

Forage yield, nutritional composition, and aerobic stability of silages from sorghum genotypes and pearl millet under warm-subhumid conditions

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ABSTRACT

Silage production from sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Cenchrus americanus* (L.) Morrone) is an important strategy to ensure feed availability and quality for ruminants in warm-subhumid regions. This study aimed to evaluate the forage yield, nutritional value, and aerobic stability of silages from 12 sorghum genotypes ('Arcos', 'Williams', 'Paloma', 'Fortuna', '195-2', '197-1', '197-1-1', 'Proconsul', 'Verde Pacas', 'Gladiador', 'Gobernador', 'Caramelo') and pearl millet to identify alternatives for ruminant feeding. Forage yield was quantified as total DM (TDM), and nutritional composition was determined by crude protein (CP), in vitro digestibility (IVD), neutral detergent fiber (NDF), and acid detergent fiber (ADF); aerobic stability was measured after silo opening. Genotypes '197-1-1' and '197-1' achieved the highest TDM (19.05 and 14.68 t ha⁻¹, respectively; $p < 0.05$), but had lower CP (51-53 g kg⁻¹) and higher NDF (674-700 g kg⁻¹), resulting in reduced IVD. Pearl millet showed higher CP (109 g kg⁻¹), lower NDF (613 g kg⁻¹) and ADF (182 g kg⁻¹), and higher IVD (602 g kg⁻¹; $p < 0.05$). Aerobic stability varied among genotypes: Materials with a greater proportion of panicle and lower fiber content ('Gobernador', 'Proconsul') deteriorated faster (40-48 h after opening), while 'Verde Pacas', 'Gladiador', and 'Williams' remained stable for 64 h. The results demonstrate that genotype selection significantly influences silage yield, nutritive value, and stability. Late-cycle genotypes produce greater biomass but lower quality, whereas early or intermediate genotypes offer a better balance between yield, digestibility, and preservation under warm-subhumid conditions.

Key words: *Cenchrus americanus*, forage conservation, forage crops, *Sorghum bicolor*, tolerance to water stress.

INTRODUCTION

In the tropical and subtropical livestock areas of the world, producers of the extensive ruminant system face a shortage of forage, a problem that is intensifying, mainly due to prolonged overgrazing, which has degraded grasslands and pastures; in addition to the recurrence of droughts that with each cycle leave less room for the natural recovery of vegetation (Garay-Martínez et al., 2024a). Faced with this scenario, it is necessary to look for strategies for animal feed, prioritizing those that are more resilient to climate change conditions

(Slayi and Jaja, 2024). Some of the options could be sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Cenchrus americanus* (L.) Morrone). Both crops have demonstrated tolerance to environments with water restrictions and have a considerable biomass production per unit area. This double advantage, tolerance and production, makes them candidates as possible forage alternatives in vulnerable systems, in addition to contributing to the rational use of water (Bhattarai et al., 2020; Marte-Pereira et al., 2025; Wihardjaka et al., 2025).

Sorghum is a grass widely used in ruminant feed, mainly due to its high DM production and nutritional value. Dry matter yields ranging from 9 to 15 t ha⁻¹ have been reported, with crude protein (CP) contents ranging from 80 to 94 g kg⁻¹ DM and digestibility reaching values above 700 g kg⁻¹ DM, in early stages of growth, depending on genotype and culture conditions (Lucio-Ruiz et al., 2023). In addition, it has been reported that this crop has greater tolerance to water stress due to moisture deficiency compared to other forage crops such as corn; while the latter requires considerable amounts of water to reach its full potential, the average water requirement for sorghum is around 450 mm, 40% lower than maize cultivation (McCary et al., 2020). On the other hand, pearl millet, a grass with a short cycle and hardiness, has been underused in many production systems, despite its remarkable capacity to produce DM, which ranges between 4 and 16 t ha⁻¹ under limiting humidity conditions, with CP contents between 60 and 110 g kg⁻¹ and digestibility around 500 g kg⁻¹ (Salama et al., 2020).

