Agriculture and Food

AIMS Agriculture and Food, 10(4): 917–930.
DOI: 10.3934/agrfood.2025047
Received: 14 August 2025
Revised: 14 November 2025
Accepted: 27 November 2025
Published: 05 December 2025

https://www.aimspress.com/journal/agriculture

Research article

Papaya peel enhances fermentation and ruminal digestibility of corn straw silage

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Abstract: The use of food and agricultural by-products in animal nutrition is gaining attention as a viable strategy to address livestock feed shortages, lower feed costs, and reduce environmental pollution. This study evaluated the fermentation characteristics, nutritional value, and in vitro ruminal digestibility of corn straw silage supplemented with papaya peel at 0 (control), 15, 30, and 45% on a fresh-weight basis. Crude protein content increased significantly at the higher inclusion levels of papaya peel (30% and 45%) compared to the control ($p < 0.05$). The organic matter and acid detergent fiber contents of papaya peel–treated silages were lower than those of the control silage ($p < 0.05$). Neutral detergent fiber content was higher in the control and 15% papaya peel–treated silage than in those treated with 30 or 45% papaya peel ($p < 0.05$). Total digestible nutrients and relative feed values were significantly improved by papaya peel addition compared to the control silage ($p < 0.05$). Silage with 15% papaya peel had a significantly lower pH and higher lactic and acetic acid contents than the other silages ($p < 0.05$). Compared with the control silage, papaya peel–treated silages showed higher in vitro ruminal dry matter digestibility, with the 15% treatment showing significantly greater digestibility than that of the control silage ($p < 0.05$). The control silage had significantly higher H_2 production than the papaya peel–treated silage ($p < 0.05$). Our findings demonstrated that papaya peel addition enhanced fermentation and nutrient digestibility of corn straw silage, with 15% papaya peel inclusion achieving the highest fermentation efficacy and ruminal digestibility.

Keywords: corn straw; papaya peel; silage quality; in vitro ruminal digestion

1. Introduction

In recent years, with the continuous promotion of straw feed utilization in China, the development of effective technologies to enhance the nutritional value of straw has become a key area of research. Corn straw, an abundant and cost-effective agricultural by-product, is widely used as a coarse fodder for ruminant animals in China [1]. Research demonstrates that bioprocessing treatments like ensiling and fermentation significantly improve the nutritional value of feed materials by enhancing their digestibility and nutrient availability [2]. The ensiling process directly alters digestive-fermentative parameters [3], and the use of specific additives further improves both the fermentation quality and nutritional characteristics of the silage [4,5]. In practice, corn straw is often fermented for use as animal feed. Lactic acid bacteria (LAB) play a vital role in enhancing silage quality through their contributions to the fermentation process [6]. During fermentation, LAB convert water-soluble carbohydrates (WSC) into organic acids, which rapidly reduce the pH and effectively inhibit the proliferation of pathogenic bacteria, consequently augmenting both the nutritive value and utilization efficiency of corn straw silage [7,8]. Although corn straw is rich in carbohydrates and serves as a roughage for ruminants, its utilization is limited by its low crude protein content, poor digestibility, and high lignin levels, which limit fiber digestion and lead to poor silage quality during fermentation [9]. LAB inocula play a key role in the preservation and fermentation of forage crops within inoculated silages [10]. However, the production of high-quality silage using conventional methods remains difficult because of corn straw nutrient content and limited population of naturally occurring LAB [11]. In recent years, co-ensiling has emerged as an innovative approach to preserve nutrients and improve silage quality, offering advantages over single-forage fermentation [12,13]. Therefore, to achieve ideal silage fermentation, co-ensiling and LAB inoculants are often employed when ensiling corn straw. Thus, ruminants can effectively utilize corn straw if its nutritional value is improved using effective conservation methods.

