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Additives and storage time for silage of pineapple crop waste

Abstract – The objective of this work was to evaluate the effects of additives and storage time on the quality and aerobic deterioration of silages of pineapple crop waste. A completely randomized design was used, in a 3×3 factorial arrangement, with three treatments: pineapple waste silage without additives or with the addition of cornmeal or wheat bran (20% fresh matter) at three storage times (60, 90, and 120 days). After each storage time, losses and aerobic deterioration were quantified, chemical composition was analyzed, and digestibility assays were performed. The storage time of 120 days resulted in higher dry matter losses in all treatments. The additives incremented the dry matter contents of the pineapple-based silages, which went from 182.1 g kg⁻¹ (control silage) to 298.7 and 297.6 g kg⁻¹ (cornmeal and wheat bran, respectively). The control silage with the addition of cornmeal showed the highest dry matter digestibility (739.7 g kg⁻¹) and lowest neutral detergent fiber content (251.9 g kg⁻¹). The production of CO₂ started to increase on the first day of air exposure in silages without additives, but only after six days in those with additives. Including cornmeal as an additive in the silage of pineapple crop waste improves its digestibility and reduces its deterioration speed.

Index terms: *Ananas comosus*, chemical composition, crop waste, effluent losses, ensilage.

Aditivos e tempo de armazenamento para silagem de restos de cultura do abacaxi

Resumo – O objetivo deste trabalho foi avaliar os efeitos de aditivos e tempos de armazenamento sobre a qualidade e a deterioração aeróbia de silagens de resíduos de cultura do abacaxi. Utilizou-se um delineamento inteiramente casualizado, em arranjo fatorial 3x3, com três tratamentos: silagem de resíduos culturais de abacaxi sem aditivo ou aditivada com fubá de milho ou farelo de trigo (20% da matéria fresca), em três tempos de armazenamento (60, 90 e 120 dias). Após cada tempo de armazenamento, realizaram-se quantificações de perdas e deterioração aeróbia, análises da composição química e ensaios de digestibilidade. O tempo de armazenamento por 120 dias resultou em maiores perdas de matéria seca em todos os tratamentos. Os aditivos incrementaram os teores de matéria seca das silagens à base de abacaxi, que passaram de 182,1 g kg⁻¹ (silagem controle) para 298,7 e 297,6 g kg⁻¹ (fubá de milho e farelo de trigo, respectivamente). A silagem controle adicionada de fubá de milho apresentou maior digestibilidade da matéria seca (739,7 g kg⁻¹) e menor teor de fibra em detergente neutro (251,9 g kg⁻¹). A produção de CO₂ aumentou a partir do primeiro dia de exposição ao ar nas silagens não aditivadas, mas apenas a partir do sexto dia nas aditivadas. A inclusão do fubá de milho como aditivo na silagem de resíduos de abacaxi melhora sua digestibilidade e reduz sua velocidade de deterioração.

Termos para indexação: *Ananas comosus*, composição química, restos de cultura, perdas por efluentes, ensilagem.

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Introduction

Brazil is the third largest producer worldwide and the first in Latin America of the pineapple [*Ananas comosus* (L.) Merr.] crop, with almost 1.5 billion fruits harvested annually in approximately 60,000 hectares (Lima et al., 2018; IBGE, 2019). The waste of this crop, i.e., leaves plus stems without fruit (Santos et al., 2014), obtained from fruit harvesting and industrial processing (Gowda et al., 2015; Salami et al., 2019; Mello et al., 2021; Cordeiro et al., 2022), presents a high fiber content (Valadares Filho et al., 2016) and a bromatological composition with average contents of 180, 70, and 59 g kg⁻¹ dry matter (DM), crude protein (CP), and neutral detergent fiber (NDF), respectively (Cunha et al., 2009). This composition highlights the potential of pineapple waste for ruminant feeding, mainly considering its fiber contents. However, the reduced contents of DM and soluble carbohydrates in pineapple residues may compromise fermentation and nutrient conservation, especially when this by-product is ensiled.

Silo storage time, which usually lasts from 7 to 45 days, may also affect the nutritional value of the silages, altering fermentation characteristics (Muck et al., 2018). In addition, air exposure time after silo opening changes the nutritional value of silages via processes of aerobic deterioration (Ogunade et al., 2016; Bernardes et al., 2018). In this scenario, moisture-absorbent additives are often used to increase DM contents and the nutritional value of silages, mainly composed of moist fodder or agricultural residues. Cornmeal and wheat bran are traditional additives used for this purpose since they are usual concentrates for animal feeding and are easy to access (Muck et al., 2018; Costa et al., 2022).