This has sparked interest among producers incorporating them into production systems. However, it should be considered that, due to the seasonality of forage production, it is essential to implement conservation strategies such as silage (Garay-Martínez et al., 2024b). Recent studies have reported that silage based on sorghum can enhance fermentation efficiency and forage availability in dryland livestock systems (Marte-Pereira et al., 2025; Wihardjaka et al., 2025). This technique preserves the nutritional value of forage through anaerobic fermentation, primarily produced by lactic acid bacteria that transform soluble sugars into lactic and acetic acids. This acidification lowers the pH and prevents the proliferation of undesirable microorganisms (Sainz-Ramírez et al., 2020). Once the fermentation process has been completed and it is time to offer the silage to the animals, the silo is opened, which represents a critical point, since the reintroduction of oxygen favors the proliferation of aerobic microorganisms such as yeasts and filamentous fungi, which degrade lactic acid and generate heat, undesirable compounds and mycotoxins that can deteriorate silage quality and health (Xia et al., 2023). One way to assess the efficiency of the preservation process is aerobic stability, understood as the resistance of silage to deterioration when exposed to air again, and which directly influences its nutritional value and health (Liu et al., 2024). We hypothesize that sorghum genotypes and pearl millet cultivated under these conditions present significant differences in forage yield, nutritional composition, and aerobic stability, with some genotypes showing superior performance. Therefore, the objective of the present study was to evaluate DM yield of forage and nutritional composition and aerobic stability of silages from sorghum genotypes and pearl millet under warm-subhumid conditions in northeastern Mexico.

MATERIALS AND METHODS

Description and location of the experiment

The study was carried out under irrigated conditions at the Sitio Experimental Aldama (SEAL) (22°51'47.38" N, 98°14'14.20" W; 98 m a.s.l.) del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Aldama, Tamaulipas, Mexico. The climate is classified as semi-warm subhumid, characterized by summer rainfall. The climatic conditions (precipitation and temperature) recorded and irrigations during the experiment are presented in Figure 1.

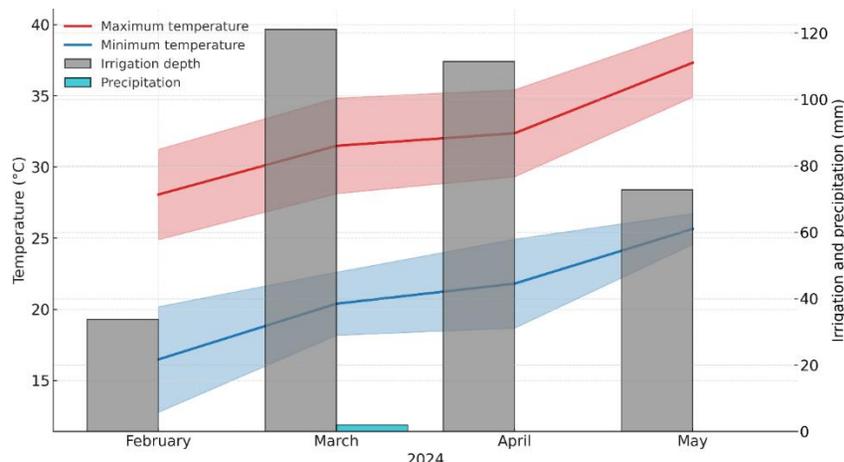


Figure 1. Monthly maximum and minimum temperatures, precipitation, and irrigation depth during the field experiment conducted at the Sitio Experimental Aldama-INIFAP, Tamaulipas, Mexico, in 2024. Shaded areas represent the monthly observed temperature range for maximum and minimum records.

