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Assessment of preservation and nutritional quality in tropical forage silage using an innovative modified silos system

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ABSTRACT

This study aimed to evaluate the physical quality of forage silage using a modified silo (MOSI) on a laboratory scale and address common problems in silage production, such as spoilage in the early phase of ensilage, by innovating a silo design that can effectively control airflow. This study used a factorial complete randomized design with two factors: wilting time (0 hours and 2 hours) and vacuum (vacuum and not vacuum). Fresh king grass (*Pennisetum purpureum*) was used as a forage material, divided into fresh and withered samples. The modified silo (MOSI) was equipped with an air valve to control air flow. Physical quality parameters such as pH, color, odor and texture were analyzed along with chemical composition, including dry matter, organic matter, crude protein and fiber content. The results showed that vacuum conditions significantly improved the physical quality of silage. The highest dry matter and organic matter contents were observed in the vacuum treatment without weathering. The study also found that vacuum conditions reduced spoilage and maintained better color, odor, and texture of silage compared to non-vacuum conditions. The interaction between weathering time and vacuum showed a significant effect on dry matter, organic matter, and crude protein content. Modified silos (MOSI) effectively improve the physical quality of tropical forage silage by controlling airflow and creating optimal anaerobic conditions. This innovation has the potential to reduce spoilage and improve overall silage quality, making it a valuable tool for forage preservation with effective air regulation within the silo during the ensilage process.

Introduction

In recent years, silage fermentation technology has garnered significant attention from researchers due to its critical role in addressing challenges related to feed availability, particularly during periods of scarcity. Over the past five years, the assessment of silage quality has predominantly emphasized quantitative variables, including nutrient content and digestibility of various forage species (Glavić *et al*., 2015; Putra *et al*., 2017; Martens *et al*., 2022; Sutaryono *et al*., 2023; Hao *et al*., 2024; Mudhita *et al*., 2024).

Despite this progress, many studies have yet to address practical issues encountered during silage production, notably the deterioration that often occurs at the surface of the silage mass during fermentation. This surface spoilage can account for 10–20% of the material, effectively reducing the usable yield to approximately 80–90% of the initial dry or fresh matter (Ferraretto, 2024; Huang *et al*., 2024; Xu *et al*., 2024). Unfortunately, research efforts to mitigate this issue remain limited, possibly due to a prevailing assumption that such spoilage is unavoidable. Consequently, current innovations in silage technology tend to prioritize enhancements in silage quality, such as through the selection of substrates and inoculants rather than improving production efficiency or addressing losses during fermentation (Serva *et al*., 2023; Huang *et al*., 2024; Qiu *et al*., 2024).

This lack of emphasis on maximizing silage yield while maintaining quality highlights the need for the development of novel methods and evaluation systems that can prevent fermentation losses, particularly those caused by aerobic deterioration. A silo, commonly used as the containment system for fermentation, plays a pivotal role in this process. These silos can take the form of vertical tubes or more flexible containers such as plastic bags. In practical applications, especially within the livestock industry, plastic is widely employed as a cost-effective silo alternative. However, these materials often fail to prevent spoilage effectively. The primary cause of this deterioration appears to be oxygen infiltration, either externally through leaks or internally via respiration during the early fermentation stages, compromising anaerobic conditions essential for optimal fermentation (Ohyama *et al*., 1975; Kung, 2010; Wilkinson and Davies, 2013).

Furthermore, the use of plastic-based silos is associated with gas accumulation during fermentation, which leads to the expansion and eventual rupture of the silo bags, thereby allowing air ingress and subsequent spoilage, especially at the top layer. To address these limitations, innovation in silo design is crucial. The Modified Silo (MOSI) represents such an innovation by enabling controlled air exchange to maintain a stable anaerobic environment. Inspired by laboratory-scale silo systems described by Tingshuang *et al*. (2002), MOSI was designed to regulate internal air composition dynamically, thus reducing spoilage and improving the overall quality and yield of silage. This system holds promise as a practical and research-oriented tool to optimize fermentation processes, particularly those involving microbial activity under specific environmental conditions.

Materials and methods

Preparation and modified of mini silos and vacuum oxygen removal

The Modified Silo (MOSI) represents an innovation in silage storage systems, designed to enable regulated air exchange by incorporating a mechanism that functions as both an air inlet and outlet. To construct the MOSI prototype, the materials used include a 1.5-liter airtight jar, a motorcycle-type American valve, industrial adhesive (glue), insulation material, and water tap sealing tape (commonly referred to as Teflon tape). The construction process begins by creating an opening in the lid of the jar, into which the American valve is installed. Adhesive was applied around the valve to ensure an airtight seal, preventing gas leakage during fermentation. The valve is then secured using the locking nut typically included with the valve unit. This modified setup is designed to accommodate controlled air removal and maintain anaerobic conditions essential for effective silage fermentation. The detailed steps of the MOSI construction are illustrated in Figure 1.