However, there are few known studies about the quality of pineapple crop waste silage (PCWS). Despite that, promising results have been reported for the use of pineapple waste silage in ruminant feeding. Cordeiro et al. (2022), for example, found high contents of 323 g kg⁻¹ DM of non-fiber carbohydrates in pineapple waste silage, which is important to maximize microbial growth. Salami et al. (2019) highlighted that pineapple crop residues have a proteolytic enzyme, called bromelain, that can increase ruminal digestibility. Moreover, Kyawt et al. (2020) reported increases of 1.23 kg per day and of 0.09 kg per day in DM intake and average daily gain, respectively,

when adding 25% of PCWS to Napier grass [*Cenchrus purpureus* (Schumach.) Morrone] silages. Considering these results, it is possible that combining moisture absorbents with adequate storage times may improve PCWS quality for ruminant nutrition.

The objective of this work was to evaluate the effects of additives and storage time on the quality and aerobic deterioration of silages of pineapple crop waste.

Materials and Methods

Waste from the 'Pérola' pineapple crop was obtained in the municipality of Sapé, in the state of Paraíba, Brazil (7°5'39"S, 35°13'58"W, at 123 m altitude). Pineapple was harvested 570 days after planting.

The experiment was carried out at the Department of Animal Science of Universidade Federal Rural de Pernambuco, located in the municipality of Recife, in the state of Pernambuco, Brazil (8°04'03"S, 34°55'00"W, at 4.0 m altitude). According to Köppen's classification, the climate of the region is Ams', warm with a high air humidity, with 1,804 mm annual rainfall and 25.8°C annual average temperature (Inmet, 2019).

The experiment was conducted in a completely randomized design, in a 3×3 factorial arrangement, with four replicates. The three evaluated factors were: PCWS with no additives or with the addition of cornmeal (PCWS+CM) or wheat bran (PCWS+WB) in three storage times (60, 90, and 120 days). The additives were acquired at local markets and manually incorporated into the ensiled mass at 80% PCWS and 20% additive based on fresh matter before ensiling, aiming to reach a silage DM content near 300 g kg⁻¹.

The contents of DM, crude protein, ether extract, neutral detergent fiber (NDF), and acid detergent fiber (ADF) were analyzed before ensilage according to the methodologies of Association of Official Analytical Chemists (AOAC) described in Horwitz (2005) (Table 1). NDF and ADF were evaluated without a heat-stable amylase and expressed with residual ash. The concentration of water-soluble carbohydrates (WSC) was also quantified (Bezerra Neto & Barreto, 2011), as well buffering capacity (Johnson et al., 1987). The fermentation coefficient of fresh forage was calculated as in Weissbach & Honig (1996), according to the equation: $FC = DM + 8 \times WSC \div BC$, in which FC is the fermentation coefficient, DM is dry matter, WSC

is the concentration of water-soluble carbohydrates, and BC is buffering capacity.

To be used, the pineapple crop waste was chopped into 2.0 to 3.0 cm particle sizes with the EVO 30 stationary forage machine (JF Máquinas Agrícolas, Itapira, SP, Brazil). The material was ensiled in 36 experimental silos, consisting of 75×15 cm PVC pipes, sealed with lids equipped with Bunsen-type valves to quantify gas losses. Cotton bags filled with dried-washed sand (5.0 kg for the control treatment and 4.0 kg for the silages with additives) were deposited at the bottom of each silo. The silos were weighed before ensiling to register the set weight (silo + lid + dried-washed sand + cotton bag). After ensilage, the silos were weighed again, filled, and sealed to determine gas and effluent losses through gravimetric calculations, as in Schmidt (2006). In addition, dry matter recovery (DMR) was evaluated according to the methodology of Jobim et al. (2007).

Gas losses were calculated using the following equation obtained by Schmidt (2006): $GL = (WCSi - WCSf) \div (FMi \times DMi) \times 100$, where GL are the gas losses ($g\ kg^{-1}\ DM$), WCSi is the weight of the filled silo at closing (kg), WCSf is the weight of the filled silo at opening (kg), FMi is the fresh forage mass at closing (kg), and DMi is the dry matter content of forage at closing.

Effluent losses were obtained using the following equation: $EL = [(WVf - ST) - (WVi - ST)] \div FMi \times 100$, where EL are the effluent losses ($kg\ Mg^{-1}$ fresh matter), WVf is the weight of the empty silo with sand at opening (kg), ST is the silo tare, WVi is the weight of the empty silo with sand at closing (kg), and FMi is the fresh forage mass at closing (kg).

DMR was calculated with the following equation: $DMR = [(FMf \times DMf) \div (FMi \times DMi)] \times 100$, where DMR is the dry matter recovery rate (%), FMf is the fresh forage mass at opening (kg), DMf is the dry matter content at opening (%), FMi is the fresh forage mass at closing (kg), and DMi is the dry matter content of forage at closing (%). In addition, silage-specific mass ($kg\ m^{-3}\ DM$) was calculated by dividing the net silage weight by the inner volume of the experimental silos (Jobim et al., 2007).

