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Management practices associated with physical, chemical characteristics and fermentation quality of whole-plant corn silage in dairy farms.

André Luis Claudino da Silva
Magister Scientiae

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Dissertation submitted to the Animal Science Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Polyana Pizzi Rotta

Co-adviser: Alex Lopes da Silva

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APPROVED: February 27, 2026.

Assent:

André Luis Claudino da Silva
Author

Polyana Pizzi Rotta
Adviser

In memoriam

Aos meus avós e padrinho, por todo carinho, apoio e ensinamentos, vocês foram e continuam sendo meu porto seguro.

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I thank God for guiding me to this moment and for being by my side through every moment of difficulty and joy. I am also grateful for my spirituality and for Mary, who have always been by my side, supporting me and helping me get back on my feet through their advice and encouragement to keep moving forward. Without them, I would not have made it this far.

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“Deus é maior!
Maior é Deus
Quem tá com Ele
Nunca está só
O que seria do mundo sem Ele?
Chega de chorar
Você já sofreu demais, agora chega
Chega de achar que tudo se acabou
Pode a dor uma noite durar
Mas um novo dia sempre vai raiar
E quando menos esperar, CLAREOU”
(Clareou, Xand de Pilares)

ABSTRACT

SILVA, André Luis Claudino da, M.Sc., Universidade Federal de Viçosa, February, 2026. **Management practices associated with physical, chemical characteristics and fermentation quality of whole-plant corn silage in dairy farms.**. Adviser: Polyana Pizzi Rotta. Co-adviser: Alex Lopes da Silva.

This study compared the physical characteristics, fermentation profile, and chemical composition of whole-plant corn silage (WPCS) produced on technologically advanced dairy farms in Brazil and evaluated the associations between production and ensiling practices and key silage quality indicators. Ninety-two dairy farms in Minas Gerais, Brazil, were evaluated. Information on herd characteristics, production systems, and corn silage harvest and ensiling practices was collected through structured questionnaires administered to farm managers. Silage density was determined by sampling 12 points across the silo face using a probe attached to an electric drill. Samples were analysed for physical characteristics (kernel processing score - KPS, density, and particle size - sieves 19 mm, 8 mm, 4 mm, and pan), chemical composition (DM, OM, CP, ether extract, starch, neutral detergent fiber corrected for protein and ash – apNDF, undigestible neutral detergent fiber – uNDF, and in vitro digestibility of NDF and OM – IVNDFD and IVOMD, respectively), and fermentation profile (pH, lactic acid, acetic acid, 1,2-propanediol, 1-propanol, propionic acid, butyric acid, ethanol, and NH-N). Data were analysed using Spearman partial correlations and principal component analysis (PCA). Farms were grouped according to PC1 and PC2 scores (explaining 35.5% of the total variance) and compared using nonparametric one-way ANOVA, whereas milk production and composition variables were analysed using one-way ANOVA and management variables were analysed using generalized linear models (SAS 9.4; = 0.05). Farms in Q1 had higher density than those in Q3. Low variability in fermentation profile was observed among quadrants; however, farms in Q1 had lower pH and higher concentrations of lactic acid, acetic acid, and propionic acid than farms in Q3 and Q4. Regarding chemical composition, farms in Q4 had higher starch concentrations and higher IVOMD than the other quadrants. For the fibrous fraction, farms in Q1 and Q4 had the lowest uNDF values. Kernel processing score did not differ among quadrants. Regarding production performance, farms in Q1 had higher mean milk production per cow across the herd and within the highest-producing group. For WPCS production and ensiling practices, only land management and harvest equipment differed among quadrants, with farms in Q4 more frequently adopting no-till planting, self-propelled forage harvesters, and kernel processors. Overall, quadrants showed low variability in silage characteristics, production performance, and WPCS production and ensiling practices. However, Q1 farms had better preservation indicators and higher milk production, whereas Q4 farms showed more desirable nutritional characteristics.

Keywords: density; fermentation profile; in vitro digestibility; survey

RESUMO

SILVA, André Luis Claudino da, M.Sc., Universidade Federal de Viçosa, fevereiro de 2026. **Práticas de manejo associadas às características físicas, quimicas e à qualidade de fermentação da silagem de milho planta inteira em fazendas leiteiras**. Orientadora: Polyana Pizzi Rotta. Coorientador: Alex Lopes da Silva.

Este estudo avaliou as características físicas, o perfil fermentativo e a composição química da silagem de milho de planta inteira (SMPI) produzida em fazendas leiteiras tecnologicamente avançadas no Brasil e avaliou as associações entre as práticas de produção e de ensilagem e os principais indicadores de qualidade da silagem. Foram avaliadas 92 fazendas leiteiras em Minas Gerais, Brasil. Informações sobre as características do rebanho, os sistemas de produção e as práticas de colheita e ensilagem da silagem de milho foram coletadas por meio de questionários estruturados aplicados aos gestores das fazendas. A densidade da silagem foi determinada pela amostragem de 12 pontos na face do silo, utilizando uma sonda acoplada a uma furadeira elétrica. As amostras foram analisadas quanto às características físicas (kernel processing score – KPS, densidade e distribuição do tamanho de partículas – peneiras de 19, 8 e 4 mm e fundo), composição química (MS, MO, PB, extrato etéreo, amido, fibra em detergente neutro corrigida para proteína e cinzas – FDNcp, fibra em detergente neutro indigestível – FDNi, e digestibilidade in vitro da FDN e da MO – DIVFDN e DIVMO, respectivamente) e perfil fermentativo (pH, ácido lático, ácido acético, 1,2-propanodiol, 1-propanol, ácido propiônico, ácido butírico, etanol e N-NH). Os dados foram analisados por meio de correlações parciais de Spearman e análise de componentes principais (PCA). As fazendas foram agrupadas de acordo com os escores de PC1 e PC2 (que explicaram 35,5% da variância total) e comparadas por meio de ANOVA não paramétrica de uma via, enquanto as variáveis de produção e composição do leite foram analisadas por ANOVA de uma via e as variáveis de manejo foram analisadas por meio de modelos lineares generalizados (SAS 9.4; = 0,05). As fazendas do Q1 apresentaram maior densidade do que as do Q3. Foi observada baixa variabilidade no perfil fermentativo entre os quadrantes; entretanto, as fazendas do Q1 apresentaram menor pH e maiores concentrações de ácido lático, ácido acético e ácido propiônico do que as fazendas do Q3 e Q4. Quanto à composição química, as fazendas do Q4 apresentaram maiores concentrações de amido e maior DIVMO do que os demais quadrantes. Para a fração fibrosa, as fazendas do Q1 e Q4 apresentaram os menores valores de FDNi. O kernel processing score não diferiu entre os quadrantes. Em relação ao desempenho produtivo, as fazendas do Q1 apresentaram maior produção média de leite por vaca no rebanho e no grupo de vacas de maior produção. Quanto à produção e às práticas de produção e ensilagem da SMPI, apenas o manejo do solo e o equipamento de colheita diferiram entre os quadrantes, com as fazendas do Q4 adotando com maior frequência o plantio direto, colhedoras de forragem autopropelidas e processadores de grãos. De modo geral, os quadrantes apresentaram baixa variabilidade nas características da silagem, no desempenho produtivo e nas práticas de produção e ensilagem da SMPI. Entretanto, as fazendas do Q1 apresentaram melhores indicadores de conservação e maior produção de leite, enquanto as fazendas do Q4 apresentaram características nutricionais mais desejáveis.

Palavras-chave: densidade; perfil fermentativo; digestibilidade in vitro; questionário

SUMÁRIO

INTERPRETIVE SUMMARY

Management practices associated with physical characteristics, fermentation quality, and chemical composition of whole-plant corn silage in dairy farms. By Silva et al. This study evaluated corn silage quality on 92 technologically advanced dairy farms in Brazil and identified management practices associated with superior silage characteristics. Although silage quality was generally consistent among farms, better-packed silages showed improved fermentation, greater starch concentration, lower indigestible fiber, and were associated with higher milk production per cow. These findings demonstrate that proper harvest and ensiling management can improve feed preservation and nutritional value, supporting greater dairy productivity while reducing nutrient losses and increasing the efficiency and sustainability of milk production systems.

Running head: Corn silage evaluation in dairy farms

MANAGEMENT PRACTICES ASSOCIATED WITH PHYSICAL CHARACTERISTICS, FERMENTATION QUALITY AND CHEMICAL COMPOSITION OF WHOLE-PLANT CORN SILAGE IN DAIRY FARMS

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INTRODUCTION

Whole-plant corn silage is the primary forage source in advanced dairy production systems, supporting high milk yields, feed efficiency, and economic sustainability (García-Chávez et al., 2022). In addition to its fiber fraction, corn silage supplies energy from grain starch. In tropical and subtropical regions, such as Brazil, where forage production is affected by seasonal variation, corn silage is essential for maintaining year-round forage availability (Daniel et al., 2019).

Whole-plant corn silage quality depends on crop management and ensiling practices, including harvest maturity, climatic conditions, particle size, cutting height, grain processing, silo packing density, and sealing efficiency (Salvati et al., 2021; Daniel et al., 2026; Diepersloot et al., 2026). Adequate DM concentration at harvest, combined with efficient grain processing and proper packing, promotes rapid acidification, minimizes nutrient losses, and improves starch digestibility (Borreani et al., 2018; Kung et al., 2018). Consequently, pH, organic acid profile, ammonia nitrogen, silage density, and KPS are widely used to assess fermentation quality, aerobic stability, and starch availability. However, interactions among these factors result in considerable variability in silage composition (St-Pierre and Weiss, 2015; Tharangani et al., 2021).

Silage density is particularly important because it determines oxygen exclusion, fermentation dynamics, and nutrient preservation. Higher densities accelerate the onset of anaerobic conditions and lactic acid production, reducing proteolysis and DM losses, whereas low density increases porosity, oxygen infiltration, heating, and aerobic deterioration (Krüger et al., 2020; Liu et al., 2024). Under commercial conditions, achieving optimal density is challenging because of variation in DM content, particle size, equipment efficiency, and silo management practices (Holmes and Muck, 2007; Borreani et al., 2018; Grant and Ferraretto, 2018)

Most knowledge regarding WPCS quality comes from controlled experiments using standardized agronomic and ensiling practices. In contrast, commercial dairy farms operate under highly variable conditions (Bernardes and do Rêgo, 2014; Silva et al., 2019; Santos et al., 2020), making it unclear to what extent recommended practices are consistently adopted in technologically advanced systems.

