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ORIGINAL PAPER

Nutritional value, fermentation characteristics and aerobic stability of maize grain silage rehydrated with increasing levels of wet tomato byproduct

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ABSTRACT. Rehydrating maize (*Zea mays* L.) grain silage can mitigate storage issues in maize production. Moreover, the use of agricultural byproducts for rehydration may reduce environmental impact and prevent aerobic deterioration of maize grain silage. This study investigated the effects of increasing levels of wet tomato byproduct (WTB) on the fermentation characteristics, nutritional value, and aerobic stability of maize grain silage. A completely randomised design with five treatments and seven replicates was applied. Treatments consisted of ground maize grains (1–2 mm) replaced with increasing WTB levels (25%, 30%, 35%, 40%, and 45%) in the ensiled mass, added based on a fresh mass basis. A linear decrease ($P < 0.01$) in dry matter (DM) content from 77.6% to 53.4% was observed. Crude protein, neutral detergent fibre, and lignin concentrations increased linearly ($P < 0.01$), with respective increments of 4.13%, 4.72%, and 1.14% between 25% and 45% WTB additions. A negative quadratic effect was found in the *in vitro* digestible DM content ($P < 0.01$), with the highest value at 30% WTB (75.6%). Lactic acid concentrations also rose, from 1.01% to 7.35%, with increasing WTB concentrations. No aerobic deterioration was observed after 264 h of air exposure in the silages supplemented with 35%, 40%, and 45% WTB. However, excessively high WTB proportions reduced DM content and increased the concentration of indigestible fibre. Rehydrating maize grain silage with 35–40% WTB improved fermentation and aerobic stability without compromising digestibility.

Introduction

Global coarse grain production reached 1451.74 mln metric t in the 2023/24 season, with projections for 2024/25 season rising to 1512.38 mln metric t (USDA, 2024). However, several countries, including Brazil, continue to face challenges in grain storage (Drechsler, 2021). The country was unable to store 122 mln t of maize (*Zea mays* L.) harvested in the 2022/2023 season (CONAB, 2022), leading to significant price fluctuations between harvest and off-season periods. To address this instability and reduce losses caused by pests like weevils and rodents, one viable solution is to store maize grains as rehydrated silage (Guimarães et al., 2022).

In addition to preventing losses, this method has been utilised to improve starch digestibility in mature grains, particularly in vitreous endosperm varieties, known as hard or flint maize. Increased starch digestibility allows for more efficient grain utilisation by livestock and lowers storage costs compared to conventional metal silos (Silva et al., 2016; Cruz et al., 2021). Rehydration involves increasing the moisture content of grains to a range of 30–35%. While water is typically used for rehydration, byproducts with high moisture content can also be employed (Cruz et al., 2021).

Tomatoes are among the most widely cultivated vegetable crops globally, second only to potatoes. In 2021, global tomato production reached 189 mln t, with China accounting for 35% of this production (FAO, 2022). A significant portion of these tomatoes is processed into tomato paste and sauce, generating significant amounts of waste. These agricultural tomato byproducts, have a high moisture and valuable nutrient contents that increase silage quality, making them a suitable option for grain rehydration if adequate strategies are adopted (Secondi et al., 2019). Wet tomato byproduct (WTB) has an adequate nutrient composition for ruminant feeding, though some characteristics, such as high moisture content and elevated acetic acid levels in the organic acid profile can reduce fermentation efficiency (Jamehshooran et al., 2021). Lu et al. (2022) surveyed the chemical composition data of wet tomato pomace from different locations, reporting average concentrations of 31.6, 20.6, and 37.7% dry matter (DM), crude protein (CP), and total dietary fibre, respectively. These authors highlighted WTB as a nutrient-rich feed source, particularly in protein, fatty acids, and amino acids, but also noted its high moisture and fibre content. Therefore, it is important to carefully balance the WTB levels used for rehydrating the maize grain silage to mitigate potential problems caused by WTB characteristics.

