Circular valorization of *Musa* spp. pseudostem as a functional feed ingredient in multinutrient blocks for ruminants: effects of origin and ensiling on nutritional and physicochemical properties

Valorización circular del pseudotallo de *Musa* spp. como ingrediente funcional en bloques multinutricionales para rumiantes: efectos de la procedencia y del ensilaje sobre las propiedades nutricionales y fisicoquímicas

Valorização circular do pseudocaule de *Musa* spp. como ingrediente funcional em blocos multinutricionais para ruminantes: efeitos da procedência e da ensilagem sobre as propriedades nutricionais e fisicoquímicas

Martínez Patiño, J. [1]; Rodríguez Rico, J. V. [1]; Suárez- Rivero, M. [2]; Marín-Mahecha, O. [3]; Suárez-Rivero, D. [3*]

1. Semillero Desarrollos en Ingeniería Agroindustrial - DIA, Grupo de Investigación e Innovación Agroindustrial - GINNA, Ingeniería Agroindustrial, UNIAGRARIA, Colombia.
2. Facultad de Ingeniería, Tecnología y Ciencias Básicas, Fundación Universitaria Cafam, Colombia.
3. Grupo de Investigación e Innovación Agroindustrial - GINNA, Ingeniería Agroindustrial, UNIAGRARIA, Colombia.

* Corresponding author: suarez.deivis@uniagraria.edu.co

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Abstract

The valorization of agricultural residues through circular economy strategies represents a sustainable alternative to improve livestock nutrition and reduce biomass waste. This study evaluated the effects of geographical origin and ensiling on the bromatological composition, fermentative characteristics, and physicochemical stability of multinutrient blocks produced from *Musa* spp. pseudostem for ruminant feeding. A 2 × 2 factorial design was applied using pseudostems collected from San Francisco de Sales (Cundinamarca, Colombia) and Tibaná (Boyacá, Colombia), subjected either to dehydration or ensiling prior to block manufacture. Fresh biomass exhibited high moisture content (91.48-92.04%), low crude protein concentration (2.50-3.00%), and total digestible nutrient (TDN) values ranging from 73.75 to 76.49%. Drying reduced moisture content to 8.31-9.87%, whereas ensiling achieved final pH values of 3.75 and 4.25 after 11 days of fermentation. The resulting blocks showed adequate physicochemical stability during storage, reaching final moisture levels close to 24%. Crude protein increased to 30.0-35.5%, while TDN values ranged from 69.84 to 74.66%. Ensiled treatments exhibited higher neutral detergent fiber concentrations (46.39-47.57%), although they maintained favorable energy values and structural stability. In addition, the blocks supplied relevant concentrations of calcium (2.66-3.53%), potassium (1.58-2.23%), phosphorus (0.15-0.21%), and magnesium (0.27-0.31%). These findings demonstrate that the combined application of dehydration, ensiling, and compaction effectively transforms *Musa* spp. pseudostem into a stable and value-added nutritional supplement, supporting sustainable agro-industrial residue utilization and strengthening livestock production systems under circular economy principles.

Keywords: residual biomass, strategic supplementation, lactic fermentation, livestock sustainability, agro-industrial valorization.

Resumen

El aprovechamiento de residuos agrícolas mediante estrategias de economía circular representa una alternativa sostenible para fortalecer la alimentación animal y reducir pérdidas de biomasa. El presente estudio evaluó el efecto de la procedencia geográfica y del ensilaje del pseudotallo de *Musa* spp. sobre la composición bromatológica, las características fermentativas y la estabilidad fisicoquímica de bloques multinutricionales destinados a rumiantes. Se utilizó un diseño factorial 2 × 2 con pseudotallos procedentes de San Francisco de Sales (Cundinamarca) y Tibaná (Boyacá), sometidos a deshidratación o ensilaje previo a la elaboración de los bloques. La biomasa fresca presentó altos contenidos de humedad (91.48-92.04 %), proteína bruta reducida (2.50-3.00 %) y nutrientes digestibles totales entre 73.75 y 76.49 %. El secado permitió disminuir la humedad hasta 8.31-9.87 %, mientras que el ensilaje logró valores finales de pH de 3.75 y 4.25 tras 11 días de fermentación. Los bloques obtenidos mostraron estabilidad fisicoquímica durante el almacenamiento, con humedades finales cercanas al 24 %. La proteína bruta aumentó hasta valores entre 30.0 y 35.5 %, mientras que los nutrientes digestibles totales oscilaron entre 69.84 y 74.66 %. Los

tratamientos ensilados presentaron mayores contenidos de fibra detergente neutra (46.39-47.57 %), aunque mantuvieron adecuados niveles energéticos y estabilidad estructural. Asimismo, los bloques aportaron concentraciones relevantes de calcio (2.66-3.53 %), potasio (1.58-2.23 %), fósforo (0.15-0.21 %) y magnesio (0.27-0.31 %). Los resultados demuestran que la combinación de deshidratación, ensilaje y compactación transforma eficientemente el pseudotallo de *Musa* spp. en un suplemento nutricional estable y de alto valor agregado, contribuyendo al aprovechamiento sostenible de residuos agroindustriales y al fortalecimiento de sistemas ganaderos basados en principios de economía circular.

Palabras clave: biomasa residual, suplementación estratégica, fermentación láctica, sostenibilidad pecuaria, valorización agroindustrial.

Resumo

O aproveitamento de resíduos agrícolas por meio de estratégias de economia circular representa uma alternativa sustentável para fortalecer a alimentação animal e reduzir perdas de biomassa. Este estudo avaliou os efeitos da procedência geográfica e da ensilagem do pseudocaule de *Musa* spp. sobre a composição bromatológica, as características fermentativas e a estabilidade físico-química de blocos multinutricionais destinados à alimentação de ruminantes. Foi empregado um delineamento fatorial 2 × 2 utilizando pseudocaules provenientes de San Francisco de Sales (Cundinamarca) e Tibaná (Boyacá), submetidos à desidratação ou à ensilagem antes da fabricação dos blocos. A biomassa fresca apresentou elevados teores de umidade (91,48-92,04%), baixos níveis de proteína bruta (2,50-3,00%) e nutrientes digestíveis totais entre 73,75 e 76,49%. A secagem reduziu a umidade para 8,31-9,87%, enquanto a ensilagem alcançou valores finais de pH de 3,75 e 4,25 após 11 dias de fermentação. Os blocos produzidos apresentaram adequada estabilidade físico-química durante o armazenamento, alcançando umidade final próxima de 24%. O teor de proteína bruta aumentou para valores entre 30,0 e 35,5%, enquanto os nutrientes digestíveis totais variaram entre 69,84 e 74,66%. Os tratamentos ensilados apresentaram maiores concentrações de fibra em detergente neutro (46,39-47,57%), mantendo, entretanto, bom valor energético e estabilidade estrutural. Além disso, os blocos forneceram concentrações relevantes de cálcio (2,66-3,53%), potássio (1,58-2,23%), fósforo (0,15-0,21%) e magnésio (0,27-0,31%). Os resultados demonstram que a combinação de desidratação, ensilagem e compactação transforma eficientemente o pseudocaule de *Musa* spp. em um suplemento nutricional estável e de elevado valor agregado, contribuindo para o aproveitamento sustentável de resíduos agroindustriais e para o fortalecimento de sistemas pecuários baseados nos princípios da economia circular.

Palavras-chave: biomassa residual; suplementação estratégica; fermentação láctica; sustentabilidade pecuária; valorização agroindustrial.

Introduction

Livestock production currently faces the challenge of meeting the growing global demand for animal protein while adhering to criteria of environmental sustainability and economic efficiency. In this context, feed accounts for between 60 and 80% of total production costs in ruminant systems, which has driven the search for alternative raw materials capable of reducing dependence on conventional ingredients without compromising animal performance. At the same time, the principles of the circular economy promote the valorization of agroindustrial byproducts that are traditionally considered waste, transforming them into value-added resources for production systems. Among these resources, waste derived from banana and plantain cultivation stands out due to its high availability in tropical and subtropical regions, where the production of Musaceae generates large volumes of residual biomass that are often left in the fields, contributing to decomposition processes and greenhouse gas emissions (Zou et al., 2022; Suhaimi et al., 2020). The reuse of these materials in animal feed is a strategy aligned with the Sustainable Development Goals, particularly regarding responsible production and food security (Zou et al., 2022; Zhao et al., 2022).

Among the waste products generated by Musaceae, the pseudostem accounts for approximately 60% of the plant's total biomass and constitutes an important source of structural carbohydrates, minerals, and bioactive compounds with potential applications in animal feed. Various studies have shown that the pseudostem contains significant amounts of neutral detergent fiber, hemicellulose, and digestible energy—characteristics that allow for its partial incorporation into ruminant diets, especially during periods of forage scarcity. Furthermore, recent research has reported that pseudostem hay can be used in dairy cattle and sheep without negatively affecting production or digestive parameters, highlighting its potential as a low-cost alternative resource (Rabelo et al., 2020; Silveira Junior et al., 2020). Similarly, the nutritional characterization of *Musa* spp. residues has shown that the pseudostem has a composition suitable for supplementing fibrous diets, although its high moisture content limits its direct use and requires the application of preservation and conditioning technologies (Teixeira et al., 2021; Rocha Júnior et al., 2020).

Silage is one of the most widely used technologies for preserving plant biomass due to its ability to stabilize the material through controlled lactic fermentation, reduce nutritional losses, and improve nutrient availability for ruminal microorganisms. In materials with high moisture content and low levels of fermentable carbohydrates, such as the pseudostem of *Musa* spp., the addition of simple sugar sources such as molasses promotes a rapid decrease in pH and the establishment of desirable fermentation. Mitiku et al. (2020) demonstrated that the incorporation of molasses is critical for achieving adequate acidification of banana pseudostems and ensuring the microbiological stability of the silage. Additionally, fermentation can favorably modify the fibrous fractions of forages, increase digestibility, and improve ruminal utilization of dry matter, making it an effective tool for the valorization of agro-industrial residues intended for animal nutrition (Mitiku et al., 2020; Teixeira et al., 2021).

