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Effects of conservation time and ingredient proportion on the nutritional composition and *in vitro* digestibility of *Musa* spp. silages for small ruminant feeding

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This study evaluated the effects of conservation time and ingredient proportion on the nutritional composition and *in vitro* digestibility of *Musa* spp. silages intended for small ruminant feeding. A 3×3 factorial design was applied, considering three conservation periods (60, 90, and 120 days) and three ingredient proportions (100% fruit, 70% fruit–30% crop residues, and 50% fruit–50% crop residues). Silage samples were analyzed for dry matter, crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), ether extract, ash, nitrogen-free extract (NFE), and *in vitro* dry matter digestibility (IVDMD). Ingredient proportion significantly affected CP content, which ranged approximately from 3.4 to 6.9% of dry matter, whereas IVDMD varied between 50.8 and 74.2%, with the highest values observed in silages produced with 100% fruit at 90 days of conservation ($p < 0.05$). NDF and ADF contents ranged from 30–40% and 15–35% of dry matter, respectively, showing a significant interaction between conservation time and ingredient proportion. Principal component analysis clearly discriminated treatments according to their nutritional composition and digestibility attributes. Overall, the results demonstrate that both conservation time and ingredient proportion play a decisive role in determining the nutritional and digestive quality of *Musa* spp. silages, supporting their potential use as a strategic feeding alternative for small ruminants in tropical production systems.

KEYWORDS
conservation time, *in vitro* digestibility, ingredient proportion, *Musa* spp. silage, nutritional composition

1 Introduction

In Peru, goat farming plays a significant socioeconomic role, particularly in coastal and highland regions. However, its productive potential is limited by several factors, including the low availability of feed resources during periods of scarcity, which directly affects animal productivity and health (Nguyen Thiet et al., 2022). This situation is especially critical in regions such as Tumbes, where climatic variability and limited access to supplementary feeding strategies exacerbate nutritional constraints (Reyes Quimi, 2015).

The use of agricultural residues derived from the cultivation and processing of *Musa* spp. has been proposed as a sustainable strategy to support feed supply in goat production systems. Banana is the fourth most important crop worldwide, and in Peru its annual production reaches approximately 1.45 million tons, with nearly 30% classified as agricultural waste, including stalks, leaves, and non-marketable fruits (MINAGRI, 2018). These by-products contain fermentable carbohydrates, particularly in fruits, and low crude protein concentrations, while vegetative residues such as pseudostems and leaves are characterized by higher fiber fractions than banana pulp and similarly low protein content (Zaini and Pindi, 2024), which limits their direct inclusion in animal diets (Vera Rodríguez et al., 2021; Macay Anchundia et al., 2023; Salim et al., 2021; Ly, 2004).

The direct use of *Musa* spp. residues in animal diets presents several limitations related to their rapid degradation, variability in nutritional quality, and low palatability (Caicedo et al., 2020; Arpíz-Guerrero et al., 2012). To overcome these constraints, conservation techniques such as silage have been explored as an effective preservation strategy (Macay Anchundia et al., 2023). Ensiling promotes anaerobic fermentation that stabilizes nutrient availability (Estrada, 2020; Koni et al., 2024; Caicedo et al., 2017; Borreani et al., 2018).

Silage has proven particularly suitable for carbohydrate-rich agricultural residues such as *Musa* spp., as it enhances feed preservation and optimizes nutrient utilization by livestock (Rodrigues et al., 2019; Hao et al., 2021). Previous studies evaluating plantain and banana silages have reported crude protein ranging from 6–12%, dry matter content above 30%, and improvements in *in vitro* dry matter digestibility after fermentation periods exceeding 60 days (Álvarez et al., 2015; Wang et al., 2016a). Studies conducted in tropical systems indicate that fermentation time influences pH decline, microbial stabilization, and fiber degradation, which may directly affect digestibility outcomes (Bustamante Hoyos, 2015; Bernardes et al., 2018).

Goat production systems, predominantly characterized by smallholder management, require sustainable and low-cost feeding strategies that can be integrated into existing practices. In this context, *Musa* spp. silages offer a potential alternative to conventional feed resources during drought periods and feed shortages (Nguyen Thiet et al., 2022; Rusdy, 2019). Digestibility is a key factor influencing goat productivity, as it determines nutrient assimilation and ultimately affects animal performance and health status (Roig, 2020).

