total TDP and energi ratio. Livestock BW is better maintained. Rumen bacterial and fungal populations increase. Protozoa populations tend to decrease. The number of parasite eggs in feces decreases significantly.
(Khampa *et al*., 2009)	Supplementation of cassava hay 1 kg $days^{-1}$	Cassava hay supplementation significantly reduced the number of parasite eggs in feces, with a reduction comparable to that of ivermectin treatment. Daily ADG of buffalo fed cassava hay was not significantly different from that of buffalo fed ivermectin. Nutrient digestibility, particularly dry matter and organic matter, tended to be higher in the cassava hay treatment. The anthelmintic effect of cassava hay is attributed to its condensed tannin content, which inhibits the development and hatching of parasite eggs and increases the flow of undegraded protein to the intestine.
(Oni *et al*., 2010)	Substituting *Panicum maxima* with dried cassava leaves 60%	Increased DM intake. Increased apparent digestibility of CP and EE. Decreased apparent digestibility of DM, NDF, and ADF. Resulted in a higher nitrogen balance. The inclusion level of dried cassava in the diet can be up to 60% level in a compounded ration for ruminant animals on DM basis.
(Régnier *et al*., 2012)	25% cassava leaf silage as forage	DMD increased by approximately 8.6%, and OMD increased by approximately 8.6%. VFA and NH_3 concentrations increased, while ruminal pH remained within the optimal range.
(Lunsin *et al*., 2012)	13% in concentrate Lactating dairy cows	Increases DMI and NDF. Increases total VFA and the population of cellulolytic rumen bacteria (*F. succinogenes, R. flavefaciens*). Does not decrease milk production and composition, and even tends to increase milk production and FCM.
(Roza *et al*., 2015)	Supplementation of dried cassava leaves 5 kg $days^{-1}$ in lactating buffalo	Increase the levels of erythrocytes, hemoglobin and hematokrit in the blood, but has no influence on the leucocyte levels which remain within the normal range.
(Syahniar *et al*., 2018)	100% silage evaluated In vitro	DMD increased by approximately 58.3% and OMD by 31.9%. No significant effects were observed on ruminal fluid characteristics.
(Wanapat *et al*., 2018)	Supplementation of cassava leaves silage 2.25 kg $days^{-1}$ in lactating dairy cows	Increase milk production 1.3-2.6 kg $days^{-1}$. Significantly affected ruminal fermentation end-products, especially increased propionate production, decreased protozoal population and suppressed methane production.
(Artanti *et al*., 2019)	Dried cassava leaf or silage cassava leaf	Dried cassava leaf or silage cassava leaf Increased on DMI, CP, and TDN. Increased digestibility, body weight gain, and feed efficiency.

Table continues on next page...................

Author	Treatment	Research findings
(Viennasay *et al*., 2019)	100% cassava leaf silage as a substitute for rice straw for male dairy cattle	Improved rumen fermentation. Rumen protozoa populations decreased significantly, while rumen bacterial populations remained relatively stable, creating more efficient fermentation conditions. Increased digestibility of DM, OM, CP, NDF, and ADF.
(Suharti *et al*., 2021)	30% Bitter cassava leaf	Cassava leaf feed inoculated with cyanide-degrading bacteria (CDB): Increases BWG and feed efficiency. Increases the total rumen bacterial population. Helps detoxify cyanide from bitter cassava leaves.
(Nascimento *et al*., 2021)	Substitution of 25 g kg^{-1} DM cassava silage in the diet of dairy goats	Improved digestibility. Increased milk yield and improved milk quality. Enhanced feed efficiency.
(Roza *et al*., 2021)	Supplementation of dried cassava leaves 5 kg $days^{-1}$ in lactating buffalo	Increase blood protein, blood glucose, and buffalo milk production levels, and they do not affect the prolactin hormone. Increase milk production.
(Winarti *et al*., 2022)	Substitution of 20–25% cassava leaf meal in the concentrate of Ongole cattle	Increased DMI, BW, and feed ratio.
(Siska *et al*., 2025)	Substitution of forage with 30% cassava leaves with bamboo activated charcoal treatment	Enhanced milk production and production efficiency. Improved hematological profiles. Improved milk quality.

Note: DMD = Dry matter digestibility; OMD = Organic matter digestibility; VFA = Volatile Fatty Acids; FCM = Fat-Corrected Mil; SNF = Solid nonfat; VFA = Volatile Fatty Acids; TDN = Total Digestible Nutrients; HCN = Hydrogen Cyanide; BW = Body Weight; TDP = Total Digestible Protein; ADG = Body Weight Gain.

Tannins may be partially neutralized by salivary proteins prior to rumen entry through hydrogen bonding and hydrophobic interactions, resulting in the formation of insoluble tannin protein complexes in the oral cavity or esophagus (Alonso-Díaz *et al*., 2010, 2012; Makkar, 2003; Ventura-Cordero *et al*., 2017). This pre-ruminal binding decreases tannin solubility and reactivity, thereby limiting interactions with dietary proteins, rumen enzymes, and microorganisms (Besharati *et al*., 2022; Mueller-Harvey *et al*., 2019). Although proline-rich proteins (PRPs) are generally regarded as the primary tannin-binding salivary proteins, goats are reported to lack PRPs while still exhibiting high tannin-binding capacity, suggesting the involvement of alternative salivary proteins, including histatin-like or other polar and charged protein fractions (Alonso-Díaz *et al*., 2012; Lamy *et al*., 2011; Ventura-Cordero *et al*., 2017). Through pre ruminal tannin binding, salivary proteins protect dietary proteins, enhance nitrogen availability for microbial fermentation, reduce microbial inhibition, support fiber degradation and volatile fatty acid production, and alleviate oral astringency, thereby contributing to the maintenance of feed intake (Mlambo *et al*., 2015; Shimada, 2006).