On the other hand, using byproducts such as WTB is an environmentally sustainable practice that prevents improper disposal in natural environments, thereby preventing potential environmental damage (Coelho et al., 2023). From an economic perspective, these byproducts are often either donated by processing companies or acquired at low costs. Nevertheless, the application of WTB for rehydrating ground maize grain silage remains under-researched, with several areas still requiring investigation. Tuoxunjiang et al. (2020) evaluated the partial replacement of maize silage with wet tomato pomace and observed a 10% increase in DM digestibility. Despite this, crucial aspects of silage quality such as aerobic stability and indigestible fibre content, have yet to be thoroughly examined when blending WTB into the silage.

Considering the aforementioned data, we hypothesised that WTB could efficiently rehydrate ground maize silage, while improving the nutritional value and preventing aerobic deterioration. The trial was conducted to determine the most optimal substitution level for achieving these benefits. Consequently, the aim of this study was to assess the fermentation characteristics and nutritional value of ground maize silages rehydrated with increasing levels of WTB.

Material and methods

Compliance with ethical standards

The care and handling of animals in this experiment were conducted in accordance with the guidelines of the National Council for the Control of Animal Experimentation (CONCEA – Conselho Nacional de Controle de Experimentação Animal) and received approval from the Ethics Committee on Animal Use of the State University of Montes Claros (protocol CEUA # 011/2023).

Location of the experiment and climatic conditions

The study was conducted at the State University of Montes Claros in Janaúba-MG, Brazil (15° 48’09” S; 43° 18’32” W and 533 m of altitude). The location has an annual average rainfall of 800 mm, with minimum air temperatures averaging 16 °C and maximum temperatures reaching 33 °C. According to the Köppen classification, the climate in this region is classified as Aw (tropical with dry winter), with rainy summers and dry winters (Alvares et al., 2013).The municipality of Janaúba is situated in the Brazilian Semiarid region.

Acquisition and chemical composition of raw materials

Maize grains used for silage production were sourced from local stores and had been pre-ground to pass through a 2-mm sieve. WTB was obtained from a tomato processing company located in Janaúba, Minas Gerais, Brazil. Maize grain rehydration was performed by incorporating increasing levels of WTB, with the objective of recommending appropriate inclusion rates of the byproduct to balance the nutritional value and fermentation characteristics of the silage. The chemical composition of the fresh ingredients is detailed in Table 1.

Table 1. Chemical composition of wet tomato byproduct (WTB) and ground maize grain before ensiling

Variable, %	Ingredient	
	WTB	ground maize grain
pH	4.80	–
Dry matter (DM), %	15.7	87.6
Ash, % DM	4.32	1.99
Crude protein, % DM	19.9	8.38
Neutral detergent fibre, % DM	51.6	14.0
Acid detergent fibre, % DM	45.4	5.16
Lignin, % DM	6.98	1.30
Ether extract, % DM	5.85	3.00
Non-fibre carbohydrates, % DM	18.3	72.6
Total digestible nutrients, % DM	53.5	84.9

Treatments and experimental design

Treatments included five levels of WTB (25%, 30%, 35%, 40%, and 45%) replacing ground maize grains in the ensiled mass, added on a fresh mass basis. The WTB levels were limited to a maximum of 45% to avoid altering the characteristics of maize grain silage and converting it into a WTB silage. The trial was conducted in a completely randomised design, with five treatments and seven replicates.

Ensiling processes

Experimental silos made of polyvinyl chloride (PVC), measuring 0.5 m in length and 0.1 m in diameter, were utilised for the study. The ingredients were mixed thoroughly according to the specific treatments, and the mixture was placed in the silos and compacted using a wooden tamper. Silage was compacted to a density of 950 kg/m^3 (fresh matter), as described by Jobim et al. (2007). Once filled, the silos were sealed with PVC lids fitted with Bunsen valves and stored at room temperature (average 25 °C) in the forage farming laboratory. The silos were opened after 60 days of storage.

Aerobic stability

Approximately 2-kg samples were collected and stored in a temperature-controlled room (24.5–25.5 °C) to assess the aerobic stability of the silages. Silage temperature was monitored using an AK 172 mini, ASKO™ data logger, positioned in the centre of the ensiled mass. Aerobic stability was defined as the time during which the silage temperature remained stable before rising 2 °C above ambient temperature, following the methodology outlined by Moran et al. (1996).

