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Research Article

Can Harvest Maturity And Theoretical Length Of Cut Be Optimized To Improve Fermentation Quality And Starch Utilization In Whole-Plant Corn Silage?

J. M. Silveira[a], K. S. Oliveira[a], A. B. Silva Neto[a], G. G. S. Salvati[a], W. P. Santos[a], V. C. Gritti[a], B. A. V. Arthur[a], L. M. Nazato[a], P. A. R. Salvo[a], G. Morais[a], A. P. Barros Neto, A. A. G. Lobo[a],*, L. G. Nussio.

Affiliations

[a] Department of Animal Science, Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil.

Abstract

Whole-plant corn silage is a central component of ruminant feeding systems due to its high energy density and consistent fermentation profile. However, silage nutritive value is strongly influenced by harvest management, particularly forage maturity, hybrid characteristics, and mechanical processing during ensiling. As corn plants advance in physiological maturity, grain filling increases dry matter and starch concentrations, while changes in kernel vitreousness and fiber composition may reduce ruminal nutrient availability. This study evaluated the combined effects of corn hybrid, forage maturity at harvest, and theoretical length of cut (TLC) on fermentation characteristics, aerobic stability, physical traits, kernel processing efficiency, and in situ ruminal degradability of whole-plant corn silage. Three corn hybrids (LG 6030, LG 6036, and AG 1051) were harvested at two maturity stages (300 and 370 g/kg dry matter) and processed at three TLCs (3, 5, and 7 mm) using a forage harvester without a kernel processor. Silages were stored for 90 days in experimental silos. Chemical composition, fermentation products, microbial populations, dry matter losses, aerobic stability, particle size distribution, kernel processing score, and in situ degradability of dry matter, neutral detergent fiber, and starch were determined. Significant interactions among hybrid, maturity, and TLC were observed for most variables. Advancing maturity increased starch concentration but reduced kernel processing efficiency and nutrient degradability, particularly at higher dry matter contents. Reducing TLC improved physical processing and starch availability at lower dry matter concentrations but was ineffective at advanced maturity stages. These results demonstrate that forage maturity and processing strategies must be aligned with hybrid characteristics to optimize silage quality, ruminal nutrient utilization, and feeding value in ruminant production systems.

Keywords: corn silage; feed quality; forage maturity; length of cut; ruminal degradability; ruminant nutrition;

INTRODUCTION

Whole-plant corn silage is the predominant forage source used in intensive dairy and beef cattle production systems in Brazil and worldwide due to its high energy concentration, moderate crude protein content, and favorable ensiling characteristics [1,2]. Approximately half of the metabolizable energy supplied by corn silage originates from starch accumulated in the grain fraction, making starch availability a key determinant of animal performance [3,4]. Consequently, factors that affect starch digestibility and fiber utilization directly influence ruminal fermentation patterns, feed efficiency, and the risk of metabolic disorders in ruminants.

The nutritional value of corn silage is not only a function of genetic potential but is strongly modulated by harvest management practices, including hybrid selection, forage maturity at harvest, and mechanical processing during ensiling [1,5]. As corn plants advance in physiological maturity, grain filling leads to increased dry matter accumulation and starch concentration, while the proportion of neutral detergent fiber (NDF) typically declines [6,7]. However, maturation is also associated with increased kernel vitreousness, characterized by a higher proportion of hard, protein-encapsulated endosperm, which acts as a physical and biochemical barrier to microbial and enzymatic starch degradation in the rumen [8–10].

Harvesting corn silage at inadequate maturity stages can compromise both fermentation quality and nutrient availability. Early harvest at excessive moisture levels (<300 g/kg dry matter) increases the risk of effluent losses, elevated

***Corresponding Author:** **Annelise Aila Gomes Lobo,** Department of Animal Science, Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil. **Email:** anneliselobo@usp.br.
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yeast activity, and aerobic instability, resulting in greater dry matter losses during storage and feed-out [11–13]. Conversely, delayed harvest (>370–400 g/kg dry matter) may impair compaction, reduce anaerobic conditions within the silo, and limit kernel fragmentation, particularly when forage harvesters lack kernel processors [6,14]. These conditions often result in reduced ruminal starch degradability and inefficient nutrient utilization by the animal [15].

Theoretical length of cut (TLC) is a critical operational parameter during forage harvesting that influences particle size distribution, silage density, oxygen exclusion, and kernel breakage [16,17]. Reducing TLC generally enhances kernel fragmentation and increases starch accessibility to ruminal microorganisms; however, excessively short particle lengths may reduce physically effective fiber, negatively affecting rumination, ruminal pH, and milk fat synthesis [18]. Therefore, TLC must be carefully adjusted to balance starch availability and rumen function.

The response to TLC adjustments is not uniform across all corn silages and is influenced by forage maturity and hybrid characteristics, particularly kernel texture and vitreousness [9,10,19]. Hybrids with harder endosperm typically exhibit lower ruminal starch degradability, especially at advanced maturity stages, and may respond differently to mechanical processing strategies compared with softer-textured hybrids [20,21]. Despite extensive research on corn silage management, limited information is available regarding the interactive effects of hybrid type, maturity stage, and TLC under practical harvesting conditions commonly adopted in tropical and subtropical production systems, where forage harvesters without kernel processors are prevalent [2].