Treatments and agronomic management

The evaluation included seven sorghum (*Sorghum bicolor* (L.) Moench) genotypes developed by INIFAP ('Arcos', 'Williams', 'Paloma', 'Fortuna', '195-2', '197-1', and '197-1-1'), five from the company Anzú Genética Seeds ('Proconsul', 'Verde Pacas', 'Gladiator', 'Gobernador', and 'Caramelo'), and pearl millet (*Cenchrus americanus* (L.) Morrone) 'Platino'. Each experimental plot was made up of four 10 m rows, at 0.8 and 0.05 m between rows and plants, respectively, $\approx 250\,000$ plants ha^{-1} density. The preparation of the soil was mechanized (one fallow, two crossed harrow passes, and furrowing). The sowing was carried out dry (3 February 2024), and later a 34 mm irrigation sheet was applied. For the irrigation system, a 5/8" ribbon (Aqua Traxx, Toro, El Paso, Texas USA) was used, with 20 cm between emitters. Watering sheets were applied every 7 or 15 d (Figure 1), giving a total of 230 mm (six irrigations) for the early cycle genotypes ('Proconsul', 'Gobernador', and pearl millet), 266 mm (seven irrigations) for intermediate cycle genotypes ('Verde Pacas', 'Gladiator', 'Caramelo', 'Arcos', 'Williams', 'Paloma', 'Fortuna', and '195-2'), and 302 mm (eight irrigations) for late cycle genotypes ('197-1' and '197-1-1'). The genotypes were classified by their maturity cycle, based on the optimal harvest time for silage, which was determined at the grain's milk to early dough stage. Accordingly, early, intermediate, and late cycle materials were harvested at 77, 90, and 105 d after sowing (DAS), respectively. Fertilization was carried out 27 d after sowing (DAS) with a dose of 90-40-00 kg ha^{-1} NPK, which was applied by fertigation during the second irrigation. Pest control was carried out when the pest population reached its economic threshold. For fall armyworm (*Spodoptera frugiperda*), spinetoram (mixture of 3'-ethyl-5,6-dihydrospinosyn J and 3'-ethylspinosyn L; 200 mL ha^{-1} ; Corteva Agriscience, Indianapolis, Indiana, USA) was applied, and 12 d later, chlorantraniliprole (3-bromo-N-[4-chloro-2-methyl-6-(methylcarbamoyl)phenyl]-1-(3-chloro-2-pyridyl)-1H-pyrazole-5-carboxamide; 100 mL ha^{-1} ; FMC Corporation, Philadelphia, Pennsylvania, USA); while, for corn flea beetle (*Chaetocnema pulicaria*), imidacloprid ((E)-1-(6-chloro-3-pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine; 350 mL ha^{-1} ; Bayer CropScience, Research Triangle Park, North Carolina, USA) was applied. Weed management was performed manually throughout the crop cycle.

Forage yield evaluation

For the determination of forage yield (kg ha^{-1}), the methodology described by Lucio-Ruiz et al. (2023) was followed. Forage within two linear meters was harvested at a height of 20 cm above the ground and weighed. Subsequently, a subsample of three plants was collected and separated into morphological components (leaf, stem, inflorescence, dead matter). Each subsample was oven-dried in a forced-air oven (OMS60, Thermo Scientific, Langensfeld, Hesse, Germany) at 65 °C for 72 h to estimate DM content.

Nutritional value of silage

To produce the silage, forage from each experimental plot was harvested at 20 cm above ground level and chopped to a particle size of 2 ± 0.5 cm. The forage was then deposited in silos of polyvinyl chloride tubes (6" x 40 cm, with a fixed lid at one end), compacted and sealed with a layer of polyethylene fixed with duct tape. The silos were stored for 325 d to simulate the long-term preservation practices commonly used by livestock producers in the region, and then opened to extract a sample from the central portion for analysis. The DM content was determined by drying 200 g silage in a forced-air oven at 65 °C until a constant weight was achieved. Once dried, the samples were ground using a 1 mm sieve (T4724CE4, Thomas-Wiley Mill, Swedesboro, New Jersey, USA). The variables evaluated were the content (g kg^{-1}) of neutral detergent fiber (NDF) and acid detergent fiber (ADF), as described by Van Soest et al. (1991). Hemicellulose (HEM) was calculated by difference ($\text{HEM} = \text{NDF} - \text{ADF}$). The crude protein was determined using the methodology described by the AOAC (2019), and in vitro DM digestibility (IVD; g kg^{-1}) was determined using the Ankom technique (Ankom Technology, 2017).

Aerobic stability of the silage

After the silos were opened, approximately 5% of the material from the upper part of each one was discarded. The central part of the silage was homogenized, and a sample of roughly 2 kg was extracted, which was then deposited in a container. The aerobic stability (pH, internal temperature of the silage, and ambient temperature) (9878E, Taylor, Shenzhen, Guangdong, China) was evaluated every 8 h for 4 d, following the methodology described by Honig (1990). The silage material was covered with paper towels to allow air to pass through, reduce dehydration, and avoid possible contamination between treatments. To determine the silage pH, 50 g sample was placed in a beaker and 500 mL distilled water (pH 7) was added. The sample was stirred for 5 min, and then the pH was measured with a potentiometer (HI98130, Hanna, Woonsocket, Rhode Island, USA).