Figure 1. Modified silo with the addition of a valve tube on the lid of the jar.

For oxygen removal, a portable vacuum pump with a suction capacity of 15,000 pascals was utilized. To facilitate compatibility between the vacuum pump and the valve system, the vacuum hose was adapted using a tire inflator extension, allowing it to interface directly with the American valve. This modification enables efficient air extraction from the silo after packing the forage material. The whole assembly and modification of both the silo and vacuum system are presented in Figure 2.

Figure 2. Vacuum modification at the suction line end using tyre inflator extensions.

Study design, sample collection, and data calculation

This study employed a factorial randomized design with two independent variables: weathering duration and vacuum treatment. Each factor consisted of two treatment levels and was replicated five times, resulting in a total of 20 Modified Silos (MOSI). The weathering factor included no weathering (T1: 0 hours) and short-term weathering (T2: 2 hours), while the vacuum factor included non-vacuumed (V1) and vacuumed (V2) treatments.

The forage used in the experiment was fresh two-month-old King Grass (*Pennisetum purpureum*), harvested in the morning under ambient conditions (27–30°C). The harvested grass was then divided into two groups: fresh and weathered. For the fresh group, the grass was immediately chopped using a mechanical cutter into lengths of approximately 2–3 cm. For the weathered group, the grass was first air-dried for 2 hours in a well-ventilated, shaded area to simulate mild pre-ensiling desiccation. The samples were laid out on multi-level shelves with a total stack height of approximately 15–20 cm to ensure uniform exposure to ambient air. After weathering, the grass was chopped using the same cutting method as the fresh group.

Following the chopping process, 500 g of forage from each treatment group was packed into the MOSI units. Before sealing, a strip of sealing tape was applied around the lid groove of each jar to minimize gas exchange. The lids were then tightly secured, and additional duct tape was applied externally to enhance airtightness. For the vacuum treatment group (V2), the sealed MOSIs were subjected to a vacuum process for one minute using the modified vacuum system described previously.

A visual representation of the sample preparation process is shown in Figure 3. The duration of the vacuum process was estimated using a basic fluid mechanics equation that relates the air volume (V), the volumetric flow rate (Q), and the time (t) required to evacuate the air from the silo:

$$t=V/Q$$

Where:

t: time taken (seconds or minutes)

V: volume of air to be sucked (cubic meter m^3)

Q: pump air flow rate (cubic meters per second, m^3/s or liters per second)

This formula provides a theoretical framework to estimate the efficiency and consistency of the vacuum process applied in each MOSI unit.

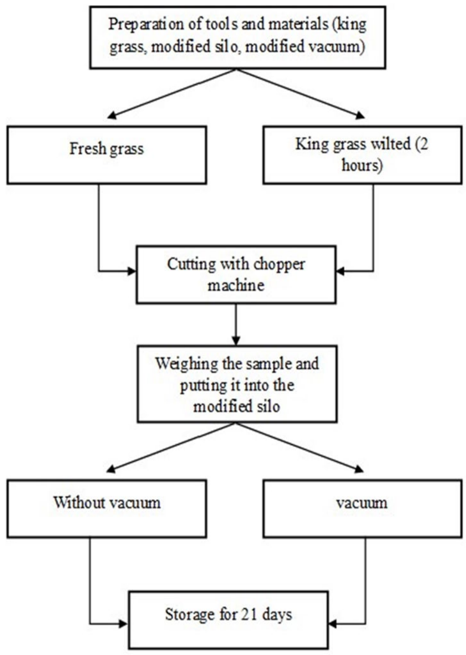

Figure 3: Sample preparation process and MOSI treatment experiment.

Silage physical quality and bromatological quality measurement

In the study, physical silage quality, including pH, color, flavor, and texture, was observed using the procedures described by Katoch (2022) and Tingshuang *et al*. (2002).

The bromatological analysis includes dry matter (DM) content, organic matter (OM), crude protein (CP), and crude fiber (CF) using (AOAC, 2012) methods. Fiber fractions comprising acid detergent fiber (ADF), neutral detergent fiber (NDF), and lignin were analyzed using the procedures specified by Van Soest *et al*. (1991).

