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Nutritional composition of corn silage produced in different regions of the State of Paraná between 2020 and 2022

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ABSTRACT. The study aimed to evaluate the nutritional composition of whole-plant corn silages produced in different geographic regions in the State of Paraná between 2020 and 2022. A database with 49 reports of chemical analysis of silage samples collected from 34 dairy cattle farms technically assisted by the Cooperativa de Trabalho e Extensão Rural (COOPERMAIS) was used. The farms are located in the Central-South, West, and Northwest meso-regions of Paraná. Due to intraregional geographic differences, the farms in the West region were grouped into three sub-regions: West-South, West-Central, and West-North. Silages with the highest ether extract content, lowest ash content, and highest total digestible nutrient (TDN) content were produced in the Northwest region. Silages produced in 2020 and 2022 had similar nutritional composition, while those produced in 2021 had lower TDN content. The whole-plant corn silage produced in the Northwest of Paraná has a better nutritional composition, which may be related to the higher proportion of grains at the time of ensiling. Rainfall and the occurrence of frost are climatic factors that affect the energy content of silages produced in the State of Paraná.

Keywords: ether extract; frost; grains; rainfall; total digestible nutrients.

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Introduction

Traditionally, whole-plant corn (*Zea mays* L.) silage is the most widely used bulk feed for dairy cows in Brazil (Bernardes & Rêgo, 2014). Silage is a form of forage preservation through anaerobic fermentation, and its production process consists of harvesting and grinding the entire corn plant, followed by storage and compaction of the ground material in a trench or surface silo. After compaction, the silo must be sealed with plastic tarpaulin and remain closed for at least 30 days so that fermentation occurs properly and the silage presents greater stability in its nutritional composition from the beginning of its supply to the animals (Weinberg & Chen, 2013). Among the reasons that justify the use of the whole corn plant for ensiling, the following stand out: ease of harvesting with the appropriate dry matter (DM) content, which varies from 28 to 40%; its fermentation potential due to the high concentration of soluble carbohydrates (sugars and starch) that are necessary for microorganisms; and its low buffering capacity, which is the ability to resist the drop in pH during the fermentation process (Jobim & Nussio, 2013).

Corn silage is the best quality among the forages used in dairy cows feeding. According to Jobim et al. (2007) and Fontaneli et al. (2012), forage quality is directly related to animal performance, in which better quality results in greater milk production or daily weight gain. When developing an index to estimate the quality of corn silage for dairy cows, Tharangani et al. (2021) observed that the contents of crude protein (CP), ether extract (EE), starch, ammonia, lactic acid of the silage, and the digestibility of neutral detergent fiber (NDF) after 30 hours of *in vitro* incubation explain 90% of the daily milk production. Considering that forage can compose up to 80% of the diet of dairy cows, evaluating the nutritional composition of silages from the moment the silos are opened is essential for the correct formulation of the total diet.

The nutritional composition of corn silage varies according to planting location, climate, corn cultivation management, ensiling process (Bernardes & Rêgo, 2014; Silva et al., 2015), hybrid used (Jaremtchuk et al., 2005; Martin et al., 2012a), harvest point (Horst et al., 2020; Neumann et al., 2020) and pest occurrence

(Balieiro Neto et al., 2013; Ávila et al., 2021; Oliveira et al., 2023). In this context, this study aimed to evaluate the nutritional composition of whole-plant corn silages produced on dairy farms located in different geographic regions of the State of Paraná between 2020 and 2022.

Material and methods

The study was carried out using a database formed from 49 reports of chemical analysis of whole-plant corn silage samples. The samples were taken between 2020 and 2022 on 34 dairy cattle farms receiving technical assistance from the Cooperativa de Trabalho e Extensão Rural (COOPERMAIS), headquartered in Francisco Alves, State of Paraná (24° 03′ 59″ S, 53° 50′ 41″ W and 352.7 m above sea level), Brazil.

The properties are located in three meso-regions of the State of Paraná: Central-South, West, and Northwest. Therefore, the silages were produced under different conditions of altitude, soil, climate, relief, and risk of pest incidence, and with different corn hybrids, technological levels, and ensiling processes. Due to intra-regional geographic differences, the West meso-region was divided into three sub-regions: West-South, West-Central, and West-North. The properties are located in the following municipalities: Laranjeiras do Sul, Nova Laranjeiras and Porto Barreiro in the Central-South meso-region; Serranópolis do Iguaçu and Três Barras do Paraná in the West-South sub-region; Cascavel and Santa Tereza do Oeste in the West-Central sub-region; Maripá, Nova Santa Rosa, Palotina, Terra Roxa and Toledo in the West-North sub-region; and Altônia, Iporã, and Tapira in the Northwest meso-region (Table 1).