Statistical analysis

The data were analyzed using a randomized complete block design with 13 treatments and three replicates. For each variable, variance was analyzed, and a comparison of means was performed using Tukey's test ($\alpha = 0.05$) in the SAS 9.0 statistical program (SAS Institute, Cary, North Carolina, USA). To analyze the dynamics of temperature and pH after opening and exposure to silage air, a group aggregation model was used as a function of treatment and time. From these groupings, 95% confidence intervals were calculated using Student's t-distribution (Montgomery, 2017). For statistical calculations and graph representation, the Python programming language (version 3.10) was used, along with specialized libraries (pandas, numpy, matplotlib, and scipy.stats; Chaudekar, 2022).

RESULTS

Forage yield

Significant differences ($p < 0.01$) were observed in total DM yield and its components in the evaluated genotypes (Table 1). The late-cycle genotypes ('197-1-1' and '197-1') showed higher DM yields with 19.05 and 14.68 t ha^{-1} , respectively. These two genotypes, along with 'Fortuna', yielded the highest leaves, with values ranging from 4.20 to 4.75 t ha^{-1} . The '197-1-1' genotype presented the highest stem yield (11.53 t ha^{-1}), followed by '197-1' and 'Caramelo' (6.70 and 3.72 t ha^{-1} , respectively; Table 1). 'Proconsul', 'Gobernador', and '197-1' presented the highest yields of panicle, with values between 2.05 and 2.13 t ha^{-1} . Late-cycle genotypes were the only ones to exhibit dead matter, as the cut-off date was extended to 105 DAS, and the first leaves initiated the senescence process (Table 1).

Table 1. Total DM yield (TDM) and morphological components in sorghum genotypes and pearl millet under warm-subhumid conditions. DAS: Days after sowing. Different letters between genotypes indicate significant differences (Tukey, $\alpha = 0.05$).

| Maturity cycle | Genotype | TDM | Leaf | Stem | Panicle | Dead matter |
|--------------------------|--------------|--------------------|--------------------|---------------------|--------------------|------------------|
| t ha ⁻¹ | | | | | | |
| Early (77 DAS) | Gobernador | 5.87 ^{ef} | 1.85 ^d | 1.94 ^{efg} | 2.08 ^a | 0.0 ^b |
| | Pearl millet | 3.64 ^h | 1.49 ^d | 0.80 ^h | 1.34 ^{ab} | 0.0 ^b |
| | Proconsul | 5.01 ^g | 1.72 ^d | 1.17 ^{gh} | 2.13 ^a | 0.0 ^b |
| Intermediate (90 DAS) | 195-2 | 5.60 ^f | 3.19 ^b | 1.19 ^{gh} | 1.22 ^{ab} | 0.0 ^b |
| | Arcos | 7.27 ^d | 3.07 ^{bc} | 2.95 ^{cde} | 1.25 ^{ab} | 0.0 ^b |
| | Caramelo | 7.12 ^d | 2.05 ^d | 3.72 ^c | 1.36 ^{ab} | 0.0 ^b |
| | Fortuna | 7.79 ^c | 4.20 ^a | 2.70 ^{def} | 0.88 ^b | 0.0 ^b |
| | Gladiator | 5.01 ^g | 1.83 ^d | 2.04 ^{efg} | 1.14 ^{ab} | 0.0 ^b |
| | Paloma | 5.70 ^f | 2.16 ^{cd} | 1.86 ^{fg} | 1.68 ^{ab} | 0.0 ^b |
| | Verde Pacas | 6.27 ^e | 1.92 ^d | 3.08 ^{cd} | 1.27 ^{ab} | 0.0 ^b |
| Late (105 DAS) | Williams | 7.11 ^d | 3.07 ^{bc} | 2.45 ^{def} | 1.59 ^{ab} | 0.0 ^b |
| | 197-1 | 14.68 ^b | 4.75 ^a | 6.70 ^b | 2.05 ^a | 1.2 ^a |
| | 197-1-1 | 19.05 ^a | 4.38 ^a | 11.53 ^a | 1.62 ^{ab} | 1.5 ^a |
| <i>p</i> -value | | < 0.0001 | < 0.0001 | < 0.0001 | 0.0015 | 0.5248 |