Papaya (*Carica papaya* L.), native to tropical America and belonging to the *Caricaceae* family, is a key fruit crop widely grown in tropical and subtropical areas [14,15]. Papaya fruits are highly nutritious, mainly consisting of water and carbohydrates, and are rich in potassium, vitamins A and C, and other essential nutrients [16–18]. During the industrial processing of papaya into dried fruits, juice, and other derivative products, substantial quantities of by-products are generated. Among these, the peel accounts for approximately 12–36% of the total fruit weight [19,20]. Papaya peel serves as a natural source of valuable nutrients, owing to the rich bioactive components present in papaya fruit [21]. It is rich in bioactive compounds, such as polyphenols and carotenoids, which are known for their health-promoting properties, and contains a high content of nutrients, such as crude protein, vitamins, minerals, and fiber, making it a value-added feed for livestock [22]. Economic and environmental concerns are driving the demand for the efficient use of food by-products. However, the high moisture content of papaya peel renders it highly perishable, highlighting the need for technologies that enable its long-term storage and preservation.

Ensiling, a common method for preserving fresh forage, can be adapted to preserve and prepare papaya peel silage. However, the high moisture content of papaya peel can cause ensiling failure. Therefore, low-moisture materials should be added to papaya peel ensiling systems to improve silage quality. Furthermore, mixed ensiling has proven to be an effective strategy for improving silage quality and fermentation stability compared to ensiling corn straw alone [23]. Incorporating pineapple residues into corn straw silage enhances its quality and increases the relative abundance of *Lactobacillus* spp. [24]. Similarly, adding orange waste to corn straw enhances the silage nutritional value [25]. Notably, feed utilization of by-products is of great importance in herbivore livestock husbandry, as it can alleviate forage shortages and environmental issues. Among the various co-ensiling materials, papaya peel has attracted interest as a potential silage ingredient [26,27]. As a by-product of papaya processing, its use in silage offers a sustainable approach to waste reduction while providing an additional feed resource [28.29]. Based on this, we hypothesized that ensiling corn straw with papaya peel would prevent undesirable fermentation and enhance silage quality, promoting the efficient use of locally available feed resources. However, to the best of our knowledge, limited information is available regarding the fermentation quality and in vitro ruminal digestion characteristics of corn straw silage combined with papaya peel.

Therefore, the objective of the present study was to evaluate the nutritional value, fermentation quality, and in vitro ruminal digestion characteristics of corn straw ensiled with varying levels of papaya peel.

2. Materials and Methods

2.1. Ethics approval of research

The care and management of buffaloes adhered to the guidelines of the Ethics Committee of the Buffalo Research Institute, Guangxi Zhuang Nationality Autonomous Region, China (Approval Number BRI-20241212).

2.2. Ensiling materials and silage preparation

Corn straw was harvested from cultivation sites in Fusui County, Chongzuo City, Guangxi Zhuang Autonomous Region, China. Papaya peel was provided by Guangxi Huichuang Animal Husbandry Co. Ltd (Chongzuo, China). The peel was of high quality, free from molds, pests and diseases, and was washed before use to remove impurities such as soil, dust, and plastic residues. Both materials were cut into approximately 2 cm pieces, and their chemical compositions and microbial population are listed in Table 1. The experiment consisted of four groups with six replicates based on fresh matter (FM): 1) a control group (CON) without papaya peel, 2) 85% corn straw + 15% papaya peel (CP1), 3) 70% corn straw + 30% papaya peel (CP2), and 4) 55% corn straw + 45% papaya peel (CP3). After mixing the corn straw and papaya peel evenly, approximately 1 kg was placed in a fermentation bag. The mixture was sealed and stored at room temperature away from light and fermented for 45 days.

2.3. Chemical analysis

Samples of corn straw, papaya peel, and their silages were dried at 65 °C in a drying box with a blast circulation system (WGL-72BE; Jinan Senya Experimental Instrument Co., Ltd., Jinan, China) until a constant weight was attained. The dried samples were then ground to pass through a 1 mm sieve using a sample mill (800Y; Yongkang Boou Hardware Products Co., Ltd., Yongkang, China). Dry matter (DM; method 934.01), crude protein (CP; method 976.05), and ash (method 942.05) contents were determined according to the Association of Official Analytical Chemists procedures [30]. The organic matter (OM) content was determined by measuring the weight loss after ashing the sample. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed as described by Van Soest et al. [31]. The WSC content was measured using the anthrone colorimetric method described by Udén [32]. Total digestible nutrients (TDN) and relative feed values (RFV) were calculated through the following equations [33].