Table 1. Area for planting corn for silage production, herd breed, and milk production on small and medium-sized properties in the meso-regions of Paraná that were assisted by COOPERMAIS between 2020 and 2022.

Property	Meso-region	Municipality	Corn planting area		Herd breed	Lactating cows	Average milk yield per cow	Average milk production volume
			Harvest (ha)	Off-season (ha)		(n)	(L cow $^{-1}$ day^{-1})	(L day^{-1})
1	Central-South	Laranjeiras do Sul	6.1	8.5	Holstein	19	28.0	533
2	Central-South	Nova Laranjeiras	14.5	14.5	Holstein	34	23.8	803
3	Central-South	Porto Barreiro	7.0	9.0	Holstein	35	20.0	709
4	West-South	Serranópolis do Iguaçu	6.8	6.8	Holstein	23	15.0	350
5	West-South	Serranópolis do Iguaçu	4.0	4.0	Holstein	25	19.6	483
6	West-South	Três Barras do Paraná	2.3	9.7	Jersolando	25	18.0	458
7	West-South	Três Barras do Paraná	5.8	5.8	Holstein	34	16.8	567
8	West-South	Três Barras do Paraná	3.6	6.1	Holstein	19	19.0	367
9	West-South	Três Barras do Paraná	3.6	3.6	Gir/Holstein	28	13.8	383
10	West-South	Três Barras do Paraná	1.2	12.1	Holstein	16	22.0	360
11	West-South	Três Barras do Paraná	8.0	8.0	Holstein	38	24.0	900
12	West-South	Três Barras do Paraná	4.0	3.5	Holstein	26	17.0	450
13	West-Central	Cascavel	0.0	16.0	Holstein	19	16.3	317
14	West-Central	Santa Teresa do Oeste	14.5	14.5	Holstein	36	23.6	857
15	West-Central	Santa Teresa do Oeste	7.3	16.9	Holstein	52	19.3	1,003
16	West-North	Maripá	2.9	5.3	Holstein	18	19.5	342
17	West-North	Maripá	12.1	0.0	Holstein	23	23.0	533
18	West-North	Maripá	4.0	6.1	Holstein	18	16.5	300
19	West-North	Maripá	2.9	10.2	Holstein	18	22.8	421
20	West-North	Maripá	5.0	5.0	Jersey	10	15.5	160
21	West-North	Maripá	3.5	2.4	Holstein	23	27.0	617
22	West-North	Nova Santa Rosa	4.4	9.7	Holstein	13	19.0	244
23	West-North	Palotina	3.6	3.6	Holstein	15	18.5	283
24	West-North	Palotina	4.4	4.4	Holstein	14	18.8	265
25	West-North	Terra Roxa	4.8	30.3	Holstein/Jersey	40	19.0	766
26	West-North	Toledo	7.3	12.1	Holstein	22	23.0	500
27	West-North	Toledo	7.3	9.7	Holstein	31	20.5	633
28	Northwest	Altônia	4.8	0.0	Jersolando	26	14.0	367
29	Northwest	Iporã	4.2	4.2	Holstein	22	21.2	466
30	Northwest	Iporã	3.6	2.4	Girolando	13	13.0	167
31	Northwest	Iporã	4.4	4.4	Girolando	15	14.5	217
32	Northwest	Iporã	11.4	11.4	Jersolando/Holstein	56	18.5	1,033
33	Northwest	Iporã	3.8	3.8	Girolando	28	20.0	567
34	Northwest	Tapira	7.3	7.3	Holstein	28	19.5	547
Mean			5.6	8.0		25	19.4	499
Minimum			0.0	0.0		10	13.0	160
Maximum			14.5	30.3		56	28.0	1,033

The farms are classified as small to medium-sized dairy farms, where production systems combine pasture feeding with corn silage and concentrate, and feeding only with corn silage and concentrate supplied in troughs distributed in open areas or compost barns. The average volume of milk production on the farms is approximately 500 L day^{-1}, ranging from 160 to 1,033 L day^{-1} (Table 1). In most farms (82.4%), the herd is formed by Holstein cows, followed by the Girolando and Jersey breeds (8.8% each), and Jersolando cows (8.8%), which are the result of crossbreeding between the Holstein and Jersey breeds. The farms have, on average, 25 lactating cows, ranging from 10 to 56 lactating cows in the herd. The average individual milk yield is 19.4 L/cow/day, varying between 13 and 28 L cow^{-1} day^{-1}. The harvest and off-season corn are cultivated for silage production on 97.1 and 94.1% of properties, respectively.