Brazil has one of the world's largest dairy industries, with increasing adoption of confined and semi-confined production systems (Silvi et al., 2021; FAO, 2024). Minas Gerais, the country's largest milk-producing state, accounts for 27.7% of national production (IBGE, 2024), making it a strategic region for evaluating corn silage quality under commercial conditions.

Few studies have investigated the variability in WPCS quality on commercial dairy farms or its relationship with production and ensiling practices. Although previous studies reported substantial variation in nutritional composition (Schmidt et al., 2015; Santos et al., 2020), part of this variability may reflect differences in production scale and the inclusion of farms with heterogeneous technological levels. In contrast, de Oliveira et al. (2017) evaluated 32 intensive dairy farms across four Brazilian states and observed lower variability, with 62.5% of farms presenting starch concentrations ≥30% and 96.1% presenting NDF concentrations ≥45%. However, the limited number of farms per state may not fully represent regional variability. Consequently, studies evaluating the relationships among production scale, technological level, and silage quality in dairy farms are still scarce.

Therefore, our objectives were to (1) evaluate the physical characteristics, fermentation profile, and chemical composition of WPCS produced on technologically advanced dairy farms, and (2) investigate the associations between production and ensiling practices and key silage quality indicators, particularly silage density and KPS. We hypothesized that, despite the high technological level of these farms, substantial variability in silage quality exists and is partially explained by differences in the adoption and monitoring of recommended harvest and ensiling practices.

MATERIAL AND METHODS

The study was conducted in the state of Minas Gerais, Brazil, on 92 dairy farms and was approved by the Ethics Committee for Animal Welfare and Use (protocol no. 54/2024) and the Human Research Ethics Committee (protocol no. 81433424.7.0000.5153) of the Universidade Federal de Viçosa.

Farms and Sampling Period

A total of 92 dairy farms were evaluated, distributed across the following mesoregions: Triângulo Mineiro/Alto Paranaíba (n = 40), Sul-Sudeste de Minas (n = 21), Oeste Mineiro and Central Mineira (n = 10), and Zona da Mata Mineira and Campo das Vertentes (n = 21) (Figure 1). The number of farms selected within each mesoregion was determined based on the relative contribution of that mesoregion to the total milk production value of the state. According to the Brazilian Institute of Geography and Statistics (IBGE, 2022), the mesoregions included in this study account for approximately 70% of the total milk production value generated in the state (Table 1). Sampling and data collection were conducted from August to November 2024. Farms were selected based on three criteria that define highly technician dairy operations in Brazil: (1) more than 50 lactating cows, (2) predominantly Holstein herds, and (3) feedlot production systems. These criteria were established to ensure the inclusion of farms with structural and productive characteristics representative of intensive dairy systems in Brazil.

Survey

We administered the questionnaire to the farmer or the technical manager responsible for the farm. The questionnaire (Supplemental material S1) included 39 questions divided into the following sections: (1) herd, (2) facilities and animal welfare, and (3) WPCS production and ensiling process.

In the herd section, data were collected on herd composition and productivity to characterize the productive profile of the evaluated farms. In the facilities and animal welfare section, information was collected on the type of animal housing, bedding management practices, and thermal comfort conditions; however, for this paper, only the data related to housing type were used for the statistical analysis.

In the “production and ensiling process section”, the questionnaire was designed to thoroughly characterize all practices and management strategies adopted throughout the production chain, from crop establishment to silage removal. The questions addressed hybrid selection and crop management, including soil preparation and management, type of cultivation, irrigation, fertilization, pest and disease control, and the criteria used for crop monitoring and evaluation.

To analyze the harvest and ensiling process, information was collected on harvest stage, estimated DM content, equipment type, use of a kernel processor, theoretical length of cut, transport logistics, layer thickness during filling, compaction, and silo sealing strategies. Additionally, structural characteristics of the silos and technologies used, such as inoculants and surface-applied additives, were evaluated. However, due to the subjectivity observed in the field responses to certain operational variables – such as silo filling rate, cutting height, and machinery weight used for compaction, among others – these variables were not included in the statistical analyses.

Sampling

For bromatological analyses, fermentation profile, KPS, and particle size determination of WPCS, samples were collected according to D’Amours and Savoie (2004), with adaptations to the sampling scheme on the silo face. Specifically, a 16-point sampling scheme was used exclusively for particle size determination, encompassing both the upper and lower portions of the silo. In contrast, samples for bromatological, fermentation profile, and KPS analyses were obtained solely from 12 points located in the lower portion. The modifications applied to the original methodology consisted of the following spatial sampling scheme on the silo face: 12 points from the lower stratum were distributed as four points positioned 50 cm from the sidewalls and 50 cm from the base, and eight points distributed equidistantly across the remaining lower face area. The four points in the upper stratum were collected within the top 50 cm layer and 50 cm from the sidewalls (Figure 2). Sampling was performed using a probe for density sampling and evaluation (Tracking Feed, Uberlândia, Minas Gerais, Brazil) attached to a 20 V impact drill (Stanley Black & Decker, New Britain, CT, USA). The internal volume of the probe was determined from dimensions measured with a caliper, considering the internal diameter of the cylinder.

During sampling, the probe was inserted into the silo face to the maximum depth permitted by material resistance. After removal, the sample inside the probe was weighed using a digital scale, and the depth reached was measured with a rod marked in centimeters. The volume of the collected material was calculated by multiplying the internal cross-sectional area of the probe (πr^2) by the depth reached at each sampling point. Density was determined as the ratio of sample mass to calculated volume and was expressed in kg/m^3 on an as-is basis.

After collection, the samples (12 points) were combined, quartered, and vacuum sealed using a commercial vacuum sealer with a reservoir (Cetro Máquinas, Bauru, São Paulo, Brazil). The composite sample was divided into three portions: one for bromatological analyses, one for fermentation profile evaluation, and one for KPS analysis.

Particle size distribution of the silage was analyzed using the Penn State Particle Separator (four sieves: 19 mm, 8 mm, 4 mm, and pan). After sample collection, samples obtained from the upper portion (4 points) and lower portion (12 points) were pooled and quartered until approximately 500 g of material was obtained for analysis.

Laboratory Analyses

Following the methodology described by Mertens (2005) for KPS evaluation, approximately 100 g of air-dried corn silage sample were placed in a set of seven sieves (6.7, 4.75, 3.35, 2.36, 1.18, 0.6 mm, and pan) mounted on a Ro-Tap Shaker (Bertel Indústria Metalúrgica Ltda., São Paulo, Brazil) and shaken for 10 minutes at medium speed. After agitation, the material retained on each sieve was removed and weighed using an analytical balance. The fractions retained above 4.75 mm and below 4.75 mm were then combined separately, and the >4.75 mm fraction was ground using a Wiley-type knife mill to pass through a 1-mm screen for subsequent starch analysis (Method G-007/1; Detmann et al., 2025).

Concentrations of volatile fatty acids (VFA) and alcohols were determined by gas chromatography (Nexis GC-2030 equipped with an AOC-20i Plus autosampler; Shimadzu Corp., Kyoto, Japan) using a capillary column (Stabilwax, 60 m × 0.25 mm i.d., 0.25 μm film thickness; Restek Corp., Bellefonte, PA). Compounds were identified based on retention times and quantified using external standards, as described by Lazzari et al. (2021). Ammonia-N concentration was determined colorimetrically according to Chaney and Marbach (1962), and lactic acid concentration was quantified by high-performance liquid chromatography (HPLC) following the methodology described by Weiss and Kaiser (1995).

For chemical composition, samples were analyzed according to the standard analytical procedures of the Instituto Nacional de Ciência e Tecnologia - Ciência Animal (INCT-CA; Detmann et al., 2025). Before processing, all samples were partially dried in a forced-air oven at 55°C (INCT-CA method G-001/2). Samples were first ground in a Wiley-type mill to pass through a 2-mm screen and then reground to pass through a 1-mm screen for chemical composition analysis, and the following were determined: DM (INCT-CA method G-003/2), CP (INCT-CA method N-001/3), ether extract (INCT-CA method G-005/2), starch (INCT-CA method G-007/1), ash (INCT-CA method M-001/3), and NDF (INCT-CA method F-002/3). In vitro DM digestibility (IVDMD) was determined according to INCT-CA method G-008/2. Samples were incubated for 48 h in DaisyII incubators (TE-150, Tecnal Equipamentos para Laboratório, Piracicaba, SP, Brazil), using nonwoven textile filter bags (100 g/m²; 4 × 4.5 cm), and no urea was added to the buffer solution. In vitro OM digestibility (IVOMD) was determined after combustion of the filter bags in a muffle furnace at 550°C for 180 min. To determine in vitro NDF digestibility (IVNDFD), samples were prepared and incubated according to the IVDMD procedure; however, at the end of the incubation period, the samples were subjected to NDF analysis, as previously described. For undigestible neutral detergent fiber (uNDF) analysis, samples were ground to pass through a 2-mm screen (INCT-CA method F-009/3). Neutral detergent fiber was corrected for protein and ash (apNDF) according to INCT-CA method N-004/3 and method N-005/3, respectively.

Statistical Analysis

Initially, the normality of variables related to the physical, chemical, fermentation and chemical characteristics of the WPCS was evaluated using the Shapiro–Wilk test. Most variables were expected to deviate from a normal distribution ($P < 0.05$). Given this pattern, partial Spearman correlation coefficients were used to assess associations among these variables.

Subsequently, a principal component analysis was performed to explore the multivariate structure and discrimination of the dataset. Prior to the principal component analysis, all variables were normalized (mean = 0 and variance = 1). As anticipated, we did not observe a predominance of variance explained by the first principal components (PC). The first five PC accounted for 60.8% of the total dataset variation. Specifically, the first and second PCs accounted for 21.0% and 14.2% of the variation, respectively. To stratify the dataset according to the physical, chemical, and fermentation characteristics of the silages, we grouped the samples according to the quadrants of the plot of the first and second PC (PC1 and PC2), as follows: first quadrant (Q1) – positive scores for both PC1 and PC2; second quadrant (Q2) – positive scores for PC1 and negative scores for PC2; third quadrant (Q3) – negative scores for both PC1 and PC2; and fourth quadrant (Q4) – negative scores for PC1 and positive scores for PC2. Hereafter, these groups are referred to as quadrants.

Because most variables did not follow a normal distribution, the quadrants were compared using a nonparametric one-way analysis of variance (Wilcoxon test). When this analysis indicated differences among quadrants ($P < 0.05$), they were subjected to pairwise multiple comparisons using the Dwass-Steel-Critchlow-Fligner method.

