

Article

Effect of Harvest Age on Forage Production and Silage Quality of Pearl Millet Hybrid in Cerrado Biome

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Abstract

Pearl millet (*Pennisetum glaucum* L.) is a promising crop for silage production in the Cerrado biome, but its use is still limited, and the ideal age for ensiling has not been well defined. This study aimed to evaluate the ADRf 6010 pearl millet hybrid at four harvest ages for ensiling: 75, 85, 95, and 105 days after planting (DAP). Forage production (green and dry forage mass), chemical composition, and fermentation parameters were analyzed. Harvested forage was chopped into 2.0 cm particles and treated with a concentration of 1×10^5 CFU/g (Colony Forming Units; *Lactobacillus plantarum* CNCM I-3736 and *Pediococcus acidilactici* CNCM I-4622) of fresh forage. Forage mass increased linearly with harvest age. At 105 days of growth, the crop yielded 65,980 kg/ha of fresh forage and 15,569 kg/ha of dry matter. The dry matter (DM) and neutral detergent fiber (NDF) concentrations also increased with advancing harvest age. The concentrations of crude protein (CP), non-fibrous carbohydrates (NFC), and in vitro dry matter digestibility (IVDMD) decreased with increasing harvest age before ensiling. In the silages, pH, ammoniacal nitrogen (NH₃-N), effluent loss, gas losses, and silage density decreased linearly, while DM recovery increased. With advancing harvest age, there was a positive linear increase in the concentrations of DM, NDF, and acid detergent fiber (ADF). On the other hand, CP, NFC, and IVDMD showed a negative linear trend. Based on the results, the ADRf 6010 pearl millet hybrid demonstrated high forage yield and favorable fermentative characteristics when harvested at different growth stages during the summer season. Advancing harvest age resulted in increased forage mass, dry matter content, and dry matter recovery, along with reduced fermentation losses such as effluents and gases. Although later harvests led to reductions in crude protein concentration and in vitro digestibility, these effects were compensated for by the higher dry matter yield per hectare and better preservation conditions. Thus, ADRf 6010 pearl millet is a promising crop for silage production under tropical conditions.

Keywords: ensilage; fermentation parameters; grass; nutritive value; *Pennisetum glaucum*



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1. Introduction

Pearl millet (*Pennisetum glaucum*), originally from Africa and the Indian subcontinent since prehistoric times [1], stands out for its tolerance to adverse conditions, where other forages would not thrive. This species is highly tolerant of factors such as drought, low soil fertility, and high temperatures and can be grown in areas where other cereal crops, such as corn and wheat, would not survive [2,3]. Due to these characteristics, pearl millet stands out as an excellent option for silage production, providing an effective solution for the recovery of degraded areas, which is incremental for animal feed in regions with challenging climatic conditions.

Therefore, pearl millet is resistant to different abiotic stresses resulting from climate change [4]. Its production is concentrated in developing countries, which account for 95% of global production and cultivated areas. India, the world's largest producer, uses pearl millet for both grain production and as a dual-purpose forage crop. Although predominantly grown in dry regions, pearl millet is also cultivated in irrigated areas [2].

Several agronomic traits enable pearl millet to survive prolonged drought and heat stress, such as thickened cell walls and dense root systems [5]. These characteristics have driven research worldwide, highlighting pearl millet's great potential as silage for ruminants [6]. An important advantage of pearl millet is the absence of antinutritional factors and toxins, ensuring high acceptability by animals. Additionally, pearl millet is an economical and resistant alternative compared to traditional crops such as corn and sorghum, which require greater investment and are less tolerant to water stress [7].

Studies have shown that pearl millet can produce more than 2300 kg/ha of dry forage mass with 14% crude protein (CP), even under rainfall conditions below 175 mm [8]. It is a short-cycle grass with rapid growth, good regrowth capacity, and high nutritive value. For instance, the cultivar ADR 300 showed DM yields between 1208 and 1466 kg/ha across three harvests, with CP concentrations ranging from 16.88% to 20.21% and neutral detergent fiber (NDF) concentrations from 62.69% to 62.78%, under different nitrogen application rates [9]. Meanwhile, the cultivar ADR 8010, harvested 65 days after emergence, exhibited CP levels of 14.9%, NDF of 54.5%, ether extract (EE) of 4.8%, total digestible nutrients (TDN) of 69.5%, and a DM forage mass of 18,200 kg/ha [10]. Among *Pennisetum glaucum* cultivars, the hybrid ADRf 6010, introduced in 2014 and recommended for grazing, stands out for its performance.