The rainfall indices for each meso-region/sub-region in each ensiling year were made available by the Paraná Environmental Monitoring and Technology System (*Sistema de Tecnologia e Monitoramento Ambiental do Paraná* – SIMEPAR, 2023). In addition to rainfall, data on altitude and minimum temperature were obtained in municipalities in each meso-region/sub-region where SIMEPAR meteorological stations are located (Table 2). The frequency of frosts was estimated from the minimum temperature data, in which temperatures equal to or below 3°C were indicative of frost according to Grodzki et al. (1996). The climatological data refer to the agricultural zoning indicated for each municipality for corn planting, considering the type of soil (sandy for the Northwest region and clayey for the others), 20% risk of crop loss, and an average of 100 days for the corn cycle for silage production.

Table 2. Altitude, rainfall, and frequency of frosts in the regions/sub-regions of the state of Paraná where samples of whole-plant corn silage were collected.

Index	Year	Region/Sub-region				
		Central-South	West-South	West-Central	West-North	Northwest
Altitude[1] (m)	-	838.0	312.0	719.3	303.0 – 516.4	368.0
Rainfall (mm)	2020	339.0	495.3	569.7	567.5	348.8
	2021	545.0	402.9	515.0	481.3	414.2
	2022	612.8	970.3	1,198.8	986.7	791.4
Frost (n)	2020	3	4	5	9	0
	2021	10	10	12	14	5
	2022	5	5	7	8	0

[1]Central-South = Laranjeiras do Sul; West-South = São Miguel do Iguaçu; West-Central = Cascavel; West-North = Palotina (lowest altitude) and Toledo (highest altitude); Northwest = Altônia.

The chemical analyses were performed at the Physical-Chemical Analysis Laboratory Ltd. (*Laboratório de Análises Físico-Químicas* – LABNUTRIS), located in Santa Maria, State of Rio Grande do Sul. Samples were collected following the laboratory's recommendations. Initially, samples were taken from 6 to 10 points on the silo panel. From these samples, a single composite sample was formed, which was homogenized on a clean surface to prevent sample contamination. After homogenization, the composite sample was quartered twice. After the first quartering, two parts of the sample were discarded. The remaining two parts were used to form a new sample, which was homogenized and quartered again. After the second quartering, the remaining sample (approximately 500 g) was placed in plastic film or a plastic bag and pressed with the hands or on a surface to remove as much air as possible. After being packaged, compacted, well-sealed (with transparent adhesive tape), and identified, the samples were sent to LABNUTRIS within 5 days. Until they were sent, the samples were kept at room temperature.

In the laboratory, the samples were dried in a forced ventilation oven at 65°C for 72 hours (method 934.01; Association of Official Analytical Chemists [AOAC], 2006), and ground to 1 mm particles. Subsequently, the DM, CP, EE, NDF, acid detergent fiber (ADF), lignin, starch, ash, calcium (Ca), phosphorus (P), potassium (K), and magnesium (Mg) contents were determined by the near-infrared spectroscopy (NIRS) method. For these nutritional components, the calibration curve of corn silage was constructed from 1,339 to 4,212 samples analyzed in the NIRS equipment (BlueSun®, model 5000, spectral band of 1,100-2,500 nm). The PTNF-001, Rev. 00, method 11 according to the Brazilian Compendium of Animal Feed (CBAA, 2023) was used. The non-fiber carbohydrate (NFC) content was calculated according to Hall et al. (1999), and the total digestible nutrient (TDN) content was calculated as described in the National Research Council (NRC, 2001).

Statistical analyses were run using the Statistical Analysis System (SAS) program, version 9.0 (SAS, 2002). In all analyses, a probability value of 0.10 was considered to declare that the effects of the factors studied were significant.

Initially, the data were subjected to the Shapiro-Wilk normality test (PROC UNIVARIATE) to assess the distribution of each variable analyzed. Subsequently, the data that did not present a normal distribution were transformed using a ranking procedure (PROC RANK). The data that presented a normal distribution and those that were normalized through transformation were tested by analysis of variance in a mixed model (PROC MIXED), in which the geographic region of the State of Paraná (Central-South, West-South, West Central, West-North, and Northwest) and ensiling year (2020, 2021 and 2022) were included as fixed effects; the type of corn crop (harvest or off-season) was included as a covariate; and rural producer nested within geographic region and year was included as a random effect. When fixed effects were significant ($p < 0.10$), means were compared using the Tukey-Kramer test (LSMEANS function of PROC MIXED).