From a veterinary and animal nutrition perspective, understanding how these factors affect fermentation dynamics, aerobic stability, and ruminal nutrient availability is essential to improve feed efficiency, reduce nutritional losses, and mitigate the risk of metabolic disorders in ruminant production systems. Therefore, the objective of this study was to evaluate the combined effects of corn hybrid, forage maturity at harvest, and theoretical length of cut on fermentation characteristics, aerobic stability, physical properties, kernel processing efficiency, and in situ ruminal degradability of whole-plant corn silage.

MATERIAL AND METHODS

Experimental Site and Corn Hybrids

The experiment was conducted at the experimental facilities of the Department of Animal Science, Escola Superior de Agricultura “Luiz de Queiroz” (ESALQ), University of São Paulo, Piracicaba, SP, Brazil. The climate of the region is classified as humid subtropical, with average annual temperature of approximately 21 °C and average annual precipitation of 1,200 mm.

Three commercial corn (Zea mays L.) hybrids commonly used for silage production in Brazil were evaluated: LG 6030, LG 6036, and AG 1051. These hybrids differ in kernel texture characteristics as described by the seed companies, with AG 1051 characterized as having softer endosperm and LG 6036 as having harder endosperm, whereas LG 6030 presents intermediate characteristics. These differences were considered relevant due to their potential impact on kernel vitreousness and ruminal starch degradability.

Experimental Design and Treatments

The experiment was arranged in a completely randomized design using a 3 × 2 × 3 factorial scheme, consisting of:

- three corn hybrids (LG 6030, LG 6036, AG 1051);
- two forage maturity stages at harvest (300 and 370 g/kg dry matter);
- three theoretical lengths of cut (TLC): 3, 5, and 7 mm.

Each treatment combination was replicated four times, resulting in a total of 72 experimental silos.

The maturity stages were selected to represent a conventional harvest window for whole-plant corn silage (approximately 300 g/kg dry matter) and a more advanced harvest stage (370 g/kg dry matter), frequently adopted in practice due to logistical constraints or attempts to increase starch yield per hectare.

Harvesting and Silage Preparation

Corn plants were harvested using a tractor-mounted forage harvester (JF AT 1600, JF Máquinas Agrícolas, Brazil) without a kernel processor, which reflects the predominant harvesting system used on Brazilian dairy farms. The harvester was adjusted to achieve the target theoretical lengths of cut (3, 5, or 7 mm) according to manufacturer specifications.

Immediately after chopping, the forage was thoroughly homogenized and packed into experimental plastic silos with a capacity of 20 L. The silos were manually compacted to achieve uniform packing density, sealed with plastic lids, and stored at ambient temperature for 90 days to allow complete fermentation.

The weight of each silo was recorded at filling and at opening to determine total dry matter losses during storage.

Sampling Procedures

Samples of fresh forage were collected at harvest for determination of dry matter content and initial chemical composition. Upon silo opening, silage samples were collected and subdivided for chemical, fermentative, microbiological, physical, and degradability analyses.

Subsamples destined for chemical analyses were dried in a forced-air oven at 55 °C for 72 h and ground through a 1-mm screen using a Wiley mill. Samples for fermentation profile and microbiological analyses were stored at −20 °C until analysis.

Chemical Analyses

Dry matter concentration was determined by oven drying at 105 °C for 24 h. Crude protein was determined using the Kjeldahl method. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed according to Van Soest et al., using heat-stable α-amylase and sodium sulfite for NDF determination. Starch concentration was determined enzymatically after appropriate sample preparation.

All chemical analyses were conducted in duplicate, and results were expressed on a dry matter basis.

Fermentation Profile and Microbiological Analyses

Silage extracts were prepared by blending 25 g of fresh silage with 225 mL of distilled water and filtering through cheesecloth. The pH of the extract was measured using a digital pH meter.

Lactic acid concentration was determined using high-performance liquid chromatography. Microbial populations, including lactic acid bacteria, yeasts, and molds, were quantified by plating serial dilutions of silage extracts on selective culture media. Microbial counts were expressed as log10 colony-forming units per gram of fresh matter.

Dry Matter Losses

Total dry matter losses during storage were calculated based on the difference between the dry matter content at silo filling and at silo opening, corrected for silage weight. Dry matter losses were expressed as a percentage of the initial dry matter content.

Aerobic Stability

Aerobic stability was evaluated by exposing silage samples (approximately 3 kg) to air at room temperature (approximately 25 °C). Silage temperature was monitored at regular intervals using digital temperature sensors inserted into the center of the silage mass.

Aerobic stability was defined as the time required for silage temperature to rise 2 °C above ambient temperature. This method is widely used to assess the resistance of silage to aerobic deterioration during feed-out.

Physical Characteristics and Particle Size Distribution

Particle size distribution was determined using the Penn State Particle Separator, consisting of sieves with apertures of 19 mm, 8 mm, 1.18 mm, and a bottom pan. Approximately 500 g of silage were placed in the separator and shaken according to standardized procedures.