The digestibility of a feed depends on both its chemical composition and its pretreatment. Studies have reported that *Musa* spp. residues ensiled present improved nutrient bioavailability and increased *in vitro* digestibility after fermentation periods longer than 60 days (Zaini and Pindi, 2024; Rodrigues et al., 2019). Such improvements may contribute to reducing feeding costs by partially substituting conventional feed inputs with accessible agricultural by-products (Estrada, 2020; Cevallos-López et al., 2025).

Despite these advances, most previous investigations have examined fermentation time and ingredient proportions independently. However, fermentation dynamics are influenced by the interaction between substrate availability and conservation period, which may modify microbial activity, acid production, and fiber degradation patterns. Consequently, the interactive effects of conservation time and ingredient proportion on the nutritional quality and *in vitro* digestibility of *Musa* spp. silages remain insufficiently characterized, particularly under conditions relevant to smallholder goat production systems.

Therefore, this study aimed to evaluate the nutritional properties and *in vitro* digestibility of silages produced from discarded *Musa* spp. fruits and stubble using different ingredient proportions and fermentation times, in a factorial arrangement to determinate whether specific combinations of these factors optimize nutrients preservation and digestive potential.

We hypothesize that (i) conservation time and ingredient proportion would interactively influence the chemical composition and *in vitro* digestibility of *Musa* spp. silages, and (ii) particular combinations of these factors would maximize nutrient availability for small ruminants feeding under tropical conditions.

2 Materials and methods

2.1 Study area

The present study was carried out at Estación Experimental Agraria Los Cedros from Instituto Nacional de Innovación Agraria. This research center is located in the district of San Jacinto-Corrales, province of Tumbes, Tumbes region, Peru. The station is located at an altitude of 6 meters above sea level (masl), with geographical coordinates of latitude 3°37’41.85 “S and longitude 80° 34’9.36 “W (SENAMHI, 2024). Nutritional analyses were performed at the Food Nutritional Evaluation Laboratory (LENA) of the Universidad Nacional Agraria La Molina.

2.2 Raw materials and silage preparation

Discarded *Musa* spp. fruits and vegetative residues (pseudostems and leaves) were collected from local banana production areas. All materials were manually cleaned to remove soil and foreign matter prior to processing. The residues were then chopped into approximately 2–3 cm particle size to facilitate compaction and uniform fermentation. The 70:30 and 50:50 mixtures represent the proportion of discarded *Musa* spp. fruit to vegetative crop residues (pseudostems and leaves) on a dry matter basis.

Silages were prepared following a conventional anaerobic fermentation procedure. The chopped materials were weighed according to the experimental proportions and thoroughly mixed before ensiling. Each mixture was packed into airtight laboratory-scale plastic silos (20 L capacity), compacted manually to expel air, and sealed to ensure anaerobic conditions. The silos were stored at ambient temperature (approximately 26-30 °C) and allowed to ferment for the predefined conservation periods. At the end of each fermentation time, silos were opened, and representative samples were collected for chemical composition and *in vitro* digestibility analyses.

2.3 Experimental design

The population of the present study consisted of 36 experimental microsilos elaborated in a 3x3 factorial design, representing nine treatments combining proportions of discarded *Musa* spp. fruit and vegetative residues (pseudostems and leaves) in 100:0, 70:30, and 50:50 fruit-to-vegetative residue ratios on a dry matter basis with three storage times (60, 90 and 120 days). For each treatment, there were four replicates, obtaining a total of 36 samples.

2.4 Chemical and digestive analyses

Chemical analyses were conducted at the Laboratory of Nutritional Evaluation of Feeds, Faculty of Animal Science, Universidad Nacional Agraria La Molina (Lima, Peru), following standardized analytical procedures. Dry matter (DM), crude protein (CP), ether extract (EE), crude fiber, and ash were determined according to the methods of the Association of Official Analytical Chemists (AOAC, 2005; methods 950.46, 984.13, 963.03, 962.09, and 942.05, respectively).

Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed using the ANKOM filter bag technique (ANKOM Technology, 2005), following the detergent fiber system described by Van Soest et al.