Studying the effect of the harvest stage of pearl millet is essential to optimize the production of high-quality silage, one of the main conserved feeds used for ruminant nutrition on livestock farms. The harvest stage directly influences the forage yield, nutrient concentration, and fermentation characteristics of the silage, impacting animal performance and farm productivity efficiency. Furthermore, in regions prone to climatic adversities such as dry spells and irregular rainfall, defining the optimal harvest stage becomes even more critical to maximize both the quantity and quality of conserved forage. This practice helps reduce losses during the ensiling process and ensures greater nutritive value throughout the year, even under variable climatic conditions. Thus, recommending the appropriate harvest stage of pearl millet provides producers with a strategic tool to improve the sustainability and profitability of livestock production.

Our hypothesis is that significant differences will occur in forage mass and silage quality when the pearl millet hybrid is harvested at different stages, highlighting the importance of harvest timing in optimizing productivity and nutritive value. Therefore, the objective of this study was to evaluate the effect of the harvest stage on the forage yield, composition, and fermentation parameters of the silage from the pearl millet hybrid ADRf 6010.

2. Materials and Methods

2.1. Location and Experimental Design

The experiment was conducted in the Forage Sector of the Escola Farm, located in the municipality of Terenos, MS, Brazil, at geographic coordinates 20°26'34.31'' S latitude and 54°50'27.86'' W longitude, at an altitude of 530.7 m. The region has a climate classified as equatorial savannah with dry winters. The analyses were performed at the Applied Animal Nutrition Laboratory and the Forage Laboratory of the School of Veterinary Medicine and Animal Science at the Federal University of Mato Grosso do Sul (UFMS).

The experimental period lasted from October 2018 to April 2019. Figure 1 shows precipitation levels as well as the minimum, average, and maximum monthly temperatures during this period.

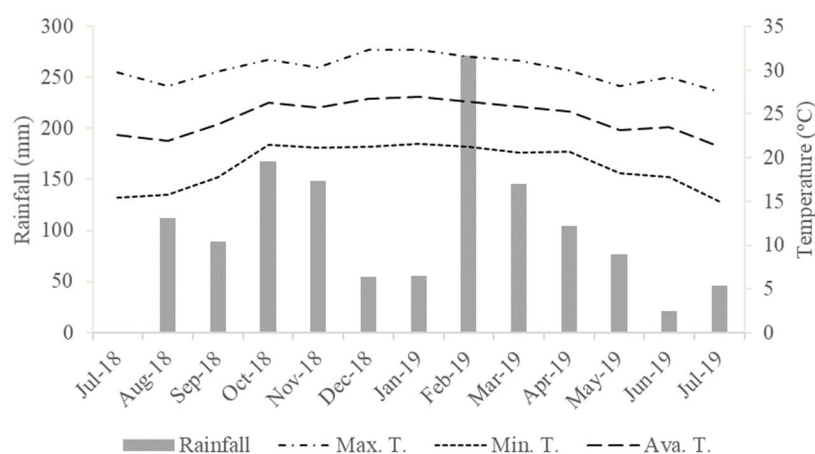


Figure 1. Maximum, minimum, and average temperatures and monthly precipitation during the experimental period.

The ADRf 6010 pearl millet was sown in rows with 60 cm spacing, using 5 kg of seeds per hectare, resulting in a planting density of 28 plants per linear meter. The seeds were weighed and pre-mixed homogeneously with the fertilizer, using only the fertilizer boxes containing the mixed products for sowing. The formulated mineral fertilizer was applied at a rate of 275 kg/ha of the 04-30-10 + 0.1 Br and 0.3 Zn formulation. Topdressing fertilization was carried out at 20 and 35 days post-germination with 200 kg of the 20-00-20 formulation, divided into two applications of 100 kg each.