To understand the differences among farms, they were also grouped according to the aforementioned quadrants. Two sets of farm characteristics were interpreted separately. The first is associated with quantitative aspects of milk production and composition. For this set of variables, a one-way analysis of variance was performed and, when pertinent, quadrants were compared using Fisher's least significant difference. The second set encompasses qualitative characteristics of the farms (i.e., management practices), which are restricted to the presence or absence of specific production resources. In this case, an analysis of variance was performed using a generalized linear model, assuming a binomial distribution for the errors.

All analyses were conducted using the UNIVARIATE, CORR, PRINCOMP, NPAR1WAY, and GLIMMIX procedures in SAS 9.4 ($\alpha = 0.05$).

RESULTS

The mean packing density across the farms was 671 kg/m³ on an as-fed basis, ranging from 252 to 1,086 kg/m³ (Table 2). The mean KPS was 77.2%, with values ranging from 35.9 to 95.0%. The mean DM content was 349 g/kg, ranging from 262 to 492 g/kg. Regarding the fibrous fraction, the farms had a mean NDFap of 365 g/kg DM (ranging from 246 to 553 g/kg DM) and a mean in vitro digestibility of 540 g/kg (ranging from 375 to 673 g/kg). The silages had an average uNDF content of 138 g/kg DM (ranging from 94.6 to 216 g/kg DM). The starch content ranged from 135 to 465 g/kg DM, with an average of 302 g/kg DM.

The mean silage pH was 3.69 (ranging from 3.48 to 3.97; Table 2). The concentrations of the main organic acids showed nearly equal average levels of lactic acid (41.9 g/kg DM) and acetic acid (42.4 g/kg DM), and very low levels of butyric acid (0.17 g/kg DM). On average, ammonia represented 9.8% of the total nitrogen.

As expected, 12 of the 24 variables describing the chemical and physical characteristics of the silages did not follow a normal distribution ($P < 0.05$; Table 2), supporting the use of Spearman's rank correlation to evaluate associations among variables. Overall, the correlation coefficients exhibited a diffuse pattern (Figure 3; Table 3 and 4). Strong positive correlations were observed between acetic and propionic acids, acetic acid and 1,2-propanediol, acetic acid and 1-propanol, KPS and starch concentration, IVOMD and IVNDFD, and apNDF and both IVNDFD and uNDF. Strong negative correlations were observed among the particle size fractions obtained with the Penn State Particle Separator.

Regarding principal component analysis, we did not observe a predominance of variance explained in the first PC. The first five PC encompassed 60.8% of the total dataset variation (Figure 4). Specifically, the first and second PC accounted for 21.0 and 14.2% of the dataset variation, respectively.

The score plots of the first three principal components (Figure 5, PC1 vs. PC2; Figure 6, PC1 vs. PC3 and PC2 vs. PC3) did not reveal distinct clustering of silages according to their chemical and physical characteristics. Overall, the silages evaluated in the present study exhibited a homogeneous distribution.

As anticipated, to allow stratification of the dataset according to the physical, chemical, and fermentation characteristics of the silages, we grouped the samples according to the quadrants of the plot between the first and second PC (PC1 and PC2), which together accounted for approximately 35.2% of the total dataset variation. For PC1, the variables with higher standardized scores were acetic acid (+), propionic acid (+), and DM (-). For PC2, the variables with higher standardized scores were NDF (-), uNDF (-), and IVOMD (+) (Table 4). Based on the information provided by the first two PC, we organized the dataset into quadrants as follows: first quadrant – positive scores for both PC1 and PC2; second quadrant – positive scores for PC1 and negative scores for PC2; third quadrant – negative scores for both PC1 and PC2; and fourth quadrant – negative scores for PC1 and positive scores for PC2. Hereafter, these groups are referred to as quadrants.

The nonparametric one-way ANOVA revealed significant differences in the physical, chemical, and fermentation characteristics of the WPCS (Table 6). Silage density was higher ($P = 0.014$) in Q1

(734 kg/m³) than in Q3 (568 kg/m³), with intermediate values for quadrants 2 and 4 (687 and 683 kg/m³, respectively). The fermentation profile of Q1 was relatively better, with a lower pH (3.65 vs. 3.74 in Q2; $P < 0.01$) and higher concentrations of lactic acid (48.2 g/kg of DM; $P < 0.01$), acetic acid (49.0 g/kg of DM; $P < 0.01$), and propionic acid (5.62 g/kg of DM; $P < 0.01$) compared with the lower quadrants Q3 and Q4. The KPS remained similar across quadrants ($P = 0.67$).

Regarding nutritional characteristics, farms in Q4 had higher starch content (351 g/kg of DM) and higher IVOMD (830 g/kg) than the other quadrants. For the fibrous fraction, farms in Q1 and Q4 had the lowest uNDF values (127 g/kg of DM and 118 g/kg of DM, respectively) compared with the other quadrants. In particular, Q1 had higher IVNDFD (581 g/kg).

The productivity, herd, and milk composition characteristics of the farms are presented in Table 6. Farms in Q1 had more cows than the other quadrants and more cows in lactation than Q2 and Q3. This quadrant also had the highest mean production per cow in the herd and in the highest-producing group (38.2 kg/d and 48.0 kg/d). Regarding milk composition, only milk fat and MUN showed significant differences, with farms in Q2 having higher milk fat and farms in Q4 having lower MUN values.

Among the evaluated WPCS production and ensiling practices, significant differences were limited to land management and type of harvest machinery (Table 8). Compared with the other quadrants, farms in Q4 more frequently used no-till planting, self-propelled machinery, and kernel processors.

DISCUSSION

We evaluated the chemical, physical, and fermentative characteristics of WPCS from highly specialized dairy farms in Minas Gerais State and their association with production and ensiling practices, enabling us to quantify variation in these components among farms and identify processes that may influence them. This approach allowed us to identify WPCS quality patterns under practical farming conditions, provide benchmarks for the Brazilian dairy industry, and highlight the relative contributions of conservation practices and nutritional composition to overall silage quality.

The chemical and fermentative composition of WPCS is influenced by several factors, including agronomic practices, plant maturity, cutting height, and ensiling conditions (Bernardes et al., 2018; Borreani et al., 2018; Ferraretto et al., 2018; Grant and Ferraretto, 2018). Nevertheless, the mean chemical and fermentative characteristics of the WPCS evaluated in the present study were within the ranges generally considered adequate for well-preserved WPCS (Table 1), indicating satisfactory preservation across the surveyed farms.

The literature clearly demonstrates differences in WPCS physical quality when comparing low-density and high-density silages (de Oliveira et al., 2017; Segato et al., 2022; Yang et al., 2025). WPCS with higher density (>700 kg as-fed/m^3) frequently exhibits lower DM losses and improved aerobic stability compared with low-density WPCS; however, CP, starch, and NDF values are generally not affected when WPCS is produced from a single crop (Randby et al., 2020; Segato et al., 2022; Assis et al., 2025). In our study, farms with lower density (Q3) had a greater DM content (+22.5%) than farms in the higher-density quadrant (Q4; 39.1 vs. 31.9%), as well as a greater concentration of uNDF (15.7 vs. 12.7%). Previous literature also showed a negative correlation between WPCS density and DM content. Segato et al. (2022) reported that WPCS harvested with a DM content greater than 34.5% exhibits lower densities (1,080 kg of DM/m^3) and higher DM losses. Additionally, (Krüger et al., 2020), when evaluating the relationship between density and physicochemical characteristics, observed an inverse correlation between DM and density. Consequently, materials harvested at higher DM contents are more difficult to compact, resulting in lower packing density. Furthermore, these silages tend to exhibit higher fiber lignification, which increases the uNDF fraction, consistent with the results of the present study, in which OM was negatively correlated with uNDF content.

Knowing that uNDF content is directly related to NDF digestibility (Ferraretto and Shaver, 2012; Vieira et al., 2025), the results of Khan et al. (2015) demonstrate a 12.6% reduction (38.8 vs. 44.4%)

in the digestibility of WPCS harvested with DM greater than 35% compared with those harvested with 30 to 35% DM. This aligns with our results, in which uNDF showed a negative correlation with OM and IVNDFD, such that farms with higher DM and uNDF (Q3) had IVNDFD values 10.8% lower than farms with lower DM and uNDF (Q1).

Well-preserved WPCS are frequently characterized by pH values between 3.7 and 4.0 and lactic acid concentrations between 3 and 6% of DM, which inhibit the growth of undesirable microorganisms during anaerobic storage. Acetic acid concentrations between 1 and 3% of DM are also considered desirable because of their role in inhibiting yeast and mold growth and reducing aerobic deterioration (Kung et al., 2018). In general, lactic acid-to-acetic acid ratios ranging from 2.5 to 3.0 are considered indicative of adequate fermentation, whereas ratios <1.0 have been associated with abnormal fermentation patterns (Kung et al., 2018). In the present study, Q1 and Q2 exhibited lactic acid-to-acetic acid ratios <1.0, a value that, if interpreted in isolation, could suggest atypical fermentation. However, 40% of the farms reported using silage inoculants during the ensiling process. It is well established that silages treated with heterofermentative bacteria exhibit greater acetic acid concentrations due to the conversion of lactic acid to acetic acid, resulting in a lower lactic acid-to-acetic acid ratio (Filya et al., 2006; Kleinschmit and Kung, 2006; Arriola et al., 2021). Although information regarding the bacterial species contained in the inoculants was not collected, it is reasonable to infer that they were composed of heterofermentative bacteria because, according to Daniel et al. (2019), Brazilian dairy farms frequently use inoculants containing these bacteria, particularly members of the Lentilactobacillus buchneri group. Supporting this hypothesis, Filya et al. (2006) evaluated different inoculation rates of L. buchneri in WPCS with different DM contents (27.0 vs. 34.1%) and reported lactic acid-to-acetic acid ratios of 1.18 and 1.26 in silages inoculated with 1×10^5 cfu g^{-1} of fresh forage, and 1.03 and 1.06 when the inoculation rate was increased to 5×10^5 cfu g^{-1}, respectively. At the highest inoculation rate evaluated (1×10^6 cfu g^{-1}), the ratio decreased to approximately 0.90 for both DM contents, demonstrating that values below 1.0 may result from intense heterofermentative activity rather than undesirable fermentation. The high average concentration of acetic acid (4.24% DM), together with relatively high concentrations of 1,2-propanediol (1.00% DM), propionic acid (0.45% DM), and 1-propanol (0.24% DM) across evaluated farms, strongly suggests the activity of heterofermentative bacteria. L. buchneri-like bacteria can convert lactic acid into 1,2-propanediol, which can be further metabolized into propionic acid and 1-propanol (Kung et al., 2018; Muck et al., 2018). In contrast, high ethanol concentrations (>3–4% of DM) indicate undesirable yeast activity, while propionic acid concentrations higher than 0.3–0.5% of DM and, especially, the presence of butyric acid are frequently considered indicative of clostridial fermentation. Overall, all quadrants presented a satisfactory fermentation profile, characterized by low pH values, adequate production of lactic, acetic, and propionic acids, the presence of secondary fermentation products (1,2-propanediol and 1-propanol), and low concentrations of ethanol and butyric acid.