In vitro dry matter digestibility (IVDMD) was determined using the DAISY II Incubator system (ANKOM Technology), based on the two-stage technique originally described by Tilley and Terry (1963) and subsequently modified by Van Soest (1970). This analysis was conducted at the Laboratory of Nutritional Evaluation of Feeds (LENA) of the Universidad Nacional Agraria La Molina (Lima, Peru), where rumen fluid inoculum was obtained and processed according to the laboratory's standardized protocols for *in vitro* incubation.

Rumen fluid used for *in vitro* incubation was supplied and handled by the Food Nutritional Evaluation Laboratory (LENA), Universidad Nacional Agraria La Molina, following its standardized procedures.

Samples were incubated for 48 h under anaerobic conditions.

2.5 Statistical analysis

A completely randomized 3 × 3 factorial design was applied, considering conservation time (60, 90, and 120 days) and ingredient proportion (100:0, 70:30, and 50:50 fruit-to-vegetative residue ratios of discarded *Musa* spp. on a dry matter basis). The design consisted of nine treatments with four replicates per treatment (36 plastic silos in total) where each plastic silo was considered the experimental unit. For each evaluated variable, data were analyzed using a two-way analysis of variance (ANOVA), including conservation time, ingredient proportion, and the interaction as fixed effects.

When significant effects were detected ($p < 0.05$), multiple mean comparisons were performed using Tukey's *post hoc* test. The magnitude of the effects of conservation time, ingredient proportion, and their interaction was quantified using partial eta squared (η^2p) as an effect size measure, which estimates the proportion of variance explained by each factor in factorial designs.

Additionally, a principal component analysis (PCA) was conducted as an exploratory multivariate approach to assess relationships among treatments, using previously standardized nutritional and digestibility variables. This analysis was applied exclusively for descriptive purposes and not for inferential statistical testing.

All statistical analyses were performed using R software (version 4.5.2). ANOVA and mean comparisons were conducted using the stats and emmeans packages, whereas PCA was performed using the FactoMineR and factoextra packages. Graphical visualization of results was carried out using the ggplot2 package.

3 Results

3.1 Effects of storage time and ingredient proportion on chemical composition and *in vitro* digestibility

The effects of storage time, ingredient proportion, and their interaction on the chemical composition and *in vitro* dry matter digestibility of *Musa* spp. silage are summarized in Table 1. Mean values (± SE) for the main effects of storage time and ingredient proportion are presented in Table 2.

Storage time and ingredient proportion affected the majority of nutritional parameters evaluated, although the magnitude and direction of the responses differed among variables.

3.2 Crude protein content

Crude protein content was significantly affected by storage time and ingredient proportion ($P < 0.05$), while the interaction between both factors was not significant (Table 1). Mean values are presented in Table 2.

Silages containing higher proportions of vegetative residues than fruit-only silages (70:30 and 50:50 fruit-to-stubble ratios) showed greater crude protein concentrations compared with silages formulated with 100% fruit (Table 2.). Across storage times, CP values varied within a relatively narrow range (4.79–5.96% DM).

3.3 Ash content

Ash concentration was significantly influenced by both storage time and ingredient proportion ($p < 0.001$), whereas their

TABLE 1 Effects of storage time, ingredient proportion, and their interaction on the chemical composition and *in vitro* digestibility of *Musa* spp. silage (two-way ANOVA).

Variable	Source of variation	df	F-value	p value	η^2 p
Crude protein (CP)	Time	2	3.66	0.039	0.43
	Proportion	2	57.11	<0.001	0.85
	Time × proportion	4	0.46	0.763	0.16
Ash	Time	2	10.05	<0.001	0.55
	Proportion	2	73.92	<0.001	0.92
	Time × proportion	4	1.32	0.288	0.41
Neutral detergent fiber (NDF)	Time	2	115.44	<0.001	0.9
	Proportion	2	0.41	0.652	0.03
	Time × proportion	4	164.11	<0.001	0.96
Acid detergent fiber (ADF)	Time	2	16.34	<0.001	0.55
	Proportion	2	145.95	<0.001	0.81
	Time × proportion	4	4.73	0.005	0.41
In vitro dry matter digestibility (IVDMD)	Time	2	3.25	0.054	0.19
	Proportion	2	39.02	<0.001	0.74
	Time × proportion	4	6.75	<0.001	0.5

Time: storage time (60, 90, and 120 days); Proportion: discarded fruit:crop residue ratio (100:0, 50:50, and 70:30); df: degrees of freedom; η^2p: partial eta squared (effect size). Significance declared at $p < 0.05$.

interaction was not significant (Table 1). Ingredient proportion accounted for most of the observed variability in ash content. Mean values are shown in Table 2.