Statistical and data analysis

The data obtained from this study were analyzed using both descriptive and inferential statistical approaches. Descriptive data were presented in graphical form to illustrate trends and patterns among treatment groups.

For quantitative measurements related to the chemical composition of the silage, statistical analysis was conducted using *RStudio* version 2025 (Posit Software, PBC) with the R programming language version 4.3.2, with the '*agricolae*' package in the CRAN module. Appropriate statistical tests were applied to determine the significance of treatment effects, ensuring robustness and reproducibility of the findings. The statistical analysis employed two-way analysis of varian and significance set at 5%.

Results and Discussion

Physical quality of silage

The findings indicate that vacuum-treated silage exhibits a 20-30% enhancement in color quality in comparison with the non-vacuum treatment, thereby categorizing it as Excellent (Figure 4). This enhancement can be attributed to the efficient extraction of air during the ensilage process, which expeditiously establishes anaerobic conditions. These conditions promote the rapid proliferation of lactic acid bacteria (LAB), which results in increased lactic acid production and the suppression of undesirable bacterial growth. This process contributes to the preservation of the silage's color. Addah (2022) posited that for silage fermentation to be effective, the population of LAB should increase by a minimum of 10%, while populations at or below 1% are inadequate to influence the process.

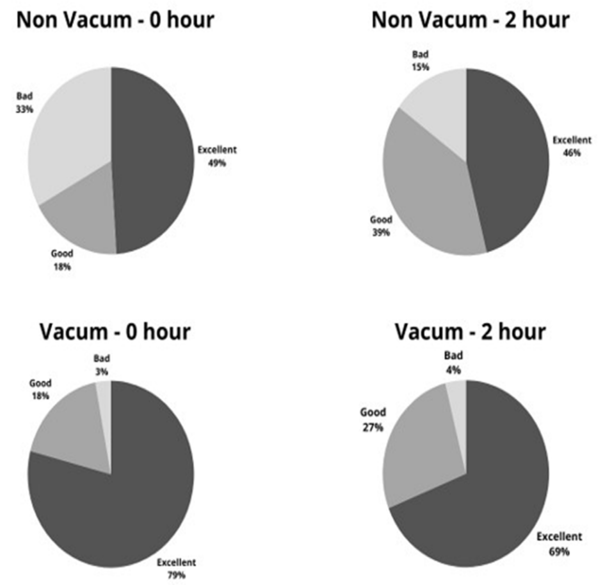

Figure 4. Percentage value of physical quality of silage in the colour category of vacuum and weathering treatments.

Umami *et al*. (2023) observed that high-quality silage typically retains its original color, with only slight changes. For instance, elephant grass, which is initially dark green, may transition to a light green. This change, while seemingly insignificant, is an indication of adequate fermentation. The color of silage serves as a key quality indicator, reflecting the suppression of respiration and proteolysis, which helps prevent clostridial activity. However, discoloration can also result from factors such as additive use, silage density, temperature, and aerobic exposure. The incorporation of water-soluble carbohydrates (WSC), such as molasses, has been demonstrated to enhance the quality of forage in both silage and fermented feeds, with consistent positive outcomes (Pratama *et al*., 2017; Sutaryono *et al*., 2023; Putra *et al*., 2025). While temperature fluctuations during fermentation offer only limited insight into its success, Sio *et al*. (2022) discovered that microbial degradation of carbohydrates could generate heat, resulting in structural alterations in forage color.

The application of vacuum treatment without weathering yielded optimal outcomes across all treatment types, as illustrated in Figure 5. This group exhibited the lowest percentage of poor scores and the highest percentage of excellent scores. The outcomes observed can be attributed to the effective removal of air during the MOSI process, which has been shown to enhance the activity of LAB by reducing oxygen availability. Lactic acid bacteria, particularly homofermentative strains, exhibit optimal growth under anaerobic conditions; conversely, high oxygen levels have been shown to suppress their activity and promote the growth of spoilage bacteria. In contrast, reduced oxygen levels have been shown to promote LAB fermentation, thereby enhancing silage quality (Toruk, 2010; Wilkinson and Davies, 2013; Addah, 2022; Martens *et al*., 2022; Qiu *et al*., 2024).