The treatments consisted of four harvest ages (75, 85, 95, and 105 days), with four plots per treatment, totaling 16 plots measuring 5.0 m in length and 3.0 m in width. Four mini-silos were made from each experimental plot, resulting in a total of 64 mini-silos.

Before the experiment was implemented, soil samples were collected from the 0–20 cm layer for the fertility analysis. The results obtained were as follows: pH (CaCl₂) = 5.31 and (H₂O) = 6.10; P = 5.30 mg/dm³; organic matter = 36.10 g/dm³; K = 0.16 cmol/dm³; Ca = 5.90 cmol/dm³; Mg = 3.80 cmol/dm³; Ca + Mg = 9.70 cmol/dm³; Al = 0.00 cmol/dm³; H + Al = 4.10 cmol/dm³; CEC = 13.98 cmol/dm³; base saturation = 70.7%; sand = 140 g/kg; clay = 650 g/kg; silt = 210 g/kg.

2.2. Forage Mass and Ensilage

On the date of each harvest age, all material from the plot was harvested and weighed to determine the green forage weight. Silages were then prepared in mini-silos, and samples were collected and sent to the Forage Laboratory and the Applied Nutrition Laboratory of UFMS for analysis of the original material to determine the forage dry matter and chemical composition.

The material intended for ensiling was chopped into 20 mm particles and homogenized with a concentration of 1×10^5 CFU/g (Colony Forming Units; *Lactobacillus plantarum* CNCM I-3736 and *Pediococcus acidilactici* CNCM I-4622) of fresh forage. Experimental PVC mini-silos were then prepared, measuring 50 cm in height and 10 cm in diameter, and equipped with lids fitted with Bunsen valves to allow the escape of fermentation gases. Each mini-silo contained 500 g of sand and a non-woven fabric ("TNT") barrier separating the forage from the sand to determine effluent losses (Figure 2). After compacting the material, the mini-silos were sealed at the top with a 200-micron canvas and adhesive tape, weighed, and stored in a covered area. All materials used inside the silo and for sealing were weighed, and their weights recorded.

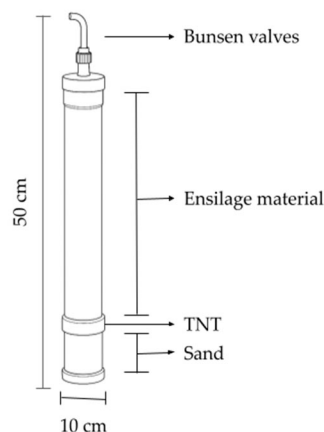


Figure 2. Structure of the experimental PVC mini-silos.

2.3. Silage Fermentation Parameters and Density

After 50 days of fermentation, total dry matter losses (TDML; Equation (1)), effluent losses (EL; Equation (2)), gas losses (GL; Equation (3)), density (expressed as kg fresh mass/m³ and kg dry mass/m³), and recovery were determined following the method described by Jobim et al. [11].

Equations:

$$\text{TDML (\%DM)} = \frac{(\text{DMi} - \text{DMf})}{\text{DMi}} \times 100 \quad (1)$$

where DMi: dry matter initial; DMf: dry matter final.

$$\text{EL (kg/ton fresh mass)} = \frac{(\text{FSWO} - \text{WSE})}{\text{FFME}} \times 1000 \quad (2)$$

where FSWO = full silo of the set (silo + lid + sand + screen + cloth) weight at opening (kg); WSE = weight of the set (silo + lid + sand + screen + cloth) at ensiling (kg); FFME = fresh forage mass ensiled (kg).

$$\text{GL (\% of initial DM)}: \frac{[(\text{FSWE} - \text{WSE}) \times \text{DMFE}] - [(\text{FSWO} - \text{WSE}) \times \text{DMFSO}]}{[(\text{FSWE} - \text{WSE}) \times \text{DMFSO}]} \times 100 \quad (3)$$

where FSWE = full silo weight at ensiling (kg); WSE = weight of the set (silo + lid + sand + screen + cloth) at ensiling (kg); DMFE = dry matter concentration of the forage at ensiling (%); FSWO = full silo weight at opening (kg); DMFSO = dry matter concentration of the forage at silo opening (%).