$$TND(\%) = (88.9 - ADF \times 0.779) \times 100 \quad (1)$$

$$RFV = (TDN \times 120/NDF)/1.29 \quad (2)$$

2.4. Fermentation characteristics analysis

Cold-water extraction was used to determine the silage fermentation products [34]. Specifically, 20 g of silage was homogenized with 180 mL of sterilized distilled water and incubated at 4°C overnight. The pH of the filtrate was measured using a glass electrode pH meter (PH8180-0-00; Smart Sensor Co., Ltd., Dongguan, China). Lactic, acetic, propionic, and butyric acid concentrations were determined using high-performance liquid chromatography with a 1260 Infinity II System (Agilent Technologies, Waldbronn, Germany) equipped with a Shodex RSpak KC-811 column (8.0 × 300 mm; Showa Denko K.K., Tokyo, Japan). Detection was performed at 210 nm, using a 3 mmol/L $HClO_4$ eluent. The flow rate was maintained at 1 mL/min, the column temperature at 50°C, and the injection volume was 5 µL. The NH_3–N content was measured using the indophenol method, as described by Byrne and McCormack [35]. LAB, yeasts, and molds in the silage were enumerated following the plate count method adapted from Cao et al. [36]. All plates were incubated at 30°C for 48 h. LAB counts were determined using De Man–Rogosa–Sharpe agar (Qingdao Hope Bio-Technology Co., Ltd., Qingdao, China), and yeasts and molds were cultivated on potato dextrose agar (Qingdao Hope Bio-Technology Co., Ltd,). Yeasts were distinguished from molds and bacteria based on their colony morphology and cell structure. Microbial populations were expressed as log_{10} colony-forming units per gram of fresh matter (lg CFU/g FM).

2.5. In vitro ruminal fermentation parameter analysis

Three healthy rumen-cannulated Murrah buffaloes in good physical condition (610 ± 10 kg) were used as rumen fluid donors. The animals were fed a basal diet twice daily at 08:00 and 15:00 with free access to water. The care and management of the buffaloes adhered to the guidelines of the Ethics Committee of the Buffalo Research Institute, Guangxi Zhuang Nationality Autonomous Region, China. Before the morning feeding, 1 L of rumen fluid was collected from each buffalo and strained through four layers of cheesecloth. The filtrates were pooled, mixed with CO_2-bubbled artificial saliva at a 1:4 ratio, and used to create buffered rumen fluid. The artificial saliva was prepared as described by Guo et al. [37]. For fermentation, 50 mL of buffered rumen fluid was added to 180 mL serum bottles containing 1 g of the sample. The bottles were flushed with CO_2 to maintain an anaerobic environment, sealed with butyl rubber stoppers and aluminum caps, and incubated at 39 °C for 72 h with shaking (100 strokes/min). Gas production was measured at regular intervals (3, 6, 12, 24, 36, 48, and 72 h) using an air syringe. H_2 and CH_4 production was analyzed using gas chromatography (GC; 8860, Agilent Technologies Co., Ltd., Shanghai, China) under the following conditions: column#1: 8Ft-5A capillary column 2.44 m × 0.2 mm × 0.25 µm (Agilent Technologies), column#2: 6Ft-N capillary column 1.83 m × 0.2 mm × 0.25 µm (Agilent Technologies); injection:10 µL, injection temperature 100 ℃, carrier gas: N_2, flow: 20 mL/min, and column temperature: 50 ℃, held for 2 min. After 72 h of incubation, the fermentation bottles were removed and immediately cooled in ice water for 10 min to terminate fermentation. The pH was measured immediately after opening using a glass electrode pH meter. The volatile fatty acids (VFAs) were determined using GC (7890A; Agilent Technologies Co., Ltd., Waldbronn, Germany), as outlined by Azizi et al. [38], using the following conditions: A capillary column (No.34292-07B, 30 m× 0.32 mm × 0.25 μm film thickness) was used with a column temperature of 130 °C and a vaporization temperature of 180 °C. Detection was performed using a hydrogen flame ionization detector at 180 °C. The carrier gases were nitrogen at 60 KPa, and hydrogen and oxygen at 50 KPa each. To assess in vitro DM digestibility (IVDMD), the contents in the fermentation vessels were filtered using pre-weighed nylon bags with a pore size of 0.0425 nm, and the residue in the bottles was thoroughly washed with hot distilled water. Subsequently, the nylon bags containing the washed residues were dried at 105 °C until a constant weight was attained. IVDMD was calculated using the formula described by Xie et al. [39].