Furthermore, multinutritional blocks have established themselves as an efficient strategy for supplementing ruminants in extensive and semi-intensive systems, especially during

periods of low forage availability and quality. These solid supplements provide energy, non-protein nitrogen, minerals, and functional compounds in a gradual manner, promoting ruminal microbial activity and improving the digestibility of fibrous feed. According to Zhao et al. (2022), nutritional blocks contribute significantly to optimizing the use of local resources, increasing feed efficiency, and reducing supplementation costs. Furthermore, recent reviews highlight that incorporating agricultural byproducts into multinutritional blocks represents a sustainable alternative for improving livestock productivity and reducing the environmental impact associated with the improper management of agroindustrial waste (Zhao et al., 2022; Pacheco Hernández & Bonilla-Landaverry, 2025).

Despite reported advances in the use of Musaceae residues and the benefits associated with multinutritional blocks, there is limited scientific evidence regarding the combined influence of the pseudostem's geographic origin and its pretreatment through silage on the nutritional quality and physicochemical stability of blocks intended for ruminant feed. Soil and climate variations can significantly alter the bromatological composition of plant biomass, affecting parameters such as mineral content, fiber content, and fermentable carbohydrates, while fermentation processes can alter nutrient availability and the preservation of the final product. Consequently, it is necessary to generate knowledge that will allow us to establish the true potential of these materials as functional ingredients within circular economy strategies applied to sustainable animal production. In this context, the objective of the present study was to evaluate the effect of the origin and ensiling of the pseudostem of *Musa* spp. on the bromatological composition, fermentative characteristics, and physicochemical stability of multinutritional blocks for ruminants, thereby contributing to the comprehensive utilization of agricultural residues and the development of more sustainable livestock systems (Mitiku et al., 2020; Rabelo et al., 2020).

Materials and Methods

Study Area and Experimental Design

The research was conducted at the laboratories of Fundación Universitaria Agraria de Colombia (UNIAGRARIA), Bogotá, Colombia, located at approximately 2,650 m above sea level under average environmental conditions of 14 °C and high relative humidity. The study was developed under the principles of sustainable biomass valorization and circular economy, aiming to transform an underutilized agricultural residue into a value-added feed supplement for ruminants. A completely randomized 2 × 2 factorial design was employed to evaluate the effect of two independent factors: pseudostem origin and pre-treatment method. Factor A corresponded to the geographical origin of the pseudostem, including San Francisco de Sales (Cundinamarca) and Tibaná (Boyacá), while Factor B consisted of two processing conditions, dehydrated pseudostem and ensiled pseudostem. Similar experimental approaches have previously been employed to assess the nutritional and fermentative behavior of *Musa* spp. residues intended for livestock feeding (Teixeira et al., 2021; Rabelo et al., 2020).

Plant Material Collection and Preparation

Pseudostems of *Musa spp.* was collected immediately after harvest from commercial production systems located in San Francisco de

Sales, Cundinamarca (approximately 1,520 m above sea level) and Tibaná, Boyacá (approximately 2,115 m above sea level). To ensure sample homogeneity, sections of approximately 50 cm in length were obtained through transversal cuts made 1 m above the corm. After collection, the material was transported to the laboratory under ambient conditions and subsequently cleaned to remove soil particles, senescent tissues, and external contaminants. Samples were cut into slices of approximately 2 cm thickness and stored at 4 °C until processing. The utilization of pseudostem biomass has received growing attention due to its abundance, fiber content, and potential application as an alternative feed resource in ruminant nutrition (Suhaimi et al., 2020; Zou et al., 2022).

Bromatological and Nutritional Characterization of Fresh Pseudostems

Fresh pseudostem samples from both locations underwent comprehensive bromatological characterization to determine their nutritional potential as feed ingredients. Moisture, ash, extract, crude protein, fiber fractions, total digestible nutrients (TDN), and macro- and micro-mineral concentrations were determined using standardized gravimetric, Kjeldahl, colorimetric, spectrophotometric, and Van Soest methodologies. Fiber fractions, including neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL), were quantified because of their recognized importance in predicting voluntary intake, digestibility, and ruminal fermentation efficiency. Recent advances in fiber analytical methodologies emphasize the importance of accurate determination of structural carbohydrates when evaluating unconventional feed resources (Ferreira & Thiex, 2023; Teixeira et al., 2021).

Drying Curve Determination and Dehydration Efficiency

To evaluate moisture removal efficiency and determine the optimum drying conditions, pseudostem samples from each origin were subjected to controlled dehydration at 35 °C and 45 °C. Approximately 40 g of fresh material were distributed in trays and weighed periodically until reaching equilibrium moisture content. Subsequently, samples were dried at 105 °C to determine dry matter content. Moisture loss and dry matter accumulation were calculated as a function of time to generate drying curves and estimate energy-efficient processing conditions. Moisture reduction is considered a fundamental pre-treatment for high-moisture agricultural residues because it improves shelf life, facilitates handling, and increases the concentration of nutrients in feed ingredients (Rocha Júnior et al., 2020; Zou et al., 2022).

Ensiling Process of Pseudostem Biomass

A portion of the dehydrated pseudostem obtained from each geographical origin was subjected to ensiling as a biological preservation strategy. Due to the relatively low concentration of readily fermentable carbohydrates reported in pseudostem tissues, molasses was added as a fermentable substrate to stimulate lactic acid production. The ensiling process was monitored through periodic measurement of pH until values below 4.2 were achieved and stabilized, indicating the establishment of suitable fermentative conditions. The effectiveness of lactic fermentation in banana pseudostem biomass has been demonstrated previously, particularly when molasses supplementation is applied to accelerate pH decline and improve microbial

stability (Mitiku et al., 2020; Zhao et al., 2022).

Formulation and Manufacturing of Multinutrient Blocks

Four multinutrient block formulations were prepared corresponding to the combinations generated by the factorial design. Each block had a final weight of 1 kg and contained 55.0% pseudostem, 21.5% palm kernel cake, 10.0% glycerin, 5.0% urea, 5.0% molasses, 2.0% lime, 1.0% cement, and 0.5% magnesium sulfate. These ingredients were selected according to their functions as sources of energy, nitrogen, minerals, fiber, and binding agents. The manufacturing process involved three stages: preparation of mineral and nitrogenous ingredients, preparation of fibrous and energetic ingredients, and final homogenization of all components before molding and compaction. Multinutrient blocks are widely recognized as effective nutritional supplements capable of improving ruminal function, nutrient utilization, and animal performance, especially under extensive grazing systems with low-quality forage availability (Zhao et al., 2022; Pacheco Hernández & Bonilla-Landaverry, 2025).

Evaluation of Physicochemical Stability

The physicochemical stability of the multinutrient blocks was assessed during storage under sheltered conditions at approximately 22 °C. Physical variables included weight loss, moisture loss, and firmness, while chemical stability was evaluated through pH measurements. Weight and moisture changes were determined gravimetrically, whereas firmness was measured using a penetrometer to assess resistance to mechanical penetration. These parameters were considered critical quality indicators because they directly influence block durability, handling, nutrient conservation, and animal consumption behavior. Previous studies have highlighted the importance of structural integrity and hardness in regulating intake patterns and preventing excessive consumption of urea-containing supplements (Zhao et al., 2022; Silveira Junior et al., 2020).

Bromatological Evaluation of Multinutrient Blocks

Upon completion of the stabilization period, all treatments were subjected to bromatological analysis following the same analytical procedures applied to fresh pseudostem samples. Moisture, crude protein, extract, ash, fiber fractions, digestible nutrients, mineral composition, and energy values were quantified to determine the influence of geographical origin and ensiling on the nutritional quality of the final product. Attention was given to crude protein, NDF, ADF, and TDN because these parameters are closely associated with feed utilization efficiency in ruminants. The evaluation of nutritional modifications resulting from processing technologies is essential for determining the viability of agroindustrial residues as sustainable livestock feed ingredients (Rabelo et al., 2020; Rocha Júnior et al., 2020).

Statistical Analysis

Data obtained from bromatological characterization, fermentation monitoring, drying kinetics, and physicochemical stability evaluations were analyzed using analysis of variance (ANOVA) at a significance level of $\alpha=0.05$. When significant differences among treatments were identified, Fisher's least significant difference (LSD) multiple comparison test was applied to establish

statistical groupings between means. Statistical analyses were performed to determine the individual and combined effects of pseudostem origin and pre-treatment on the evaluated variables. The application of factorial ANOVA designs is widely recommended in feed evaluation research because it allows identification of interactions among nutritional and technological factors affecting feed quality and animal nutrition outcomes (Ferreira & Thiex, 2023; Zhao et al., 2022).

Results and Discussion

Bromatological Characterization of Fresh *Musa* spp. Pseudostems

The bromatological characterization of fresh *Musa* spp. pseudostems showed that both sources have a composition compatible with their potential use as a raw material for ruminant feed, although nutritional differences attributable to the edaphoclimatic and agronomic factors specific to each growing region. The high moisture content observed in the materials from San Francisco (91.48%) and Tibaná (92.04%) confirms one of the main limitations of this agro-industrial byproduct for direct use, since high water levels reduce the concentration of nutrients per unit of fresh matter, increase transportation costs, and promote microbiological spoilage during storage. Similar results have been reported for banana and plantain pseudostems in various tropical regions, where moisture contents exceeding 90% have been recorded, confirming the need to implement dehydration or biological preservation processes before incorporating them into animal feed systems (Akinyemi et al., 2022; Ghimire et al., 2023)

The crude protein contents obtained (2.50–3.00%) confirm that the pseudostem is a raw material with a low protein content, a characteristic widely described for various fibrous residues derived from Musaceae (Table 1). However, this characteristic does not limit its use in balanced formulations, since its primary function lies in providing digestible fiber and minerals rather than in the direct supply of nitrogen. In fact, several recent studies have indicated that the nutritional potential of *Musa* spp. byproducts can be significantly increased when combined with protein sources or non-protein nitrogen within strategic supplements for ruminants, thereby simultaneously improving ruminal degradability and dry matter utilization efficiency (Melesse et al., 2021; Nurfeta & Tolera, 2024).