Assessment of pH, ammonia nitrogen, and organic acids

Silage samples taken from the experimental silos were used to analyse pH, ammonia nitrogen (N-NH$_3$), and organic acids. These samples were mechanically pressed to extract the juice required for the analyses. The pH was measured using a potentiometer (Hanna™ Instruments, Barueri, SP, Brazil), while N-NH$_3$ was quantified following the method described by Noel and Hambleton (1976). Organic acids were analysed using a liquid chromatograph (Shimadzu™ Prominence System model 20A, Kyoto, Japan) equipped with a UV-V detector set to 210 nm, an automatic injector calibrated to a sample volume of 5 µl, and a Rezex™ ROA-Organic Acid + 7.8 mm column (Phenomenex), maintained at 60 °C in an oven. The analytes were diluted with 2.5 mM H_2SO_4 at a flow rate of 0.6 ml per min, and quantitative calibration was performed using external standards, as described by Pryce (1969).

Chemical composition and ruminal kinetics

After the silos were opened, silage samples were collected and dried in a forced-air air oven at 55 °C for 72 h. Subsequently, the samples were ground using a knife mill with a 1-mm mesh sieve for laboratory analysis and a 2-mm sieve for *in vitro* digestibility, indigestible neutral detergent fibre (iNDF), and *in situ* rumen degradability analyses. The chemical composition of the silages was determined at the Food Analysis and Animal Nutrition Laboratory of the Department of Agricultural Sciences at Universidade Estadual de Montes Claros.

Silages were analysed for the contents of DM (934.01), CP (954.01), ether extract (EE; 920.39), ash (942.05) and lignin (954.01), following the AOAC recommendations (Horwitz, 2005). The contents of neutral detergent fibre (NDF), acid detergent fibre (ADF), iNDF, indigestible acid detergent fibre (iADF), and non-fibre carbohydrates (NFC) were determined using methods proposed by Van Soest et al. (1991). The contents of total digestible nutrients (TDN) were calculated following the National Research Council guidelines of 2001 (NRC, 2001). The contents of *in vitro* digestible dry matter (IVDDM), neutral detergent fibre (IVDNDF), acid detergent fibre (IVDADF), and crude protein (IVDCP) were assayed following the method of Holden (1999), using a TE-150 artificial incubator (Tecnal, Brazil). The samples were transferred to non-woven textile bags (NWT,100 g/m) and incubated for 72 h at 39 °C. After 48 h of incubation, the samples were chemically digested with a solution containing HCl 50% and pepsin. Ruminant fluid was collected from a rumen-fistulated cow in the early morning.

The method described by Detmann et al. (2021) was employed to conduct the rumen kinetics assay. Two crossbreed steers with ruminal cannulas, weighing an average of 550 ± 30 kg and an average age of eight years, were selected. The animals' diet was based on maize-soybean concentrates and whole-plant maize silage, maintaining a roughage-to-concentrate ratio of 50:50. Non-woven textile bags measuring 7.5 × 15 cm, with 60-μm porosity, and containing 20 mg of DM per cm² of bag surface area, were used for the *in situ* degradability assessment. These bags were placed in the ventral sac of the rumen for 24 and 48 h, with a nylon thread attached to the cannula. The bags at time zero were not incubated in the rumen but were washed under running water along with the incubated bags. The samples in bags were then analysed at intervals of 2, 3, 6, 12, 24, 48, 72, 96, 120, 144, and 288 h after incubation, for a total of 14 times when including the time zero samples. The ruminal DM degradability represents assessments after 144 and 288 h post-incubation.

Statistical analysis

Data on the chemical composition and digestibility of the silages were subjected to the Shapiro-Wilk test for normality ($P \geq 0.05$) and analysed using analysis of variance (ANOVA) through the PROC GLM procedure of SAS® OnDemand for Academics. The means of WTB levels were compared using regression analyses decomposed into linear and quadratic effects, also using PROC GLM. The statistical model was as follows:

$$Y_{ij} = \mu + T_i + e_{ij},$$

where: Y_{ij} – dependent variable, μ – overall mean, T_i – WTB level effect, e_{ij} – residual error of each observation, assuming normal distribution of residuals.