Nutritional value of silage

The genotypes evaluated showed significant differences ($p < 0.01$) in all nutritional value variables (Table 2). The pearl millet stood out as having the highest CP content (109 g kg⁻¹), while '197-1-1' presented the minimum value (51 g kg⁻¹; Table 2). The NDF content was higher in genotypes '197-1' and '197-1-1', with values of 700 and 674 g kg⁻¹, respectively; while 'Proconsul' and 'Caramelo' showed the lowest contents, with 566 and 593 g kg⁻¹, respectively (Table 2). Regarding the ADF content, 'Proconsul' and pearl millet presented lower content, at 179 and 182 g kg⁻¹, respectively; in contrast, 'Verde Pacas', 'Williams', 'Paloma', and '197-1' presented higher content, with values ranging from 232 to 240 g kg⁻¹ (Table 2).

Regarding the values of hemicellulose, '197-1', '197-1-1', pearl millet, and 'Williams' presented the highest contents, which were from 429 to 468 g kg⁻¹; while 'Proconsul' and 'Caramelo' presented the lowest values, between 382 and 387 g kg⁻¹ (Table 2). In vitro digestibility was higher in genotypes '195-2', 'Paloma', 'Williams', 'Proconsul', 'Gladiator', and pearl millet, with values ranging from 602 to 634 g kg⁻¹; however, '197-1-1', 'Caramelo', and 'Verde Pacas' presented lower digestibility, with values ranging from 520 to 549 g kg⁻¹ (Table 2).

Aerobic stability of silage

At the time of silo opening, the silage showed no visible signs of spoilage or fungal growth. During the first 32 h of aerobic exposure, all evaluated genotypes maintained an internal temperature of less than 2 °C compared to the ambient temperature. After this period, the genotypes 'Gobernador' and 'Proconsul' lost aerobic stability at 40 and 48 h, with temperature increases of 3.3 and 2.4 °C, respectively. Genotypes '197-1', '197-1-1', 'Paloma', and pearl millet lost stability at 56 h, followed by 'Verde Pacas', 'Gladiator', and 'Williams' at 64 h. The remaining genotypes maintained aerobic stability until 72 h. Between 80 and 96 h after opening, all genotypes exhibited peak temperatures (Figure 2). At the moment of opening, silage pH ranged between 3.5 and 4.0, indicating proper fermentation and preservation. This level remained stable for up to 48 h in 'Proconsul' and up to 56 h in the other genotypes. Beyond 104 h, a pH above 6.0 was recorded in nearly all treatments, except for 'Gladiator' and pearl millet (Figure 3).

Table 2. Nutritional value in silages of sorghum genotypes and pearl millet under warm-subhumid conditions. CP: Crude protein; NDF: neutral detergent fiber; ADF: acid detergent fiber; HEM: hemicellulose; IVD: in vitro digestibility; DAS: days after sowing. Different letters between genotypes indicate a significant difference (Tukey; $\alpha = 0.05$).

| Maturity cycle | Genotype | g kg ⁻¹ | | | | |
|--------------------------|--------------|--------------------|--------------------|--------------------|---------------------|--------------------|
| | | CP | NDF | ADF | HEM | IVD |
| Early (77 DAS) | Gobernador | 65 ^d | 604 ^{fg} | 202 ^f | 402 ^{cde} | 562 ^{cd} |
| | Pearl millet | 109 ^a | 613 ^{efg} | 182 ^g | 431 ^{abc} | 602 ^{abc} |
| | Proconsul | 80 ^b | 566 ^h | 179 ^g | 387 ^{de} | 610 ^a |
| Intermediate (90 DAS) | 195-2 | 65 ^d | 644 ^{bcd} | 220 ^{cde} | 424 ^{bcd} | 634 ^a |
| | Arcos | 61 ^e | 648 ^{bcd} | 227 ^{bcd} | 421 ^{bcde} | 565 ^{bcd} |
| | Caramelo | 62 ^{de} | 593 ^{gh} | 211 ^{ef} | 382 ^e | 544 ^{de} |
| | Fortuna | 72 ^c | 626 ^{def} | 220 ^{de} | 406 ^{cde} | 563 ^{bcd} |
| | Gladiador | 72 ^c | 631 ^{def} | 218 ^{de} | 413 ^{bcde} | 605 ^{ab} |
| | Paloma | 73 ^c | 648 ^{bcd} | 233 ^{ab} | 414 ^{bcde} | 623 ^a |
| | Verde Pacas | 56 ^f | 638 ^{cde} | 240 ^a | 398 ^{cde} | 520 ^e |
| | Williams | 65 ^d | 664 ^{bc} | 235 ^{ab} | 429 ^{abc} | 619 ^a |
| Late (105 DAS) | 197-1 | 62 ^e | 700 ^a | 232 ^{abc} | 468 ^a | 564 ^{bcd} |
| | 197-1-1 | 51 ^g | 674 ^{ab} | 227 ^{bcd} | 447 ^{ab} | 549 ^{de} |
| <i>p</i> -value | | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 |