Results and discussion

Regions of the State of Paraná

The contents of DM, CP, NDF, ADF, lignin, NFC, starch, and minerals Ca, P, K, and Mg of whole-plant corn silage were similar ($p > 0.10$) between the regions of the State of Paraná (Table 3). The mean values and standard deviation (SD) of these components were 32.82 ± 6.72% for DM, 8.50 ± 0.69% for CP, 43.62 ± 3.84% for NDF, 26.08 ± 3.49% for ADF, 2.30 ± 0.55% for lignin, 40.24 ± 4.15% for NFC, 23.01 ± 9.93% for starch, 0.20 ± 0.03% for Ca, 0.19 ± 0.01% for P, 1.36 ± 0.19% for K, and 0.20 ± 0.02% for Mg. Zardin et al. (2017) performed a meta-analysis of studies conducted in Brazil on the nutritional composition of corn silage and reported similar DM, starch, Ca and P contents (32.52, 20.15, 0.17 and 0.19%, respectively), higher NDF, ADF and lignin contents (54.82, 29.93 and 5.41%, respectively) and lower CP and NFC contents (7.56 and 29.18%, respectively). These results indicate that the silages produced in the evaluated regions in Paraná presented high quality, which may be related to the harvest of the plant containing grains at a more advanced maturity stage. Under this condition, there is an increase in the proportion of grains and a reduction in the proportion of fiber components in the ensiled mass, resulting in a better nutritional composition of the silage when the corn plant is harvested with grains in the dough and dent stages (R_4 to R_5 stages) (Horst et al., 2020; Neumann et al., 2020).

The EE content was higher ($P = 0.030$) in silages produced in the Northwest region, with 3.17%, followed by the West-South and West-North regions, which did not differ from the other regions and presented an average of 2.91%, and by the Central-South and West-Central regions with an average of 2.65% (Table 3). The ash content was lower ($P = 0.082$) in silages produced in the Northwest region, with 4.36%, compared to those produced in the other regions, which were similar to each other and presented an average of 4.84%. Although the proportion of grains was not evaluated in the silages, possibly those produced in the Northwest region presented a higher proportion of grains, resulting in a higher EE content and lower ash content. This is corroborated by the high lipid content of the germ in the grains (Magalhães et al., 2002; National Research Council [NRC], 2021; Noormohammadi et al., 2022). The EE content is one of the nutritional components that most affect milk production in dairy cows and, therefore, is a strong indicator of the nutritional quality of corn silage (Tharangani et al., 2021). Regardless of the differences between regions, the EE and ash contents were close to those reported by Zardin et al. (2017), who found 2.84 and 5.02%, respectively.

Table 3. Dry matter content (% natural matter), nutrients, and energy (% dry matter) of corn silage produced in dairy farms assisted by COOPERMAIS located in different geographic regions/sub-regions of the State of Paraná.

Composition[I]	Region/Sub-region					*P*-value
	Central-South	West-South	West-Central	West-North	Northwest	
Samples (n)	3	10	10	19	7	
Dry matter	29.42 ± 3.84	30.54 ± 1.99	34.10 ± 2.14	33.72 ± 1.84	33.25 ± 0.86	0.894
Crude protein	8.08 ± 0.26	8.05 ± 0.17	8.75 ± 0.17	8.59 ± 0.19	8.71 ± 0.19	0.243
Ether extract	2.50 ± 0.19 b	2.89 ± 0.11 ab	2.81 ± 0.12 b	2.94 ± 0.07 ab	3.17 ± 0.08 a	0.030
NDF	46.02 ± 2.88	45.19 ± 1.29	43.52 ± 1.23	43.69 ± 0.85	40.27 ± 0.65	0.163
ADF	27.66 ± 2.95	27.55 ± 1.11	26.29 ± 1.05	26.20 ± 0.76	22.71 ± 0.75	0.164
Lignin	3.02 ± 0.66	2.29 ± 0.13	2.16 ± 0.06	2.37 ± 0.13	2.14 ± 0.32	0.308
NFC	38.44 ± 3.28	38.93 ± 1.33	40.10 ± 1.27	40.09 ± 1.01	43.49 ± 0.67	0.324
Starch	15.51 ± 9.23	20.19 ± 3.17	22.02 ± 3.17	23.71 ± 2.25	29.79 ± 1.43	0.311
Ash	4.95 ± 0.45 a	4.89 ± 0.11 a	4.85 ± 0.10 a	4.68 ± 0.11 a	4.36 ± 0.10 b	0.082
Calcium	0.19 ± 0.03	0.20 ± 0.01	0.19 ± 0.01	0.20 ± 0.01	0.23 ± 0.01	0.242
Phosphorus	0.19 ± 0.01	0.21 ± 0.01	0.19 ± 0.01	0.19 ± 0.01	0.20 ± 0.01	0.346
Potassium	1.37 ± 0.14	1.46 ± 0.05	1.37 ± 0.05	1.27 ± 0.04	1.48 ± 0.05	0.193
Magnesium	0.21 ± 0.02	0.20 ± 0.01	0.20 ± 0.01	0.20 ±0.01	0.18 ± 0.01	0.120
TDN	62.23 ± 5.71 b	65.99 ± 1.75 b	68.29 ± 1.58 b	68.50 ± 1.02 b	73.08 ± 0.99 a	0.044