The proportion of material retained on each sieve was recorded and expressed as a percentage of the total sample. Mean particle length was calculated based on sieve distribution.

Kernel Processing Score

Kernel processing score (KPS) was determined as the proportion of starch passing through a 4.75-mm sieve, following standardized laboratory procedures. This parameter was used to evaluate the effectiveness of kernel fragmentation achieved under different maturity stages and theoretical lengths of cut.

In Situ Ruminal Degradability

In situ ruminal degradability of dry matter, NDF, and starch was evaluated using the nylon bag technique. Ground silage samples were weighed into nylon bags with a pore size of approximately 50 µm and incubated in the rumen of cannulated cattle for predetermined incubation times.

After incubation, bags were removed, washed with cold water until clear, dried, and weighed to determine nutrient disappearance. Degradability values were expressed as the percentage of nutrient disappearance relative to the initial amount.

Statistical Analysis

Data were analyzed using mixed-model procedures. The fixed effects included hybrid, maturity stage, theoretical length of cut, and their interactions. Replicate was considered a random effect. When significant effects were detected, means were compared using appropriate post hoc tests.

Statistical significance was declared at ≤ 0.05, and trends were discussed when P values ranged between 0.05 and 0.10.

RESULTS

Chemical Composition of Corn Silages

The chemical composition of whole-plant corn silages as affected by hybrid, forage maturity stage, and theoretical length of cut is presented in **Table 1**. Significant interactions among hybrid, maturity, and TLC were observed for dry matter concentration, starch content, and fiber fractions (P ≤ 0.05).

Advancing forage maturity from 300 to 370 g/kg dry matter resulted in a consistent increase in silage dry matter and starch concentrations across all hybrids. This increase was accompanied by a reduction in neutral detergent fiber (NDF) and acid detergent fiber (ADF) concentrations, reflecting the greater contribution of the grain fraction to total plant dry matter at more advanced maturity stages.

Differences among hybrids were evident, particularly for starch concentration. Hybrid AG 1051 exhibited higher starch content compared with LG 6030 and LG 6036 at both maturity stages, whereas LG 6036 generally showed higher fiber concentrations, especially at 300 g/kg dry matter. Theoretical length of cut had no consistent effect on chemical composition, although minor variations were observed due to interactions with hybrid and maturity stage.

Table 1. Chemical composition of corn plants in corn silage (g/kg of Dry Matter)

Variables	Treatments																	
	AG1051						LG6030						LG6036					
	300 g/kg DM			370 g/kg DM			300 g/kg DM			370 g/kg DM			300 g/kg DM			370 g/kg DM		
	3 mm	5 mm	7 mm	3 mm	5 mm	7 mm	3 mm	5 mm	7 mm	3 mm	5 mm	7 mm	3 mm	5 mm	7 mm	3 mm	5 mm	7 mm
DM, g/kg	305	299	295	375	377	371	308	320	317	381	392	395	297	315	303	370	369	368
CP, g/kg DM	90	101	95	93	90	87	76	76	72	84	90	80	89	86	98	87	86	84
aNDFom, g/kg DM	475	496	511	400	437	488	481	469	470	464	426	424	467	464	508	426	452	443
ADFom, g/kg DM	272	273	301	220	256	290	260	252	245	257	232	239	271	270	310	249	269	267
EE, g/kg DM	22	20	17	30	26	24	27	27	28	25	25	30	21	21	17	25	17	24
Ash, g/kg DM	34	37	36	29	32	32	31	32	30	28	30	30	36	39	40	34	29	32
SC, g/kg DM	88	85	84	73	70	71	87	85	87	75	72	71	93	87	107	74	71	78
NFC, g/kg DM	398	366	359	471	432	386	441	452	468	414	489	483	403	406	357	442	432	434
Starch, g/kg DM	251	225	209	355	311	298	298	316	314	302	356	315	254	256	265	303	278	288
LAB, log cfu/g	8.8	8.8	8.8	9.0	9.0	9.0	9.1	9.1	9.1	8.6	8.6	8.6	9.0	9.0	9.0	9.1	9.1	9.1
Yeast log cfu/g	7.6	7.6	7.6	8.0	8.0	8.0	7.3	7.3	7.3	7.8	7.8	7.8	7.3	7.3	7.3	7.1	7.1	7.1

DM – dry matter; FM – fresh matter; CP – crude protein; aNDFom – ash- and starch-corrected neutral detergent insoluble fiber; ADFom – ash-corrected acid detergent insoluble fiber; EE – ether extract; SC – soluble carbohydrates; NFC – non-fiber carbohydrates; LAB – lactic acid bacteria.

Hybrid: AG1051, LG6030 and LG6036; Maturity: 300 and 370 g/kg DM; Theoretical length of cut: 3 mm, 5 mm and 7 mm.

Fermentation Profile and Microbial Populations

Fermentation characteristics and microbial populations are summarized in Table 1. Silage pH values were within the expected range for well-preserved corn silage, although differences were observed among maturity stages. Silages harvested at 300 g/kg dry matter exhibited lower pH values compared with those harvested at 370 g/kg dry matter, indicating more extensive fermentation.