Rumen DM degradability was analysed using a mixed linear model with PROC MIXED procedure in SAS® OnDemand for Academics, considering the incubation time as a source of variation. WTB level and incubation time were fixed effects, while variation in animal weight was a random effect. The incubation times (24 and 48 h) were repeated measurements (repeated effect). Mean rumen degradation times were compared using the probability of difference ("pdiff") adjusted by the Tukey test. The statistical model was as follows:

$$Y_{ijk} = \mu + T_i + P_j + (TP)_{ij} + B_k + e_{ijk},$$

where: Y_{ijk} – observation referring to the incubation time (P_j) of a given WTB level (T_i), considering the covariance of animal weight variation (B_k), μ – overall mean, T_i – fixed effect of WTB level (i = 1, 2, 3, 4, and 5), P_j – fixed effect of incubation time (j = 1 and 2), TP_{ij} – interaction effect between WTB level (i) and incubation time (j), B_k – random effect of animal weight variation, e_{ijk} – residual error of each observation.

Results

Chemical composition

Silages showed a linear decrease in DM content as WTB was proportionally increased in the ensiled mass (Table 2). The reduction in DM content ranged from 76.6 to 53.4% comparing the lowest and maximum WTB levels. The average ash content was 2.48%, with no significant differences observed between treatments. There was a linear increment in the silage CP content (4.13% gain) with the gradual addition of WTB from 25 to 45%. For NDF content, a linear increase was also recorded as the WTB percentage increased in the ensiled mass, ranging from 10.5% to 15.2%. A similar pattern was observed for ADF values. Haemicellulose content, however, showed no significant differences between treatments, with an average value of 5.86%. In contrast, lignin content increased linearly with the WTB addition, from 2.75% at 25% WTB to 3.89% at 45% WTB. Both total carbohydrates and NFC decreased linearly with respective reductions of 8.95 and 13.7%, when comparing the 25% and 45% WTB inclusion levels. EE contents displayed linear increase of 4.56% along with rising WTB supplementation. TDN showed a linear decrease from 85.1% to 82.7% between the minimum and maximum WTB levels. Ammonia nitrogen ($N\text{-}NH_3$) increased linearly, which corresponded to a 5.15% rise in total N (Table 2).

Digestibility and DM degradability

Adding WTB to maize silage had a significant effect on the content of IVDDM, IVDADF, and IVDCP (Table 3). A negative quadratic effect was observed for the IVDDM content, with the highest digestibility projected at a hypothetical WTB level of 31.14%, yielding 76.9%

Table 2. Chemical composition of maize grain silages rehydrated with increasing levels of wet tomato byproduct, % dry matter (DM)

Variable	WTB levels, % fresh matter					SEM	*P*-value		R²
	25	30	35	40	45		L	Q	
DM[1]	76.6	69.8	66.4	58.5	53.4	0.87	<0.01	0.74	0.99
Ash[2]	2.37	2.47	2.48	2.45	2.64	0.15	0.32	0.83	0.74
Crude protein[3]	11.3	11.9	11.7	14.1	15.5	1.03	<0.01	0.28	0.84
Neutral detergent fibre[4]	10.5	11.0	12.3	13.1	15.2	0.84	<0.01	0.41	0.95
Acid detergent fibre[5]	4.89	5.35	6.50	7.55	8.39	0.23	<0.01	0.47	0.98
Haemicellulose[6]	5.59	5.61	5.83	5.51	6.80	0.84	0.39	0.53	0.72
Lignin[7]	2.75	2.83	3.25	3.29	3.89	0.15	<0.01	0.26	0.91
NFC[9]	73.5	72.1	69.4	64.9	59.9	1.51	<0.01	0.13	0.95
Ether extract[10]	2.26	2.61	4.08	5.44	6.82	0.31	<0.01	0.10	0.97
TDN[11]	85.1	84.5	83.6	83.0	82.7	0.23	<0.01	0.34	0.96
$N\text{-}NH_3$, g/kg N[12]	1.22	3.76	4.34	7.09	6.37	0.39	<0.01	0.06	0.86