From a nutritional standpoint, the main advantage of WPCS, when properly produced, is its combination of high-quality, physically effective fiber and high energy content from kernel starch. Starch is the primary energy nutrient for dairy cows and directly influences productive performance (Khan et al., 2015). However, utilization of this starch depends on adequate kernel processing, as poorly processed kernels reduce total starch digestibility (Ferraretto and Shaver, 2012). Previous studies have demonstrated that the use of kernel processors leads to substantial increases in KPS and total starch digestibility. Salvati et al. (2021) observed that, while maintaining the same theoretical length of cut, areas harvested with a kernel processor showed approximately 68% greater KPS compared with those without processing, as well as higher total starch digestibility (95.2 vs. 93.1%). Similarly, Andrade et al. (2026) reported a 78% increase in KPS (83.2 vs. 46.7%) and higher 12-hour starch digestibility (79.1 vs. 62.7%) when a kernel processor was used. No differences in KPS were observed among density quadrants, which seems plausible, as more than 90% of farms used some type of kernel processing (kernel processor or kernel breaker). This likely reflects the profile of the farms included in the study, which were considered high-technology operations because they housed Holstein cows in confinement. However, Q4 exhibited a greater starch concentration compared with the other quadrants. The literature consistently reports a positive relationship between starch concentration and DM content (Khan et al., 2015; Segato et al., 2022; Yang et al., 2025). Khan et al. (2015) observed increased starch deposition in corn silages harvested at 38 to 40% DM, which is consistent with our findings, as farms classified in Q4 had an average DM concentration of 37.8% and the highest starch concentration.

Nevertheless, a negative correlation between these variables was observed in our dataset. This result may be associated with climatic factors that impaired kernel filling, resulting in farms with high DM concentrations but lower starch contents (e.g., Q3). Consequently, DM concentration alone may not accurately reflect starch accumulation in corn silage, particularly under conditions where environmental factors affect grain development and maturation. Water deficit during the vegetative and reproductive phases is detrimental to corn yield because it reduces both the rate and duration of kernel filling, thereby decreasing corn productivity (Li et al., 2018; Na et al., 2018). Alam et al. (2021) demonstrated that water restriction during the reproductive stages limits the supply of assimilates, shortens the grain-filling period, advances maturity, and increases the ratio of DM to grain water content, ultimately resulting in the cessation of kernel growth. They also observed that plants not subjected to water stress (control) had greater kernel weight. Thus, by altering kernel weight and size, water deficit may change the cob-to-grain mass ratio, leading to increased DM and reduced starch concentration.

In this context, analyzing the interaction between two variables (DM and starch) in isolation under controlled conditions may not reflect the interactions observed in commercial systems, where multiple structural, environmental, and management factors operate simultaneously. St-Pierre and Weiss (2015) evaluated the composition of diet ingredients from 11 farms in two geographic regions of the United States and found that between-farm variation was the main source of variability for silage and other ingredients, with a large portion of this variation indicating that feed composition is farm-specific.

Fiber concentration is directly related to ruminal metabolism and milk production efficiency. An increase in NDF concentration, particularly when associated with greater particle size and lower digestibility, increases chewing activity and rumen retention time, which may reduce DMI due to the physical fill effect (Ferraretto et al., 2018). Farms classified in Q2 exhibited the greatest concentrations of aNDF and uNDF, accompanied by the lowest NDF digestibility (IVDNDF) and organic matter digestibility (IVDOM) values. In the correlation analysis, aNDF was positively correlated with uNDF and IVDNDF, and negatively correlated with IVDOM. The apparent discrepancy between the quadrant results and the positive correlation between aNDF and IVDNDF highlights the importance of interpreting these data in an integrated manner. Q2 also exhibited the greatest uNDF concentration, a fraction that exerts a major influence on the extent of fiber digestion (Van Soest, 1965; Smith, 1972), and was negatively correlated with IVDNDF. This relationship is likely attributable to lignin, the primary component associated with this fraction, which alters cell wall structure and reduces the accessibility of ruminal microorganisms to structural polysaccharides, thereby limiting fiber degradation (Van Soest, 1994).

Furthermore, the positive correlation between uNDF and starch concentration reinforces that, although advancing maturity may increase starch accumulation, it can also impair fiber digestibility (Grant and Ferraretto, 2018) and, consequently, animal performance. Ferraretto and Shaver (2015) reported that cows fed more digestible corn silages exhibited greater DMI and milk production. Similarly, Vieira et al. (2025) observed a linear increase in DMI, total-tract apparent digestibility of DM and NDF, and milk yield in cows fed corn silages with lower uNDF concentrations (9.0 vs. 11.1%). These findings are consistent with the results of the present study, in which farms classified in Q1 had the greatest IVDNDF values, the lowest uNDF concentrations, and the highest average milk production per cow in the herd.

The greater starch concentration, DM content, and OM digestibility observed in Q4 were not reflected in productive performance, as the farms with the highest average milk yield per cow, both for the entire herd and for the highest-producing group, were classified in Q1. These findings show that evaluating a single dietary component, even one of considerable nutritional importance, is insufficient to explain the performance differences observed among groups. Milk production results from the interaction of multiple factors, including environmental conditions, diet formulation, feeding management, and overall farm management practices. Therefore, silage quality should be interpreted as an indicator of the overall efficiency of the production system rather than as the sole factor responsible for the performance differences observed among quadrants.

CONCLUSION

Overall, the results showed that although statistically significant differences were observed among quadrants, the magnitude of these differences was not sufficient to establish the absolute superiority of a single group. Nevertheless, farms classified in Q1 were distinguished by better silage preservation indicators, including higher packing density and a more favorable fermentation profile. In contrast, farms in Q4 exhibited more desirable nutritional characteristics, including higher starch concentration, lower fiber content, and consequently greater in vitro OM digestibility. Taken together, the results reinforce that silage quality evaluation should account for the inherent complexity of commercial production systems, where agronomic conditions, environmental factors, and operational management practices interact to influence both feed characteristics and animal performance.

NOTES

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Nonstandard abbreviations used: apNDF= neutral detergent fiber was corrected for protein and ash; uNDF= undigestible neutral detergent fiber; KPS=kernel processing score; IVNDFD=in vitro digestibility of neutral detergent fiber; IVOMD= in vitro digestibility of organic matter

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Figures

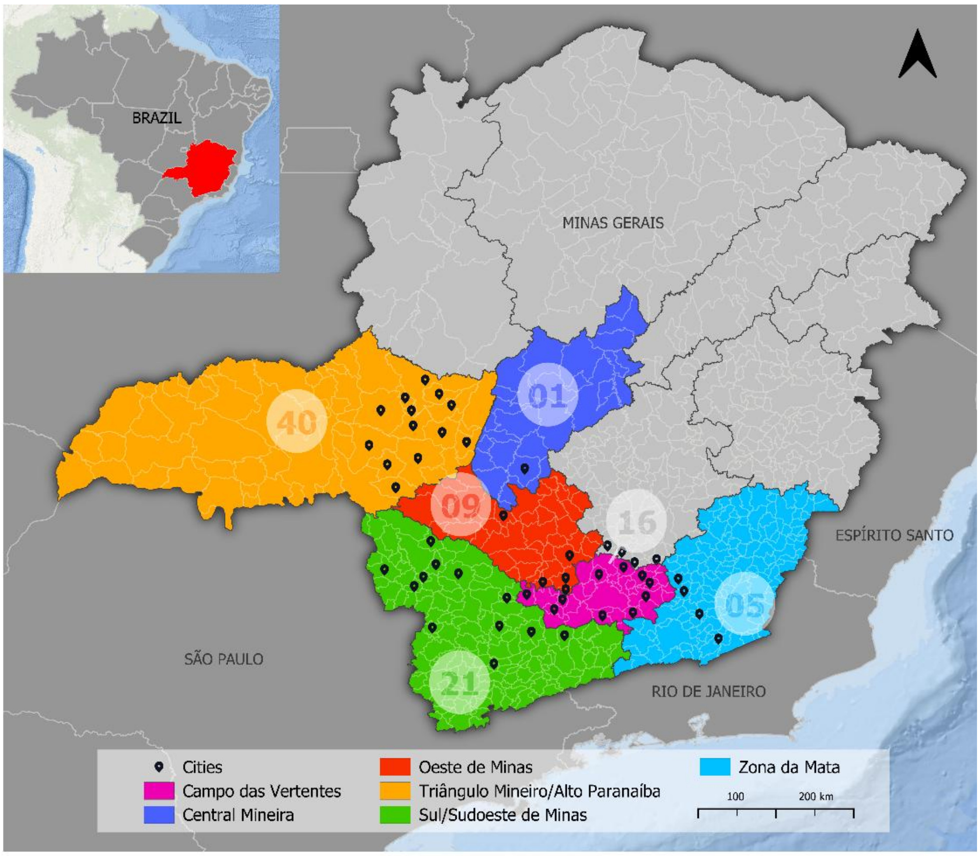

Figure 1. Geographic location of the evaluated dairy farms across the mesoregions of Minas Gerais, Brazil.