Aerobic deterioration was evaluated using 500 g fresh silage samples, considering the silage (PWCS, PWCS+CM, and PWCS+WB) treatments and storage time (60, 90, and 120 days). The samples were placed in systems constructed with polyethylene bottles, adapted from Ashbell et al. (1991). There were 12 systems per treatment, exposing silages to air for 1, 3, 6, and 9 days, with four replicates, totaling 48 experimental units (polyethylene bottles). The carbon dioxide (CO₂) released from silage deterioration after opening was measured according to Ashbell et al. (1991). The silage samples were also analyzed for DM, ash, organic matter, crude protein, and NDF contents, as well as for pH values and ammonia nitrogen (NH₃-N) contents at each air exposure time, using the previously cited methods.

Fresh silage samples were collected immediately after silo opening to measure pH values and NH₃-N contents according to Bolsen et al. (1992). The remaining silage samples were dried in a forced-air oven, at 55°C, for 72 hours and ground in a Willey mill to pass a 1.0 mm screen. After these procedures, the silages were analyzed to determine the contents of DM, ash, organic matter, NDF, ADF, and crude protein, following the methodologies of AOAC (Horwitz,

Table 1. Chemical composition and fermentative potential of the used ingredients before ensiling pineapple (*Ananas comosus*) crop waste alone (PCW) or mixed with cornmeal (CM) or wheat bran (WB).

Ingredient	Dry matter ($g\ kg^{-1}$ of fresh matter)	Organic matter ($g\ kg^{-1}\ DM$)	Ashes ⁽¹⁾	Ether extract ($g\ kg^{-1}\ DM$)	Crude protein ($g\ kg^{-1}\ DM$)	NDF ($g\ kg^{-1}\ DM$)	ADF ($g\ kg^{-1}\ DM$)	WSC ($g\ kg^{-1}\ DM$)	BC (n.e.mg 100 $g^{-1}\ MS$)	Fermenta- tion coef- ficient	WSC: CP
Commeal	832.2	976.5	23.5	44.8	96.4	247.6	24.6	206.2	25.8	-	-
Wheat bran	800.8	941.3	58.7	31.3	160.8	478.7	128.3	7.5	56.8	-	-
PCW	165.0	930.5	69.5	27.5	45.1	471.2	224.6	98.2	52.3	18.0	2.17
PCW+CM	282.7	942.9	57.1	30.3	67.7	374.1	168.3	130.5	59.7	30.0	1.93
PCW+WB	289.2	937.9	62.1	28.4	95.1	435.3	168.5	75.7	65.6	29.8	0.79

⁽¹⁾Estimated on a dry matter (DM) basis ($g\ kg^{-1}$). NDF, neutral detergent fiber; ADF, acid detergent fiber; WSC, water-soluble carbohydrates; BC, buffering capacity; and WSC:CP, water soluble carbohydrates:crude protein ratio.

2005). Acid detergent insoluble protein (ADIP) and soluble protein contents were also analyzed (Licitra et al., 1996), as well as NDF corrected for ash and protein (NDFap). Moreover, the in vitro digestibility of DM (IVDDM), organic matter (IVDOM), and NDF (IVDNDF) was evaluated as proposed by Holden (1999). Silage samples were incubated artificially in the DAISY II incubator (ANKOM Technology, Macedon, NY, USA), being ground into 1.0 mm particles, stored in non-woven textile bags (100 g m⁻²), and kept in the apparatus for 72 hours at 39°C. After 48 hours of incubation, the samples were subjected to chemical digestion by a solution containing HCl 50% and pepsin. The used ruminant fluid was collected in the early morning from a rumen-fistulated cow.

For chemical composition analyses, silage losses, and digestibility assays, the experimental design was completely randomized, in a 3×3 factorial arrangement with four replicates. The used mathematical model was: $Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}$, where Y_{ijk} is the observed value, μ is the overall mean, α_i is the additive effect (1 to 3), β_j is the storage time effect (1 to 3), $(\alpha\beta)_{ij}$ is the additive-storage time interaction, and ε_{ijk} is the residual error of each observation.

A 3×3 factorial arrangement with repeated measurement in times was performed to determine aerobic deterioration, at four air exposure intervals (1, 3, 6, and 9 days), assumed as repeated effects. In this case, the used mathematical model was: $Y_{ijk} = \mu + \alpha_i + \beta_j + \delta_k + (\alpha\beta)_{ij} + (\alpha\delta)_{ik} + (\beta\delta)_{jk} + (\alpha\beta\delta)_{ijk} + \varepsilon_{ijk}$, where Y_{ijk} is the observed value, μ is the overall mean, α_i is the additive effect (1 to 3), β_j is the storage time effect (1 to 3), δ_k is the air exposure time effect, $(\alpha\beta)_{ij}$

is the additive-storage time interaction, $(\alpha\delta)_{ik}$ is the additive-air exposure time interaction, $(\beta\delta)_{jk}$ is the storage time-air exposure time interaction, $(\alpha\beta\delta)_{ijk}$ is the triple interaction effect, and ε_{ijk} is the residual error of each observation.