Lactic acid concentration was higher in silages harvested at 300 g/kg dry matter, consistent with greater availability of fermentable substrates at lower dry matter concentrations. Yeast counts were also higher in these silages, particularly for LG 6030 and LG 6036, suggesting increased susceptibility to aerobic deterioration.

At 370 g/kg dry matter, silage exhibited lower yeast populations and reduced lactic acid concentration, reflecting a more restricted fermentation process. Hybrid effects were evident, with AG 1051 generally exhibiting lower yeast counts and more stable fermentation profiles compared with the other hybrids.

Dry Matter Losses During Storage

Total dry matter losses during storage are presented in **Table 2**. Dry matter losses were significantly affected by forage maturity stage ($P \leq 0.05$), with greater losses observed in silages harvested at 300 g/kg dry matter compared with those harvested at 370 g/kg dry matter.

Higher dry matter losses at lower maturity were associated with increased microbial activity and greater production of fermentation end-products. Differences among hybrids were also observed, particularly at 300 g/kg dry matter, where LG 6030 exhibited greater losses compared with AG 1051.

Theoretical length of cut did not exert a main effect on dry matter losses; however, interactions between TLC and maturity stage were observed. At 300 g/kg dry matter, shorter TLCs tended to increase dry matter losses slightly, whereas no consistent pattern was observed at 370 g/kg dry matter.

Table 2. P-values of interactions between hybrid (H), maturity (M) and theoretical length of cut (TLC) on chemical composition, microbial profile, fermentative profile, aerobic stability, physical score and in situ disappearance of whole plant corn silages.

Variables	H x M	H x TLC	M x TLC	H x M x TLC
Chemical composition				
DM, g/kg	0.02	0.14	0.98	0.52
Ash, g/kg DM	<0.01	0.46	0.70	<0.01
EE g/kg DM	<0.01	0.60	0.48	0.12
CP g/kg DM	<0.01	0.02	0.03	0.08
aNDFom g/kg DM	<0.01	0.22	0.55	0.11
ADFom g/kg DM	<0.01	0.79	0.89	0.26
NFC g/kg DM	<0.01	0.21	0.71	0.17
Starch g/kg DM	<0.01	0.19	0.01	0.01
SC g/kg DM	0.24	0.76	0.19	0.81
DM loss g/kg	0.01	0.01	0.01	0.01
Microbial profile				
LAB log ufc/g	0.01	0.02	0.05	0.09
Yeast log ufc/g	<0.01	<0.01	0.72	<0.01
Fungi log ufc/g	<0.01	<0.01	<0.01	<0.01
Fermentative profile				
Lactic acid	0.01	0.41	0.11	0.34
NH3-N g/kg	0.02	<0.01	0.08	0.01
pH	0.01	0.26	0.53	0.24
Aerobic stability				
Aerobic stability, h	<0.01	<0.01	<0.01	<0.01
Tmax, °C	<0.01	0.06	0.21	0.28
TTmax, °C	<0.01	0.25	0.02	0.04
Physical score				
> 19 mm	0.01	0.19	0.62	0.23
8 - 19 mm	0.01	0.06	0.07	<0.01
1.18 - 8 mm	0.03	0.66	<0.01	0.06
< 1.18 mm	0.02	0.43	0.14	<0.01
MPL, mm	0.01	0.46	0.16	0.67
GMPS, µm	0.16	<0.01	<0.01	0.02
CSPS, g/kg DM	0.01	0.82	0.21	0.01
Grains < 4.75 mm, g/kg DM	0.01	<0.01	<0.01	0.01
Density, Kg OM m^{-3}	<0.01	0.91	0.35	0.03
In situ disappearance				
DM 12 h, %	0.73	0.01	0.05	0.01
DM 30 h, %	0.01	0.01	0.02	0.01
aNDFom, %	<0.01	0.49	0.04	0.01
Starch, %	0.71	0.05	0.02	0.66
Degradable starch, %	<0.01	0.01	<0.01	0.01

DM – dry matter; EE – ether extract; CP – crude protein; aNDFom – ash- and starch-corrected neutral detergent insoluble fiber; ADFom – ash-corrected acid detergent insoluble fiber; NFC – non-fiber carbohydrates; SC – soluble carbohydrates; LAB – lactic acid bacteria; NH3-N – ammonia nitrogen; Tmax – maximum temperature; TTmax – time to achieve maximum temperature; MPL – mean particle length; GMPS – geometric mean particle size; CSPS – corn silage processing score.

Aerobic Stability

Aerobic stability results are shown in Table 2. Silages harvested at 370 g/kg dry matter exhibited greater aerobic stability compared with those harvested at 300 g/kg dry matter ($p \leq 0.05$). Lower yeast populations and reduced concentrations of fermentable substrates likely contributed to improved stability at higher dry matter levels.

Hybrid AG 1051 consistently showed greater aerobic stability across maturity stages, whereas LG 6030 and LG 6036 were

more susceptible to heating during air exposure. Theoretical length of cut did not significantly affect aerobic stability as a main factor; however, interactions with hybrid and maturity were detected.