This salivary defense mechanism operates in synergy with post-ingestive processes in the rumen, where adapted microbial populations further degrade residual tannins and phenolic compounds into less toxic metabolites (Makkar, 2003; McSweeney *et al*., 2001). Goats consuming tannin-rich diets develop specific rumen microbial communities that enhance tannin degradation and digestive efficiency, indicating that tannin tolerance arises from the integration of salivary protein interactions, microbial adaptation, and feeding behavior rather than a single physiological mechanism (Alonso-Díaz *et al*., 2010; Makkar, 2003; McSweeney *et al*., 2001). Consequently, salivary tannin neutralization constitutes an important adaptive strategy supporting the utilization of tannin-rich feed resources, such as cassava leaves, in sustainable ruminant production systems.

Within the rumen, tannins interact with microbial proteins and enzymes, leading to reduced protein degradation, inhibition of microbial growth, and suppression of specific microbial groups, including proteolytic bacteria, protozoa, fibrolytic bacteria (*Ruminococcus albus* and *R. flavefaciens*), and methanogenic archaea, thereby decreasing ruminal NH_3-N concentrations and methane production (McSweeney *et al*., 2001; Min and Hart, 2003; Mueller-Harvey *et al*., 2019). Despite these antimicrobial effects, prolonged exposure to tannins induces microbial adaptation through shifts in community composition and physiological traits, including the proliferation of tannin-tolerant bacteria, production of extracellular polysaccharides or tannin-binding proteins, and synthesis of tannase enzymes capable of degrading hydrolysable tannins (Makkar, 2003; Mueller-Harvey, 2006; Mueller-Harvey *et al*., 2019; Schmitt *et al*., 2020).

Microbial adaptation to tannins is strongly influenced by dietary history, duration of exposure, and tannin structure, with condensed tannins of lower molecular weight generally permitting greater microbial adaptation than highly polymerized forms (Frutos *et al*., 2020; Mueller-Harvey, 2006). From a nutritional standpoint, such adaptation underpins the strategic use of tannin-containing feeds as natural protein protectants by increasing the flow of undegraded dietary protein to the small intestine without substantially compromising rumen fermentation, provided that tannin levels remain within the adaptive capacity of the rumen microbiota (Frutos *et al*., 2020; Jayanegara *et al*., 2009; Min and Hart, 2003).

CONCLUSION

By-product cassava (*Manihot esculenta* Crantz) or Cassava leaves are valuable agricultural by-products with strong potential as sustainable feed resources for ruminant livestock due to their high crude protein content, essential minerals, vitamins, and fermentable carbohydrates. However, the presence of anti-nutritional factors, particularly HCN and condensed tannins, remains the main limitation to their direct use. This review confirms that appropriate processing methods such as wilting, sun-drying, boiling, fermentation, ensiling, and ammoniation are effective in reducing HCN and tannin concentrations to safe levels, thereby improving nutrient digestibility, rumen fermentation, feed intake, and animal performance. Furthermore, moderate levels of condensed tannins exert beneficial effects by protecting dietary protein from excessive ruminal degradation, enhancing nitrogen utilization, and improving milk yield and quality. Properly processed cassava leaves therefore represent a viable alternative protein source that supports feed cost reduction, circular bioeconomy principles, and sustainable ruminant production systems.

At an industrial scale, cassava leaves offer significant opportunities as a sustainable, protein-rich ruminant feed that supports feed cost reduction and circular bioeconomy principles, but their utilization is constrained by variability in HCN and tannin contents, the need for standardized processing and quality control, and logistical challenges related to large-scale preservation and safety assurance.

RECOMMENDATIONS

Processing-based functional feeding strategies: Cassava leaves should be included in ruminant rations only after being processed using methods specifically selected to optimize tannin function, not simply to remove antinutritional factors. The selection of the most appropriate cassava leaf processing method can be tailored to specific feeding objectives, as different livestock species, growth stages, and production objectives require different nutritional standards.

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NOVELTY STATEMENT

The novelty of this review lies in its integrative synthesis of nutritional, antinutritional, processing, and physiological evidence that repositions cassava leaves from a high-risk by-product to a safe and functional protein source for ruminant feeding. This article emphasizes a processing-driven functional feeding strategy that optimizes condensed tannin functionality rather than focusing solely on detoxification, providing practical relevance for sustainable livestock systems in tropical regions.

AUTHOR'S CONTRIBUTION

Imelda Siska: Designed the manuscript, wrote the manuscript and revising the manuscript and approved the final manuscript.

Yoshi Lia Anggrayni: Help the first author revising the manuscript and approved the final manuscript.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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