2.6. Statistical analyses

Data were analyzed using a general linear model in SAS software (version 9.2; SAS Institute Inc., Cary, NC, USA). A one-way analysis of variance (ANOVA) was performed to evaluate differences between treatment means, and Duncan's multiple range test was used for post-hoc comparisons. Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Chemical composition of raw material and silage

Before ensiling, papaya peel contained lower contents of DM, OM, NDF, ADF, and yeast counts, but higher CP, WSC, RFV, and TDN contents as well as LAB counts than corn straw (Table 1).

Table 1. Chemical composition and microbial population of papaya peel and corn straw before ensiling.

Item	Papaya peel	Corn straw
Chemical composition		
DM (%)	5.77	26.6
CP (% DM)	32.8	12.9
OM (% DM)	89.5	91.6
NDF (% DM)	34.2	62.2
ADF (% DM)	16.4	36.6
WSC (% DM)	12.0	8.27
TDN (% DM)	76.1	60.4
RFV	431	153
Microbial population		
LAB (lg CFU/g FM)	5.47	5.03
Yeasts (lg CFU/g FM)	4.39	4.87
Molds (lg CFU/g FM)	ND	ND

Note: ADF, acid detergent fibre; CP, crude protein; DM, dry matter; LAB, Lactic Acid Bacteria; ND, not detected; NDF, neutral detergent fibre; OM, organic matter; RFV, relative feed value; TDN, total digestible nutrients; WSC, water-soluble carbohydrates.

The highest DM content was observed in corn straw silage without additives, followed by those treated with 15, 30, and 45% papaya peel ($p < 0.05$; Table 2). The CP content increased significantly with increasing papaya peel levels in the silage ($p < 0.05$). The OM and ADF contents of the silages treated with papaya peel were lower than those of the control silage ($p < 0.05$). However, the silage treated with 45% papaya peel had significantly higher OM and ADF contents than those treated with 15 and 30% papaya peel ($p < 0.05$). The NDF content was higher in control and 15% papaya peel-treated silages than in those treated with 30 or 45% papaya peel ($p < 0.05$). The WSC content did not differ significantly among the four silage groups ($p > 0.05$). Compared with the control silage, corn straw silage treated with papaya peel exhibited significantly higher TDN and RFV contents ($p < 0.05$), increasing in the following order: control silage < 15% < 30% < 45% papaya peel-treated silage.

Table 2. Chemical composition of corn straw silage supplement with papaya peel.

Item	Silage†				SEM	P-Value
	CON	CP1	CP2	CP3		
DM (%)	23.6^{a}	20.8^{b}	18.1^{c}	15.3^{d}	0.18	<0.0001
CP (% DM)	12.9^{d}	14.4^{c}	16.3^{b}	17.8^{a}	0.17	<0.0001
OM (% DM)	91.3^{a}	90.0^{b}	89.8^{b}	89.1^{c}	0.15	<0.0001
NDF (% DM)	62.4^{a}	62.0^{a}	59.7^{b}	55.2^{c}	0.31	<0.0001
ADF (% DM)	37.6^{a}	36.1^{b}	35.4^{b}	33.6^{c}	0.31	<0.0001
WSC (% DM)	6.35	6.86	7.29	7.57	0.59	0.50
TDN (% DM)	59.6^{c}	60.8^{b}	61.3^{b}	62.7^{a}	0.24	<0.0001
RFV	147^{c}	156^{b}	160^{b}	173^{a}	1.99	<0.0001

Note: Means with different lowercase superscripts in the same row differ significantly ($p < 0.05$) among the treatments. ADF, acid detergent fibre; CP, crude protein; DM, dry matter; NDF, neutral detergent fibre; OM, organic matter; RFV, relative feed value; SEM, standard error of the mean; TDN, total digestible nutrients; WSC, water-soluble carbohydrates. †Silage, corn straw with 0% (CON), 15% (CP1), 30% (CP2), or 45% (CP3) papaya peel based on fresh weight.