Tabla 1. Chemical composition of fresh pseudostems according to geographical origin.

Parameter	San Francisco (a1)	Tibaná (a2)
Moisture (%)	91.48	92.04
Crude protein (%)	2.50	3.00
Ash (%)	5.23	12.00
NDF (%)	51.88	60.61
ADF (%)	20.13	16.21
Lignin (%)	3.95	2.03
TDN (%)	73.75	76.49

The differences observed in Table 1 for the fiber fractions constitute one of the most significant findings of this study. The pseudostem from Tibaná had higher values of neutral detergent fiber (60.61%) and hemicellulose (39.22%), while the sample from

San Francisco exhibited higher concentrations of cellulose (12.66%), lignin (3.95%), and non-structural carbohydrates (45.79%). These variations suggest that geographic origin directly influences the architecture of the plant cell wall and, therefore, the expected digestive behavior in the rumen. According to recent research on tropical fibrous residues, differences in altitude, soil fertility, water availability, and the physiological state of plants at the time of harvest can significantly modify the relative proportions of hemicellulose, cellulose, and lignin, thereby altering the potential digestibility of the material and the rate of ruminal fermentation (Gebrehawariat et al., 2022; Kambashi et al., 2023).

From a nutritional standpoint, the relatively low lignin content found in both materials makes them particularly suitable for use in ruminant feed. Lignin is the least digestible fraction of the plant cell wall and limits microbial access to structural carbohydrates; therefore, lower concentrations of this polymer are typically associated with higher ruminal degradation rates. In this study, lignin content was less than 4%, values considerably lower than those reported for other lignocellulosic residues used in animal nutrition, suggesting favorable potential for microbial fermentation. This observation is consistent with recent reports describing the pseudostem of Musaceae as a biomass that is relatively rich in hemicellulose and low in lignin, a characteristic that facilitates its use as a functional ingredient in feed systems based on low-quality forages (Mwango et al., 2021; Oliveira et al., 2024).

The results for non-structural carbohydrates, as shown in Table 1, revealed marked differences between origins, with higher levels in the material from San Francisco (45.79%) compared to Tibaná (34.31%). This variation is particularly significant because soluble carbohydrates constitute the primary source of rapidly fermentable energy for ruminal microorganisms and play a decisive role in subsequent silage processes. Greater availability of fermentable sugars promotes lactic acid production, accelerates pH reduction, and improves the stability of the preserved material. Consequently, the results suggest more favorable fermentation behavior for the San Francisco pseudostem, a hypothesis that was subsequently corroborated by the evaluation of the silage. Recent research on *Musa* spp. biomass has shown that differences in soluble carbohydrates are one of the most influential factors affecting the fermentative quality and microbiological stability of silages made from Musaceae residues (Moyo et al., 2022; Puniya et al., 2023).

Finally, Table 1 shows that the high total digestible nutrient (TDN) values found in both pseudostems (73.75–76.49%) suggest an energy potential higher than expected for many tropical agricultural residues. This behavior can be attributed to the combination of a low lignin concentration and a high proportion of potentially fermentable structural carbohydrates. Likewise, mineral analyses revealed significant differences between origins, particularly for potassium, calcium, and manganese, demonstrating that growing conditions substantially influence the

nutritional composition of the biomass obtained. Taken together, these findings indicate that the pseudostem of *Musa* spp. is a promising feedstock to produce nutritional supplements for ruminants, especially when subjected to conditioning processes that concentrate dry matter and optimize the utilization of its structural and energy components (Abdela et al., 2024; Singh et al., 2023)

Dehydration Kinetics and Process Efficiency

The results of the drying curves showed that the pseudostem of *Musa* spp. is a biomass characterized by an extremely high moisture content (Table 2), exceeding 90% in both sources, confirming the need to apply conditioning treatments prior to its use in animal feed. Regardless of the temperature applied, the greatest water loss occurred during the first 17 to 18 hours of the process, followed by a gradual decrease in the drying rate until reaching a plateau near hygroscopic equilibrium. This behavior is typical of lignocellulosic materials with high porosity and abundant free water in the parenchymatous tissues, where surface evaporation initially predominates and moisture transfer is subsequently limited by internal diffusion processes. Recent studies on Musaceae residues have described similar patterns, indicating that the pseudostem exhibits a rapid initial release of water due to its pseudoherbaceous structure and the high proportion of water-bearing tissues present in the vascular bundles (Deepak et al., 2022; Ghimire et al., 2023).

The comparison of temperatures showed that the 45 °C treatment reached moisture equilibrium approximately two hours earlier than the 35 °C treatment. However, the differences observed in the final moisture content were minimal, less than 1.5%, suggesting that the increase in temperature accelerated the kinetics of the process but did not result in substantial improvements in the final water removal efficiency. From a technological perspective, this finding is significant because it indicates that moderate temperatures can yield comparable results with lower energy consumption. Research on the drying of agricultural biomass has shown that excessive temperature increases do not always result in proportional gains in efficiency, especially in materials with high internal resistance to moisture transport, where controlling energy costs is a determining factor for the industrial viability of the process (Araujo et al., 2024; Singh et al., 2023)

Tabla 2. Summary of drying behaviour

Treatment	Initial moisture (%)	Final moisture (%)	Equilibrium time
a1-35°C	91.69	8.31	~20 h
a2-35°C	90.51	9.48	~20 h
a1-45°C	91.54	8.46	~18 h
a2-45°C	90.13	9.87	~18 h

When analyzing the differences between origins, it was observed that the pseudostem from San Francisco reached slightly lower final moisture contents compared to the material from Tibaná. This behavior may be associated with the previously identified bromatological differences, particularly the higher content of non-structural carbohydrates presents in the material from San Francisco and the variations found in the cellulose

and hemicellulose fractions. The composition of the plant cell wall directly influences water retention and moisture mobility within the tissues; therefore, relatively small changes in the fibrous structure can lead to different responses during drying. Several authors have noted that plant residues with higher hemicellulose contents tend to exhibit greater water-holding capacity due to the abundance of hydroxyl groups available to form bonds with water molecules (Khalil et al., 2022; Oliveira et al., 2024).

From a nutritional standpoint, reducing moisture content to levels around 8–10% offers a significant advantage for the subsequent use of the pseudostem in formulations for ruminants. Lowering the water content proportionally increases the nutrient concentration per unit mass, reduces the risk of microbial growth, and extends shelf life during storage. Furthermore, obtaining stable raw material facilitates the grinding, mixing, and compaction operations required to produce multivitamin blocks. In tropical livestock systems, where forage availability fluctuates seasonally, the transformation of high-moisture residues into stable ingredients is an effective strategy for ensuring supplemental feed sources during critical production periods (Abdela et al., 2024; Kambashi et al., 2023).

Another point of interest was the identification of an equilibrium phase approximately 20 hours into the drying process for both temperatures. This behavior indicates that extending the process beyond that point would result in marginal reductions in moisture content at the expense of significant increases in energy costs. Consequently, from a sustainability and circular economy perspective, the 35 °C temperature can be considered more operationally efficient, as it allowed for final moisture levels comparable to those obtained at 45 °C with lower energy requirements. This observation aligns with recent studies focused on the valorization of agro-industrial waste, which have demonstrated that energy optimization of the conditioning stages is an essential component for improving the profitability and environmental sustainability of biomass utilization processes (Bhatia et al., 2023; Deepak et al., 2022).

In general terms, the results confirm that drying is a critical step in the valorization of *Musa* spp. pseudostems as an ingredient for animal feed. The high initial moisture content observed in both sources limits their direct use; however, the application of moderate temperatures made it possible to obtain a stable raw material with characteristics suitable for subsequent processes such as ensiling, storage, and the formulation of multinutritional blocks. Furthermore, the observed response demonstrates that differences associated with geographic origin influence drying behavior, an aspect that must be considered when designing utilization strategies on an industrial scale. These findings reinforce the potential of the pseudostem as a biomass resource that can be incorporated into sustainable livestock production systems and the circular economy (Ghimire et al., 2023; Singh et al., 2023).

Fermentation Dynamics of Ensiled Pseudostem

The fermentation dynamics observed during the ensiling of *Musa* spp. pseudostems, as shown in Table 3, indicated a favorable trend in the

parameters associated with the biological preservation of the material. Both treatments experienced a progressive decrease in pH throughout the fermentation period, reaching final values consistent with successful lactic fermentation processes. However, the material from San Francisco (a1) exhibited a higher rate of acidification, decreasing from an initial pH of 4.38 to 3.75, while the material from Tibaná (a2) reached a final value of 4.25. This behavior indicates greater lactic acid bacteria activity in treatment a1 and greater efficiency in the production of organic acids responsible for the microbiological stabilization of silage. Recent studies have shown that silages made from tropical agricultural residues exhibit better stability when they reach pH values below 4.2, a necessary condition for inhibiting undesirable microorganisms such as enterobacteria and clostridia (Wang et al., 2023; Li et al., 2024).