To determine the density, the weight (kg) of the silage inside the mini-silo was recorded. The cross-sectional area of the mini-silo was calculated (in m²) based on the circumference and then multiplied by the length of the mini-silo. The final volume was estimated to be 1.0 m³.

Approximately 5 cm from each end of the silo concentrations was discarded. The central material was homogenized and divided into two samples. The first portion was used to determine pH [12] and ammoniacal nitrogen (NH₃-N) according to Bolsen et al. [13] (% of total nitrogen).

2.4. Chemical Composition and In Vitro Digestibility

The original material sample and the second portion of the separated silage sample were pre-dried in a forced-air oven at 55 °C for 72 h and then ground in a Wiley knife mill. The concentrations of dry matter, organic matter, crude protein, and ether extract were determined according to AOAC [14] methods 930.15, 942.05, 976.05, and 920.39, respectively. Ash concentration was calculated as the difference (100—OM). The non-fibrous carbohydrates were calculated using the following formula:

$$100 - (\%CP + \%ash + \%EE + \%NDF).$$

The neutral detergent fiber (NDF) corrected for ash was determined according to Mertens [15]. Acid detergent fiber (ADF) concentrations were obtained by solubilization with sulfuric acid (H₂SO₄), as described by Van Soest and Robertson [16].

In vitro dry matter digestibility was assessed using the technique described by Tilley and Terry [17], adapted for an artificial rumen developed by ANKON[®], as described by Holden [18].

2.5. Statistical Analysis

The data were analyzed using an analysis of variance (ANOVA) and regression, performed with the Proc Glimix procedure in the SAS Studio software, version 9.2 (SAS Institute Inc., Cary, NC, USA). Regression model selection was based on the adjusted coefficient of determination (R²), calculated as the ratio between the sum of squares of the regression and the sum of squares of the treatments, as well as on the significance of treatment effects, evaluated using the F-test at a 5% significance level ($p \leq 0.05$). The regression coefficients were tested for significance using the *t*-test, also at the 5% probability level.

3. Results

3.1. Forage Mass and Composition Before Ensilage

Before ensiling, pearl millet showed a linear increase in green and dry forage mass (kg/ha) and crude protein concentration (kg/ha) ($p < 0.001$), as well as in dry matter (DM) and neutral detergent fiber (NDF) concentrations with advancing harvest age (Table 1). In contrast, crude protein (CP) concentration and in vitro DM digestibility decreased linearly with increasing harvest age. The non-fibrous carbohydrate concentration of pearl millet before ensiling did not differ ($p > 0.05$) as a function of harvest age.

3.2. Fermentation Parameters of Silage

DM recovery increased with advancing harvest age (Table 2). A significant effect ($p > 0.05$) of harvest age was observed on effluent losses, while pH, ammoniacal nitrogen (NH₃-N), DM losses, gas losses, and fresh silage mass density decreased linearly ($p < 0.001$). There was no effect of the harvest age on the dry matter density of the silages (Table 2).

3.3. Chemical Composition and In Vitro DM Digestibility of Silage

In the silages, as the harvest age increased, DM, NDF, and acid detergent fiber (ADF) concentrations also showed a linear increase ($p < 0.05$). However, CP and non-fibrous carbohydrates (NFC) concentrations, as well as in vitro DM digestibility, exhibited an inverse relationship (Table 3).

Table 1. Forage yields and chemical composition and in vitro dry matter digestibility (IVDMD) of ADRf 6010 pearl millet at different harvest ages before ensiling.