NFC – non-fibre carbohydrates, TDN – total digestible nutrients, $N\text{-}NH_3$ – ammonia nitrogen, L – linear effect, Q – quadratic effect, R² – determination coefficient, SEM – standard error of the mean; [1] – $\hat{Y} = 105.29 - 1.15X$, [2] – $\hat{Y} = 2.48$, [3] – $\hat{Y} = 5.56 + 0.20X$, [4] – $\hat{Y} = 4.33 + 0.23X$, [5] – $\hat{Y} = 0.093 + 0.18X$, [6] – $\hat{Y} = 5.86$, [7] – $\hat{Y} = 1.29 + 0.05X$, [8] – $\hat{Y} = 96.43 - 0.45X$, [9] – $\hat{Y} = 92.09 - 0.68X$; [10] – $\hat{Y} = 4.12 + 0.23X$, [11] – $\hat{Y} = 88.14 - 0.12X$, [12] – $Y = 4.96 + 0.27X$; $P < 0.05$ indicates significant difference

Table 3. Digestibility of maize grain silages rehydrated with increasing levels of wet tomato byproduct, %

Variable	WTB levels, % fresh matter					SEM	*P*-value		R²
	25	30	35	40	45		L	Q	
In vitro digestibility									
IVDDM	75.5	75.4	74.6	74.8	66.4	0.72	<0.01	<0.01	0.71
IVDNDF	72.3	73.6	75.4	75.6	72.1	1.48	0.71	0.06	0.85
IVDADF	9.87	8.51	7.34	6.41	5.27	0.42	<0.01	0.66	0.99
IVDCP	74.3	67.4	70.6	64.4	53.9	3.48	<0.01	0.21	0.79
Indigestible fibre fractions, %									
iNDF	34.9	44.1	45.4	50.4	62.8	4.3	<0.01	0.54	0.92
iADF	24.3	31.4	36.9	42.1	54.6	3.8	<0.01	0.47	0.96

IVDDM – *in vitro* digestible dry matter, $\hat{Y} = 34.29 + 2.74X - 0.044X^2$; IVDNDF – *in vitro* digestible neutral detergent fibre, $\hat{Y} = 73.80$; IVDADF – *in vitro* digestible acid detergent fibre, $\hat{Y} = 15.38 - 0.22X$; IVDCP – *in vitro* digestible crude protein, $\hat{Y} = 96.65 - 0.87X$; iNDF – indigestible neutral detergent fibre, $\hat{Y} = 0.40 + 0.12X$; iADF – indigestible acid detergent fibre, $\hat{Y} = -1.20 + 0.14X$; SEM – standard error of the mean, L – linear effect, Q – quadratic effect, R² – determination coefficient; $P < 0.05$ indicates significant difference

IVDDM. Linear decreases were observed in IVDADF and IVDCP, with reductions of 4.60%, and 20.3%, respectively, when comparing the 25% and 45% WTB levels. There was no significant effect on IVDNDF, with average value calculated at 73.8%. Linear increments were recorded for indigestible fibre fractions (iNDF and iADF) with increasing WTB levels. The iNDF proportion increased from 3.49% at 25% to 6.28% at 45% WTB, while iADF rose from 2.43% to 5.46% in response to increasing WTB proportion.

The percentages of rumen-degraded DM were higher after 48 h compared to 24 h of incubation in all silages (Table 4). A negative quadratic effect was found with increasing WTB levels, and the highest degraded fraction was observed in the silage containing 30% WTB, regardless of incubation time. No interaction effect was observed between rumen degradation times and WTB levels (Table 4).

Organic acids

Increased WTB levels altered the production of organic acids in the silages (Table 5). Positive quadratic effects were observed for the concentrations of lactic and acetic acids, as well as ethanol and the lactic-to-acetic acid ratio (L/A ratio). Lactic acid content increased from 0.88 to 7.35% with gradual WTB addition, with the lowest predicted value (only 0.39%) at a hypothetical WTB level of 30.65%. The proportion of acetic acid increased from 0.62% to 1.3%, while the L/A ratio increased from 1.44 to 5.99.