Ash values increased with increasing inclusion of vegetative residues, with concentrations ranging from 3.81 to 9.22% DM depending on formulation (Table 2).

3.4 Fiber fractions (NDF and ADF)

Neutral detergent fiber and acid detergent fiber contents were significantly affected by storage time, ingredient proportion, and their interaction ($p < 0.01$; Table 1). The significant interaction indicates that fiber responses across storage times depended on ingredient proportion. NDF values ranged from 28.28 to 46.12% DM, while ADF values ranged from 13.75 to 20.74% DM across treatment combinations (Table 2).

3.5 Ether extract and nitrogen-free extract

Ether extract and nitrogen-free extract contents were significantly influenced by ingredient proportion and by the interaction between storage time and ingredient proportion ($p < 0.05$; Table 1). EE values ranged from 2.29 to 4.28% DM, whereas NFE values ranged from 68.11 to 85.44% DM depending on treatment (Table 2), reflecting differences in carbohydrate availability among formulations.

3.6 *In vitro* dry matter digestibility

In vitro dry matter digestibility was significantly affected by ingredient proportion and by its interaction with storage time ($p < 0.05$; Table 1), whereas the main effect of storage time alone was marginal. IVDMD values ranged from 52.20 to 67.31% depending on treatment combination (Table 2), IVDMD ranged from 52.20 to 67.31% depending on treatment combination (Table 2).

Principal component analysis showing associations among nutritional variables and sample distribution (Figure 1). The first two principal components explained most of the total variance, allowing a clear separation of silages primarily according to ingredient proportion and, to a lesser extent, storage time. Fiber-related variables (neutral detergent fiber and acid detergent fiber), ash, and crude protein showed positive loadings along the first principal component, whereas *in vitro* dry matter

TABLE 2 Effects of storage time and ingredient proportion on the chemical composition and *in vitro* dry matter digestibility of *Musa* spp. silage.

A) Main effect of storage time							
Conservation time (days)	CP (% DM)	EE (% DM)	Ash (% DM)	NDF (% DM)	ADF (% DM)	NFE (% DM)	IVDMD (%)
60	5.96 ± 0.28	2.52 ± 0.24	7.72 ± 0.29	31.12 ± 1.94	18.61 ± 1.22	72.40 ± 1.61	58.01 ± 1.68
90	4.79 ± 0.23	4.28 ± 0.31	6.28 ± 0.42	46.12 ± 2.13	13.75 ± 1.01	76.71 ± 1.43	56.87 ± 1.12
120	5.35 ± 0.31	2.29 ± 0.29	7.24 ± 0.51	28.28 ± 1.87	16.56 ± 1.09	75.21 ± 1.58	60.76 ± 1.94
B) Main effect of ingredient proportion							
Ingredient proportion	CP (% DM)	EE (% DM)	Ash (% DM)	NDF (% DM)	ADF (% DM)	NFE (% DM)	IVDMD (%)
100% fruit	3.53 ± 0.11	3.38 ± 0.41	3.81 ± 0.19	35.27 ± 2.61	7.99 ± 0.74	85.44 ± 0.71	67.31 ± 2.06
70:30	6.28 ± 0.19	2.33 ± 0.13	8.20 ± 0.39	33.09 ± 0.97	19.52 ± 0.58	73.94 ± 1.02	55.47 ± 0.84
50:50	6.29 ± 0.28	3.39 ± 0.21	9.22 ± 0.42	35.70 ± 1.22	20.74 ± 0.77	68.11 ± 1.36	52.20 ± 0.91

Values are expressed as mean ± standard error (n = 12 for storage time and n = 12 for ingredient proportion). CP, crude protein; EE, ether extract; Ash, mineral matter; NDF, neutral detergent fiber; ADF, acid detergent fiber; NFE, nitrogen-free extract; IVDMD, *in vitro* dry matter digestibility.