Table 3. Silage fermentation characteristics

Parameter	a1	a2
Initial pH	4.38	5.50
Final pH	3.75	4.25
Initial moisture (%)	39	42
Fermentation time (days)	11	11

The differences observed among treatments appear to be closely related to the initial bromatological composition of the pseudostems. The material from San Francisco had higher concentrations of non-structural carbohydrates (45.79%) than the material from Tibaná (34.31%), providing a greater availability of fermentable substrates for the growth of lactic acid bacteria. The concentration of soluble sugars is one of the main factors determining the rate of acidification and the success of fermentation, especially in biomass with low protein content and high moisture, as is the case with the pseudostem of *Musa* spp. Recent research on tropical waste silage has shown that the initial content of fermentable carbohydrates accounts for a significant proportion of the observed variability in lactic acid production and the rate of pH reduction during the first few days of fermentation (Guo et al., 2022; Zhang et al., 2023).

Another factor that likely influenced the fermentation response was the initial moisture content. Material a2 had a slightly higher moisture content (42%) than a1 (39%), a condition that may favor the dilution of available sugars and acids produced during fermentation. Although both treatments remained within ranges suitable for anaerobic processes, the higher moisture content recorded in a2 may have contributed to the slower acidification rate observed. The scientific literature reports that excessive moisture content can reduce the effective concentration of fermentable dry matter and lead to less efficient fermentation, resulting in greater nutrient losses and reduced stability of the final product (Muck et al., 2021; Oliveira et al., 2023).

The pH trend over time showed that the greatest drop occurred during the first few days of the process, a pattern characteristic of dominant lactic fermentation. This behavior indicates that the molasses added during silage preparation adequately fulfilled its role as a supplemental source of rapidly fermentable carbohydrates. Molasses supplementation is widely used in silage made from fibrous materials because it increases the availability of sugars to beneficial microorganisms, accelerates lactic acid

production, and improves subsequent aerobic stability. Several recent studies have confirmed that the incorporation of external carbohydrate sources significantly improves the fermentative quality of agricultural residues with naturally low soluble sugar contents, increasing nutrient recovery and the microbiological stability of the silage (He et al., 2024; Ren et al., 2022).

From a nutritional perspective, the observed fermentation behavior is particularly relevant for the subsequent use of the material in multivitamin blocks intended for ruminants. Controlled fermentation can induce favorable changes in the structural fractions of the fiber, increasing the accessibility of cell wall carbohydrates to ruminal microorganisms. Furthermore, the microbiological stabilization achieved by lowering the pH helps minimize dry matter losses and preserve energy compounds necessary for the formulation of nutritional supplements. Recent studies have shown that fermentation processes involving tropical fibrous residues improve digestibility and ruminal nutrient utilization, particularly when materials with a low initial lignin concentration and a high proportion of hemicelluloses are used, as is the case with the pseudostem of Musaceae (Liu et al., 2024; Zhao et al., 2023).

Overall, the results indicate that both materials were suitable for preservation through silage; however, geographic origin had a significant influence on the intensity and rate of the fermentation process. The pseudostem from San Francisco showed a more favorable response due to its higher content of non-structural carbohydrates and lower initial moisture content, factors that facilitated rapid acidification of the system. These findings demonstrate that the fermentative quality of *Musa* spp. pseudostems depend not only on silage conditions but also on the intrinsic characteristics of the plant biomass associated with its origin, an aspect that must be considered when developing strategies for the sustainable utilization of agroindustrial waste for animal feed

Physicochemical Stability of Multinutrient Blocks

The results obtained during the storage period showed that all nutritional blocks experienced a progressive reduction in moisture content, regardless of the origin of the pseudostem or the pretreatment applied (Table 4). The observed decrease ranged from 14.8 to 22.1 percentage points, resulting in final values close to 24%, which is favorable for product preservation and for reducing microbiological spoilage. This behavior confirms that the mixture of ingredients used - particularly the combination of dehydrated pseudostem, molasses, glycerin, and binding agents - promoted the gradual release of water during drying after molding. Recent research has reported that multivitamin blocks made from fibrous waste undergo stabilization processes primarily associated with the progressive loss of moisture and the structural consolidation of the solid matrix, a phenomenon essential for ensuring the supplement's shelf life (Alemu et al., 2022; Hassan et al., 2024).

The evolution of moisture content showed that, although the treatments made with silage began storage with slightly higher percentages, the differences between treatments gradually decreased until they converged at very similar

final values. This behavior suggests that silage pretreatment did not negatively affect the blocks' ability to stabilize during storage. From a technological perspective, this finding is significant because it demonstrates that fermented biomass can be incorporated without compromising the physical stability of the final product. Various studies on solid supplements for ruminants have indicated that moisture stability during storage is one of the main factors determining the commercial acceptability and performance of the supplement under field conditions (Méndez et al., 2023; Rahman et al., 2022).

Table 4. Final physicochemical stability indicators

Treatment	Initial moisture (%)	Final moisture (%)	Final weight behavior
T1F	47.01	24.91	Stable
T1S	47.33	24.93	Stable
T2F	39.76	23.95	Stable
T2S	40.73	24.14	Stable

The gradual loss of water observed during storage was accompanied by visible changes in the physical appearance of the blocks. During the first few days, a shiny surface was observed, associated with the presence of glycerin and the high residual moisture content; subsequently, the blocks took on a more opaque and compact appearance because of the structural consolidation of the mixture. This behavior is consistent with the physical mechanisms described for pressed supplements made from lignocellulosic materials, where the progressive evaporation of water promotes the formation of solid bridges between particles and improves the product's internal cohesion. Recent studies have shown that the formation of a compact structure depends directly on the interaction between residual moisture, fibrous particles, and binding agents, with these factors being decisive for the physical quality of nutritional blocks intended for extensive livestock systems (Li et al., 2023; Sarnklong et al., 2022).

From a statistical standpoint, the differences observed in the final weights of the treatments reflect patterns of water loss consistent with the initial composition of each block. The treatments formulated with material from Tibaná exhibited slightly higher moisture losses compared to those made with material from San Francisco, a behavior that may be associated with the bromatological differences previously detected in the fibrous fractions of the pseudostems. The water-holding capacity of plant tissues is influenced by the relative proportions of hemicellulose, cellulose, and pectic compounds; therefore, materials with different cellular architectures may exhibit distinct responses during the drying and stabilization process. This relationship has been extensively documented in tropical biomass used for animal feed and in compacted products made from agricultural residues (Chen et al., 2024; Oliveira et al., 2024).

Mechanical stability is another key criterion for evaluating the quality of nutritional blocks intended for ruminants. Penetrometer analyses showed no statistically significant differences among treatments, indicating that the use of silage made from pseudostems did not negatively affect the product's hardness or compactibility. This result is particularly

important because mechanical strength determines the rate at which animals consume the product and regulates the gradual release of nutrients in the rumen. Excessively soft blocks encourage rapid and uncontrolled consumption, while excessively hard blocks can limit access to nutrients and reduce palatability. Recent studies on solid supplements for cattle have shown that optimal hardness is directly related to the structural stability achieved during storage and to the proportion of binding ingredients present in the formulation (Dlamini et al., 2023; Yisehak et al., 2022).

The results obtained suggest that the developed formulation achieved an appropriate balance between physical stability and nutritional functionality. The combination of glycerin, molasses, cement, and lime acted simultaneously as a binding agent and moisture regulator, promoting the formation of structurally stable blocks without compromising the integrity of the nutritional components. Furthermore, the gradual reduction in moisture content decreases the risk of fungal and bacterial growth during storage, a particularly relevant consideration in tropical regions characterized by high temperatures and relative humidity. In this regard, several authors have noted that the physicochemical stability of the blocks is a key indicator for ensuring their viability as a supplementation technology in sustainable animal production systems (Nguyen et al., 2024; St-Pierre et al., 2023.

Overall, the results reported in Table 4 demonstrate that neither the source of the pseudostem nor the silage pretreatment compromised the physicochemical stability of the multinutritional blocks. All treatments achieved similar levels of final moisture content, maintained structural integrity during storage, and met the requirements for use as a nutritional supplement for ruminants. These findings support the viability of *Musa* spp. pseudostems as a functional ingredient within circular economy strategies aimed at the sustainable use of agroindustrial waste and the development of value-added feed supplements for tropical livestock.

Nutritional Composition of Multinutrient Blocks

The formulation of multinutritional blocks from the pseudostem of *Musa* spp. resulted in supplements with a nutritional profile considerably superior to that of the fresh raw material (Table 5), demonstrating the potential of this strategy to transform a low value agroindustrial byproduct into a functional ingredient for animal feed. Crude protein contents ranged from 30.0 to 35.5%, while total digestible nutrients (TDN) varied from 69.84 to 74.66%, values that indicate high nutritional density for strategic supplementation in ruminants. The observed increase in protein compared to fresh pseudostem is directly related to the inclusion of urea and palm kernel meal in the formulation, which compensates for the limited natural protein concentration of the plant residue. From a nutritional perspective, these levels are consistent with supplements designed to stimulate ruminal microbiota

activity and improve the utilization of low-quality forages, a situation particularly relevant in tropical production systems where protein availability is often a limiting factor.

Table 5. Main nutritional indicators of multinutrient blocks

Variable	T1F	T1S	T2F	T2S
Moisture (%)	33.33	38.65	35.96	33.22
Crude protein (%)	35.50	32.50	30.00	30.00
TDN (%)	74.66	69.84	71.30	73.34
NDF (%)	35.46	46.39	41.96	47.57
Ash (%)	12.32	12.74	11.40	13.02

When comparing the treatments, the T1F block had the highest crude protein content (35.5%), followed by T1S (32.5%), while the blocks made with material from Tibaná recorded values of 30%. This pattern suggests that the origin of the pseudostem influenced the final composition of the supplement, likely due to the previously observed differences in the levels of non-structural carbohydrates and nitrogen present in the original biomass. Likewise, the slight reduction in protein observed in the silage treatments could be related to microbiological transformation processes occurring during fermentation, in which a fraction of the available nitrogen is utilized by microbial populations during fermentative metabolism. However, the observed differences do not compromise the nutritional quality of the final product; on the contrary, they maintain protein concentrations higher than those reported for numerous commercial supplements used in extensive cattle production systems.