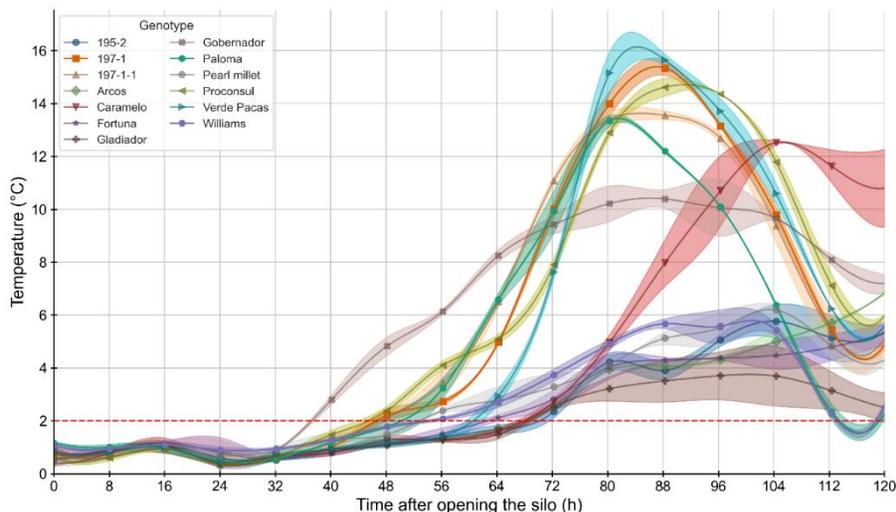


Figure 2. Variation of the thermal difference during the aerobic exposure period of sorghum genotypes and pearl millet ensiled under warm-subhumid conditions. The red dashed line represents the 2 °C threshold above ambient temperature, used as the criterion for the onset of aerobic deterioration. Shaded areas indicate the 95% confidence intervals for the fitted temperature curves of each genotype.

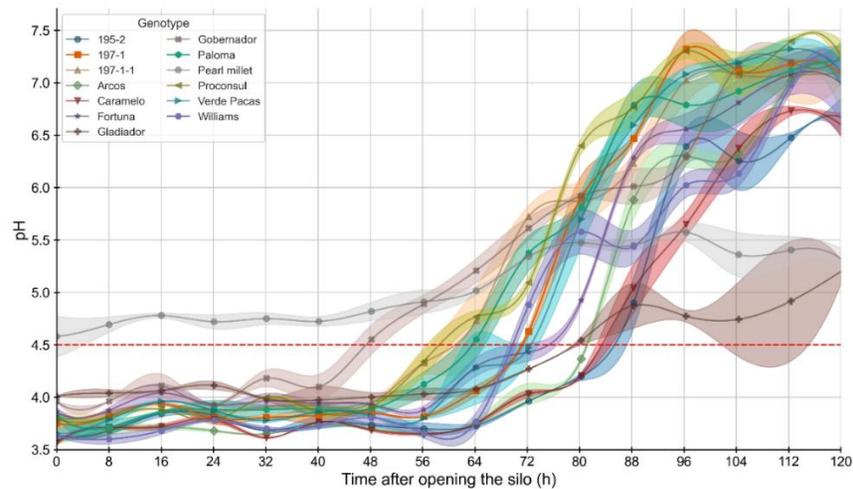


Figure 3. Variation in pH during the aerobic exposure period of sorghum genotypes and pearl millet ensiled under warm-subhumid conditions. The red dashed line represents the threshold pH value of 4.5, used as an indicator of the onset of aerobic deterioration. Shaded areas correspond to the 95% confidence intervals for the fitted pH curves of each genotype.