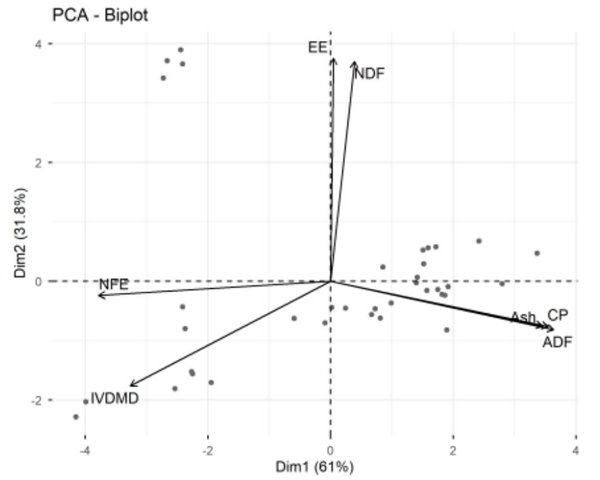

FIGURE 1
Principal component analysis (PCA) biplot showing relationships among nutritional variables and sample distribution of *Musa* spp. silages. Dim1 and Dim2 explain the largest proportion of total variance.

digestibility and nitrogen-free extract loaded in the opposite direction, highlighting contrasting nutritional profiles among silage formulations.

4 Discussion

4.1 Effects of storage time and ingredient proportion on crude protein

Crude protein (CP) concentration in *Musa* spp. silage was influenced by both ensiling duration and the relative contribution of fruit and vegetative residues. Silages incorporating banana crop residues, particularly pseudostems and leaves, consistently exhibited higher CP contents than those produced exclusively from discarded fruit. This difference reflects the intrinsic compositional characteristics between banana plant tissues, as vegetative fractions typically contain higher nitrogen concentrations than fruit pulp (Huy Sokchea et al., 2018).

Across all treatments, CP concentration tended to increase during the early to mid stages of fermentation, reaching a maximum around 90 days, followed by stabilization or a slight decline at 120 days. This trend is commonly attributed to changes in substrate utilization during ensiling, whereby microorganisms preferentially metabolize water-soluble carbohydrates, reducing dry matter and proportionally increasing nitrogen concentration in the remaining material (Saricicek et al., 2016; Campbell et al., 2020; Yang et al., 2022). Comparable trends have been reported in other silage systems; for instance, Saricicek et al. (2016) observed an initial rise in CP during corn silage fermentation, followed by protein losses when storage was excessively prolonged.

The peak in CP observed at 90 days in the present study agrees with findings by Álvarez et al. (2015), who reported moderate increases in CP after two to three months of fermentation in banana by-product silages. However, extended ensiling beyond this period may promote proteolytic activity, leading to nitrogen losses in the form of ammonia or other non-protein compounds, which may account for the slight decline observed at 120 days (Saricicek et al., 2016).

Ingredient proportion appeared to exert a greater influence on CP content than storage time alone. Treatments containing 50% or 30% fruit, with the remainder composed of nitrogen-rich vegetative residues, consistently achieved higher CP levels than fruit-only silages. Banana leaves and stems may contain up to 11% CP, whereas pseudostems typically range between 2 and 7% CP on a dry matter basis (Huy Sokchea et al., 2018). Consequently, combining fruit with vegetative tissues enhanced the overall protein concentration of the silage.

Despite these improvements, absolute CP values remained relatively low across all treatments, rarely exceeding 7% DM. These values are consistent with the generally protein-limited nature of banana-based silages compared with legume forages (Mitiku et al., 2023) and highlights the need for protein supplementation when such silages are used in high-producing ruminant diets (Zhang et al., 2021; Sampaio et al., 2021; Salim et al., 2021). Similar CP levels have been reported in silages prepared by mixing banana pseudostem with maize stover, reinforcing the characterization of *Musa* spp. silage as an energy-dense but protein-deficient feed resource (Mitiku et al., 2022).

4.2 Ash content and mineral concentration dynamics

Variations in ash content during storage are likely associated with shifts in mineral distribution within the ensiling mass rather than true mineral losses or gains. In the present study, ash concentration was significantly affected by ensiling time, with an initial decrease observed at 90 days followed by an increase at 120 days. This temporal trend indicates that, during early fermentation, soluble minerals may be diluted or temporarily redistributed within silage juices or immobilized by microbial biomass, resulting in lower measured ash concentrations (Campbell et al., 2020; Silva et al., 2021; Agustin et al., 2024).

As fermentation progressed, continued degradation of fermentable organic matter may have increased the relative proportion of inorganic components, explaining the rebound in ash content at 120 days. Similar trends have been documented in corn silage, where ash concentration remained relatively stable during early ensiling and showed slight increases with extended storage (Saricicek et al., 2016). In the present study, ash levels at 120 days approximated initial values, indicating that minerals were largely retained within the silage mass over time.