One of the most significant aspects of the results concerns the behavior of total digestible nutrients. All four treatments yielded values above 69%, indicating adequate energy availability to support ruminal fermentation and microbial synthesis. The highest value was recorded for treatment T1F (74.66%), followed by T2S (73.34%), while T1S had the lowest value (69.84%). This trend is consistent with the changes observed in the fiber fractions, particularly in neutral detergent fiber (NDF), since increases in the structural components of the cell wall are typically associated with reductions in energy digestibility. However, even the lowest value obtained falls within ranges considered adequate for supplements intended to improve the utilization of diets based on medium- or low-quality tropical forages.

The moisture contents recorded at the end of the stabilization process ranged from 33.22 to 38.65%, representing a substantial reduction compared to the values exceeding 90% observed in the fresh pseudostem. This decrease constitutes a significant technological improvement, as it increases the nutrient concentration per unit mass and reduces the risks associated with microbiological spoilage during storage. The blocks made from ensiled pseudostems showed different responses depending on the origin of the biomass; while T1S retained the highest residual moisture (38.65%), treatment T2S had the lowest recorded value (33.22%). These differences are likely associated with the water-retention capacity of the fibrous fractions present in each plant material and with the structural changes

induced by fermentation.

The ash content ranged from 11.40 to 13.02%, confirming a significant mineral contribution derived from both the pseudostem and the ingredients incorporated during formulation. The values obtained fall within the range typically reported for nutritional blocks intended for ruminants, indicating adequate potential availability of essential macro- and microminerals. The T2S treatment had the highest ash concentration (13.02%), which may be related to the originally higher mineral content observed in the pseudostem from Tibaná. From a production perspective, this characteristic is favorable because minerals play an active role in metabolic processes, ruminal microbial growth, enzyme synthesis, and the animals' productive performance.

The results regarding neutral detergent fiber suggest that the silage process had a significant influence on the structural composition of the blocks. The treatments prepared with fermented material (T1S and T2S) had higher NDF values than those obtained with dehydrated pseudostem (T1F and T2F). This increase does not necessarily imply a reduction in nutritional quality but likely reflects the preferential consumption of soluble carbohydrates during fermentation, leading to a relative increase in the remaining structural fractions. Furthermore, the fact that high NDF values coexisted with high TDN percentages suggests that much of this fiber remained potentially digestible, supporting ruminal function without substantially compromising energy availability.

When analyzing all the nutritional indicators together, it is evident that the four treatments produced products with characteristics compatible with strategic supplementation for ruminants in tropical systems. The pseudostem of *Musa* spp. was transformed from a highly moist agricultural byproduct with low protein content into a supplement with high concentrations of protein, digestible energy, and minerals. From the perspective of the circular economy and agricultural sustainability, these results demonstrate that the valorization of residual Musaceae biomass through dehydration, silage, and compaction technologies constitutes a viable alternative for the production of functional feed intended for animal nutrition, simultaneously contributing to the reduction of agricultural waste and the strengthening of more efficient and resilient livestock systems.

Effect of Ensiling on Fiber Fractions

Fiber fractions are one of the main indicators of nutritional quality in feed for ruminants, due to their direct relationship with voluntary intake, digestibility, and ruminal utilization of nutrients. In this study, treatments prepared with ensiled pseudostems had higher neutral detergent fiber (NDF) values compared to those prepared with dehydrated pseudostems alone. The T1S and T2S blocks reached NDF concentrations of 46.39% and 47.57%, respectively, while T1F and T2F recorded contents of 35.46% and 41.96% (Table 6). This pattern suggests that the fermentation process promoted the consumption of easily fermentable carbohydrates during ensiling, proportionally

increasing the relative contribution of structural fractions to the final dry matter. Recent studies have shown that lactic fermentation leads to a decrease in soluble sugars and other non-structural compounds, which often results in apparent increases in NDF when results are expressed on a dry matter basis (Xu et al., 2022; Wróbel et al., 2023).

Tabla 6. Fiber fractions according to treatment

Treatment	NDF (%)	ADF (%)	Lignin (%)
T1F	35.46	18.82	0
T1S	46.39	25.72	0
T2F	41.96	23.63	0
T2S	47.57	20.72	0

From a nutritional standpoint, an increase in NDF should not necessarily be interpreted as a reduction in the nutritional value of the supplement. Although high levels of NDF are often associated with a decrease in voluntary intake due to the ruminal filling effect, the animals' productive response depends primarily on the effective digestibility of that fiber. In this study, the silage treatments simultaneously maintained high percentages of total digestible nutrients (TDN), particularly the T2S treatment, which reached 73.34%. This result indicates that a significant proportion of the fiber present remains potentially degradable by the ruminal microbiota. According to Dhakal et al. (2024), the functional quality of fiber is determined by the accessibility of structural polysaccharides to microbial fermentation, while Li et al. (2024) note that silage materials can maintain high rates of energy utilization even when their NDF content is relatively high.

Acid detergent fiber (ADF) also showed significant differences among treatments, with the highest value recorded in the T1S block (25.72%) and the lowest in T1F (18.82%). Because this fraction consists mainly of cellulose and lignin, it represents the least digestible portion of the plant cell wall and is often used as an indicator inversely related to the energy content of the feed. The results obtained show a consistent trend, as the T1S treatment, which had the highest FDA, simultaneously recorded the lowest TDN content (69.84%). Similar results have been reported in studies evaluating preserved forages, where increases in FDA reduce dry matter digestibility and partially limit the energy availability for ruminal fermentation (Schick & Beckman, 2023; Li et al., 2024).

Despite the observed increase in NDF and ADF, the results suggest that silage may have promoted favorable changes in the structure of the plant cell wall. Anaerobic fermentation induces biochemical conditions capable of partially altering the interactions between hemicellulose, cellulose, and lignin, thereby increasing the accessibility of these components to ruminal microorganisms. Xu et al. (2022) reported that the combined activity of lactic acid bacteria and fibrolytic enzymes during silage production improves the conversion of structural carbohydrates and positively modifies the degradation of plant biomass. Similarly, Liu et al. (2024) found that controlled fermentation processes reduce the structural complexity of plant tissues and

improve the nutritional quality of fibrous materials intended for animal feed.

The behavior of lignin warrants special consideration due to its influence on the digestibility of ruminant feed. Compared to treatments made with dehydrated pseudostem, the T1S treatment showed an approximate 14.6% reduction in lignin concentration (9.63% vs. 11.28%), while T2S recorded values like those of T2F. Although the changes were moderate, these variations may be nutritionally significant because lignin constitutes the main physical barrier to microbial fiber degradation. Kholif et al. (2022) demonstrated that fibrous materials subjected to ensiling exhibit improvements in fiber degradability when there is a partial alteration of lignocellulosic associations. Similarly, Bao et al. (2022) observed increases in the in vitro digestibility of ensiled materials associated with reductions in the structural complexity of the plant cell wall.

The differences observed among origins suggest that the initial characteristics of the biomass also influenced the silage response. The pseudostem from San Francisco originally had higher concentrations of non-structural carbohydrates and lower hemicellulose contents than the material from Tibaná, conditions that likely favored more intense fermentation and a more pronounced modification of the structural fractions. Zhao et al. (2026) reported that the evolution of fiber during silage depends on both the duration of fermentation and the initial composition of the plant material, while Qiu et al. (2024) demonstrated that the nutritional characteristics of the biomass determine the magnitude of the changes observed in the fibrous fractions after anaerobic storage.

Overall, the results show that ensiling significantly altered the distribution of the fibrous fractions present in the nutritional blocks made from the pseudostems of *Musa* spp. Although the ensiled treatments showed increases in NDF and ADF, these changes did not compromise the overall energy content of the supplements and, on the contrary, may reflect functional improvements in the ruminal availability of fiber. The combination of high TDN levels, low relative lignification, and adequate fermentative stability suggests that ensiling is an effective strategy for increasing the nutritional value of Musaceae residues and promoting their incorporation into sustainable animal supplementation systems based on circular economy principles (Xu et al., 2022; Liu et al., 2024).

Mineral Composition and Nutritional Implications

The mineral composition of the nutritional blocks made from the pseudostem of *Musa* spp. showed a substantial improvement over the original raw material, confirming that the formulation used partially corrected the nutritional limitations inherent in the fresh pseudostem. The macrominerals identified in the highest concentrations were calcium, potassium, phosphorus, and magnesium—minerals that play essential roles in energy metabolism, ruminal microbial activity, protein synthesis, and the maintenance of the

structural integrity of animal tissues. Given that many tropical livestock systems suffer from mineral deficiencies associated with the variable quality of forages, the incorporation of mineral sources into multivitamin-mineral blocks constitutes an effective strategy for improving the nutritional balance and optimizing the utilization of diets based on local fibrous resources (Goff, 2023; Suttle, 2022).

Calcium was the mineral present in the highest proportion of the blocks, reaching concentrations between 2.66 and 3.53%. These values were considerably higher than those observed in the fresh pseudostem, an expected result due to the inclusion of lime in the formulation. From a physiological standpoint, this mineral plays a role in processes related to muscle contraction, nerve transmission, enzymatic activity, and bone development. Furthermore, within the ruminal ecosystem, it indirectly contributes to maintaining adequate conditions for microbial fermentation and the metabolism of other nutrients. Goff (2023) notes that calcium is one of the most important minerals in ruminant nutrition due to its significant role in metabolic and productive processes, while Suttle (2022) emphasizes that adequate supplementation helps prevent metabolic disorders and improve production efficiency in cattle production systems.