DISCUSSION

Forage yield

Among the genotypes evaluated, two stood out for their ability to generate biomass: '197-1-1' and '197-1', both of which are late-cycle (105 d to forage harvest). Its yield was high and was associated with stem development; since in the case of '197-1-1', the stem came to represent more than 60% DM obtained, which was related to its longer cycle and thus accumulated more biomass in fibrous structures. However, this type of growth also results in increased structural tissue, which decreases the digestibility of the forage and directly impacts its nutritional value (Silva et al., 2025). On the contrary, there are materials such as 'Fortuna', which have a higher proportion of leaves, which provide greater nutritional value, but a lower DM volume (7.79 t ha^{-1}). This once again brings us back to a classic dilemma in forage production: Is it better to prioritize higher biomass yields, even if the forage is less digestible, or to opt for materials that offer better quality, even if their yield is lower? This dilemma between quantity and quality has been a central theme in various research studies with forage crops (Lucio-Ruiz et al., 2023; Silva et al., 2025). In the end, the choice will depend on the objective of the production system; if the sustained animal load is prioritized over time, a material that provides a higher biomass yield may be preferable; but if you are looking for efficiency in consumption and greater nutritional value per bite ingested, then it will be more appropriate to use those materials that present higher forage quality.

In forage production under water-constrained conditions, it is not enough to look at how much biomass a material produces. There is another point, equally or more important, which is the efficiency with which the available water is used. In this study, for example, the early cycle genotypes completed their development at 77 DAS with only 230 mm irrigation. The intermediate cycle (90 DAS) needed a little more, around 266 mm, and the late cycle (105 DAS), such as the '197-1-1' and '197-1' materials, reached up to 302 mm. This is particularly important in regions where water is becoming increasingly scarce or where rainfall is concentrated in brief periods of time. In these scenarios, having a forage that can complete its cycle with less water can make the difference between successful production and facing a significant limitation in obtaining forage (Lucio-Ruiz et al., 2023). Long-cycle genotypes indeed tend to produce more biomass, but if the cost is higher water consumption, they may not always be the best option. On the other hand, early materials, although they produce a little less, do so more efficiently, and that, in the face of current climate variability, can be decisive (Bhattarai et al., 2020).

Nutritional value of silage

The results obtained in this study clearly show that genotypes do not respond in the same way, confirming a phenomenon often observed in practice: Producing more biomass is not always related to higher forage quality. Both aspects must be analyzed together because the nutritional value of the harvested material is as essential as its yield, especially if efficient use is sought in animal production systems. In this case, it is worth highlighting pearl millet, which showed a high content of crude protein (CP) (109 g kg^{-1}). This value is acceptable, as a forage with around 100 g kg^{-1} CP is suitable for maintenance in adult ruminants and dry cows; it may be sufficient, provided that the energy balance is well-designed (NASEM, 2021). In contrast, the '197-1' and '197-1-1' genotypes had a very different response. Their protein levels were relatively low (between 51 and 53 g kg^{-1}), while neutral detergent fiber (NDF) was very high (over 670 g kg^{-1}). This is a common phenomenon in long-cycle materials, as they grow, they generate more biomass, and the N content is diluted, which is reflected in the protein content (Lucio-Ruiz et al., 2023). Ultimately, what accumulates is more stem and structural tissue, which can make it difficult for the animal to consume and utilize (Galyon et al., 2024).

Another interesting point was the behavior of the acid detergent fiber (ADF); here, 'Proconsul' and pearl millet obtained the lowest values (between 179 and 182 g kg^{-1}), which usually indicates lower lignification and, therefore, greater digestibility of the forage (Stypinski et al., 2024). Although some genotypes, such as '197-1', '197-1-1', pearl millet, and 'Williams', exhibited high levels of hemicellulose (HEM), ranging from 429 to 468 g kg^{-1} , this did not always translate into a high digestibility value. For example, '197-1-1', despite having a high HEM content, was one of the least digestible (520 g kg^{-1}). This suggests that the way fibers are organized, and the thickness of the fabric may also limit degradation by microorganisms (Tedeschi et al., 2023). In contrast, materials such as 'Proconsul', 'Paloma', and 'Gladiator' were able to combine low fiber levels with IVD values above 605 g kg^{-1} , making them attractive for livestock systems seeking efficiency in consumption and improved productive performance. In short, there is no single genotype that yields the highest value, but strategic decisions can be made depending on the objective of each production system.