Particle Size Distribution

Particle size distribution data are presented in **Table 3**. Reducing theoretical length of cut resulted in a marked decrease in the proportion of particles retained on the 19-mm sieve and an increase in the proportion of particles retained on the 1.18–8 mm sieves ($P \leq 0.05$).

Table 3. Effect of hybrid on the chemical composition, microbial profile, aerobic stability, physical characteristics, and in situ degradability of whole-plant corn silage.

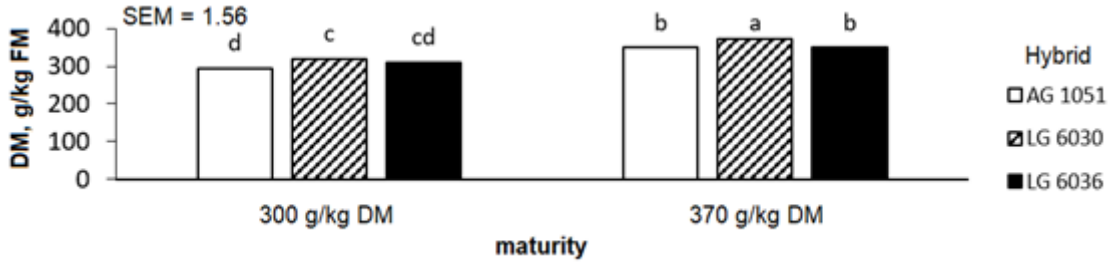
Variables	AG 1051	LG 6030	LG 6036	SE	P-value
Chemical composition					
DM, g/kg	318^{b}	336^{a}	318^{b}	3.94	0.01
Ash, g/kg DM	36^{c}	40^{b}	46^{a}	0.58	<0.01
EE g/kg DM	29	29	28	0.73	0.58
CP g/kg DM	76^{a}	59^{c}	68^{b}	0.61	<0.01
aNDFom g/kg DM	452^{b}	459^{b}	513^{a}	10.8	<0.01
ADFom g/kg DM	255^{b}	245^{c}	285^{a}	6.89	<0.01
NFC g/kg DM	407^{a}	410^{a}	343^{b}	7.81	<0.01
Starch g/kg DM	245^{b}	293^{a}	213^{c}	6.14	<0.01
SC g/kg DM	193^{a}	182^{a}	138^{b}	6.20	<0.01
DM loss g/kg	40^{a}	32^{b}	33^{b}	1.10	<0.01
Microbial profile					
LAB log ufc/g	6	5.9	6.2	0.15	0.14
Yeast log ufc/g	4.5	4.3	4.4	0.10	0.20
Fungi log ufc/g	3.4^{b}	4.5^{a}	4.6^{a}	0.11	<0.01
Fermentative profile					
Lactic acid	4.4^{a}	3.2^{c}	3.9^{b}	0.11	<0.01
NH3-N g/kg	25^{a}	17^{c}	20^{b}	0.49	<0.01
pH	4.2	4.1	4.1	0.04	0.68
Aerobic stability					
Aerobic stability, h	39.2^{b}	57.6^{a}	38.7^{b}	1.86	<0.01
Tmax, ºC	44.8^{a}	40.6^{b}	42.2^{b}	0.48	<0.01
TTmax, ºC	149.1^{a}	110.2^{b}	98.6^{b}	6.21	<0.01
Physical score					
> 19 mm	192^{a}	130^{b}	177^{a}	5.10	<0.01
8 - 19 mm	700^{b}	750^{a}	696^{b}	4.61	<0.01
1.18 - 8 mm	94^{b}	104^{ab}	110^{a}	3.14	0.01
< 1.18 mm	12^{b}	15^{a}	14^{a}	0.73	0.06
MPL, mm	13.3^{a}	12.4^{c}	12.9^{b}	0.08	<0.01
GMPS, µm	3674^{c}	4556^{a}	3972^{b}	57.14	<0.01
CSPS, g/kg DM	602^{a}	482^{b}	664^{a}	19.70	<0.01
Grains < 4.75 mm, g/kg DM	481^{a}	337^{c}	446^{b}	7.92	<0.01
Density, Kg OM m^{-3}	644.5^{a}	609.3^{c}	620.8^{b}	4.69	<0.01
In situ disappearance					
DM 12 h, %	50.9^{a}	44.9^{b}	50.0^{a}	0.69	<0.01
DM 30 h, %	59.9^{a}	54.9^{b}	58.6^{a}	0.63	<0.01
aNDFom, %	46.8^{b}	44.3^{b}	50.7^{a}	1.10	0.01
Starch, %	78.8^{a}	60.1^{c}	68.0^{b}	1.26	<0.01
Degradable starch, %	18.4^{a}	17.4^{a}	14.4^{b}	0.41	<0.01

SE – Standard error; DM – dry matter; EE – ether extract; CP – crude protein; aNDFom – ash- and starch-corrected neutral detergent insoluble fiber; ADFom – ash-corrected acid detergent insoluble fiber; NFC – non-fiber carbohydrates; SC – soluble carbohydrates; LAB – lactic acid bacteria; NH3-N – ammonia nitrogen; Tmax – maximum temperature; TTmax – time to achieve maximum temperature; MPL – mean particle

length; GMPS – geometric mean particle size; CSPS – corn silage processing score.
a-c Means with different letters in the same row varied for P<0.05 (Tukey).