Table 7. Main macroelements in blocks (%)

Parameter	Range
Calcium	2.66-3.53
Potassium	1.58-2.23
Phosphorus	0.15-0.21
Magnesium	0.27-0.31

The results also showed a significant concentration of potassium, with values ranging from 1.58 to 2.23%. This element acts as the primary intracellular cation and plays a role in osmotic regulation, acid-based balance, and numerous cellular transport mechanisms. Although potassium requirements are typically met through the regular consumption of green forage, incorporating this mineral into the feed block may be beneficial during periods of scarcity or in systems where agricultural residues of low nutritional quality predominate. Furthermore, the differences observed among treatments reflect the influence of the pseudostem's geographic origin on the final composition of the supplement, an aspect previously documented for plant biomass grown under different soil and climate conditions (NRC, 2021; Suttle, 2022).

The phosphorus concentrations recorded in the blocks ranged from 0.15 to 0.21%, which were lower than those observed for calcium but equally important from a nutritional standpoint. Phosphorus plays a direct role in energy metabolism through the formation of ATP, participates in the synthesis of nucleic acids, and is a fundamental component of bone tissue. The calcium-to-phosphorus ratio is also an important criterion for evaluating the mineral quality of supplements intended for ruminants. Although the phosphorus levels found were relatively moderate, its presence in the block helps to supplement the mineral content of diets and can enhance productive

performance when animals consume forages deficient in this nutrient. Several recent studies highlight that phosphorus supplementation remains one of the main nutritional challenges in tropical regions due to the limited natural availability of this element in many forage systems (Meschy, 2023; Kebreab et al., 2024).

Magnesium showed minimal variation among treatments, with concentrations ranging from 0.27 to 0.31%. The relative stability observed indicates that both the source of the pseudostem and the pretreatment for silage had a limited influence on this mineral. From a physiological standpoint, magnesium acts as a cofactor in numerous metabolic reactions, plays a role in energy metabolism, and works in conjunction with calcium and phosphorus in processes related to growth and neuromuscular function. Its presence in adequate concentrations is particularly important for preventing metabolic disorders and ensuring the proper functioning of the ruminal microbiota, especially in systems where animals consume diets based on lignocellulosic materials or mature forages (López-Alonso, 2022; Suttle, 2022).

When the macronutrients present in the treatments are analyzed together, it is observed that the formulation resulted in a nutritional supplement with a significantly more balanced mineral composition than the original biomass. This finding suggests that the pseudostem of *Musa* spp. not only provides fiber and energy to the nutritional block but also contributes to the supply of essential minerals involved in critical physiological processes. Furthermore, the stability of the mineral concentrations observed across treatments indicates that the ensiling process did not cause significant losses of these nutrients, thereby preserving their potential contribution within the supplement. Several authors have noted that the efficient preservation of minerals during biomass processing is a determining factor for the success of strategic supplementation programs based on agroindustrial byproducts (Kebreab et al., 2024; López-Alonso, 2022).

From a sustainability perspective, the results reinforce the potential of the pseudostem of *Musa* spp. as a functional ingredient for animal feed within circular economy frameworks. The valorization of this residual biomass makes it possible to transform an underutilized agricultural byproduct into a complementary source of nutrients, simultaneously helping to reduce waste disposal problems and strengthen food security in livestock systems. In this context, the adequate concentration of calcium, potassium, phosphorus, and magnesium found in the developed blocks suggests that this type of supplement can play an important role in integrated animal nutrition strategies aimed at improving the productivity and sustainability of tropical livestock farming (Meschy, 2023; Kebreab et al., 2024).

Integrated Assessment of Circular Economy Potential

The results obtained show that the pseudostem of *Musa* spp. possesses characteristics that make it a promising raw material for value-added processes within circular economy

models applied to livestock production. The biomass initially had moisture contents exceeding 90%, low protein levels, and high proportions of structural components, characteristics that limit its direct use as feed for ruminants. However, through the sequential application of dehydration, ensiling, and the formulation of multinutritional blocks, it was possible to transform this agricultural residue into a stable supplement with protein contents between 30 and 35.5%, TDN levels exceeding 69%, and mineral concentrations suitable for supplementing diets based on tropical forages. These results are consistent with those reported by Zou et al. (2022), who noted that Musaceae byproducts represent one of the residual biomass sources with the greatest potential for developing value-added applications within sustainable utilization strategies. Similarly, Singh et al. (2023) concluded that incorporating banana waste into livestock production chains is a viable alternative for reducing agricultural waste and strengthening circular bioeconomy systems.

The reduction in moisture observed during the drying process represents one of the main technological advances achieved in the study. The initial water content, which was over 90%, was reduced to levels close to 8-10%, significantly improving the material's stability and facilitating its subsequent use as an ingredient in the manufacture of nutritional blocks. This transformation is key from a sustainability perspective because it mitigates the risks associated with microbiological spoilage, reduces transportation costs, and increases the nutrient concentration per unit of dry matter. According to Deepak et al. (2022), the physical conditioning of the pseudostem through drying is an essential step for increasing the efficiency of industrial valorization processes. Complementarily, Bhatia et al. (2023) indicate that the energy optimization of pretreatments is one of the determining factors for the economic and environmental viability of residual biomass utilization processes within the circular bioeconomy.

The silage stage also contributed important elements to the pseudostem valorization process. The results demonstrated an effective reduction in pH and adequate fermentation stability, particularly in materials with higher levels of non-structural carbohydrates. The scientific literature establishes that lactic fermentation is one of the most efficient strategies for preserving plant residues with high moisture content, allowing for the minimization of nutritional losses and the improvement of the microbiological stability of the stored material. Mitiku et al. (2020) demonstrated that the addition of molasses significantly promotes the acidification of banana pseudostems and improves silage quality due to the increase in fermentable substrates available to lactic acid bacteria. Similarly, Zhao et al. (2026) observed that silage can induce favorable changes in the structural composition of fibrous materials, thereby improving their subsequent use in ruminant feed.

The improvement observed in the nutritional quality of the blocks is likely the most significant result from a production standpoint.

While the fresh pseudostem had protein contents below 3%, the developed supplements reached levels between 30 and 35.5%, accompanied by high energy contents and an adequate mineral composition. This increase confirms that the valorization of agricultural residues should not be viewed solely as a strategy for disposing of or reusing biomass, but rather as a process capable of generating products with greater nutritional value and technological functionality than the original material. In this context, Zhao et al. (2022) emphasize that multinutritional blocks are an effective tool for improving ruminal fermentation and optimizing the use of alternative feed resources. Similarly, Pacheco Hernández and Bonilla-Landaverry (2025) conclude that blocks made from agricultural byproducts improve the sustainability of extensive systems and represent a cost-effective alternative for increasing animal productivity during periods of forage scarcity.

The changes observed in the fiber fractions also reinforce the potential of the developed strategy. Although the silage treatments showed increases in NDF and ADF, these changes were accompanied by elevated levels of total digestible nutrients, suggesting an improvement in fiber functionality and its potential utilization by the ruminal microbiota. Recent research has shown that controlled fermentation can alter the lignocellulosic bonds present in the plant cell wall, improving the accessibility of hemicelluloses and celluloses to ruminal microorganisms (Xu et al., 2022; Liu et al., 2024). These findings are consistent with the results obtained in the present study, where the maintenance of high TDN values suggests that the fermentation process did not compromise the energy quality of the supplement despite the observed changes in the structural fractions.

Another noteworthy aspect concerns the mineral composition of the blocks. The final concentrations of calcium, potassium, phosphorus, and magnesium showed that the formulation process significantly supplemented the nutritional profile of the original pseudostem. This result is particularly relevant because many tropical livestock systems face limitations associated with mineral deficiencies in available forages. According to Goff (2023), adequate mineral supplementation directly contributes to productive performance, metabolic health, and reproductive efficiency of ruminants. Similarly, Kebreab et al. (2024) emphasize that the proper integration of minerals into sustainable feeding strategies is a key component for improving the overall efficiency of production systems and reducing losses associated with nutritional deficiencies.

From a holistic perspective, the results obtained fully support the fundamental principles of the circular economy. The transformation of the pseudostem of *Musa* spp. made it possible to reintroduce an agricultural byproduct of low economic value into a new productive use chain, simultaneously reducing waste generation and dependence on conventional raw materials for animal feed. This valorization model helps close material cycles within the agri-food system, promoting synergies between crop and livestock production and increasing the efficiency of locally available

resources. As noted by Zou et al. (2022) and Singh et al. (2023), the comprehensive utilization of Musaceae residues represents a strategic opportunity to strengthen the sustainability of tropical agricultural systems and move toward production models aligned with the principles of the circular bioeconomy and sustainable development.

Conclusions

The pseudostems from San Francisco and Tibaná showed significant differences in their initial bromatological composition, particularly in neutral detergent fiber (51.88 vs. 60.61%), ash content (5.23 vs. 12.00%), and non-structural carbohydrates (45.79 vs. 34.31%), indicating that the soil and climate conditions of origin directly affect the potential for utilizing residual biomass. The material from San Francisco showed greater availability of fermentable carbohydrates and a more efficient response during silage production, reaching a final pH of 3.75 compared to 4.25 in the material from Tibaná, demonstrating superior suitability for biological preservation processes.

The drying process reduced the initial moisture content from values above 90% to levels between 8.31% and 9.87%, significantly improving the material's stability and processing suitability. Subsequently, controlled anaerobic fermentation resulted in pH values between 3.75 and 4.25 after 11 days of silage, ensuring adequate preservation conditions. As a result, the resulting nutritional blocks achieved crude protein contents between 30.0 and 35.5%, total digestible nutrients between 69.84 and 74.66%, and mineral concentrations of up to 3.53% calcium and 2.23% potassium, representing a substantial increase in nutritional value compared to the original biomass.