Item	Harvest Age (Days)				SEM	p-Value		Equation (R ²)
	75	85	95	105		L	Q	
Forage mass (kg/ha)								
Green mass	33,114	48,574	52,581	65,980	881.65	<0.001	0.792	$Y = -42280.677 + 1026.0273x$ (R ² = 0.73)
Dry mass	6666	9851	11,372	15,569	402.72	<0.001	0.544	$Y = -14544.065 + 282.3157x$ (R ² = 0.81)
CP concentration	1071	1284	1340	1650	102.0	<0.001	0.235	$Y = -989.845 + 25.5632x$ (R ² = 0.86)
Chemical composition								
Dry matter (%)	16.70	19.85	21.80	23.50	0.31	<0.001	0.565	$Y = 0.601 + 0.2056x$ (R ² = 0.94)
Organic matter (%DM)	94.00	94.20	94.30	94.50	0.17	0.387	0.899	-
Crude protein (%DM)	15.10	14.00	11.80	10.90	0.20	<0.001	0.487	$Y = 31.027 - 0.1923x$ (R ² = 0.93)
Ether extract (%DM)	3.1	3.2	3.5	3.3	0.04	0.425	0.252	-
NDF (%DM)	58.90	60.80	62.30	63.20	0.13	<0.001	0.367	$Y = 52.524 + 0.2092x$ (R ² = 0.91)
NFC (%DM)	16.90	16.30	16.70	17.20	0.10	0.275	0.325	-
IVDMD (%DM)	72.30	70.10	67.30	65.60	0.37	<0.001	0.207	$Y = 91.027 - 0.2375x$ (R ² = 0.90)

DM: dry matter; CP: crude protein; NDF: neutral detergent fiber; SEM: standard error of the mean.

Table 2. Fermentation parameters of ADRf 6010 pearl millet silage at different harvest ages.

Item	Harvest Age (Days)				SEM	p-Value		Equation (R ²)
	75	85	95	105		L	Q	
pH	4.25	3.92	3.76	3.60	0.009	<0.001	0.384	$Y = 6.159 - 0.0252x$ (R ² = 0.95)
NH ₃ -N (% TN)	2.05	1.75	1.49	1.22	0.090	0.003	0.987	$Y = 3.449 + 0.0197x$ (R ² = 0.86)
Total DM loss (% DM)	15.52	12.54	10.31	5.82	0.415	<0.001	0.563	$Y = 40.034 - 0.3133x$ (R ² = 0.98)
Effluent loss (kg/ton)	43.25	39.90	34.80	31.05	2.140	<0.001	0.464	$Y = 72.627 - 0.3967x$ (R ² = 0.95)
Gas loss (% DM)	8.50	7.04	5.25	2.82	0.234	<0.001	0.056	$Y = 24.063 - 0.2023x$ (R ² = 0.96)
DM recovery (%)	80.20	85.62	87.00	95.50	0.281	<0.001	0.185	$Y = 38.537 + 0.5339x$ (R ² = 0.93)
Density fresh mass (kg/m ³)	770.00	695.80	656.50	620.10	7.896	<0.001	0.116	$Y = 1135.951 - 5.0623x$ (R ² = 0.89)
Density dry mass (kg/m ³)	145.00	143.00	143.80	145.70	2.652	0.356	0.265	-

NH₃-N: ammoniacal nitrogen; TN: total nitrogen; DM: dry matter; SEM: standard error of the mean.**Table 3.** Chemical composition and in vitro DM digestibility (IVDMD) of ADRf 6010 pearl millet silage at different harvest ages.

Item	Harvest Age (Days)				SEM	p-Value		Equation (R ²)
	75	85	95	105		L	Q	
Dry matter (%)	18.83	20.56	21.90	23.50	0.200	0.002	0.181	$Y = 4.157 + 0.1925x$ (R ² = 0.87)
Organic matter (% DM)	94.40	94.60	94.00	94.70	0.109	0.052	0.194	-
Crude protein (%DM)	14.00	13.30	11.10	10.20	0.118	<0.001	0.716	$Y = 27.744 - 0.1793x$ (R ² = 0.95)
NDF (% DM)	59.80	62.00	64.40	66.30	0.338	<0.001	0.458	$Y = 25.702 + 0.4085x$ (R ² = 0.90)
ADF (%DM)	34.00	36.70	39.60	41.20	0.383	<0.001	0.164	$Y = 09.032 + 0.3383x$ (R ² = 0.90)
Ether extract (%DM)	3.20	3.15	3.10	3.10	0.080	0.409	0.926	-
NFC (%DM)	16.90	15.70	15.40	14.90	0.196	<0.001	0.739	$Y = 31.019 - 0.2167x$ (R ² = 0.92)
IVDMD (%DM)	77.30	75.20	72.60	70.50	0.384	<0.001	0.375	$Y = 115.801 - 0.4337x$ (R ² = 0.92)