The data were subjected to the analysis of variance using the PROC MIXED procedure of the SAS OnDemand for Academics software (SAS Institute, Inc., Cary, NC, USA), at a 5% probability of error. When the F-test was significant, means were compared by the probability of difference adjusted by Tukey's test, at 5% probability.

Results and Discussion

There was an additive-storage time interaction effect on gas and effluent losses (Table 2). Higher gas losses were observed in PCWS with additives, which could have been due to the rapid degradation by bacteria of many compounds, such as WSC (Table 1), resulting in a higher gas production during fermentation (Muck et al., 2018). Silva et al. (2017) found that secondary fermentations performed by heterofermentative bacteria can produce CO₂, ethanol, and mannitol, which increase gas losses.

Effluent losses were higher after 120 days of storage regardless of the treatment (Table 2). However, because of their high DM contents and specific mass, the CM and WB additives helped to reduce effluent losses in PCWS. Gebrehanna et al. (2014) linked effluent production to silage moisture content and compression degree, whereas Yitbarek & Tamir (2014) concluded that the retention capacity of absorbent additives varies

Table 2. Specific mass (SM), dry matter recovery (DMR), and dry matter losses (DML) of silages composed of pineapple (*Ananas comosus*) crop waste alone (PCWS) or with the addition of cornmeal (CM) or wheat bran (WB) at different storage times (days)⁽¹⁾.

Variable	Additive (A)			Storage time (S)			SEM	p-value		
	PCWS	PCWS+CM	PCWS+WB	60	90	120		A	S	A × S ⁽²⁾
SM (kg m ⁻³ DM)	182.6B	282.4A	284.8A	242.2	255.5	252.1	6.1	<0.001	0.296	0.467
DMR (%)	91.89	90.83	93.24	93.0a	95.1a	87.9b	1.3	0.453	0.002	0.728
DML (% DM)	8.19	9.17	6.76	7.0b	4.9b	12.1a	1.3	0.443	0.002	0.746
GL (% DM)	0.41C	1.50B	1.67A	1.20	1.20	1.20	0.05	<0.001	0.998	0.031
EL (kg Mg ⁻¹ FM)	139.3A	110.8B	57.2C	68.7b	79.5b	159.1a	5.3	<0.001	<0.001	0.030

⁽¹⁾Means followed by equal letters, uppercase for additive and lowercase for storage time effects, do not differ by Tukey's test, at 5% probability.

⁽²⁾Interaction effect of additive and storage time. GL, gas losses; and EL, effluent losses. Results were based on dry matter (DM) content, except for effluent losses, estimated on a fresh matter (FM) basis.

according to the nature of the used material. Grinding degree is another characteristic affecting moisture content since thin particles often retain more humidity than coarse ones (Faria et al., 2010). In this sense, CM and WB effectively absorbed the moisture content of PCWS. Borreani et al. (2018) highlighted that, to improve silage quality (nutritional value), it is essential to avoid losses of effluents, which are composed of sugars and organic acids that are leached at the bottom of silos.

The specific mass of PCWS without additives was lower than that of the PCWS+CM and PCWS+WB treatments. Despite the great moisture content of pineapple crop waste, this reduced mass was likely due to the lower density of PCWS, compared with the materials of the other silages. Moreover, pineapple crop waste was more fibrous, which probably impaired silage compression and created a higher porosity (Krüger et al., 2020). After 120 days of storage, all silages showed a lower DMR, confirming the higher effluent losses at this storage time.

Only additives influenced PCWS fermentation parameters (pH and NH₃-N) and almost all chemical variables (Table 3), except crude protein content,

which was also affected by storage time, without any interaction between the studied factors. The silages with the addition of WB had a higher pH than the others, although suitable pH values, varying from 3.6 to 4.2 (Kung Jr. et al., 2018), were found for all of them. The WSC:crude protein ratio was considerably lower in PCWS+WB before ensiling (Table 1), which may justify the observed values. Borreani et al. (2018) found that the sugar:protein ratio is essential for silage pH since sugars supply lactic acid fermentation, while proteins are degraded to ammonia and fatty acids.

Higher concentrations of NH₃-N were registered in the control treatment (Table 3). The high moisture content found in PCWS with no additives probably favored protein hydrolysis by *Clostridium* bacteria (Gusmão et al., 2018). However, all silage treatments showed ammonia contents below 100 g kg⁻¹ total N, indicating acceptable proteolysis during fermentation (Kung Jr. et al., 2018; Lemos et al., 2021).