As illustrated in Figure 5, there is an increase in the bad category (less acidic) in the vacuum treatment after 2 hours of weathering. This suggests that while the vacuum process may influence the fermentation, it is not effective under these conditions. During weathering, the feed is highly susceptible to contamination by undesirable bacteria, which thrive and increase the pH in the silo. A higher pH environment suppresses the growth of LAB, which rely on low pH to develop effectively. According to Andraskar *et al*. (2021), the activity of spoilage or putrefactive bacteria during composting is typically associated with elevated pH and a strong foul odor, resulting from the production of ammonia and butyric acid. In contrast, during proper ensilage, a fresh acidic odor is usually a sign of active LAB fermentation producing lactic acid. However, when lactic acid formation is incomplete or shifts toward butyric acid production, the resulting odor becomes less pleasant. This shift may occur when heterofermentative LAB dominate the fermentation process (Blajman *et al*., 2020; Stephen and Saleh, 2023).

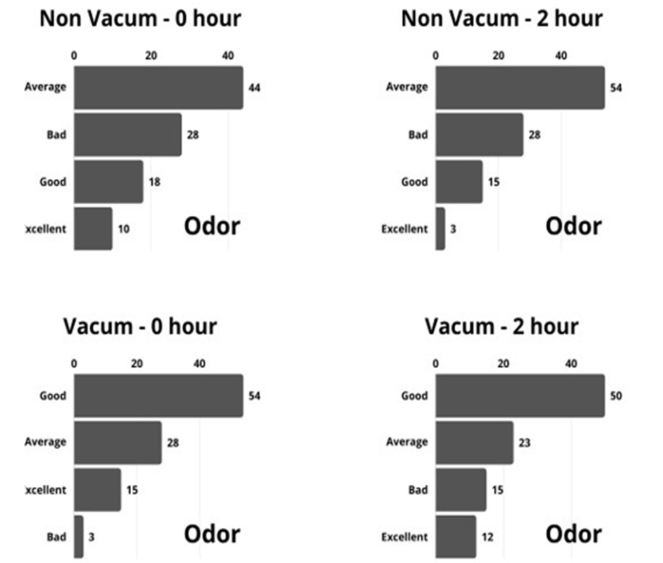

Figure 5. Value (%) of the physical quality of silage in the Odor category of vacuum and weathering treatments.

The physical quality, as determined by texture (Figure 6), indicates that the vacuum treatment without weathering (0 hours) consistently yielded the optimal results across all treatment types, surpassing the 2-hour weathering treatment and the no-vacuum treatment. This treatment demonstrated the highest percentage of "excellent" scores. Although the vacuum process is essential, the high-water content of the forage, particularly *Pennisetum purpureum*, appears to be a substantial contributing factor in preserving the desired texture, color, and aroma. King Grass contains a high concentration of water-soluble carbohydrates (WSC), which are essential for enhancing the activity of LAB during the ensilage process (Chengli *et al*., 2012). However, the process of weathering can lead to a reduction in water and WSC content, which has the potential to impact the fermentation process adversely. Research has demonstrated that while weathering can prolong the storage life of feed, it concomitantly results in substantial loss of WSC, particularly in forages with high moisture content (Saricicek *et al*., 2016; Yi *et al*., 2023).

Furthermore, the process of ensiling leads to the generation of heat due to microbial metabolism. High moisture levels have been shown to mitigate the effects of heat by retaining water, thereby preserving the texture and color of forage and protecting it from thermal damage. It has been demonstrated that elevated temperatures during the fermentation process can result in a degradation of color and texture, particularly in feeds with high soluble carbohydrate content, through the Maillard reaction (Al-Abbasy *et al*., 2024). Fermentation heat has also been demonstrated to soften forage texture by loosening the cell wall structure, resulting in a less firm appearance (Coblentz and Hoffman, 2008; Hu *et al*., 2024).

pH value and chemical composition of silage

The results of the present study indicate that there was no significant interaction between vacuum treatment and weathering time on the pH value, CF, NDF, ADF, and lignin content of the silage. However, a significant interaction was observed for DM, OM, and CP contents (p<0.05, Table 1). Among all treatment combinations, the vacuumed, non-weathered treatment (V2T1) produced the highest values for dry matter, organic matter, and crude protein. These findings suggest that silage produced using the MOSI with vacuum application, particularly without prior weathering, results in superior nutritional quality. The higher dry matter and organic matter values are closely related, as organic matter typically constitutes the majority of dry matter content. This strong correlation reinforces the role of MOSI in preserving nutrient integrity during the ensiling process.