NDF: neutral detergent fiber; ADF: acid detergent fiber; NFC: non-fiber carbohydrates; SEM: standard error of the mean.

4. Discussion

Alternative feedstuffs have been used to feed production animals, particularly during the dry season, as replacements for traditional feeds such as corn silage. Although corn is the most widely used forage for silage production, other plants have been evaluated, especially those tolerant of extended drought periods in spring and summer, such as pearl

millet. Our objective was to conduct a study applicable to basic production systems by harvesting the ADRf 6010 pearl millet hybrid at different ages to determine the optimal ensiling time during the summer. Harvest age influenced both biomass production and forage quality before ensiling, as well as the nutritive value and fermentation parameters of the silage, as observed in this study.

The forage yields of ADRf 6010 pearl millet increased with harvest age, from 33,114 to 65,979 kg/ha of green forage mass and from 6665 to 15,570 kg/ha of dry mass when harvested between 75 and 105 days, respectively. Simão et al. [19] evaluated ADR 500 pearl millet harvested at 80 days and reported a dry forage mass of 6284 kg DM/ha and a CP concentration of 6.8%, which were lower than the values found in the present study at 75 days (6665 kg DM/ha and 16.07% CP) (Table 1). Pearl millet demonstrated high forage productivity in spring and summer, as it is a long-day plant adapted to high temperatures, which explains the increase in forage mass throughout the experimental period (Figure 1). Although CP concentration decreased with the harvest age before ensiling (Table 1), the final protein concentration (kg/ha) in dry mass forage was highest at 105 days, reaching 1650 kg CP/ha. This was due to the higher dry forage mass at 105 days, which compensated for the reduced CP concentration at this stage (Table 1).

There was an increase in the forage dry matter (DM) concentration prior to ensiling as the plant matured (Table 1). According to Muck et al. [20], the optimal DM concentration for forages destined for silage is around 30%, and 25% is recommended by McDonald et al. [21], which allows for better compaction within the silo and reduces the oxygen presence, promoting more efficient fermentation. Very low DM levels can result in higher losses due to effluent production and undesirable fermentations, while excessively high DM levels make compaction more difficult and increase the risk of aerobic deterioration. The advancement in plant age at harvest led to a higher forage DM concentration before ensiling (Table 1), which helped reduce losses effluent, gases, and overall DM loss during the ensiling process (Table 2). At 105 days of growth, the forage had a DM concentration of 23.5%, still below the 30% recommended by Muck et al. [20]. However, the fermentation characteristics (Table 2) were within acceptable ranges, indicating that the ensiled material stabilized effectively, minimized losses, and preserved well.

As the plant's age at harvest increased, a decline in the crude protein (CP) concentration was observed. Between 75 and 105 days of growth, there was a 32.5% reduction in the CP concentration (Table 1). This decline is attributed to the plant's natural maturation process, during which there is an increase in structural components—such as cell wall material—due to stem elongation, at the expense of younger, nitrogen-rich tissues like leaves. This concentration of neutral detergent fiber (NDF) (Table 1) with increasing maturity reduced the relative protein concentration in the total biomass.

As the plant matured, CP concentration decreased while NDF concentration increased. This trend may be attributed to the crop's rapid initial growth, stem elongation with advancing age (reaching up to 4.0 m in height), and its short growth cycle, particularly due to panicle emergence after 85 days.

A similar trend was observed for in vitro dry matter digestibility (IVDMD). The digestible fraction of the forage is closely linked to its NDF concentration. As the grass matures, the proportion of cell wall components increases, primarily due to stem elongation and thickening, which negatively impacts digestibility [22].