The PCWS+CM and PCWS+WB treatments showed higher DM contents than PCWS, meaning that the additives effectively incremented the DM content of the ensiled mass. According to Borreani et al. (2018), DM contents over 250 g kg⁻¹ ensure a

Table 3. Chemical-bromatological composition and digestibility coefficients of silages of pineapple (*Ananas comosus*) crop waste alone (PCWS) or with the addition of cornmeal (CM) or wheat bran (WB) at different storage times in days⁽¹⁾.

Variable ⁽²⁾	Additive (A)			Storage time in days			SEM	p-value		
	PCWS	PCWS+CM	PCWS+WB	60	90	120		A	S	A × S ⁽³⁾
pH	3.70B	3.66B	3.82A	3.69	3.74	3.74	0.03	0.005	0.465	0.314
NH ₃ -N (g kg ⁻¹)	86.1A	56.9B	51.7B	68.5	62.4	63.5	0.4	<0.001	0.509	0.629
Dry matter (g kg ⁻¹ FM)	182.1B	298.9A	297.6A	251.4	263.4	263.8	3.9	<0.001	0.055	0.317
Ashes (g kg ⁻¹ DM)	75.5A	50.1B	70.1A	64.8	67.6	63.3	1.5	<0.001	0.157	0.580
Organic matter (g kg ⁻¹ DM)	924.5B	949.9A	929.9B	935.2	932.4	936.7	1.5	<0.001	0.157	0.580
Crude protein (g kg ⁻¹ DM)	69.4C	82.2B	122.6A	85.1b	95.6a	93.4a	2.4	<0.001	0.011	0.313
Soluble protein (g kg ⁻¹ CP)	50.2A	32.8B	40.4B	38.2	41.4	43.9	2.4	<0.001	0.264	0.419
Ether extract (g kg ⁻¹ DM)	32.4	39.8	34.3	34.5	33.6	38.3	2.3	0.084	0.328	0.511
NDF (g kg ⁻¹ DM)	456.2A	251.9C	395.4B	365.0	373.7	365.7	6.3	<0.001	0.720	0.155
NDFap (g kg ⁻¹ DM)	417.3A	236.7A	382.9A	358.1	338.2	340.5	9.8	<0.001	0.304	0.768
ADF (g kg ⁻¹ DM)	332.9	164.4	235.8	237.1	253.8	241.8	4.6	<0.001	0.050	0.039
ADIP (g kg ⁻¹ CP)	110.2A	84.0B	80.5C	103.0a	84.0c	88.0b	0.5	0.003	0.024	0.002
IVDDM (g kg ⁻¹)	530.2C	739.7A	612.8B	630.5	613.0	639.3	7.3	<0.001	0.060	0.034
IVDOM (g kg ⁻¹ DM)	509.6C	750.7A	592.6B	621.0a	596.6b	635.6a	10.2	<0.001	0.037	0.053
IVDNDf (g kg ⁻¹ DM)	515.7C	704.8A	603.9B	614.8	593.8	616.7	8.5	<0.001	0.119	0.020

⁽¹⁾Means followed by equal letters, uppercase for additive and lowercase for storage time effects, do not differ by Tukey's test, at 5% probability. ⁽²⁾NH₃-N, ammonia nitrogen based on total nitrogen content; NDF, neutral detergent fiber; NDFap, neutral detergent fiber corrected for ash and proteins; ADF, acid detergent fiber; ADIP, acid detergent insoluble protein; IVDDM, in vitro dry matter digestibility; IVDOM, in vitro organic matter digestibility; and IVDNDf, in vitro neutral detergent fiber digestibility. ⁽³⁾Interaction effect of additive and storage time. Results were estimated on a dry matter (DM) basis, except for NH₃-N, soluble protein, and ADIP, which were estimated on a crude protein (CP) basis.

good silage fermentation process. Furthermore, higher organic matter and lower ash contents were observed in PCWS+CM, confirming the nutrient composition of each silage ingredient before ensiling (Table 1).

Pineapple crop waste has considerable fiber fractions in its composition (Santos et al., 2014). For this reason, higher contents of NDF, NDFap, and ADF were found in the control silage (Table 3), also confirming the chemical composition of the used materials before ensiling. There may have been a higher consumption of soluble carbohydrates in PSWS, resulting in higher contents of fiber compounds (Borreani et al., 2018). However, extremely high contents of NDF are undesirable since they may limit ruminant feed intake, causing animal performance losses (Valadares Filho et al., 2016).