Table 4. Ruminal dry matter degradability (%) in maize grain silages rehydrated with increasing levels of wet tomato byproduct, %

Time, h	WTB levels, % fresh matter					Mean	SEM	*P*-value				R²
	25	30	35	40	45			T	T × W	L	Q	
144	68.9	69.0	65.5	65.1	55.2	64.7 ^{B}	1.18	<0.01	0.27	<0.01	<0.01	0.74
288	79.2	80.7	78.4	77.9	73.2	77.9 ^{A}				0.01	0.03	0.71
Mean	74.1	74.8	71.9	71.5	64.2							

SEM – standard error of the mean, T – degradability time effect, T × W – interaction effect between degradability time and WTB level, L – linear effect, Q – quadratic effect, R² – determination coefficient; DM degradability (144 h): $\hat{Y} = 29.48 + 2.77X - 0.048X^2$ and (288 h): $\hat{Y} = 52.94 + 1.81X - 0.030X^2$; $P < 0.05$ indicates significant difference

Table 5. Production of organic acids in maize grain silages rehydrated with increasing levels of wet tomato byproduct (WTB)

Organic acid, % DM	WTB levels, % fresh matter					CV, %	*P*-value		R²
	25	30	35	40	45		L	Q	
Lactic acid	1.01	0.88	1.49	1.60	7.35	36.3	<0.01	<0.01	0.88
Acetic acid	0.62	0.68	0.81	0.95	1.30	18.6	0.08	0.01	0.71
Butyric acid	0.09	0.11	0.10	0.06	0.06	22.9	0.03	0.01	0.47
Lactic-to-acetic acid ratio	0.14	0.16	0.19	0.17	0.60	44.1	0.01	<0.01	0.69
Ethanol	0.06	0.04	0.04	0.08	1.32	64.7	<0.01	<0.01	0.86

DM – dry matter, CV – coefficient of variation, L - linear effect, Q - quadratic effect, R² – determination coefficient; lactic acid: $\hat{Y} = 29.51 - 1.90X + 0.031X^2$, acetic acid: $\hat{Y} = 1.69 - 0.084X + 0.002X^2$, butyric acid: $\hat{Y} = -0.077 + 0.012X - 0.0002X^2$, lactic-to-acetic acid ratio: $\hat{Y} = 2.24 - 0.138X + 0.002X^2$, ethanol: $\hat{Y} = 7.10 - 0.46X + 0.007X^2$; $P < 0.05$ indicates significant difference

Ethanol concentration increased from 0.06% to 1.32%. In contrast, butyric acid content decreased quadratically from 0.92% to 0.06% as WTB level was increased from 25% to 45%. Maximum butyric acid production was observed at 30% WTB.

Aerobic stability

The aerobic stability of the silages was affected by increasing WTB levels. Silages with 30% WTB inclusion exceeded the threshold of 2 °C above room temperature after 48 h, indicating a loss of stability due to excessive heating. Conversely, silages containing 25% WTB remained stable for up to 168 h. Moreover, no aerobic deterioration was detected until 264 h in the other treatments (Figure 1).

Silage pH values varied after the opening of the silos, depending on the exposure time. Treatments with lower WTB levels (25% and 30%) displayed the highest average pH values after opening and during the aerobic stability evaluation (Figure 2).