3.2. Fermentation characteristics of silage

Table 3. Fermentation quality and microbial compositions of corn straw silage supplemented with papaya peel.

Item	Silage†				SEM	P-Value
	CON	CP1	CP2	CP3		
pH	4.19^{a}	4.08^{c}	4.13^{b}	4.23^{a}	0.01	<0.0001
Lactic acid (g/kg DM)	46.7^{b}	50.3^{a}	44.2^{b}	39.1^{c}	3.60	0.007
Acetic acid (g/kg DM)	16.7^{b}	19.2^{a}	16.2^{b}	15.3^{b}	0.60	0.001
Propionic acid (g/kg DM)	0.91	1.27	1.01	0.85	0.15	0.30
Butyric acid (g/kg DM)	ND	ND	ND	ND	–	–
NH_3–N (g/kg DM)	1.76	1.70	1.79	1.84	0.04	0.14
LAB (lg CFU/g FM)	6.45^{b}	6.86^{a}	6.73^{ab}	6.60^{ab}	0.10	0.02
Yeasts (lg CFU/g FM)	5.80	5.53	5.66	5.57	0.16	0.63
Molds (lg CFU/g FM)	ND	ND	ND	ND	–	–

Note: Means with different lowercase superscripts in the same row differ significantly ($p < 0.05$) among the treatments. DM, dry matter; FM, fresh matter; LAB, Lactic Acid Bacteria; ND, not detected; SEM, standard error of mean. †Silage, corn straw with 0% (CON), 15% (CP1), 30% (CP2), or 45% (CP3) papaya peel based on fresh weight.

Corn straw silage treated with 15% papaya peel had a significantly lower pH and the highest concentrations of lactic and acetic acids compared to the other silages ($p < 0.05$; Table 3). However, the propionic acid, NH_3–N contents, and yeast counts did not differ significantly among the four treatments ($p > 0.05$). The LAB count in silage treated with 15% papaya peel was higher than that in the control silage ($p < 0.05$). Butyric acid and molds were not detected in any of the silages.

3.3. In vitro ruminal fermentation parameters of silage

Papaya peel–treated silages exhibited higher IVDMD than the control silage. Moreover, the IVDMD of silage treated with 15% papaya peel was significantly higher than that of the control silage ($p < 0.05$; Table 4). H_2 production was significantly lower in papaya peel-treated silages than in the control silage ($p < 0.05$). The pH of silage treated with 30% and 45% papaya peel was significantly higher than that of the control silage ($p < 0.05$). The total VFA concentration was significantly higher in the control silage than in the 45% papaya peel-treated silage ($p < 0.05$). The propionate acid content in the control silage was significantly higher than that in the silages treated with 30 and 45% papaya peel ($p < 0.05$). Accordingly, the highest acetate-to-propionate ratio was observed in silages treated with 45 and 30% papaya peel, followed by those treated with 15% papaya peel and the control silage ($p < 0.05$). However, total gas production, CH_4 production, and acetate, isobutyrate, butyrate, isovalerate, valerate, and NH_3–N concentrations did not differ among the four silages ($p > 0.05$).

Table 4. In vitro ruminal dry matter digestibility, gas production, and fermentation characteristics of corn straw silage supplemented with papaya peel.

Item	Silage†				SEM	P-Value
	CON	CP1	CP2	CP3		
IVDMD (%)	49.2[b]	52.7[a]	50.0[ab]	51.1[ab]	1.00	0.017
Gas production (mL/g DM)						
Total	76.2	78.8	77.8	77.3	1.29	0.74
H_2	0.26[a]	0.16[b]	0.19[b]	0.15[b]	0.02	0.002
Methane	15.5	15.4	16.1	15.7	0.34	0.55
pH	6.56[c]	6.58[bc]	6.60[ab]	6.61[a]	0.01	0.002
VFAs (mmol/L)						
Total	20.6[a]	19.0[ab]	18.9[ab]	18.0[b]	0.77	0.14
Acetate	10.4	9.81	9.95	9.56	0.35	0.40
Propionate	6.93[a]	6.14[ab]	5.85[b]	5.48[b]	0.27	0.009
Isobutyrate	0.19	0.17	0.17	0.16	0.02	0.55
Butyrate	2.40	2.23	2.22	2.14	0.10	0.31
Isovalerate	0.43	0.39	0.41	0.39	0.03	0.77
Valerate	0.30	0.27	0.29	0.27	0.02	0.43
Acetate/propionate	1.50[c]	1.61[b]	1.70[a]	1.75[a]	0.02	<0.0001
NH_3–N (mg/L)	69.3	70.8	72.1	72.7	1.79	0.56

Note: Means with different lowercase superscripts in the same row differ significantly ($p < 0.05$) among the treatments. DM, dry matter; IVDMD, in vitro ruminal dry matter digestibility; SEM, standard error of the mean; VFAs, volatile fatty acids.