The chemical composition before ensilage justified the lower crude protein content of PCWS with no additives. The higher proteolysis observed in the control silage also caused a decrease in crude protein content, as confirmed by the $\text{NH}_3\text{-N}$ levels. The highest crude protein content was found in the PCW+WB silage because the wheat-based additive had more protein in its composition before ensilage than the other ingredients (Table 1). Moreover, crude protein contents were higher at 90 and 120 days of storage time than at 60 days in PCWS with no additives. Some nutrients were probably concentrated into silage DM under longer storage periods, increasing crude protein content. Balieiro Neto et al. (2009) concluded that high protein contents, at longer storage times, suggest more soluble carbohydrate losses due to effluent and gas production.

An alternative to obtain the actual value of degradability in feedings with protein ingredient is measuring protein solubility (Licitra et al., 1996; Souza et al., 2021). The control silages had higher soluble protein contents (Table 3) than those mixed with CM or WB. However, because of their association with the liquid phase, soluble proteins can pass intact by the rumen and in higher proportions than insoluble ones, meaning that soluble proteins remain in the rumen for less time, resulting in low-enzyme ruminal degradation (Medeiros et al., 2015).

The highest content of ADIP was observed in the control silage. ADIP is an indigestible protein fraction bound to lignin, responsible for significant decreases in digestibility (Licitra et al., 1996; Muir et al., 2019),

and its content has been a suitable parameter to indicate protein use efficiency or inefficiency in animal feeding (Lemos et al., 2021).

Interaction effects of additives and storage time were observed on the coefficients of IVDDM and IVDNDF, but single effects on those of IVDOM. The PCWS+CM treatment showed a higher digestibility of DM, organic matter, and NDF at all storage times, likely because of the lower NDF and ADF contents in CM and a higher soluble carbohydrate content before ensilage (Table 1). Because of these characteristics, CM has excellent digestibility parameters (Huuskonen, 2013). Higher coefficients of IVDDM, IVDOM, and IVDNDF were found in PCWS+WB at most storage times, compared with the control. These improvements in digestibility could be explained by several alterations in the fermentation parameters caused by the inclusion of CM and WB in the ensiled mass. The additives incremented DMR and reduced effluent losses, so more digestible nutrients remained in the PCWS+CM and PCWS+WB treatments after sealing time. Another variable affecting DM digestibility is ADIP (Licitra et al., 1996; Silva et al., 2023), which impairs protein digestion by ruminal bacteria because it is an insoluble fraction bound to lignin (Muir et al., 2019). Higher ADIP contents were observed in PCWS (Table 3).

Air exposure increased pH values over time (Figure 1 A), which was attributed to aerobic microorganism activities (Daniel et al., 2019). Conversely, the PCWS without additives produced more CO_2 until the sixtieth day (Figure 1 B). After that, CO_2 production remained stable and inferior to those of the silages mixed with CM and WB. This stabilization in CO_2 production was probably caused by the exhaustion in the energetic substrates for aerobic microbiota (Kung Jr. et al., 2018). Contrarily, silages with additives produced more CO_2 only after six days of exposure, delaying the deterioration process and stabilizing silage quality after silo opening. However, CO_2 production in PCWS+WB reached its highest value after six days, especially after storage for 120 days.

After air exposure, PCWS with no additives showed a greater $\text{NH}_3\text{-N}$ content (Figure 1 C). The control silage, combined with the storage time of 120 days, presented the highest $\text{NH}_3\text{-N}$ concentration from the third day of air exposure onwards due to a depletion

in soluble sources for oxidation, driving fungi to use the remaining protein. $\text{NH}_3\text{-N}$ content increased after three days of air exposure in the silage with the addition of WB and stored for 90 days, but varied little in the silage with the addition of CM at all storage times. Therefore, CM was the most effective moisture-absorbent in inhibiting aerobic deterioration. Considering that longer storage times impair the aerobic stability of the silage and that PCWS+CM had a low variation in crude protein contents for all storage times and exposure days (Figure 1 D), with a lower ammonia production (Figure 1 C), CM stabilizes the silage before and after silo opening.

At all storage times, the DM content was the lowest in the control silage, reducing in those with the addition of CM or WB only six days after silo opening; the

exception were the silages containing CM and sealed for 90 days (Figure 2 A). However, silage deterioration is inevitable during silo management or feed-out, which may result in substantial DM losses caused by bacterial and fungal activities (Taylor et al., 2002).