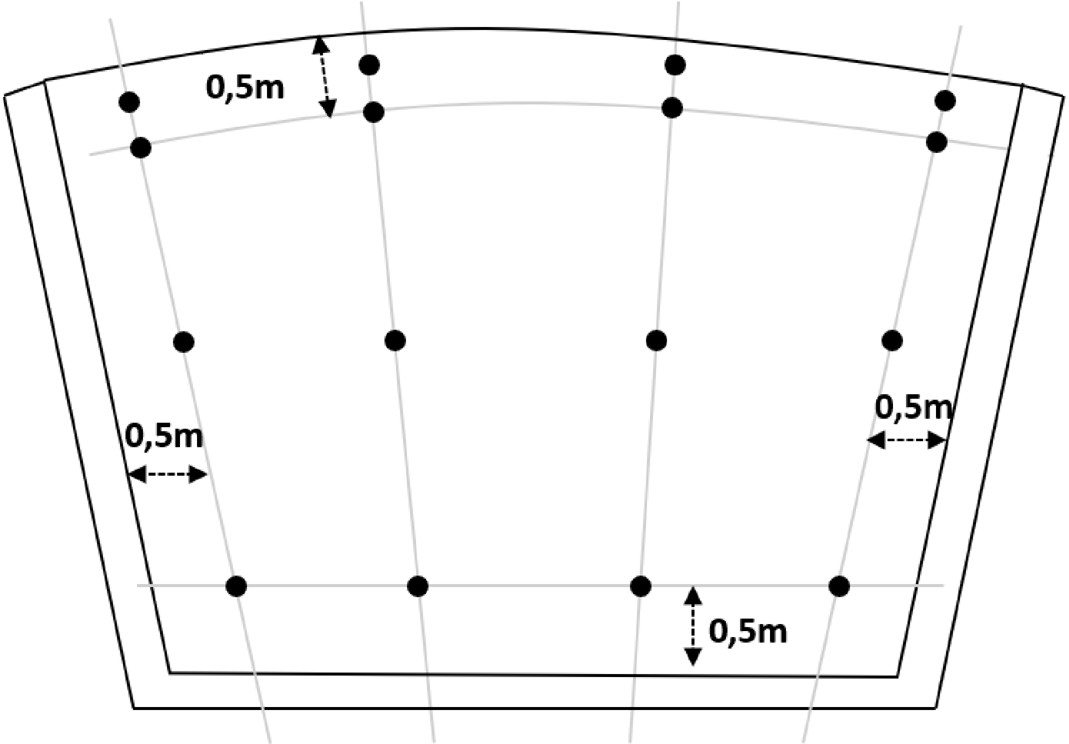

Figure 2. Sampling points used for silage density determination on the silo face.

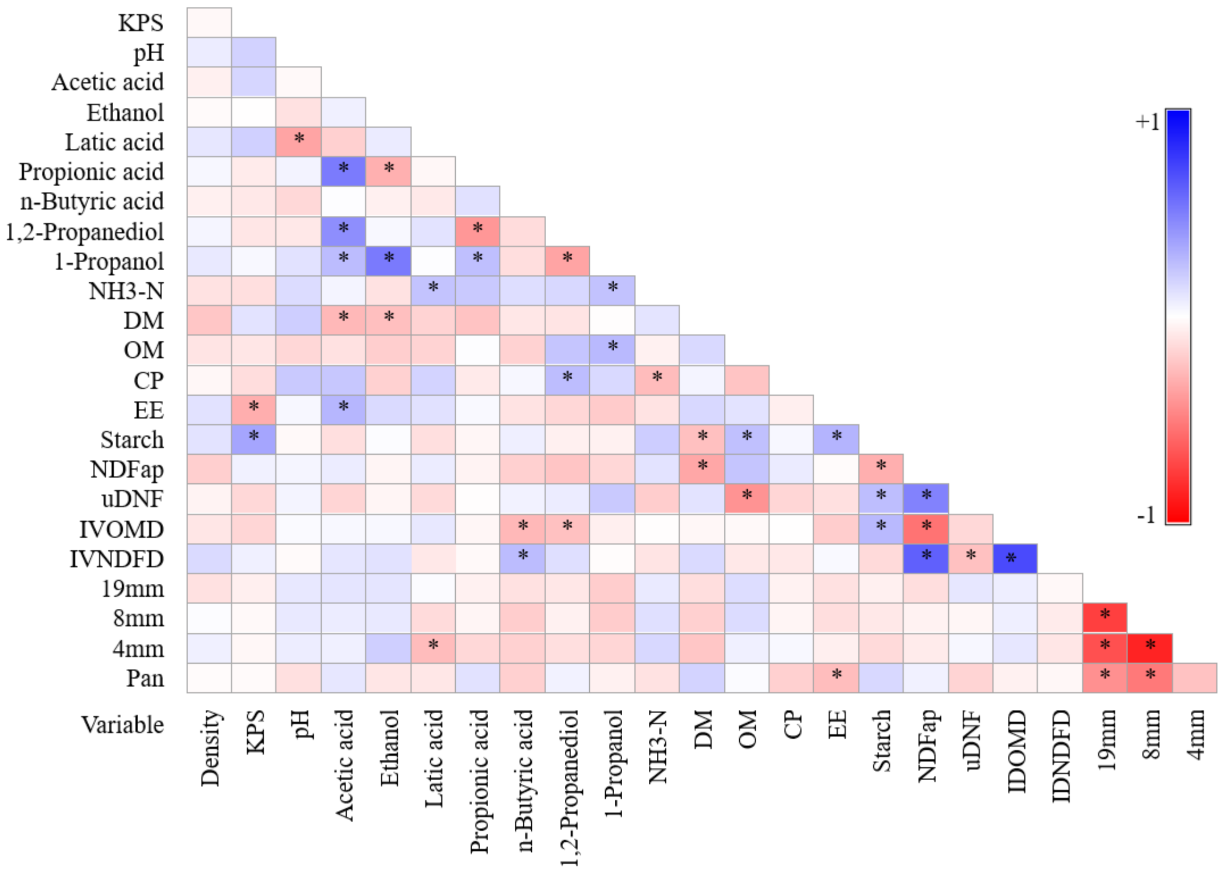

Figure 3. Heatmap of Spearman correlation coefficients among fermentation, nutritional, and physical characteristics of corn silages (* indicate significant correlations, P ≤ 0.05).

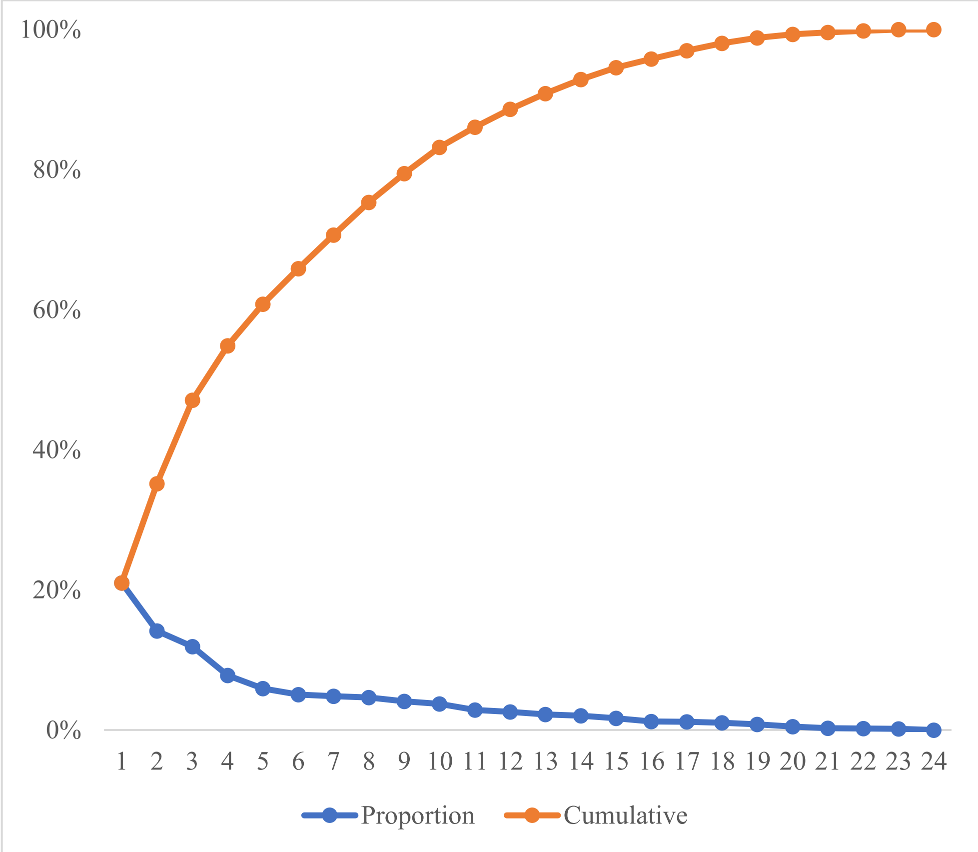

Figure 4. Scree Plot of proportional variance, and cumulative variance explained by the principal components.