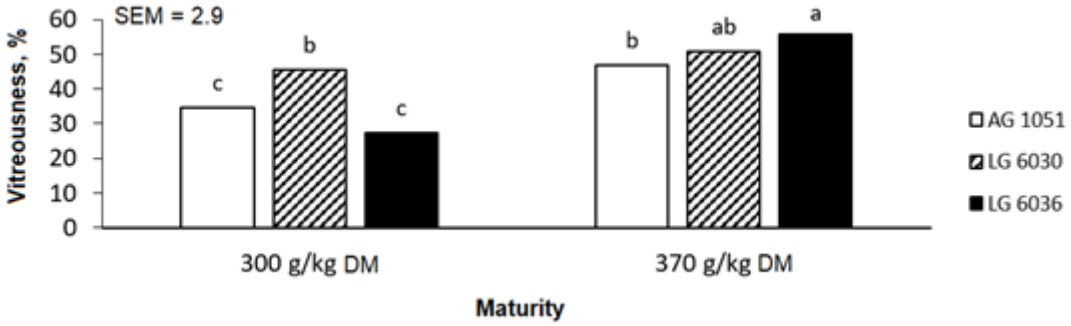
At 300 g/kg dry matter, silages processed at a TLC of 3 mm exhibited the lowest proportion of large particles and the smallest mean particle length, indicating more intensive physical processing. At 370 g/kg dry matter, the effect of TLC on particle size distribution was less pronounced, reflecting increased plant rigidity and reduced susceptibility to cutting at advanced maturity stages, illustrated in **Figure 1**.
Hybrid effects were evident, particularly for LG 6036, which exhibited a greater proportion of large particles at longer TLCs, especially at 370 g/kg dry matter.

Figure 1. Interaction between maturity and hybrid for dry matter content (P=0.02) of AG 1051, LG 6030, LG 6036 silages (Hybrids); 300 and 400 g/kg (DM content); SEM: standard error of the mean. Means followed by the same letter do not differ according to Tukey's test at 5%.



Kernel Processing Score
Kernel processing score (KPS) results are presented in Table 3, above. KPS was significantly influenced by hybrid and forage maturity stage (P ≤ 0.05), with higher scores observed at 300 g/kg dry matter compared with 370 g/kg dry matter.
Reducing TLC from 7 to 3 mm increased KPS at 300 g/kg dry matter for all hybrids, indicating improved kernel fragmentation under these conditions. However, at 370 g/kg dry matter, reducing TLC did not significantly improve KPS, demonstrating the limited effectiveness of cutting length reduction to compensate for increased kernel hardness at advanced maturity.
Among hybrids, AG 1051 consistently exhibited higher KPS values compared with LG 6030 and LG 6036, particularly at advanced maturity, reflecting differences in kernel texture, as presented in **Figure 2**.

Figure 2. Interaction between maturity and hybrid for NFC content (P<0.01) of AG 1051, LG 6030, LG 6036 silages (Hybrids); 300 and 400 g/kg (DM content); SEM: standard error of the mean. Means followed by the same letter do not differ according to Tukey's test at 5%.



In Situ Ruminal Degradability
In situ ruminal degradability of dry matter, NDF, and starch is presented in **Table 4**. Degradability values were significantly affected by hybrid and forage maturity stage (P ≤ 0.05).

Table 4. Effect of maturity on chemical composition, microbial and fermentation profile, aerobic stability, physical characteristics, and in situ degradability of whole-plant corn silage.