Higher NDF contents were found when silages were exposed to air over days (Figure 2 B), with the highest concentration of 395.2 g kg^{-1} on the ninth day. Kung Jr. et al. (2018) concluded that the consumption of soluble compounds may concentrate fiber fractions in silages exposed to air for longer times during feed-out. The NDF contents in the PCWS+CM treatment were the lowest at all storage times and exposure days. In addition, no effects were observed on ashes and organic matter contents (Figures 2 C and D). Velho et al. (2006) evaluated bromatological alterations

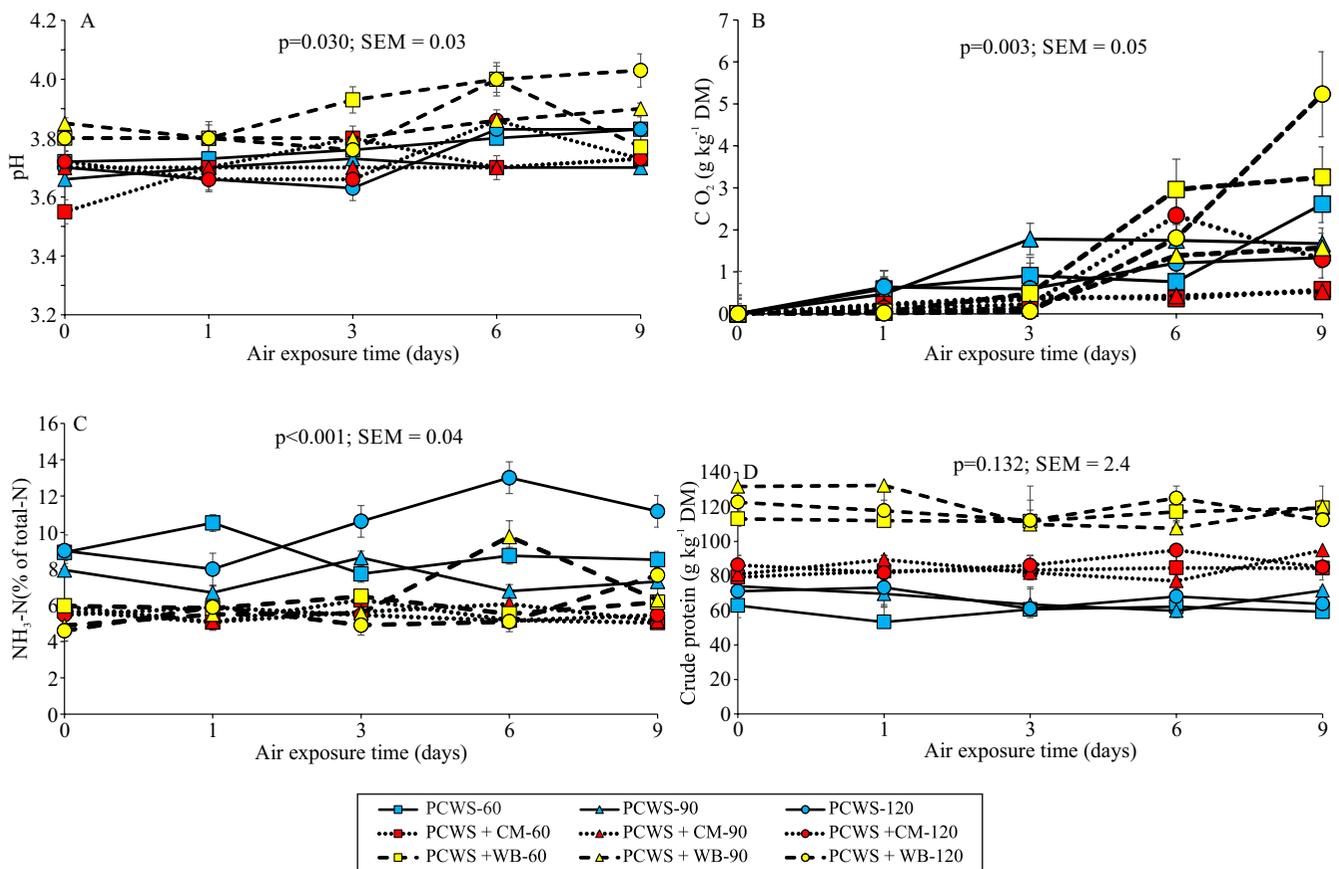


Figure 1. Air exposure time effect on pH (A), carbon dioxide (CO_2) production (B), ammonia nitrogen ($\text{NH}_3\text{-N}$) content (C), and crude protein (CP) content (D) of silages composed of pineapple crop waste alone (PCWS) or with the addition of cornmeal (CM) or wheat bran (WB) at different storage times (60, 90, and 120 days). Means differ by Tukey's test, at 5% probability. SEM, standard error of the mean. P-values are related to the triple interaction (additive \times storage time \times air exposure time).