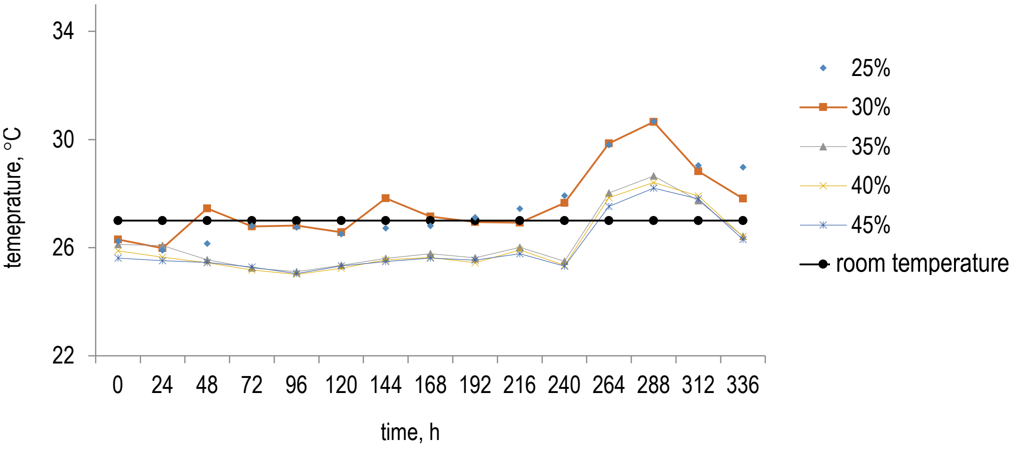

Figure 1. Temperatures (°C) in maize grain silages rehydrated with increasing levels of wet tomato byproduct (WTB) (25%, 30%, 35%, 40% and 45%) during the aerobic stability test

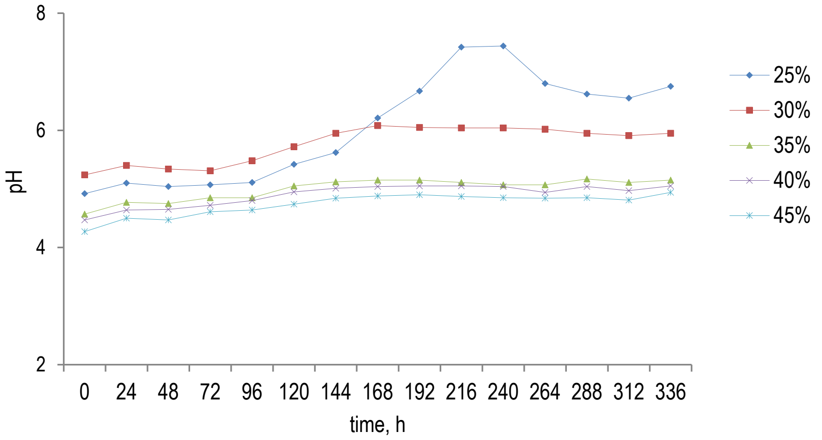

Figure 2. pH values in maize grain silages rehydrated with increasing levels of wet tomato byproduct (WTB) (25%, 30%, 35%, 40% and 45%) during the aerobic stability test

Discussion

Tomato processing waste can exhibit varying moisture levels as it is an industrial residue subjected to different processing methods, thus generating byproducts with varying nutrient composition (Silva et al., 2009). A DM contents between 65.0% and 70.0% must be achieved to rehydrate maize grain silage and minimize fermentation losses (Cruz et al., 2021), and incorporating 30–35% WTB successfully met this target. On the other hand, WTB did not change the silage ash content as horticulture byproducts generally contain low mineral matter (Moreno et al., 2021), insufficient to alter the mineral composition of the silage.

The higher CP content in WTB compared to maize led to its increased proportion in the silages. Despite this increase, the CP levels in all silages remained sufficient to meet the nutritional requirements of finishing beef cattle, whose diets typically contain between 10.0% and 14.0% of CP (Menezes et al., 2022).

WTB's NDF content exceeded 25.0% (51.6%), classifying it as a roughage source (Silva et al., 2024). Increasing dietary NDF stimulates chewing and salivation without negatively affecting dry matter intake due to ruminal distention (Pereira et al., 2023), and the inclusion of tomato byproduct contributed to this effect. Conversely, increasing lignin content with higher WTB levels in the ensiled mass negatively affected DM digestibility. Lignin is an antinutritional factor that forms a physical barrier that prevents microorganisms and enzymes from breaking down the plant cell wall, rendering it indigestible (Halpin, 2019).

The reductions in NFC and TDN could be attributed to the higher fibre content in WTB compared to maize grain. Maize is a primary energy source in animal diets, with starch being its main component. However, this reduction in TDN with the rising WTB level was partially offset by the high EE content of WTB (5.85%). Maize grain silages typically have high NFC and EE contents, resulting in elevated TDN and digestibility, since NFC and EE are significant sources of energy. The recommended upper limit for EE concentration in ruminant diets is 7%, as exceeding this limit may reduce ruminal fermentation and fibre digestibility, while increasing passage rates (Valadares Filho et al., 2018). It should be noted that the inclusion of 45% WTB led to 6.82% EE content, which suggests that intermediate WTB levels such as 30% and 35% are safer for rehydrating maize grain silage without compromising fibre digestibility.