Ingredient proportion did not significantly interact with storage time with respect to ash content, indicating a consistent temporal response across treatments. Nevertheless, absolute ash levels differed among silages due to inherent differences in the mineral composition of fruit and vegetative residues. Banana fruit pulp is primarily composed of carbohydrates and typically exhibits low ash content (approximately 3–5% DM), whereas pseudostems and leaves are considerably richer in minerals, with reported ash contents reaching 10–14% DM (Huy Sokchea et al., 2018).

Banana pseudostems, in particular are characterized by relatively high potassium concentrations, along with appreciable levels of calcium, magnesium, silicon, and phosphorus (Huy Sokchea et al., 2018; Marques et al., 2021). These characteristics explain why residue-inclusive silages consistently showed higher ash concentrations than fruit-only silages. Ensiling generally preserves mineral elements effectively, as they are not degraded during fermentation; therefore, observed changes in ash content are mainly attributable to concentration effects rather than mineral losses, especially under well-sealed microsilo conditions where leachate production is minimal (Saricicek et al., 2016).

From a feeding standpoint, these mineral dynamics are relevant for ration formulation. High potassium levels typical of banana residues may influence electrolyte balance in ruminants, while the relatively higher calcium content in residue-inclusive silages could partially offset the low calcium concentration characteristic of tropical fruits (Pillai et al., 2024).

4.3 Fiber fractions (NDF and ADF): structural changes during storage

Neutral detergent fiber (NDF) and acid detergent fiber (ADF) are widely used indicators of silage structural composition and are closely linked to intake regulation and digestibility. In the present study, fiber fractions were more strongly associated with ingredient composition rather than storage duration. Silages produced exclusively from discarded banana fruit consistently exhibited the lowest NDF values, which is consistent with the predominance of non-structural carbohydrates in banana pulp. In contrast, the incorporation of pseudostems and leaves markedly increased NDF concentrations, reaching values typical of residue-based tropical silages (Silva et al., 2021; Salim et al., 2021).

A similar pattern was observed for ADF, which represents the less digestible fraction of plant cell walls. ADF concentrations were highest in silages containing equal proportions of fruit and residues, whereas fruit-only silages maintained comparatively low ADF levels. These differences align with the structural composition of banana vegetative tissues, particularly pseudostems, which are rich in cellulose and hemicellulose, while contributing relatively little lignin compared with other fibrous crops (Huy Sokchea et al., 2018).

Fiber levels across all treatments remained within acceptable ranges for ruminant feeding, with NDF below 50% DM and ADF below 30% DM. This is particularly relevant for small ruminants, as excessive fiber concentrations can limit voluntary intake and digestibility (Rincón et al., 2017; Wang et al., 2016a; Umunezero et al., 2025). The moderate fiber content observed in residue-inclusive silages suggests that structural enrichment did not compromise their nutritional usability.

Storage time exerted a secondary but detectable influence on fiber fractions. At 90 days, a slight increase in NDF—and to a lesser extent ADF—was observed in residue-containing silages. This response may be related to proportional changes arising from the preferential utilization of readily fermentable carbohydrates during active fermentation, which proportionally increases the relative fiber fraction. By 120 days, however, fiber levels tended to stabilize or decline slightly, indicating that prolonged ensiling may offset concentration effects through partial hemicellulose solubilization or structural modifications induced by fermentation acids (Xie et al., 2012).

The limited magnitude of fiber changes during extended storage indicates that structural components in Musa silages are relatively stable under conventional ensiling conditions. Similar stability has been reported by Álvarez et al. (2015), who observed minimal variation in fiber fractions during banana silage storage. The modest fluctuations observed between 90 and 120 days in the present study may reflect the balance between concentration effects and minor hemicellulose losses rather than extensive cell wall degradation.

When compared with silages derived from other crop mixtures, the present findings illustrate the flexibility of banana-based systems. For example, Rodrigues et al. (2019) reported that the inclusion of banana fruit in sugarcane silage reduced fiber concentration by diluting a highly fibrous base. In contrast, our formulation strategy enriched a low-fiber substrate (banana fruit) with vegetative residues, resulting in increased NDF. Both scenarios demonstrate that fiber content in silage can be effectively manipulated through ingredient selection, as also observed in mixtures of banana pseudostem with other agricultural residues (Mitiku et al., 2023).