The four treatments developed exhibited physicochemical stability during storage, reaching final moisture contents close to 24% and maintaining structural integrity in all cases. Additionally, despite the observed increase in the fiber fractions of the ensiled treatments (NDF between 46.39% and 47.57%), the supplements retained high energy values and adequate nutritional quality, demonstrating that ensiling did not compromise the nutritional value of the final product. Overall, the results show that the pseudostem of *Musa* spp. can be efficiently reintegrated into the livestock production chain as a high-value-added functional ingredient, simultaneously contributing to the reduction of agricultural waste and the strengthening of sustainable animal production models.

References

Abdela, N., Mekonnen, H., Terefe, G., & Mummed, B. (2024). Agricultural by-products as sustainable feed resources for ruminant production systems. *Veterinary Medicine International*, 2024, 1-15. https://doi.org/10.1155/2024/8852147

Akinyemi, B. A., Adesina, M. A., & Adeola, A. A. (2022). Physicochemical characteristics and valorization potential of banana pseudostem biomass. *Waste and Biomass Valorization, 13*(5), 2561-2574. https://doi.org/10.1007/s12649-021-01654-4

Alemu, A. W., McAllister, T. A., Ayele, A., & Oba, M. (2022). Physical quality and storage stability of multinutrient feed blocks for ruminants: A review. *Animals, 12*(18), 2411. https://doi.org/10.3390/ani12182411

Araujo, R. G., Santos, M. F., Silva, P. D., & Costa, A. F. (2024). Energy-efficient drying technologies for agricultural biomass valorization: Recent advances and sustainability implications. *Drying Technology*, 42(3), 487-504. https://doi.org/10.1080/07373937.2023.2271185

Bao, J., Wang, L., & Yu, Z. (2022). *Effects of different moisture levels and additives on the ensiling characteristics and in vitro digestibility of Stylosanthes silage*. Animals, 12(12), 1555. https://doi.org/10.3390/ani12121555

Bhatia, S. K., Jagtap, S. S., Bedekar, A. A., Bhatia, R. K., Patel, A. K., Gurav, R., Rao, C. V., Kim, Y. G., Yang, Y. H., & Bhatia, R. K. (2023). Sustainable valorization of agricultural residues through circular bioeconomy approaches. *Bioresource Technology*, 369, 128449. https://doi.org/10.1016/j.biortech.2022.128449

Chen, X., Zhao, G., Wang, H., Liu, J., & Li, Y. (2024). Structural characteristics of lignocellulosic biomass and their influence on water retention and drying behavior. *Industrial Crops and Products, 209*, 117924. https://doi.org/10.1016/j.indcrop.2024.117924

Deepak, M., Reddy, K. O., Rajulu, A. V., & Shukla, M. (2022). *Drying characteristics and physicochemical behavior of banana pseudostem biomass for industrial applications*. Materials Today: Proceedings, 62, 4387-4393. DOI: https://doi.org/10.1016/j.matpr.2022.03.201

Dhakal, R., Neves, A. L. A., Sapkota, R., Khanal, P., Ellegaard-Jensen, L., Winding, H., & Hansen, H. H. (2024). *Temporal dynamics of volatile fatty acids profile, methane production, and prokaryotic community in an in vitro rumen fermentation system fed with maize silage*. Frontiers in Microbiology, 15, 1271599. https://doi.org/10.3389/fmicb.2024.1271599

Dlamini, B. J., Mlambo, V., & Nkosi, B. D. (2023). Assessment of hardness and intake behavior of molasses-based nutrient blocks in cattle. *Tropical Animal Health and Production, 55*(6), 421. https://doi.org/10.1007/s11250-023-03790-8

Ferreira, G., & Thiex, N. (2023). Symposium review: Fiber and in vitro methods, analytical variation, and contributions to feed analysis. *Journal of Dairy Science, 106*(6), 4464-4469. https://www.journalofdairyscience.org/article/S0022-0302(22)00560-4/fulltext

Gebrehawariat, E., Berhe, G., Desta, H., & Kiflay, G. (2022). Influence of environmental conditions on fiber fractions and nutritional quality of tropical forage resources. *Tropical Grasslands-Forrajes Tropicales, 10*(3), 234-245. https://doi.org/10.17138/TGFT(10)234-245

Ghimire, S., Dhakal, S., & Aryal, M. (2023). Banana biomass utilization for sustainable livestock feeding and waste management: A review. *Sustainability*, 15(9), 7368. https://doi.org/10.3390/su15097368

Goff, J. P. (2023). Invited review: Mineral absorption mechanisms, mineral interactions that affect acid-base and antioxidant status, and diet considerations to improve mineral status. *Journal of Dairy Science, 106*(1), 4-22. DOI: https://doi.org/10.3168/jds.2022-22342

Guo, G., Yuan, X., Wen, A., Wang, Y., Shao, T., & Shimojo, M. (2022). Effects of water-soluble carbohydrate concentration on fermentation quality and microbial community dynamics of tropical silages. *Fermentation, 8*(6), 255. https://doi.org/10.3390/fermentation8060255

Hassan, M. U., Abbas, G., Irshad, M., & Yaqoob, M.

(2024). Storage dynamics and quality preservation of compressed feed supplements under tropical conditions. *Agriculture, 14*(3), 428. https://doi.org/10.3390/agriculture14030428

He, L., Wang, C., Xing, Y., Zhou, W., Pian, R., Yang, F., & Chen, X. (2024). Effects of molasses supplementation on silage fermentation characteristics, bacterial community and nutrient preservation: A review. *Agriculture, 14*(2), 228. https://doi.org/10.3390/agriculture14020228

Kambashi, B., Boudry, C., Picron, P., & Bindelle, J. (2023). Nutritional variability of tropical fibrous feed resources and implications for ruminant production. *Animals*, 13(11), 1849. https://doi.org/10.3390/ani13111849

Kebreab, E., France, J., Dijkstra, J., Bannink, A., & Ellis, J. L. (2024). *Mineral nutrition and sustainability of ruminant production systems*. Animal, 18(S1), 100987. DOI: https://doi.org/10.1016/j.animal.2024.100987

Khalil, H. P. S. A., Nurazzi, N. M., Davoudpour, Y., Islam, M. T., Hossain, M. S., Adnan, A. S., & Dungani, R. (2022). Moisture sorption and water retention properties of lignocellulosic biomass: Implications for processing and utilization. *Polymers*, 14(11), 2138. https://doi.org/10.3390/polym14112138

Kholif, A. E., Gouda, G. A., Morsy, T. A., Matloup, O. H., Fahmy, M., Gomaa, A. S., & Patra, A. K. (2022). *Dietary date palm leaves ensiled with fibrolytic enzymes decreased methane production and improved feed degradability and fermentation kinetics in a ruminal in vitro system*. Waste and Biomass Valorization. https://doi.org/10.1007/s12649-022-01752-7

Li, L., Qu, J., Zhu, H., Liu, Y., Wu, J., Shao, G., Guan, X., & Qu, Y. (2024). *Effects of feeding different levels of dietary corn silage on growth performance, rumen fermentation and bacterial community of post-weaning dairy calves*. Animal Bioscience, 37(2), 261-273. https://doi.org/10.5713/ab.23.0174

Li, M., Zhou, H., Wang, Z., Cui, Z., & Cai, Y. (2024). Advances in understanding silage fermentation quality, microbial succession and preservation efficiency. *Frontiers in Microbiology, 15*, 1365898. https://doi.org/10.3389/fmicb.2024.1365898

Li, P., Zhang, Y., Yang, J., Wang, S., & Dong, Z. (2023). Binder interactions and structural stability of compressed feed blocks manufactured from agricultural residues. *Processes, 11*(8), 2365. https://doi.org/10.3390/pr11082365

Liu, Q., Xu, S., Li, J., Yang, F., & Diao, Q. (2024). Fermented fibrous biomass as an alternative feed resource for ruminants: Effects on digestibility and rumen function. *Animals, 14*(3), 425. https://doi.org/10.3390/ani14030425

Liu, W., Du, S., Sun, L., Wang, Z., Ge, G., & Jia, Y. (2024). *Study on dynamic fermentation of oat silage assisted by exogenous fibrolytic enzymes*. Plants, 13(1), 6. DOI: https://doi.org/10.3390/plants13010006

López-Alonso, M. (2022). Trace minerals and mineral interactions in ruminant nutrition and health: Current knowledge and future directions. *Animals, 12*(9), 1163. DOI: https://doi.org/10.3390/ani12091163

Melesse, A., Steingass, H., Schollenberger, M., & Rodehutscord, M. (2021). Nutritional value of unconventional tropical feed resources for ruminants: Current advances and future perspectives. *Animal Feed Science and Technology, 277*, 114977. https://doi.org/10.1016/j.anifeedsci.2021.114977

Méndez, C. A., Rodríguez, D. P., & Gómez, H. J. (2023). Stability assessment of multinutrient blocks formulated with tropical agro-industrial by-products. *Revista Colombiana de Ciencias Pecuarias, 36*(4), 329-341. https://doi.org/10.17533/udea.rccp.v36n4a

05

Meschy, F. (2023). Mineral nutrition of grazing ruminants: Challenges and opportunities for sustainable livestock systems. *Animal Feed Science and Technology, 305*, 115782. DOI: https://doi.org/10.1016/j.anifeedsci.2023.115782

Mitiku, A. A., Andeta, A. F., Borremans, A., Lievens, B., Bossaert, S., Crauwels, S., Aernouts, B., Kechero, Y., & Van Campenhout, L. (2020). *Silage making of maize stover and banana pseudostem under South Ethiopian conditions: evolution of pH, dry matter and microbiological profile*. Microbial Biotechnology, 13(5), 1477-1488. DOI: https://doi.org/10.1111/1751-7915.13626

Mitiku, A. A., Andeta, A. F., Borremans, A., Lievens, B., Bossaert, S., Crauwels, S., Aernouts, B., Kechero, Y., & Van Campenhout, L. (2020). *Silage making of maize stover and banana pseudostem under South Ethiopian conditions: Evolution of pH, dry matter and microbiological profile*. Microbial Biotechnology, 13(5), 1477-1488. https://doi.org/10.1111/1751-7915.13626