4. Discussion

4.1. Chemical composition of raw material and silage

Chemical composition is a critical indicator of silage quality in practical production, and the nutritional composition of raw materials is crucial for the success of silage [40]. In the present study, DM content differed significantly between fresh papaya peel and corn straw at 5.77 and 26.60%, respectively. The CP content of papaya peel was higher than that reported by Pathak et al. [20] before ensiling. These differences likely resulted from variations in cultivation regions, climate, and ripening stages. Moreover, papaya peel exhibited higher CP, WSC, RFV, and TDN contents than corn straw, suggesting its potential as a livestock feed resource. The raw material DM and WSC contents, along with its epiphytic microbiota, significantly influence silage quality [41]. High-quality silage generally requires a DM content of 30 - 40% [42]. The higher WSC content of papaya peel compared to corn straw provides a suitable substrate for LAB fermentation, stimulating the acidification process in silage. In contrast, the high DM content of rice straw may reduce effluent loss in papaya peel when ensiled alone, a finding consistent with studies on other fruit by-products, such as banana [43]. Consequently, given their chemical compositions, we attempted to use these two raw materials in an ensiling system to produce high-quality silage. In the current study, the highest DM content was observed in corn straw silage without additives, followed by silages treated with 15, 30, and 45% papaya peel. This may be because the DM content of corn straw was greater than that of papaya peel. The CP, TDN, and RFV contents increased significantly, whereas the OM and ADF contents decreased with increasing papaya peel levels in the silage compared to those in the control silage. This may be because papaya peel possesses superior nutritional properties, such as higher CP, WSC, RFV, and TDN, than corn straw, indicating that papaya peel addition enhances nutrient complementation between the raw materials, thereby improving the overall quality of corn straw silage. These results support the conclusion of Wang et al. [25] that incorporating various fruit and vegetable residues into maize stover can improve silage value. In general, adequate WSC levels (≥5% DM) are essential for achieving satisfactory fermentation quality in the production of high-quality silage [44]. Another study demonstrated that co-ensiling rice straw with whole sugar beet improves WSC availability, fermentation efficiency, and animal intake [45]. In the present study, the WSC content did not differ remarkably among the four silages. However, the addition of papaya peel led to a slight increase in the WSC content of corn straw silage, achieving 6.35–7.57% DM, thereby ensuring proper fermentation in all silage.

4.2. Fermentation characteristics of silage

Silage quality is typically influenced by the type of raw material, storage temperature, and type and quantity of epiphytic LAB [46]. During fermentation, LAB convert starch and sugars into lactic acid, which lowers the pH and inhibits the growth of harmful bacteria such as butyrate-producing bacteria, *Escherichia coli*, and molds, thereby enhancing silage quality [47]. In the present study, silage treated with 15% papaya peel had a significantly lower pH, the highest lactic and acetic acid contents, and a higher LAB count than the other silages. This indicated that 15% papaya peel was the optimal inclusion level, ensuring satisfactory fermentation and the highest fermentation efficacy. Furthermore, papaya peel contains a higher WSC content than corn straw, providing more substrate for LAB to convert into lactic acid during fermentation, thereby improving fermentation quality. In contrast, papaya peel has higher CP, TDN, and RFV and lower DM, NDF, and ADF, which can complement the nutrients of the two raw materials. However, the DM content of forage during ensiling substantially affects silage fermentation, feed intake, and animal performance [48]. The poor fermentation quality of forage silages is often associated with high moisture content; therefore, substances (such as papaya peel) with high moisture content cannot be added in excess. Papaya peel is a rich natural source of papain [49]. Plant proteases and harmful microbes play crucial roles in proteolysis [50]. However, in this study, propionic acid and NH_3–N contents and yeast counts did not differ significantly among the four silages. Furthermore, butyric acid and molds were not detected in any of the silages. This indicated that low pH and high lactic acid levels reduced protein degradation and suppressed undesirable spoilage bacteria. These results demonstrate that the addition of papaya peel improved the fermentation quality of corn straw silage.