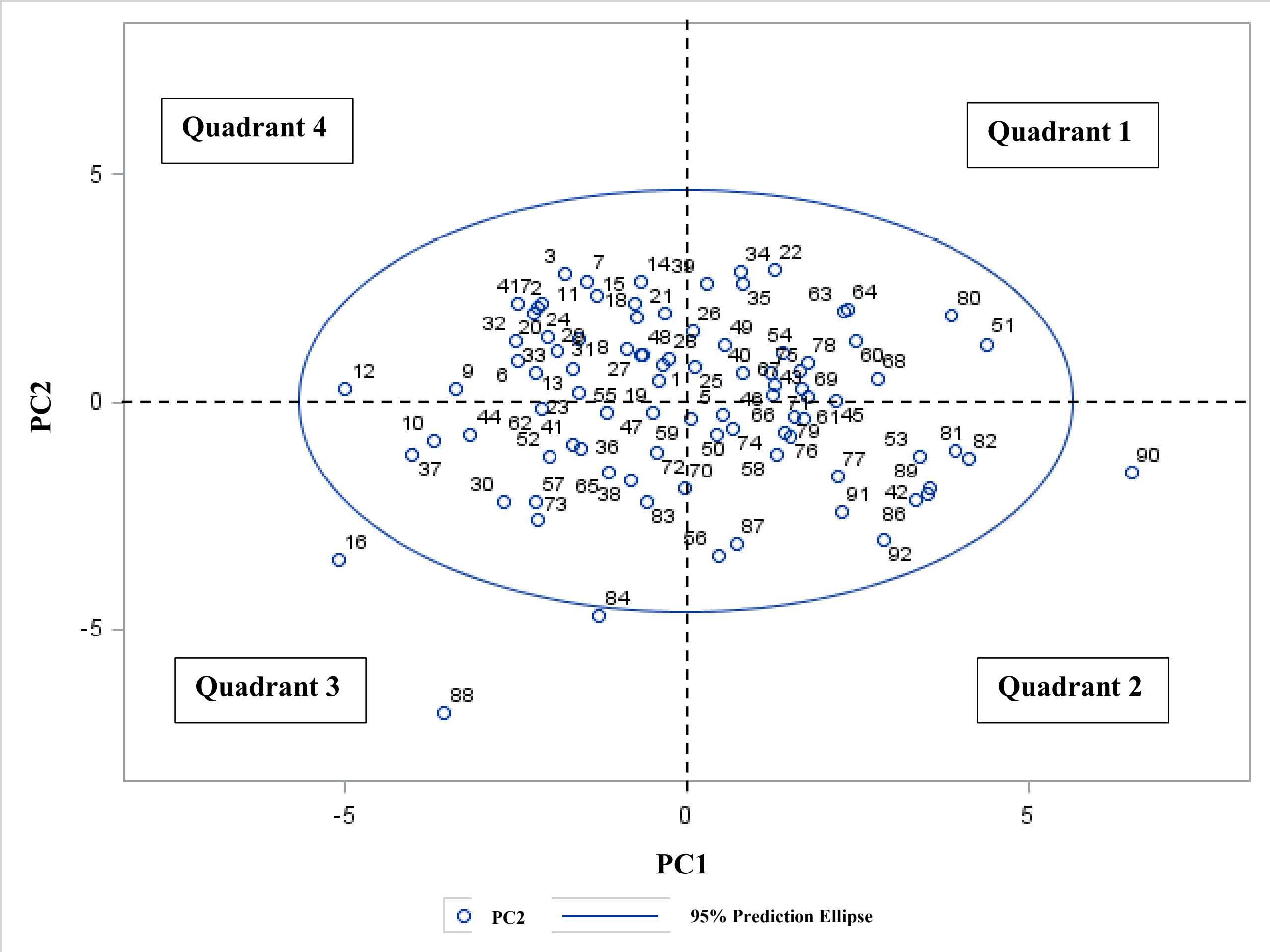

Figure 5. Principal component analysis score plot (PC1 vs. PC2) of the evaluated whole-plant corn silage samples.

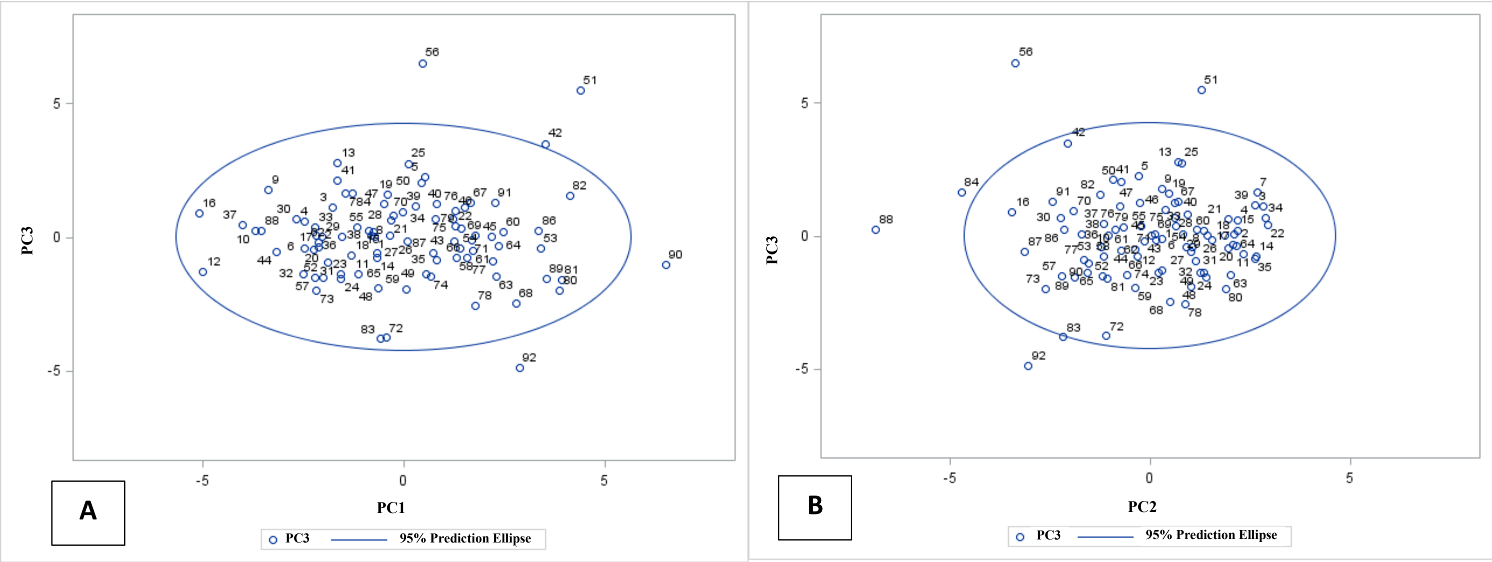

Figure 6. Principal component analysis score plot (**A**: PC1 vs. PC3; **B**: PC2 vs. PC3) of the evaluated whole-plant corn silage samples.

Tables

Table 1. Contribution of the main mesoregions to the total value of milk production in Minas Gerais, Brazil.

Region	Production value (thousand dollars)	%
State of Minas Gerais	4.670.616	100,0%
Triângulo Mineiro/Alto Paranaíba	1.208.187	25,9%
Sul/Sudoeste de Minas	769.899	16,5%
Zona da Mata e Campo das Vertentes	651.009	13,9%
Oeste de Minas e Central Mineira	678.462	14,5%
Total mesoregion	3.307.557,14	70,8%

Table 2. Descriptive statistics of corn silage variables.

Item	Statistics									
	Mean	Minimum	Q1	Median	Q3	Maximum	n	SD	PS[1]	p-Value[2]
Density (kg/m^3 as-fed)	671	252	588	688	755	1086	92	156.2	123.7	0.193
KPS[3] (%)	77.2	35.9	72.5	79.0	83.7	95.0	92	10.72	8.296	<0.001
pH	3.69	3.48	3.62	3.68	3.74	3.97	92	0.092	0.089	0.013
Acetic acid (g/kg DM)	42.4	22.3	36.0	41.1	48.4	66.7	92	9.107	9.190	0.664
Ethanol (g/kg DM)	3.00	0.64	2.04	2.66	3.64	9.30	92	1.595	1.185	<0.001
Latic acid (g/kg DM)	41.9	23.8	55.3	77.9	102	216	92	10.23	34.59	0.485
Propionic acid (g/kg DM)	4.47	0.76	2.72	3.85	5.85	13.4	92	2.530	2.319	<0.001
n-Butyric acid (g/kg DM)	0.17	0.03	0.06	0.09	0.16	1.39	92	0.218	0.070	<0.001
1,2-Propanediol (g/kg DM)	9.95	0.28	5.21	8.61	14.38	32.22	92	6.260	6.790	<0.001
1-Propanol (g/kg DM)	2.36	0.17	1.30	1.97	3.16	9.88	92	1.595	1.380	<0.001
NH3-N (% of N)	9.80	5.80	8.86	10.08	10.84	12.84	92	1.633	1.470	0.009
Dry matter (g/kg DM)	349	262	315	342	383	492	92	47.19	50.37	0.120
Organic matter (g/kg DM)	965	913	962	968	971	980	92	11.80	6.667	<0.001
Crude protein (g/kg DM)	71.8	55.4	67.2	71.2	76.2	89.8	92	7.330	6.667	0.664
Ether extract (g/kg DM)	25.4	8.40	22.2	25.8	28.6	36.5	92	5.162	4.741	0.005
Starch (g/kg DM)	302	135	267	308	353	465	92	70.69	63.70	0.157
NDFap (g/kg DM)	365	246	323	361	404	553	92	62.24	60.00	0.387
uDNF (g/kg DM)	138	94.6	119	139	151	216	92	24.60	23.70	0.031
IVOMD[4] (g/kg)	80.0	67.2	77.1	80.2	82.9	87.5	92	4.105	4.300	0.022
IVNDFD[5] (g/kg)	54.0	37.5	49.6	54.7	59.0	67.3	92	6.567	6.960	0.190
Particule size (% as-fed)										
19mm	6.82	0.60	4.00	5.70	8.30	19.0	91	3.97	3.190	<0.001
8mm	63.2	34.9	59.6	64.1	68.8	83.5	91	8.825	6.810	0.015
4mm	15.5	7.60	10.9	13.0	17.9	32.5	91	6.074	5.190	<0.001
Pan	14.5	7.3	12.2	14.3	16.4	29.1	91	3.823	3.110	<0.001

[1]PS= Pseudo-sigma;
[2]Shapiro-Wilk test for normality;
[3]KPS= Kernel process score
[4] INOMD= *in vitro* digestibility organic matter
[5] IVNDFd= *in vitro* digestibility of neutral detergent fiber

Table 3. Partial Spearman correlations among corn silage variables.

Variable	Density	KPS	pH	Acetic acid	Ethanol	Latic acid	Propionic acid	Butyric acid	1,2-Propanediol	1-Propanol	NH3-N	DM	OM	CP	EE	Starch	NDFap	uDNF	IVOMD	IVNDFD	19mm	8mm	4mm
KPS	-0,025																						
pH	0,076	0,178																					
Acetic acid	-0,058	0,164	-0,021																				
Ethanol	-0,016	-0,001	-0,117	0,061																			
Latic acid	0,094	0,187	-0,356	-0,183	0,079																		
Propionic acid	0,035	-0,075	0,047	0,520	-0,307	-0,029																	
Butiric acid	-0,056	-0,089	-0,149	0,010	-0,055	-0,086	0,121																
1,2-Propanediol	0,041	-0,096	-0,088	0,447	0,031	0,112	-0,408	-0,134															
1-Propanol	0,089	0,028	0,115	0,265	0,524	0,010	0,252	-0,126	-0,357														
NH3-N	-0,110	-0,123	0,137	0,045	-0,114	0,239	0,213	0,133	0,153	0,241													
DM	-0,220	0,111	0,196	-0,276	-0,249	-0,170	-0,232	-0,093	-0,103	-0,008	0,109												
OM	-0,105	-0,097	-0,154	-0,114	-0,191	-0,170	0,009	-0,173	0,231	0,275	-0,051	0,150											
CP	-0,030	-0,131	0,213	0,220	-0,178	0,175	-0,079	0,032	0,263	0,153	-0,262	0,047	-0,229										
EE	0,115	-0,314	0,032	0,288	0,149	0,119	0,027	-0,108	-0,155	-0,201	-0,106	0,155	0,113	-0,061									
Starch	0,113	0,353	-0,022	-0,124	0,015	-0,122	-0,032	0,065	-0,056	-0,054	0,199	-0,246	0,250	0,035	0,295								
NDFap	-0,187	0,058	0,042	0,076	-0,035	0,076	-0,045	-0,183	-0,224	-0,154	0,113	-0,345	0,230	0,080	-0,015	-0,312							
uDNF	-0,046	-0,150	0,046	-0,163	-0,036	-0,143	-0,007	0,054	0,077	0,214	-0,195	0,113	-0,420	-0,160	-0,121	0,255	0,493						
IVDOM	-0,097	-0,157	0,022	0,030	0,029	0,091	-0,034	-0,276	-0,242	-0,060	-0,007	-0,030	-0,020	-0,003	-0,195	0,276	-0,546	-0,149					
IVDNDF	0,148	0,060	-0,018	0,099	0,116	-0,087	-0,021	0,264	0,127	-0,011	-0,103	0,147	-0,089	-0,089	0,027	-0,143	0,624	-0,240	0,710				
19mm	-0,117	-0,061	0,093	0,104	0,103	0,018	-0,053	-0,114	-0,094	-0,196	0,086	-0,128	0,135	-0,049	-0,117	-0,056	-0,128	0,096	0,067	-0,027			
8mm	0,012	-0,023	0,086	0,078	0,089	-0,139	-0,036	-0,195	-0,054	-0,198	0,123	-0,181	0,139	-0,037	-0,126	-0,087	-0,048	-0,033	0,066	-0,077	-0,751		
4mm	0,061	-0,030	0,074	0,060	0,190	-0,261	-0,153	-0,177	-0,124	-0,160	0,156	-0,221	0,061	0,028	-0,061	-0,142	-0,078	0,032	0,095	-0,097	-0,684	-0,860	
Pan	-0,013	-0,018	-0,120	0,097	-0,094	-0,094	0,115	-0,184	0,053	-0,051	-0,113	0,173	0,018	-0,181	-0,256	0,154	0,058	-0,167	-0,055	-0,031	-0,433	-0,524	-0,237