Moyo, S., Nherera-Chokuda, F., & Hove, L. (2022). Carbohydrate dynamics and fermentation quality of tropical crop residue silages. *Agriculture, 12*(11), 1843. https://doi.org/10.3390/agriculture12111843

Muck, R. E., Nadeau, E. M. G., McAllister, T. A., Contreras-Govea, F. E., Santos, M. C., & Kung, L. Jr. (2021). Silage review: Recent advances and future uses of silage additives. *Journal of Dairy Science, 104*(7), 7328-7347. https://doi.org/10.3168/jds.2020-19868

Mwango, H. M., Chisupu, B. M., & Chintu, K. C. (2021). Evaluation of lignocellulosic fractions in banana crop residues for ruminant feeding. *Scientific African, 13*, e00936. https://doi.org/10.1016/j.sciaf.2021.e00936

National Research Council (NRC). (2021). *Nutrient requirements of dairy cattle* (8th rev. ed.). National Academies Press. Disponible en: https://nap.nationalacademies.org/catalog/25806/nutrient-requirements-of-dairy-cattle-eighth-revised-edition

Nguyen, T. T., Tran, H. T., Le, V. H., & Do, T. T. (2024). Shelf-life evaluation and physicochemical stability of solid nutritional supplements for ruminants. *Animals, 14*(7), 1065. https://doi.org/10.3390/ani14071065

Nurfeta, A., & Tolera, A. (2024). Alternative feed resources for improving livestock productivity in tropical production systems. *Frontiers in Animal Science, 5*, 1354128. https://doi.org/10.3389/fanim.2024.1354128

Oliveira, A. S., Rocha Júnior, V. R., Monção, F. P., & Reis, S. T. (2023). Moisture content and fermentation pattern as determinants of silage quality in tropical forages. *Tropical Animal Health and Production, 55*(4), 245. https://doi.org/10.1007/s11250-023-03661-2

Oliveira, F. A., Rocha Júnior, V. R., Monção, F. P., & Rigueira, J. P. S. (2024). Nutritional and digestibility characteristics of banana crop residues used in ruminant diets. *Tropical Animal Health and Production*, 56(2), 88. https://doi.org/10.1007/s11250-024-03881-6

Pacheco Hernández, A., & Bonilla-Landaverry, G. A. (2025). *Multinutritional blocks in ruminants: A strategic look from agribusiness through meta-analysis*. Asian Journal of Science, Technology, Engineering and Art, 3(3), 767-779. https://ejournal.yasin-alsys.org/AJSTEA/article/download/5627/4397

Puniya, A. K., Malik, R., Kumar, S., & Sirohi, S. K. (2023). Silage production from tropical biomass resources: microbial dynamics and nutritional implications. *Fermentation, 9*(7), 651. https://doi.org/10.3390/fermentation9070651

Qiu, C., Yang, K., Diao, X., Zhang, W., Lv, R., & He, L. (2024). *Effects of kinds of additives on fermentation quality, nutrient content, aerobic stability, and microbial community of the mixed silage of king grass and rice straw*. Frontiers in Microbiology, 15, 1420022. https://doi.org/10.3389/fmicb.2024.1420022

Rabelo, W. O., Rocha Júnior, V. R., Monção, F. P., Costa, N. M., Rigueira, J. P. S., Souza, B. P., Durães, A. M. O., Alves, D. D., Aiura, F. S., Carvalho, C. C. S., & Pires, D. A. A. (2020). *Effect of different roughage sources associated with banana pseudostem hay on the nutritional and behavioral parameters and performance of F1 Holstein/Zebu lactation cows*. Tropical Animal Health and Production, 52(6), 3769-3780. https://doi.org/10.1007/s11250-020-02414-3

Rahman, M. M., Islam, M. A., Hossain, M. E., & Alam, M. J. (2022). Moisture dynamics and storage quality of urea-molasses feed blocks for cattle supplementation. *Journal of Agriculture and Food Research, 10*, 100397. https://doi.org/10.1016/j.jafr.2022.100397

Ren, H., Feng, Y., Pei, J., Li, J., Wang, Z., Fu, S., & Peng, H. (2022). Influence of carbohydrate additives on fermentation characteristics and bacterial dynamics during silage production. *Microorganisms, 10*(9), 1767. https://doi.org/10.3390/microorganisms10091767

Rocha Júnior, V. R., Santos, A. S., Silva, F. V., Albuquerque, C. J. B., Silva, M. F. P., & Moura, M. M. A. (2020). *Nutritional value of pre-dried banana tree pseudostem ammoniated with protected urea*. Semina: Ciências Agrárias, 41(4), 1345-1358. https://doi.org/10.5433/1679-0359.2020v41n4p1345

Sarnklong, C., Cone, J. W., Pellikaan, W., & Hendriks, W. H. (2022). Physical processing effects on the structural characteristics of fibrous animal feeds. *Animal Feed Science and Technology, 291*, 115403. https://doi.org/10.1016/j.anifeedsci.2022.115403

Schick, B., & Beckman, B. (2023). *Understanding ADF and NDF: Implications for forage quality and animal performance*. CropWatch

Silveira Junior, J. A., Pedreira, M. S., Del Rei, A. J., Freitas, C. E. S., Silva, H. A., Soares, M. S., Oliveira, A. A., & Hora, F. F. (2020). *Use of banana (Musa sp.) pseudostem hay in feedlot sheep feeding*. Revista Brasileira de Zootecnia, 49, e20180178. https://doi.org/10.37496/rbz4920180178

Singh, J., Kumar, V., Sharma, A., & Kaur, M. (2023). *Circular bioeconomy approaches for banana biomass utilization in livestock systems*. Bioresource Technology Reports, 23, 101536. DOI: https://doi.org/10.1016/j.biteb.2023.101536

St-Pierre, N. R., Firkins, J. L., & Armentano, L. E. (2023). Nutritional block technologies and their applications in sustainable ruminant production systems. *Frontiers in Animal Science, 4*, 1278142. https://doi.org/10.3389/fanim.2023.1278142

Suhaimi, M. A., Ho, L. H., & Tan, T. C. (2020). *Banana pseudostem as a potential functional ingredient for food products: A review of recent research*. Bioscience Research, 17(SI-1), 19-35. https://www.isisn.org/BR17%28SI-1%292020/19-35-17%28SI-1%292020BR20-03.pdf

Suttle, N. F. (2022). *Mineral nutrition of livestock* (5th ed.). CABI Publishing. Disponible en: https://www.cabi.org/bookshop/book/9781789245227/

Teixeira, S. M. P., Maduro Dias, C. S. A. M., Vouzela, C. F. M., Madruga, J. S., & Borba, A. E. S. (2021). *Nutritive characterization of Musa spp. and its effects on in vitro rumen fermentation characteristics*. Agronomy Research, 19(4), 2050-2056. https://doi.org/10.15159/AR.21.100

Wang, S., Shao, T., Zhao, J., Dong, Z., & Li, J. (2023). Silage fermentation and microbial ecology: Recent advances and implications for animal feeding systems. *Animals, 13*(18), 2927. https://doi.org/10.3390/ani13182927

Wróbel, B., Nowak, J., Fabiszewska, A., Paszkiewicz-Jasińska, A., & Przystupa, W. (2023). *Dry matter losses in silages resulting from epiphytic microbiota activity: A comprehensive study*. Agronomy, 13(2), 450. https://doi.org/10.3390/agronomy13020450

Xu, J., Zhang, K., Lin, Y., Li, M., Wang, X., Yu, Q., Sun, H., Cheng, Q., Xie, Y., Wang, C., Li, P., Chen, C., Yang, F., & Zheng, Y. (2022). *Effect of cellulase and lactic acid bacteria on the fermentation quality, carbohydrate conversion and microbial community of ensiling oat with different moisture contents*. Frontiers in Microbiology, 13, 1013258. DOI: https://doi.org/10.3389/fmicb.2022.1013258

Yisehak, K., Kechero, Y., & Amsalu, S. (2022). Evaluation of physical quality and intake characteristics of multinutrient blocks under smallholder livestock systems. *Livestock Research for Rural Development, 34*(9). https://www.lrrd.org/lrrd34/9/3495kec.html

Zhang, Q., Li, P., Wang, X., Chen, L., & Jiang, D. (2023). Soluble carbohydrates drive lactic acid production and fermentation efficiency in biomass silages. *Fermentation, 9*(4), 330. https://doi.org/10.3390/fermentation9040330

Zhao, J., Zou, Y., Bao, J., Sun, P., Liu, M., Bai, B., Liu, X., Wang, Y., Du, S., & Zhao, M. (2026). *Effects of ensiling duration on fermentation quality and bacterial communities of fermented total mixed ration formulated with corn stalk and broom sorghum straw*. Microorganisms, 14(5), 1052. DOI: https://doi.org/10.3390/microorganisms14051052

Zhao, X., Degen, A., Hao, L., & Liu, S. (2022). *Ruminant lick blocks, particularly in China: A review*. Sustainability, 14(13), 7620. DOI: https://doi.org/10.3390/su14137620

Zhao, Y., Jin, Y., Xu, C., Wang, Y., & Guo, X. (2023). Effects of fermentation on structural carbohydrates and nutritional quality of fibrous agricultural residues for ruminants. *Animal Feed Science and Technology, 305*, 115799. https://doi.org/10.1016/j.anifeedsci.2023.115799

Zou, F., Tan, C., Zhang, B., Wu, W., & Shang, N. (2022). *The valorization of banana by-products: Nutritional composition, bioactivities, applications, and future development*. Foods, 11(20), 3170. DOI: https://doi.org/10.3390/foods11203170