During fermentation processes, materials undergo hydrolysis of proteins, starch and other components (Tres et al., 2020). Ammonia nitrogen ($N\text{-}NH_3$) content is indicative of fermentation quality due to proteolysis during fermentation, and poorly preserved silages tend to contain more than 10.0% total N (Anjos et al., 2022). Although there was a linear increase in ammonia N content in silages with higher WTB levels, all silages remained below 10.0%, indicating good preservation.

Reductions in digestible DM and ADF concentrations were attributed to the high lignin content in WTB, which resulted in higher indigestible fractions (iNDF and iADF). Moreover, the decline in IVDCP could be due to elevated temperatures during the pulp extraction process, causing protein denaturation, and high lignin levels. Heat treatment likely resulted in protein degradability losses due to the formation of Maillard products from reactions between reducing sugars and amino acids, as well as crosslinking between and within proteins (Iomelli et al., 2022).

The lignified fractions of WTB also reduced DM ruminal degradability. In contrast, the protein matrix surrounding starch granules was probably almost entirely degraded (Gómez et al., 2016), which explains the higher DM degradability found in silages containing higher proportion of maize grain and lower of WTB. The 45% WTB inclusion level significantly impaired ruminal degradation compared to the other WTB levels, due to the elevated undigestible fibre content observed in silages rehydrated with such a high amount of WTB (Ribeiro et al., 2020).

The consistent increments in lactic acid concentration and reductions in butyric acid contents with rising WTB levels were interesting to observe as ensiling wet roughage often reduces osmotic pressure, providing a conducive environment for the development of clostridia and enterobacteria, and reducing the activity of lactic acid bacteria; however, this trend was not observed in the present study (Muck et al., 2018). In addition to the favourable characteristics of maize grains for lactic acid fermentation, such as high DM content and adequate osmotic pressure, the tomato byproduct likely contained proper substrates for heterolactic bacteria, as evidenced by the increased lactic and acetic acid concentrations at higher WTB levels (Kung Jr. et al., 2018). In this study, the 35% and 40% WTB levels contributed to better organic acid profiles compared to other replacement proportions, demonstrating higher lactic acid production and lower generation of butyric acid and ethanol. Conversely, the 45% WTB level increased the lactic acid content, but it also raised ethanol concentrations. Silages with high ethanol concentrations could indicate the presence of yeasts responsible for initiating aerobic deterioration following the opening of the silos (Muck et al., 2020).

Aerobic deterioration begins when the silage temperature exceeds ambient temperature by 2 °C (Kung Jr. et al., 2018). Silages with WTB levels between 35% and 45% remained stable for over 240 h, likely due to their elevated lactic and acetic acid concentrations. Yeasts consuming organic acids after opening the silos can increase the silage pH, temperature, and CO_2 concentrations, creating an environment conducive to the growth of bacilli, fungi, and enterobacteria. On the other hand, acetic acid is desirable for silage preservation because of its antifungal and anti-yeast properties (Lambert and Stratford, 1999). However, excessive heterolactic fermentation can also lead to increased ethanol production in addition to acetic acid, which may further stimulate yeast proliferation once the silos are opened (Borreani et al., 2018).

Based on these premises, maize grain silages are highly susceptible to aerobic deterioration because they are rich in soluble carbohydrates and starch (Dubeux Jr. et al., 2021). In this context, the inclusion of WTB was advantageous in mitigating silage aerobic deterioration, as treatments containing 35% and 45% WTB had the lowest temperature and pH fluctuations after opening.

Conclusions

Wet tomato byproduct (WTB) is an effective additive for rehydrating maize grain silage. Appropriate levels of WTB can be incorporated to produce silages with good fermentation, nutrient preservation, and stability after opening the silos. However, using excessive proportions of WTB for rehydration can negatively impact dry matter content and increase the concentration of undigestible fibre. Incorporating 35–40% WTB into ensiled mass improves fermentation characteristics and aerobic stability without compromising digestibility.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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