Table 4. P-value of Partial Spearman correlations among corn silage variables.

Variable	Density	KPS	pH	Acetic acid	Ethanol	Latic acid	Propionic acid	Butyric acid	1,2-Propanediol	1-Propanol	NH3-N	DM	OM	CP	EE	Starch	NDFap	uDNF	IVOMD	IVNDFD	19mm	8mm	4mm
KPS	0,838	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	0,537	0,144	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acetic acid	0,635	0,178	0,864	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ethanol	0,895	0,990	0,336	0,619	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Latic acid	0,441	0,124	0,002	0,133	0,517	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Propionic acid	0,776	0,540	0,699	<0,001	0,010	0,814	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Butyric acid	0,645	0,469	0,220	0,937	0,652	0,481	0,321	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1,2-Propanediol	0,740	0,819	0,471	<0,001	0,798	0,360	<0,001	0,274	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-Propanol	0,469	0,819	0,344	0,028	<0,001	0,934	0,037	0,302	0,002	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NH3-N	0,366	0,314	0,260	0,711	0,352	0,048	0,078	0,277	0,208	0,045	-	-	-	-	-	-	-	-	-	-	-	-	-
DM	0,069	0,364	0,106	0,021	0,039	0,162	0,055	0,447	0,398	0,950	0,373	-	-	-	-	-	-	-	-	-	-	-	-
OM	0,390	0,426	0,207	0,351	0,116	0,226	0,938	0,154	0,056	0,022	0,677	0,219	-	-	-	-	-	-	-	-	-	-	-
CP	0,804	0,282	0,079	0,069	0,144	0,151	0,520	0,792	0,029	0,210	0,029	0,701	0,058	-	-	-	-	-	-	-	-	-	-
EE	0,347	0,008	0,791	0,016	0,222	0,330	0,828	0,378	0,202	0,098	0,386	0,202	0,355	0,616	-	-	-	-	-	-	-	-	-
Starch	0,353	0,002	0,859	0,311	0,904	0,316	0,796	0,595	0,649	0,658	0,101	0,041	0,038	0,777	0,014	-	-	-	-	-	-	-	-
NDFap	0,123	0,635	0,730	0,533	0,772	0,534	0,715	0,133	0,064	0,205	0,355	0,003	0,057	0,511	0,899	0,009	-	-	-	-	-	-	-
uDNF	0,704	0,218	0,706	0,182	0,769	0,240	0,954	0,661	0,528	0,077	0,108	0,353	<0,001	0,190	0,322	0,034	<0,001	-	-	-	-	-	-
IVOMD	0,427	0,197	0,857	0,808	0,814	0,456	0,780	0,021	0,045	0,625	0,952	0,808	0,867	0,982	0,108	0,021	<0,001	0,221	-		-	-	-
IVNDFD	0,226	0,623	0,881	0,419	0,342	0,477	0,863	0,028	0,298	0,928	0,398	0,228	0,467	0,468	0,826	0,239	<0,001	0,046	<0,001	-	-	-	-
19mm	0,338	0,620	0,448	0,397	0,397	0,886	0,668	0,349	0,444	0,106	0,483	0,292	0,269	0,690	0,339	0,645	0,295	0,433	0,582	0,826	-	-	-
8mm	0,923	0,854	0,480	0,523	0,466	0,255	0,770	0,108	0,660	0,102	0,312	0,136	0,256	0,763	0,301	0,478	0,694	0,788	0,589	0,529	<0,001	-	-
4mm	0,618	0,804	0,547	0,625	0,117	0,030	0,209	0,146	0,310	0,189	0,199	0,067	0,619	0,820	0,616	0,245	0,522	0,793	0,439	0,427	<0,001	<0,001	-
Fundo	0,918	0,882	0,327	0,426	0,440	0,443	0,345	0,129	0,665	0,676	0,355	0,155	0,880	0,136	0,033	0,205	0,636	0,170	0,656	0,801	<0,001	<0,001	0,050

Table 5. Eigenvectors for the first five principal components extracted for the evaluated variables.

	Principal components				
	Prin1	Prin2	Prin3	Prin4	Prin5
Density	0.088	0.193	0.302	0.042	-0.033
KPS	-0.064	0.039	0.069	-0.235	-0.269
pH	-0.014	-0.225	0.033	-0.370	-0.046
Acetic acid	0.393	0.055	0.109	-0.017	-0.104
Ethanol	0.176	-0.013	0.315	0.259	-0.027
Latic acid	0.160	0.251	-0.150	0.215	0.102
Propionic acid	0.344	-0.036	0.174	-0.279	0.032
n-Butyric acid	0.115	-0.124	0.068	0.119	0.590
NH3-N	0.253	0.116	0.057	-0.275	0.177
1-Propanol	0.278	-0.064	0.351	-0.174	-0.031
1,2-Propanediol	0.052	0.151	-0.270	0.336	-0.265
DM	-0.387	-0.058	-0.077	-0.119	-0.001
OM	-0.130	0.255	-0.121	-0.141	-0.077
PB	0.210	-0.028	-0.106	0.145	-0.368
EE	0.063	0.181	0.102	0.079	0.120
Starch	-0.239	0.237	0.239	-0.238	0.077
apNDF	0.259	-0.314	-0.199	0.099	-0.024
uNDF	0.038	-0.453	-0.163	-0.029	0.056
IVOMD	-0.163	0.349	0.244	0.133	0.028
IVNDFD	0.124	0.122	0.094	0.311	-0.001
19mm	-0.074	0.033	-0.162	0.098	0.488
8mm	0.214	0.264	-0.285	-0.251	-0.079
4mm	-0.116	-0.282	0.366	0.236	-0.092
Pan	-0.234	-0.196	0.244	0.103	-0.177

Table 6. Comparison of physical, fermentation, and chemical characteristics of corn silage among quadrants.

Variable	Quadrants				p-value[1]
	1º (n=23)	2º (n=21)	3º (n=20)	4º (n=27)	
Density (kg/m³ as-fed)	734[a] ± 29.4	687[ab] ± 31.3	568[b] ± 38.4	683[ab] ± 26.6	0.014
KPS[2] (%)	76.1 ± 2.83	75.2 ± 2.51	77.3 ± 2.13	79.5 ± 1.59	0.672
pH	3.65[b] ± 0.01	3.74[a] ± 0.02	3.71[ab] ± 0.02	3.67[ab] ± 0.02	0.010
Acetic acid (g/kg DM)	49.0[a] ± 1.43	48.4[a] ± 1.67	34.8[b] ± 1.27	37.2[b] ± 1.11	<0.001
Ethanol (g/kg DM)	3.52[a] ± 0.27	3.89[a] ± 0.5	2.18[b] ± 0.21	2.48[b] ± 0.2	<0.001
Latic acid (g/kg DM)	48.2[a] ± 2.10	40.7[ab] ± 2.06	35.0[b] ± 2.19	42.3[a] ± 1.58	<0.001
Propionic acid (g/kg DM)	5.62[a] ± 0.46	6.55[a] ± 0.60	2.77[b] ± 0.27	3.01[b] ± 0.26	<0.001
n-Butyric acid (g/kg DM)	0.20[a] ± 0.05	0.23[a] ± 0.07	0.16[ab] ± 0.03	0.11[b] ± 0.03	0.002
1-Propanol (g/kg DM)	2.93[a] ± 0.39	3.57[a] ± 0.36	1.47[b] ± 0.16	1.58[b] ± 0.18	<0.001
1,2-Propanediol (g/kg DM)	11.5 ± 1.58	8.2 ± 1.15	7.7 ± 0.98	11.3 ± 1.22	0.151
NH_3-N (% of N)	10.8[a] ± 0.26	10.4[a] ± 0.30	8.6[b] ± 0.35	9.3[b] ± 0.28	<0.001
Dry matter (g/kg DM)	319[b] ± 5.20	310[b] ± 5.48	391[a] ± 9.5	378[a] ± 6.29	<0.001
Organic matter (g/kg DM)	966[b] ± 1.50	957[b] ± 3.40	963[b] ± 3.06	971[a] ± 1.07	<0.001
Crude protein (g/kg DM)	74.2[ab] ± 1.47	75.0[a] ± 1.81	68.3[b] ± 1.12	69.6[ab] ± 1.29	0.005
Extract eter (g/kg DM)	27.1[a] ± 0.85	25.6[ab] ± 1.33	22.1[b] ± 1.34	26.4[a] ± 0.66	0.021
Starch (g/kg DM)	300[b] ± 13.4	251[b] ± 15.0	298[b] ± 14.1	351[a] ± 10.1	<0.001
NDFap (g/kg DM)	375[b] ± 6.90	420[a] ± 13.6	377[b] ± 10.3	302[c] ± 5.90	<0.001
uDNF (g/kg DM)	127[b] ± 2.94	159[a] ± 4.04	157[a] ± 4.62	118[b] ± 2.77	<0.001
IVOMD[3] (g/kg)	814[ab] ± 5.58	762[b] ± 8.22	785[b] ± 8.30	830[a] ± 5.00	<0.001
IVNDFD[4] (g/kg)	581[a] ± 10.8	526[b] ± 13.8	518[b] ± 14.9	531[b] ± 12.7	0.005
Particule size (% as-fed)					
19mm	6.81 ± 0.67	5.85 ± 0.61	7.67 ± 1.15	6.95 ± 0.84	0.834
8mm	67.9[a] ± 1.11	64.9[a] ± 2.29	55.0[b] ± 1.8	64.0[a] ± 1.2	<0.001
4mm	12.4[b] ± 0.93	16.5[ab] ± 1.58	19.7[a] ± 1.55	14.1[b] ± 0.63	<0.001
Pan	12.8[c] ± 0.52	12.8[c] ± 0.99	17.7[a] ± 0.88	15.0[b] ± 0.45	<0.001

[1]P-value refers to the non-parametric one-way analysis of variance (Wilcoxon test)
[2]Kernel process score
[3] INOMD= *in vitro* digestibility organic matter
[4] IVNDFd= *in vitro* digestibility of neutral detergent fiber
[a,b,c] Different superscript letters within a row indicate significant differences (P < 0,05) among quadrants according to the Dwass, Steel, Critchlow-Fligner multiple comparison test.