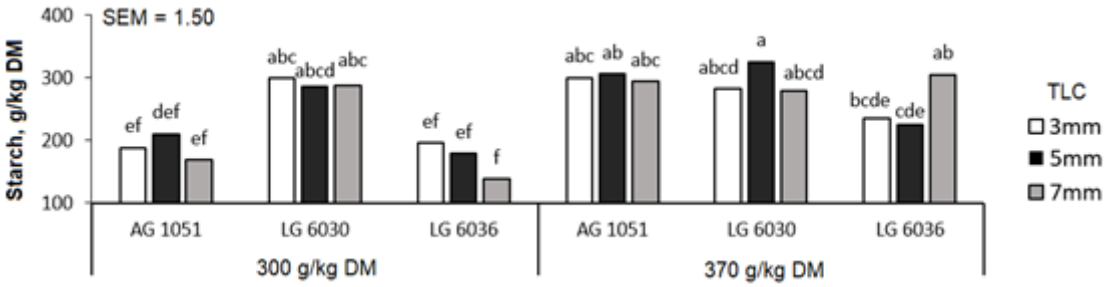
Variables	300 g/kg DM	370 g/kg DM	SE	P-value
Chemical composition				
DM, g/kg	303	367	3.21	<0.01
Ash, g/kg DM	41	41	0.67	0.98
EE g/kg DM	26	31	0.59	<0.01
CP g/kg DM	64	72	0.50	<0.01
aNDFom g/kg DM	489	459	8.83	0.01
ADFom g/kg DM	272	245	5.63	<0.01
NFC g/kg DM	378	395	6.37	0.05
Starch g/kg DM	217	283	5.01	<0.01
SC g/kg DM	169	172	5.06	0.72
DM loss g/kg	44	26	0.90	<0.01
Microbial profile				
LAB log ufc/g	5.7	6.3	0.11	0.01
Yeast log ufc/g	4.7	4.0	0.08	<0.01
Fungi log ufc/g	4.3	4.1	0.09	0.12
Fermentative profile				
Lactic acid	3.7	3.9	0.09	0.09
NH3-N g/kg	14	27	0.40	<0.01
pH	4.1	4.1	0.03	0.58
Aerobic stability				
Aerobic stability, h	39.9	50.4	1.49	<0.01
Tmax, °C	41.8	43.3	0.39	0.01
TTmax, °C	126.1	112.5	4.99	0.07
Physical score				
> 19 mm	147	186	4.16	<0.01
8 - 19 mm	735	695	3.77	<0.01
1.18 - 8 mm	105	101	2.56	0.28
< 1.18 mm	11	17	0.60	<0.01
MPL, mm	12.7	13.0	0.07	0.01
GMPS, µm	3605	4530	46.6	<0.01
CSPS, g/kg DM	663	503	16.0	<0.01
Grains < 4.75 mm, g/kg DM	485	358	6.46	<0.01
Density, Kg OM m-3	632.3	614.3	3.83	0.01
In situ disappearance				
DM 12 h, %	49.9	47.3	0.56	0.01
DM 30 h, %	59.2	56.4	0.51	0.01
aNDFom, %	49.2	45.4	0.91	0.01
Starch, %	74.8	63.0	1.03	<0.01
Degradable starch, %	15.9	17.6	0.33	0.01

SE – Standard error; DM – dry matter; EE – ether extract; CP – crude protein; aNDFom – ash- and starch-corrected neutral detergent insoluble fiber; ADFom – ash-corrected acid detergent insoluble fiber; NFC – non-fiber carbohydrates; SC – soluble carbohydrates; LAB – lactic acid bacteria; NH3-N – ammonia nitrogen; Tmax – maximum temperature; TTmax – time to achieve maximum temperature; MPL – mean particle length; GMPS – geometric mean particle size; CSPS – corn silage processing score.

Dry matter degradability was greater for hybrids AG 1051 and LG 6036 compared with LG 6030. Neutral detergent fiber degradability was highest for LG 6036, whereas starch degradability was highest for AG 1051, particularly at 300 g/kg dry matter.

Across all hybrids, silages harvested at 300 g/kg dry matter exhibited greater degradability of dry matter, NDF, and starch (**Figure 3**) compared with silages harvested at 370 g/kg dry matter. Reducing TLC improved degradability at lower maturity but had no consistent effect at advanced maturity.

Figure 3. Interaction between maturity and hybrid for starch content of silages (P<0.01) of AG 1051, LG 6030, LG 6036 silages (Hybrids); 300 and 400 g/kg (DM content); SEM: standard error of the mean. Means followed by the same letter do not differ according to Tukey's test at 5%.



DISCUSSION

The results of the present study demonstrate that forage maturity at harvest, theoretical length of cut, and corn hybrid characteristics interact to determine the fermentation quality, physical properties, aerobic stability, and ruminal nutrient degradability of whole-plant corn silage. These interactions highlight the importance of integrated silage management strategies to optimize feed quality and nutrient utilization in ruminant production systems.

Effects of Forage Maturity on Chemical Composition and Fermentation

The increase in dry matter and starch concentrations observed with advancing forage maturity is consistent with the physiological process of grain filling, during which soluble carbohydrates are progressively converted into starch within the kernel endosperm [1,4,6]. The concomitant reduction in NDF and ADF concentrations reflects the dilution effect of grain accumulation on the fibrous fraction of the plant, as widely reported in the literature [6,7].

Despite the apparent nutritional advantage of increased starch concentration, advanced maturity negatively affected several fermentation and utilization parameters. Silages harvested at 370 g/kg dry matter exhibited reduced lactic acid concentrations and higher pH values compared with those harvested at 300 g/kg dry matter, indicating a more restricted fermentation process. Similar responses have been reported by Allen et al. [1] and Ferraretto and Shaver [9], who attributed these effects to reduced water activity and limited microbial growth at higher dry matter concentrations.

Moreover, lower yeast populations and improved aerobic stability at advanced maturity suggest that restricted fermentation may reduce the availability of substrates for spoilage microorganisms during feed-out [13,14]. However, this apparent benefit must be weighed against the observed reductions in kernel processing efficiency and ruminal nutrient degradability, particularly starch, which are critical for animal performance.

Dry Matter Losses and Aerobic Stability

Greater dry matter losses observed in silages harvested at 300 g/kg dry matter are consistent with increased microbial activity and greater production of fermentation end-products under wetter conditions [11,12]. Although enhanced fermentation at lower dry matter levels promotes rapid pH decline, it may also increase nutrient losses through gaseous and effluent pathways, particularly when compaction is not optimal.