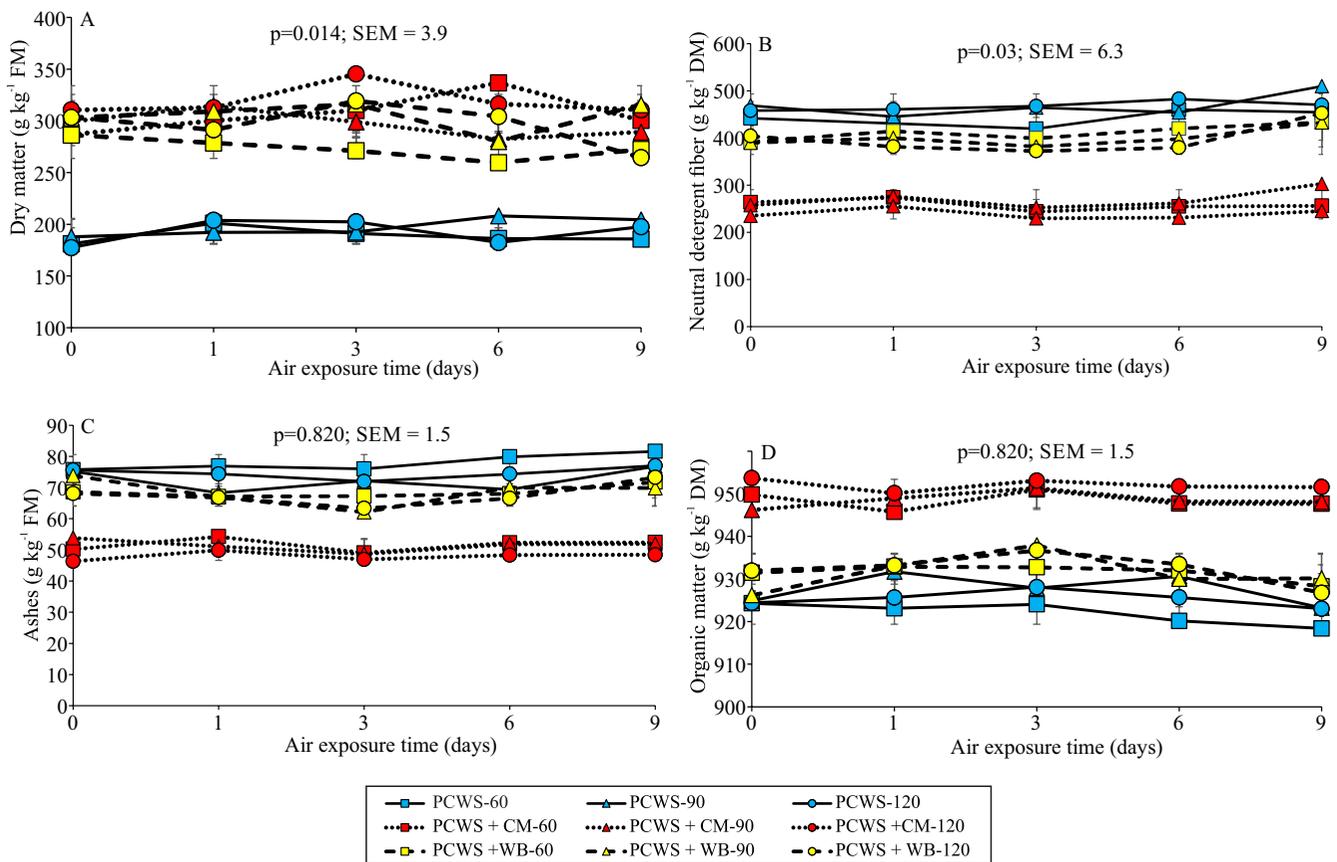


Figure 2. Effect of air-exposure time on contents of dry matter (A), neutral detergent fiber (B), ashes (C), and organic matter (D) of silages composed of pineapple crop waste alone (PCWS) or with the addition of cornmeal (CM) or wheat bran (WB) at different storage times (60, 90, and 120 days). Means differ by Tukey's test, at 5% probability. SEM, standard error of the mean. P-values are related to the triple interaction (additive \times storage time \times air exposure time). DM, dry matter; NDF, neutral detergent fiber; and OM, organic matter.

in whole-plant corn silages subjected to increasing levels of air exposure (12, 24, and 36 hours), finding reductions in the nutritional value of the silage due to significant increments in NDF contents, from 514.7 to 533.3 g kg⁻¹ from 0 to 12 hours, respectively. According to McDonald et al. (1991), soluble compounds are the first nutrients degraded by aerobic microorganisms when the silage is exposed to air, via silo management, or during feed-out, explaining why increases in NDF, ADF, and ashes are commonly observed.

Conclusions

1. The cornmeal and wheat bran moisture-absorbent additives improve pineapple (*Ananas comosus*) waste silage by increasing dry matter content and reducing

gas and effluent losses, but a maximum storage time of 90 days is recommended to avoid effluent production and silage losses.

2. When mixed with silages of pineapple crop waste, cornmeal and wheat bran maintain aerobic stability by delaying the deterioration process, and cornmeal also improves aerobic stability by decreasing nutrient variation over days of air exposure.

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