4.4 Ether extract and nitrogen-free extract responses

Ether extract (EE) concentrations in Musa silages were low across all treatments, which is consistent with the inherently low lipid content of banana tissues. Nevertheless, ingredient proportion and storage time produced measurable, although these effects were nutritionally modest. Fruit-only silages tended to show slightly higher EE values than residue-inclusive treatments, particularly at 90 days, which is consistent with the presence of waxes and oils in banana peel and pulp (Huy Sokchea et al., 2018). In contrast, banana pseudostems contain minimal lipid fractions, and their inclusion diluted overall EE content.

Even the highest EE values observed in pure fruit silage remained within a range generally regarded as low for ruminant nutrition, as banana pulp and peel typically contain no more than 3–5% EE on a dry matter basis (Yang et al., 2022; Marques et al., 2021). The slight increase in EE at 90 days may be associated with proportional changes during active fermentation, as water and volatile solids are lost, temporarily increasing the proportion of lipid components. By 120 days, EE values declined or stabilized, likely due to oxidation, dilution effects, or the relative accumulation of other components.

Nitrogen-free extract (NFE), with represents readily fermentable carbohydrates, exhibited a pattern opposite to that of fiber fractions. NFE was highest in fruit-only silages and declined progressively as the proportion of vegetative residues increased. This response aligns with the high sugar and starch content of banana pulp, which typically contributes 85–90% NFE on a dry matter basis. During ensiling, NFE decreased as soluble carbohydrates were consumed during lactic fermentation, particularly in fruit-only silages where fermentable substrates were abundant (Campbell et al., 2020).

An interaction effect was evident at 90 days. Treatments initially rich in NFE exhibited marked reductions at this stage, whereas residue-inclusive silages showed relative stability or slight increases in NFE. This could be related to slower fermentation dynamics in fiber-rich mixtures, where the consumption of soluble carbohydrates is less rapid and residual sugars become proportionally more concentrated as other fractions decline. Comparable patterns were reported by Saricicek et al. (2016) in corn silage, where extended storage resulted in relative increases in NFE as CP and fiber fractions declined.

From a feeding perspective, these trends highlight a clear trade-off between energy density and structural adequacy. Fruit-only silages provide highly fermentable energy but are deficient in protein and physically effective fiber, whereas residue-enriched silages sacrifice part of their NFE content in exchange for improved rumen structure and protein contribution. The present results indicate that approximately 90 days of ensiling may represent a practical compromise, allowing sufficient fermentation to stabilize the silage without excessive depletion of fermentable carbohydrates. Depending on production objectives, adjusting the fruit-to-residue ratio offers a viable strategy to tailor Musa silages for different classes of ruminants and feeding systems.

4.5 *In vitro* dry matter digestibility and nutritional implications

In vitro dry matter digestibility (IVDMD) varied widely among treatments, which may be related to differences in substrate composition and fermentation dynamics. In the present study, digestibility ranged from approximately 50% to more than 70% of dry matter, with the highest values consistently observed in silages produced exclusively from banana fruit, particularly at 90 days of conservation.

This pattern aligns with the high content of soluble carbohydrates and starches in banana pulp, which are readily fermented and result in silages with low fiber concentrations and high digestible energy. Similar digestibility values have been reported for fruit-rich or carbohydrate-based silages in tropical systems (Yang et al., 2022; Silva et al., 2021). In contrast, increasing the proportion of banana residues (pseudostems and leaves) was associated with a marked reduction in IVDMD, a consequence of higher structural fiber content and a lower proportion of rapidly fermentable substrates (Wang et al., 2016a; Mitiku et al., 2023).

Ensiling time exert an additional influence on digestibility. IVDMD tended to increase between 60 and 90 days of storage and then stabilized or declined slightly at 120 days. This pattern indicates that fermentation was associated with improvement digestibility up to an intermediate point, after which prolonged storage offered limited additional benefits. Comparable trends have been described for banana and plantain silages, where digestibility increased during the first two to three months of ensiling and subsequently plateaued or declined slightly (Álvarez et al., 2015; Wang et al., 2025b).