Aerobic stability was markedly improved at higher dry matter levels, likely due to lower yeast counts and reduced availability of fermentable substrates [13]. However, improved aerobic stability does not necessarily translate into superior nutritional value if ruminal nutrient availability is compromised. From a veterinary nutrition perspective, these findings reinforce the need to balance fermentation quality, feed-out stability, and nutrient utilization when selecting harvest maturity.

Influence of Theoretical Length of Cut on Physical Characteristics and Kernel Processing

Reducing theoretical length of cut significantly altered particle size distribution, decreasing the proportion of long particles and increasing the proportion of medium-sized particles. This effect is consistent with previous studies demonstrating that shorter TLC improves physical processing of the forage mass and enhances compaction potential [16,17].

At 300 g/kg dry matter, reducing TLC effectively increased kernel processing score, indicating greater kernel fragmentation and improved access of ruminal microorganisms to starch. These findings align with those of Shinners et al. [10] and Dias Junior et al. [11], who reported enhanced starch digestibility when physical processing effectively disrupted the kernel structure. In contrast, at 370 g/kg dry matter, reducing TLC failed to improve kernel processing score, demonstrating that cutting length reduction alone cannot compensate for increased kernel hardness and vitreousness at advanced maturity stages. This limitation has important practical implications, particularly in production systems relying on forage harvesters without kernel processors, as is common in tropical regions [2].

Hybrid Effects and Kernel Texture

Differences among hybrids observed in starch concentration, kernel processing score, and ruminal degradability underscore the importance of genetic traits, particularly kernel texture and vitreousness, in determining silage feeding value. Hybrid AG 1051 consistently exhibited higher starch degradability and kernel processing scores, reflecting its softer endosperm characteristics.

Hybrids with harder endosperm, such as LG 6036, showed greater resistance to kernel fragmentation and reduced starch degradability at advanced maturity stages, consistent with previous reports linking increased vitreousness to reduced ruminal starch degradation [5,7,20]. These findings support the hypothesis that hybrid selection should be integrated with harvest maturity and processing strategies to optimize silage utilization.

Implications for Ruminal Nutrient Degradability

The reductions in dry matter, NDF, and starch degradability observed at advanced maturity stages highlight the trade-off between increased starch concentration and reduced nutrient accessibility. Although total starch content increased with maturity, its availability to ruminal microorganisms declined, likely due to increased protein encapsulation of starch granules within the vitreous endosperm matrix [8,9].

From a ruminal health perspective, reduced starch degradability may limit microbial growth and energy supply, potentially affecting animal performance. Conversely, excessive starch availability resulting from aggressive processing at lower maturity stages may increase the risk of ruminal acidosis if not properly balanced with physically effective fiber [18]. Therefore, optimal silage management requires careful alignment of maturity stage, processing intensity, and diet formulation.

Practical and Veterinary Implications

The findings of this study have direct implications for veterinary nutrition and herd management. Selecting appropriate harvest maturity and processing strategies can improve nutrient utilization, reduce feed losses, and mitigate the risk of metabolic disorders associated with inefficient ruminal fermentation.

Specifically, harvesting corn at approximately 300 g/kg dry matter and reducing theoretical length of cut can enhance kernel processing and ruminal starch availability when kernel processors are unavailable. However, once forage dry matter exceeds approximately 370 g/kg, hybrid selection becomes the primary determinant of starch utilization, as mechanical processing adjustments alone are insufficient to overcome increased kernel hardness.

CONCLUSIONS

Forage maturity at harvest and theoretical length of cut interact with corn hybrid characteristics to determine fermentation quality, aerobic stability, kernel processing efficiency, and ruminal nutrient degradability of whole-plant corn silage. Advancing maturity increased dry matter and starch concentrations but reduced kernel processing efficiency and nutrient degradability, particularly under harvesting conditions without kernel processors.

Reducing theoretical length of cut was an effective strategy to improve kernel fragmentation and ruminal nutrient availability when corn was harvested at approximately 300 g/kg dry matter. However, at advanced maturity stages (370 g/kg dry matter), reducing cutting length did not compensate for increased kernel hardness and vitreousness, indicating limited effectiveness of this strategy under such conditions.

Hybrid selection played a central role in determining silage nutritive value, particularly starch degradability, with softer-textured hybrids exhibiting superior kernel processing and ruminal starch utilization. These findings demonstrate that optimizing whole-plant corn silage quality requires an integrated approach that considers hybrid characteristics, harvest maturity, and processing strategy.

From an animal nutrition perspective, aligning these factors is essential to improve feed efficiency, enhance ruminal nutrient utilization, reduce feed losses, and mitigate the risk of metabolic disorders in ruminant production systems. Therefore, harvest management strategies should be tailored to hybrid characteristics and available harvesting technology to maximize the feeding value of corn silage.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests.

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Authors’ contributions

JMS conceived the study, conducted the experiment, analyzed the data, and drafted the manuscript. LGN supervised the research, contributed to experimental design and data interpretation, and critically revised the manuscript. All authors read and approved the final manuscript.

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