The concentration of NFC (non-fiber carbohydrates) prior to ensiling did not show a significant effect, with an average value of 16.8%. It is important to note that ADRf 6010 pearl millet is a hybrid forage, originally developed for grazing purposes, and therefore not intended for grain production. At the harvest stage, 105 days after planting, many of

the panicles were still not fully expanded or had not yet formed grains, which explains the similar NFC values observed.

The pH values ranged from 4.2 to 3.6 (Table 3), falling within the recommended range of 3.8 to 4.2 suggested by McDonald et al. [21]. These values indicate high-quality silage, as [23] stated that DM concentrations below 28% can result in silages more susceptible to the presence of clostridia and greater buffering capacity, which can hinder pH reduction. This was not observed in the present study, as the material, despite its low DM concentration, effectively reduced the pH.

The $\text{NH}_3\text{-N}$ found in the silage decreased with the increasing harvest age (Table 3). The values obtained for the pearl millet silages, regardless of harvest age, were below 2.0 $\text{NH}_3\text{-N}$ (% TN). These values are below the maximum of 10% recommended by Tolentino et al. [24] for the silage to be classified as excellent quality. According to Dias et al. [25], the rapid decrease in pH inhibited the degradation of the protein fraction by clostridia.

Dry matter, gas and effluents losses, as well as fresh silage density, decreased with the harvest age in ADRf 6010 pearl millet silages (Table 3). This reduction may be attributed to the increase in DM concentration with advancing harvest age (Table 1). Likewise, the higher DM recovery rates at later harvest ages can be explained by the lower DM losses observed (Table 3).

Gas losses during the ensiling process typically occur due to the activity of enterobacteria, *Clostridium* spp., and aerobic microorganisms, which thrive in less acidic conditions, i.e., with higher pH, leading to secondary fermentations in the ensiled mass [26]. However, the pH levels in ADRf 6010 silages effectively reduced gas losses, thereby limiting the growth of these microorganisms. According to Woolford [27], high moisture concentration can stimulate gas losses, as a humid environment promotes microbial activity (lactic acid bacteria and clostridia), which is responsible for significant losses.

The density of the fresh ensiled mass was significantly affected ($p < 0.05$), with a decrease in green forage density (kg/m^3) inside the silo as the harvest age increased. This effect was correlated with the dry matter (DM) concentration of the forage prior to ensiling. However, when forage density was expressed as kilograms of DM per cubic meter ($\text{kg DM}/\text{m}^3$), no significant effect was observed.

As the harvest age increases, the forage exhibits higher dry matter concentration, leading to improved quality and reduced losses. According to Sucu et al. [28], greater compaction of the ensiled material enhances the preservation of soluble carbohydrates and proteins in the silage, while minimizing losses due to gases, effluents, and dry matter. Although silages produced at younger harvest ages have higher crude protein concentrations, they also generate greater effluent production, resulting in increased dry matter losses and lower dry matter recovery.

The increased effluent production observed at earlier harvest ages is primarily attributed to the lower dry matter (DM) concentration at harvest. Effluent loss during the ensiling process results in a reduction of DM, and, consequently, a decrease in the nutritive value of the silage as a feed resource [29].

The silage harvested at 105 days showed greater dry matter (DM) recovery (Table 2), indicating higher efficiency in the forage preservation process and resulting in lower losses during fermentation and storage. This improvement is associated with better compaction, rapid oxygen exclusion, and predominant fermentation by lactic acid bacteria, which effectively lower the pH. Higher DM recovery means that more of the nutrients originally present in the harvested forage are retained in the final silage, ensuring improved nutritive value.

It is important to highlight that the forage was treated with an inoculant during ensiling, which may have contributed to improvements in the fermentation process and

helped preserve the silage mass. Silages treated with heterofermentative bacteria generally exhibit lower pH, acetic acid, butyric acid, and ammonia nitrogen levels, but higher lactic acid concentration, resulting in better dry matter recovery compared to untreated silages [30].