4.3. In vitro ruminal fermentation parameters of silage

An important indicator of the nutritional value of feed is its utilization in animal feed. Feed nutrient digestibility is affected by several factors, including dietary quality, animal intake, chyme flow rate, and rumen microbial activity [51]. IVDMD is a measure of feed digestibility in the rumen, with higher values indicating greater digestibility and nutritional value [52]. In the current study, papaya peel–treated silage showed a higher IVDMD. Furthermore, the IVDMD was significantly higher in silage treated with 15% papaya peel than in the control silage. This is likely because the incorporation of papaya peel enhanced the corn straw silage quality and supported the growth and activity of rumen microorganisms, thereby improving the digestion and nutrient absorption [53], with 15% being identified as the optimal level. In vitro gas production is commonly used to assess the nutritional value of ruminant feeds by incubating the substrate in buffered rumen fluid [54]. However, in this study, total gas production did not differ significantly among the treatments; silage with papaya peel tended to increase total gas production. These results indicate that the addition of papaya peel to corn straw silage enhances rumen fermentation. During the microbial fermentation of dietary carbohydrates in the rumen, H_2 is generated and subsequently utilized as an energy source by hydrogen-consuming microorganisms, particularly methanogens, which are responsible for methane production [55]. In the current study, the control silage had significantly higher H_2 production than the papaya peel-treated silage. This may be attributed to papaya peel, which contains bioactive compounds such as the digestive enzyme papain and has the potential to modulate rumen fermentation and enhance energy utilization in ruminants [56]. The rumen of ruminants effectively hydrolyses straw biomass, with microorganisms converting it into short-chain VFAs [57,58]. In the current study, corn straw ensiled alone had a higher VFAs content than corn straw ensiled with papaya peel. This may be attributed to the higher NDF and ADF contents in corn straw, which facilitate the breakdown of fiber into VFAs by rumen microorganisms. Rumen pH significantly influences anaerobic fermentation, thereby affecting the hydrolysis and acidogenesis processes of ruminal microorganisms [59]. In the present study, although the silage treated with 30% and 45% papaya peel exhibited a significantly higher ruminal fermentation pH than the control silage, the four silages maintained pH levels between 6.56 and 6.61, which is within the normal range of variation and does not disrupt microbial growth [60]. Ahmed et al. found a significant correlation between chemical composition of silage, in vitro rumen fermentation, and silage quality parameters, with pomegranate peels and molasses having potentially improved silage quality and positively influenced rumen fermentation parameters [61]. Our findings suggest that papaya peel-treated corn straw silage enhances ruminal digestion kinetics and possesses superior nutritional value.

5. Conclusions

Our results indicate that ensiling corn straw with papaya peel improves its utilization efficiency and fermentation quality. The optimum mixing ratio of corn straw to papaya peel was determined to be 85:15 (w/w). Silage prepared at these proportions exhibited improved fermentation quality and in vitro rumen fermentation characteristics compared to the other experimental groups. Nevertheless, additional research is required to evaluate the feeding value of this mixed silage in animal trials, including palatability and feed conversion efficiency.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

This work was supported by the National Key R&D Program of China (No.2024YFD1301304), the Guangxi Natural Science Foundation (2025GXNSFAA069166), and the Guangxi Dairy Buffalo Innovation Team of National Modern Agricultural Industry Technology System (nycytxgxcxtd-2021-21-03).

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, C.Y. and H.X.; methodology, H.X. and F.Z.; software, X.L., and J. L.; validation, C.Y., H.X. and L.L.; formal analysis, F.X., and F.Z.; investigation, H.X.; resources, L.Z.; data curation, X.L., and L.L.; writing—original draft preparation, H.X.; writing—review and editing, H.X. and C.Y.; supervision, C.Y.; project administration, H.X.; funding acquisition, H.X., and C.Y.

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