Table 7. Herd structure, milk production, milk composition, and days in milk (DIM) according to quadrants of density.

Item	Quadrants				p-value[1]
	1	2	3	4	
	means ± SEM				
Total cows (n)	326^{a} ± 52.26	202^{ab} ± 57.77	174^{b} ± 54.81	299^{ab} ± 48.07	<0.001
Lactating cows (n)	270^{a} ± 45.15	162^{ab} ± 49.68	131^{b} ± 48.42	266^{a} ± 42.47	<0.001
High-production group cows (n)	68 ± 8.036	51 ± 8.841	43 ± 8.617	71 ± 7.558	0.053
LC/TC ratio[2]	0.86 ± 0.025	0.83 ± 0.027	0.79 ± 0.026	0.87 ± 0.023	0.077
Total daily milk yield (L/d)	10396 ± 1803	5772 ± 1887	4259 ± 1934	9811 ± 1664	0.051
High group mean yield (L/cow/d)	48.0^{a} ± 1.455	42.4^{b} ± 1.455	39.5^{b} ± 1.495	42.8^{b} ± 1.244	0.001
Herd mean yield (L/cow/d)	38.2^{a} ± 1.147	34.9^{b} ± 1.206	32.3^{b} ± 1.239	35.0^{b} ± 1.011	0.009
Days in milk, herd (d)	187 ± 5.562	179 ± 6.62	193 ± 6.620	187 ± 5.003	0.539
Days in milk, high group (d)	135 ± 8.521	137 ± 9.263	139 ± 9.263	141 ± 8.211	0.968
Milk Protein (%)	3.33 ± 0.027	3.33 ± 0.026	3.27 ± 0.029	3.3 ± 0.023	0.318
Milk Fat (%)	3.66^{ab} ± 0.066	3.8^{a} ± 0.064	3.64^{ab} ± 0.070	3.55^{b} ± 0.057	0.045
Milk Lactose (%)	4.71 ± 0.062	4.68 ± 0.087	4.59 ± 0.087	4.6 ± 0.062	0.542
MUN (mg/ dL)	15.0^{a} ± 0.485	14.5^{a} ± 0.531	15.0^{ab} ± 0.531	13.1^{b} ± 0.385	0.007

[1]P-value refers to the main effect of quadrants evaluated by one-way analysis of variance;
[2]LC/TC ratio= Ratio between lactating cow and total cows in herd;
[a,b,c]Within a row, means followed by different superscript letters differ significantly ($P < 0.05$) according to Fisher's least significant difference test.

Table 8. Percentage of production practices adopted during harvest and ensiling processes according to quadrants.

Management practices	Quadrants				p-value[1]
	1 (23)	2 (21)	3 (20)	4 (27)	
Compost barn system	95.7	85.7	90.0	85.2	0.675
Land leasing	69.6	61.9	65.0	59.3	0.893
Machinery rental	87.0	81.0	90.0	96.3	0.464
Use of outsourced labor	34.8	33.3	20.0	25.9	0.631
Crop rotation	30.4	9.50	10.0	25.9	0.220
No-tillage system	47.8[bc]	42.9[c]	75.0[ab]	81.5[a]	0.019
Silage purchase	17.4	33.3	10.0	22.2	0.343
Yield estimation	73.9	61.9	80.0	77.8	0.555
Irrigated area	30.4	9.50	0.0	3.70	0.110
Soil correction	91.3	70.0	100	84.6	0.363
Fertilizer application	95.7	95.0	100	96.2	0.998
Fertigation	47.8	42.9	40.0	48.1	0.935
Refuge area implementation	13.0	5.00	0.0	14.8	0.781
Biological control	40.9	19.0	20.0	37.0	0.279
Herbicide application	100	95.0	100	100	>0.999
Fungicide application	82.6	75.0	95	96.2	0.017
Insecticide application	91.3	80.0	100	100	0.781
Harvest timing evaluation	95.5	100	100	92.6	0.982
Milk line evaluation	86.4	100	100	92.6	0.918
DM content evaluation	36.4	30.0	15.0	51.9	0.094
Pull-type forage harvester	8.70[b]	38.1[a]	30.0[ab]	7.40[b]	0.039
Self-propelled forage harvester	91.3[ab]	61.9[c]	65.0[bc]	96.3[a]	0.021
Kernel processing evaluation	100	81.0	90.0	100	0.883
Kernel processing rolls	95.7[a]	57.1[b]	60.0[b]	96.3[a]	0.007
Kernel breaker	4.30	19.0	20.0	7.40	0.324
Shredlage® processing rolls	4.30	0.00	5.0	0.00	0.999
Monitoring of the ensiling process	65.2	75.0	70.0	88.9	0.276
Dry matter analysis	69.6	65.0	70.0	85.2	0.429
Kernel processing score analysis	56.5	60.0	70.0	74.1	0.551
Penn State Particle Separator analysis	65.2	75.0	75.0	88.9	0.300
Use of silage inoculant	56.5	38.1	40.0	40.7	0.580
Use of chemical additive on top layers	13.0	10.0	5.0	7.40	0.819
Tractor packing	73.9	81.0	75.0	77.8	0.948
Wheel loader packing	73.9	61.9	70.0	63.0	0.797
Other packing equipment	4.30	0.00	5.0	25.9	0.152
Number of packing machines:					
<=2	78.3	76.2	95.0	70.4	0.320
>2<=4	17.4	23.8	5.0	18.5	0.492
>4	0.00	0.00	0.0	11.1	>0.999
Packing rate greater than harvest rate	43.5	47.6	70.0	74.1	0.088
Silage removal using:					
Mixer wagon	65.2	57.1	70.0	48.1	0.449

Wheel loader	26.1	38.1	25.0	59.3	0.063
Manual fork	4.30	4.80	5.00	7.40	0.964
Other methods	4.30	0.00	0.00	0.00	>0,999
Bunker silo	100	95.2	95.0	96.3	0.996
Drive-over pile silo	0.00	4.80	5.00	3.70	0.996

[1]P-value refers to the main effect of quadrants evaluated by a generalized linear model assuming a binomial error distribution;

[a,b,c]Within a row, means followed by different superscript letters differ significantly ($P < 0,05$) according to Fisher's least significant difference test.

Supplemental Material

Supplemental material S1.

1.IDENTIFICATION
1.1. Name of the farmer or technical manager:
1.2. Farm name:
1.3. City:

2. HERD	
2.1. Total Animals	
2.2. Total cows:	
2.3. Number of lactating cows:	**2.4.** Number of cows in high-production group:
2.5. Milk production (L/d):	
2.6. Milk composition: Protein_____ Fat_____ Lactose_____ MUN______	
2.7. High group mean milkyield:	**2.8.** Herd mean milk yield:
2.9. DIM herd:	**2.10.** DIM high group:

3. FACILITIES
3.1. Housing: ( ) Compost Barn ( ) Free Stall

4. WHOLE-PLANT CORN SILAGE PRODUCTION AND ENSILING PROCESS
4.1. Land leasing: ( ) Yes ( ) No
4.2. Machinery rental: ( ) Yes ( ) Not

4.3. Outsourced labor: ( ) Yes ( ) Not
4.4. Crop rotation: ( ) Yes ( ) Not
4.5. Type of plantation: ( ) No-tillage ( ) Conventional tillage ( ) Minimum tillage
4.6. Silage is purchased? ( ) Yes ( ) Not
4.7. Irrigated area: ( ) Yes ( ) Not
4.8. Fertigation area: ( ) Yes ( ) No
4.9. Soil correction practice: ( ) Yes ( ) Not
4.10. Mineral fertilizer application: ( ) Yes ( ) Not
4.11. Refuge area implementation: ( ) Yes ( ) Not
4.12. Herbicide application: ( ) Yes ( ) Not
4.13. Fungicide application: ( ) Yes ( ) Not
4.14. Insecticide application: ( ) Yes ( ) Not
4.15. How is the harvest maturity assessed? ( ) Milk line evaluation ( ) Dry matter evaluation ( ) Outro ( ) Not evaluation
4.16. What model of machinery is used for harvesting: ( ) Pull-type forage harvester ( ) Self-propelled forage harvester
4.17. Was the forage harvester equipped with a kernel processor?: ( ) Yes ( ) Not ( ) Kernel breaker ( ) no answer
4.18. Use of Shredlage processing: ( ) Yes ( ) Nao
4.19. Which analyses are conducted during harvest: ( ) DM ( ) %Corn <4,75mm "KPS" ( ) Penn State particle size separator
4.20. Does the farm use a silage inoculant? ( ) Yes ( ) Not

4.21. Does the farm apply a chemical additive to the silo face or surface? ( ) Yes ( ) Not
4.22. How is silage compaction carried out? ( ) tractor ( ) wheel loader ( ) Others______
4.23. Compaction time: ( ) < harvest ( ) = harvest ( ) > harvest
4.24. How silage is removed: ( ) Mixer wagon ( ) Wheel loader ( ) Silage fork ( ) Others_______
4.25. Which type of silo is used? ( ) Bunker silo ( ) Drive-over pile silo ( ) Others______