In general, forage crops for ruminants typically have water content ranging from 20–30%, with dry matter accounting for 70–80% of total weight. Organic matter comprises approximately 80–95%, while inorganic material (ash content) contributes around 1–5% (Dynes *et al*., 2003; Dewhurst *et al*., 2009; Kariyani *et al*., 2021; McDonald *et al*., 2022; Mamphogoro *et al*., 2024). Interestingly, while dry matter and organic matter levels increased under vacuum conditions, the crude protein content showed a significant decrease under certain treatment combinations, indicating that vacuum treatment may influence nitrogen preservation dynamics during fermentation. This warrants further investigation into the mechanisms affecting protein degradation under varying anaerobic conditions.

The elevated DM and OM contents observed in the vacuum-treated silage, alongside the noted reduction in CP, are attributed to the enhanced activity of LAB during the ensiling process facilitated by the MOSI system. This pattern of response demonstrates a synergistic relationship among the treatment variables, wherein each factor contributes to creating an optimal environment for LAB proliferation. The key mechanism underlying this outcome is the rapid establishment of anaerobic conditions resulting from vacuum. These conditions inhibit plant cell respiration at an early stage, thereby preserving fermentable substrates and allowing LAB populations to dominate quickly (Wilkinson and Davies, 2013; Addah, 2022; Martens *et al*., 2022; Qiu *et al*., 2024). Additionally, the use of fresh (non-weathered) king grass plays a critical role by preserving high levels of water-soluble carbohydrates (WSC), which serve as essential substrates for LAB growth. Previous studies have reported WSC contents in king grass ranging from 70 to 90 g/kg DM (Chengli *et al*., 2012; Long *et al*., 2022), underscoring its potential as a favorable ensiling material.

Table 1. pH value and chemical composition of *Pennisetum purpureum* silage in different aerobicity and weathering time using modified silo (MOSI).

Chemical composition	Non-Vacuum		Vacuum		V × T	*P value*
	0 h	2 h	0 h	2 h		
pH silages	4.2	4.2	4.3	4.25		0.70
Dry matter (g/kg)	827.47[b]	819.01[b]	854.14[a]	746.72[c]	*	0.00
Organic matter (g/kg DM)	693,62[b]	672.40[b]	721,43[a]	623.82[c]	*	0.03
Crude protein (g/kg DM)	117.71[a]	106.53[ab]	73,17[c]	86.06[bc]	*	0.02
Crude fiber (g/kg DM)	284.23	239.18	348,87	276.69	Ns	0.07
NDF (g/kg DM)	474.02	455.3	485.09	406.33	Ns	0.15
ADF (g/kg DM)	437	402.59	434.79	336.02	Ns	0.20
Lignin (g/kg DM)	121.62	104.21	112.8	87.57	Ns	0.74

[abc] within rows indicate significant differences between treatments (p<0.05); Ns: Not significant; V: vacuum; T: weathering time; *indicates interaction between treatments.

The combination of high WSC availability and oxygen-limited conditions in MOSI accelerates lactic acid fermentation, resulting in increased lactic acid concentrations within the silo. Elevated lactic acid levels facilitate the hydrolysis of structural carbohydrates, such as hemicellulose and cellulose, as well as crude protein. These biochemical changes explain the observed reductions in fiber fractions and protein content during the fermentation process (Usman *et al*., 2022; Putra *et al*., 2025). The crude protein degradation, in particular, is closely linked to acid hydrolysis, where protein bonds are weakened under acidic conditions, rendering them more susceptible to breakdown (Fijałkowska *et al*., 2015). Additionally, the length of fermentation time may exacerbate CP loss, as prolonged exposure to acidic environments accelerates proteolytic activity and ammonia formation (Widiyastuti *et al*., 2014; Wang *et al*., 2024).

The MOSI system, as a model for controlled silage fermentation, has demonstrated its effectiveness in several silage studies. Its principal innovation lies in its ability to regulate internal air availability through an integrated valve system. This feature is critical for maintaining anaerobic conditions, thereby reducing the risk of aerobic spoilage and ensuring consistent silage quality. Given that oxygen exposure is a key factor contributing to silage deterioration, the ability of MOSI to minimize oxygen ingress represents a significant advancement in experimental silage technology.

Conclusion

This study highlights the considerable potential of silo and vacuum modifications to enhance silage quality, both physically and chemically. The optimal outcomes are attained when the vacuum process implemented subsequent to a two-hour weathering period, signifying a pivotal synergy between time and treatment. Conversely, the omission of the vacuum step resulted in silage of noticeably inferior quality, as evidenced by diminished physical integrity and nutrient content.

Conflict of interest

The authors have no conflict of interest to declare.

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