Aerobic stability of silage

Regarding the aerobic stability of silages, different behaviors were observed among the evaluated genotypes. Some genotypes began to deteriorate very soon after the opening of the silos, especially those with lower fibrous tissue values (NDF, ADF, and HEM), such as 'Gobernador' and 'Proconsul', which broke aerobic stability before 48 h, probably due to their high proportion of panicle (35% and 42%, respectively) where it is found in grain and this is a substrate easily used by microorganisms when oxygen is present (Ma et al., 2023). In contrast, materials such as '197-1-1', 'Paloma', and 'Williams' were able to remain stable for more than 48 h, exhibiting a slower increase in temperature and pH, which suggests a more controlled initial fermentation and lower subsequent microbial activity. This behavior aligns with the findings of Holmes and Muck (2007), who emphasize that good silage compaction and a low initial pH are key factors in maintaining stability once the silo is opened. However, when silage compaction is inadequate, it generates a low density and high porosity, allowing faster air to enter after the silo is opened and affecting aerobic stability (Da Silva et al., 2018a). After aerobic exposure, aerobic mushrooms develop abundantly and release heat as they metabolize nutrients. This allows for the rapid proliferation of aerobic microorganisms, such as filamentous fungi, which metabolize silage nutrients and generate considerable heat as a byproduct of catabolism, thereby raising the internal temperature of the silage (Da Silva et al., 2018a; 2018b). This accelerates the aerobic deterioration of silage, which can affect digestibility and nutritional value, as energy compounds are degraded and mycotoxins are produced (Muck et al., 2018). These mycotoxins can commonly be produced by fungi of the genera *Aspergillus*, *Fusarium*, and *Penicillium*, which can develop during fermentation or storage of silage, especially when humidity, aeration, and temperature conditions are inadequate (Gallo et al., 2015; Xia et al., 2023).

Likewise, it should be considered that the consumption of silages containing toxic metabolites could represent a significant risk to the health of ruminants, as they could affect multiple physiological, immunological, and productive functions (Gallo et al., 2015; Muñoz-Solano et al., 2024). In this sense, genotypes '195-2', 'Gladiator', 'Caramelo', 'Verde Pacas', 'Arcos', and 'Fortuna' presented the highest aerobic stability, as it was broken after 64 h exposure to air (Figure 3). This behavior indicates that these genotypes, after the opening of the silos, showed a greater capacity to resist oxidation and limit the proliferation of yeasts and molds, which could preserve its nutritional quality, safety and acceptability by ruminants (Kung et al., 2018).

CONCLUSIONS

This study demonstrates that forage genotype selection has a significant influence on biomass yield, forage quality, and aerobic stability of silage. Late-cycle genotypes ('197-1-1' and '197-1') achieved the highest biomass yields but with lower nutritive characteristics, whereas early-cycle ('Gobernador', 'Proconsul', and pearl millet) and intermediate-cycle genotypes ('Fortuna', 'Caramelo', 'Arcos', 'Williams', 'Verde Pacas', and 'Gladiator') provided a more favorable balance between production, protein content, and post-opening stability. These results reinforce the well-known trade-off between forage quantity and quality, indicating that genotype selection should align with livestock production goals: Late-cycle materials when yield is prioritized, and early- or intermediate-cycle genotypes when nutritional quality and silage stability are the main objectives. Ultimately, optimizing genotype selection can support more efficient and sustainable forage-based feeding systems.

Author contribution

Conceptualization: M.F.V., J.R.G.M. Methodology: G.G.O., F.L.R. Software: B.E.D. Validation: S.J.C., U.A.L. Formal analysis: J.R.G.M., B.E.D. Investigation: M.F.V., J.R.G.M. Resources: S.J.C., F.L.R. Data curation: B.E.D., U.A.L. Writing-original draft: G.G.O., S.J.C. Writing-review & editing: J.R.G.M., S.J.C. Visualization: M.F.V., J.R.G.M. Supervision: J.R.G.M., S.J.C. All co-authors reviewed the final version and approved the manuscript before submission.

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