A dry matter (DM) concentration of 25% is recommended by McDonald et al. [21] as a requirement to minimize effluent losses in the silo and ensure nutrient preservation in silages. None of the harvest ages reached this concentration.

Harvest age led to a reduction in the crude protein (CP) concentration of the silages. As previously discussed, this decline is associated with plant development, particularly stem elongation and the increased deposition of cell wall components, as reflected by the rise in the neutral detergent fiber (NDF) concentration in the silage (Table 3).

The decrease in CP concentration from the time of ensiling fresh forage to the opening of the silo is primarily due to plant and microbial respiration, fermentation processes, and losses resulting from organic matter decomposition. Another important factor is proteolysis—a natural process that occurs during fermentation and storage—where proteins are broken down into smaller molecules. This breakdown can lead to nitrogen loss, and, consequently, a reduction in the silage's CP concentration.

The pH values observed in the silages (Table 2) indicate stabilization of the ensiled material, which is associated with increased lactic acid production. This environment inhibits the formation of other undesirable organic acids and reduces proteolysis, resulting in low ammonia nitrogen ($\text{NH}_3\text{-N}$) levels. Comparing the CP concentration at ensiling with that of the final silage, an average reduction of 5% was observed—an acceptable range for silages made from forage grasses.

The NFC concentration of pearl millet before ensiling showed no significant effect (Table 1), with an average of 16.7%. However, the non-fibrous carbohydrate (NFC) concentration of ADRf 6010 pearl millet silage decreased with advancing harvest age (Table 3), corroborating the findings of Machado et al. [31], who evaluated BRS 1502 pearl millet silages at two harvest ages (60 and 80 days) and found that early harvesting at 60 days resulted in 8.1% more NFC compared to harvesting at 80 days (42.9%). In ADRf 6010 pearl millet silages (Table 3), the NFC concentration decreased linearly with the increasing harvest age, showing a 12% reduction from 75 to 105 days.

According to Adesogan et al. [32], NDF and ADF concentrations increase with the development of the cell wall, which is essential for providing structural support to plants during growth. As cellular components such as CP and NFC declined and cell wall components like NDF and ADF increased in the silages, *in vitro* dry matter digestibility (IVDMD) also decreased with later harvests. Machado et al. [31] reported a reduction in IVDMD from 71.14% to 55.68% as the harvest age increased from 60 to 80 days, indicating lower digestibility than that observed in the ADRf 6010 silage. Tolentino et al. [24] evaluated 24 sorghum genotypes and found an average digestibility of 62.99%, which was lower than that of the ADRf 6010 pearl millet silage, suggesting that pearl millet may offer superior forage quality compared to sorghum.

The silage (Table 3) exhibited higher dry matter digestibility compared to the fresh plant prior to ensiling (Table 1). The ensiling process may facilitate the degradation of certain structural components, such as neutral detergent fiber (NDF), thereby increasing their accessibility to ruminal microorganisms and enhancing digestibility. Silage harvested at 105 days showed an 8.8% decrease in digestibility compared to that harvested at 75 days. Nevertheless, this reduction is compensated for by greater forage mass and improved fermentative quality.

5. Conclusions

The ADRf 6010 pearl millet hybrid demonstrated high forage yield and favorable fermentative characteristics when harvested at different growth stages during the summer season. Advancing harvest age resulted in increased forage mass, dry matter content, and dry matter recovery, along with reduced fermentation losses such as effluents and gases. Although later harvests led to reductions in crude protein concentration and in vitro digestibility, these effects were compensated for by the higher dry matter yield per hectare and better preservation conditions.

Harvesting at 105 days after planting proved to be the most suitable strategy, balancing forage productivity, nutritional composition, and silage quality. Despite the decline in digestibility, the enhanced silage stability and reduced nutrient losses make this harvest age a viable and efficient alternative to traditional forages, especially during periods of feed scarcity. The use of inoculants likely contributed to the improved fermentation profile observed across all harvest stages. Thus, ADRf 6010 pearl millet is a promising crop for silage production under tropical conditions, contributing to the sustainability of livestock production systems.

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