The slight reduction in digestibility observed at extended storage times could be associated with prolonged fermentation processes, including secondary reactions that bind soluble carbohydrates or modify cell wall structure, thereby reducing nutrient availability (Neira et al., 2024). Nevertheless, digestibility values at 120 days remained within the range reported for many tropical forages and were still suitable for goat feeding.

From a practical feeding standpoint, residue-inclusive silages, despite their lower digestibility, provided higher crude protein concentrations and greater physically effective fiber than fruit-based silages. These attributes are beneficial for rumen function, particularly in small ruminants, although they do not fully compensate for the reduction in digestible energy. Consequently, fruit-rich silages may be more appropriate for animals with high energy demands, whereas residue-rich silages may be better suited for maintenance diets or periods of forage scarcity, provided that nutritional limitations are appropriately managed (Rodrigues et al., 2019; Rincón et al., 2017).

4.6 Multivariate interpretation of nutritional profiles (PCA)

To integrate the multiple nutritional variables evaluated in this study, a principal component analysis (PCA) was performed using chemical composition and *in vitro* digestibility parameters. The PCA allowed visualization of the clustering of treatments according to their overall nutritional profiles in relation to ingredient proportion and, to a lesser extent, storage time.

The ordination revealed a separation of silages primarily along the axis associated with ingredient composition. Fruit-dominated silages clustered in regions characterized by higher *in vitro* dry matter digestibility and nitrogen-free extract compared with residue-rich formulation, whereas residue-rich silages were positioned toward areas associated with higher fiber fractions (NDF and ADF) than fruit-dominated silages, ash content, and crude protein. This pattern illustrates the contrasting nutritional roles of discarded fruit versus vegetative banana residues and aligns with multivariate analyses reported for residue-based silages in other studies (Mitiku et al., 2023).

The second principal component appeared to capture more subtle variation related to fermentation dynamics. Treatments ensiled for 90 days tended to occupy intermediate positions between early (60 days) and prolonged (120 days) storage, suggesting modest compositional stabilization at intermediate ensiling durations. However, separation along this axis was less pronounced than that observed for ingredient proportion, suggesting that substrate composition may have exerted a greater influence on overall silage quality than storage time.

From a practical standpoint, the PCA illustrates the nutritional trade-offs inherent in Musa silage formulation. Increasing the proportion of discarded fruit tends to increase digestible energy content, whereas incorporation of crop residues enhances fiber and crude protein content at the expense of digestibility. Intermediate formulations, such as the 70:30 fruit-to-residue silage, tended to occupy central positions in the multivariate space, indicating a more balanced nutritional profile.

The use of PCA as a tool for synthesizing complex nutritional datasets is well established in forage and feed evaluation studies. Previous work has demonstrated its utility in classifying forages based on nutritional attributes and reducing multidimensional data into interpretable components relevant to animal feeding strategies (Gallo et al., 2013). In the present study, PCA provided an integrated summary of the combined effects of ingredient proportion and ensiling time, supporting its value as an exploratory approach for interpreting silage quality.

5 Conclusions

The results of this study suggest that the nutritional quality and digestibility of Musa silages are jointly influenced by ingredient proportion and storage duration. Fruit-based silages were generally associated with higher digestible energy and *in vitro* dry matter digestibility than residue-rich silages, whereas the incorporation of crop residues increased fiber and ash content, resulting in lower overall digestibility but greater structural fiber content than fruit-based silages.

Multivariate analysis identified distinct nutritional profiles associated with different formulation strategies, reflecting a clear trade-off between energy availability and fiber content. These patterns indicate that no single silage type is universally optimal; rather, formulation should be aligned with specific feeding objectives.

From a practical perspective, fruit-rich silages may be more appropriate for animals with higher energy requirements, whereas residue-inclusive silages may contribute to forage bulk and protein supply under maintenance or forage-scarcity conditions Discarded Musa by-products can serve as flexible feed resources in tropical livestock systems when appropriately formulated and managed.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

VT: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DV: Data curation, Investigation, Methodology, Writing – review & editing. OJ: Data curation, Investigation, Resources, Writing – review & editing. DG: Formal Analysis, Methodology, Validation, Writing – review & editing. HS: Writing – review & editing. CV: Data curation, Investigation, Resources, Writing – review & editing. JS: Formal Analysis, Visualization, Writing – review & editing. ES: Formal Analysis, Methodology, Validation, Writing – review & editing. JC: Investigation, Resources, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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