[I]Values expressed as mean ± standard error; NDF: neutral detergent fiber; ADF: acid detergent fiber; NFC: non-fiber carbohydrates; TDN: total digestible nutrients. Different lowercase letters, in the same row, indicate significant differences by the Tukey-Kramer test ($p < 0.10$).

The differences in EE and ash contents between regions affected the TDN content of the silages (Table 3). The silages produced in the Northwest region had a higher (P = 0.044) TDN content, with 73.08%, while the other regions were similar to each other, with an average value of 66.25%. In addition to the nutritional profile, the difference in TDN content between regions may be related to the incidence of corn leafhopper (*Dalbulus maidis*) in the crop.

The hypothesis that the high infestation of leafhoppers affected the quality of the silages was raised based on the field knowledge of COOPERMAIS agronomists. When providing technical assistance on dairy farms, they observed the increasing presence of leafhoppers in the crops, the great challenge of controlling infestations, and, mainly, the damage caused to the corn, resulting in a decrease in silage production and quality. This observation corroborates Ávila et al. (2021), who reported that since 1990, there have been epidemic outbreaks of leafhoppers in corn crops, and in 2020 and 2021 the southern region of Brazil began to present more severe problems.

The leafhopper can transmit three pathogens that cause stunting by mollicutes (maize bushy stunt phytoplasma [MBSP] and corn stunt spiroplasma [CSS]) and the maize rayado fino virus (MRFV) (Oliveira et al., 2023), reducing grain production by more than 40% (Ávila et al., 2021; Canale et al., 2023). The North, Central-West, and West regions of Paraná are the most affected by the leafhopper, mainly where corn is sown at different times, in addition to being warmer and lower altitude regions (Ávila et al., 2021). In addition, most dairy producers grow soybeans in the harvest season and corn for silage only in the off-season. This results in the emergence of volunteer corn that develops from grains lost during harvest in soybean crops, which favors the leafhopper cycle until the next corn harvest. With the reduction in grain production, there is a reduction in the energy content of corn silage, which explains the lower TDN content in silages produced in the Center-South, West-North, West-Central, and West-South regions of Paraná. However, the TDN contents of these silages were close to those reported in studies with different corn hybrids and cultivars for whole-plant silage, which range from 57.9 to 71.9% (Jaremtchuk et al., 2005; Martin et al., 2012a; Zardin et al., 2017). The TDN content of silages produced in the Northwest region was closer to half-plant silages, which have a higher proportion of ears, in which the TDN content varies from 66.5 to 74.9% (Jaremtchuk et al., 2005; Aoki et al., 2013).

Ensiling year

The P content differed (P = 0.079) between the years of silage production (Table 4), with the highest value in 2021 (0.20%), followed by 2020 (0.19%), which did not differ from the other years, and by 2022 (0.18%). Despite the significant difference, there was little variation in the P content of silages between the years of production, with an average of 0.01 percentage points and a range of 0.02 percentage points between 2021 and 2022. The average P content of silages was similar to that reported by Zardin et al. (2017), 0.19% P in corn silages produced in Brazil.

Table 4. Dry matter content (% natural matter), nutrients, and energy (% dry matter) of corn silage in different ensiling years on dairy farms assisted by COOPERMAIS.

Composition[I]	Year			*P*-value
	2020	2021	2022	
Samples (n)	9	28	12	
Dry matter	32.95 ± 1.46	31.46 ± 1.34	35.89 ± 1.93	0.404
Crude protein	8.63 ± 0.20	8.36 ± 0.14	8.71 ± 0.19	0.528
Ether extract	3.00 ± 0.09	2.82 ± 0.07	3.04 ± 0.09	0.173
NDF	42.30 ± 0.95	44.45 ± 0.84	42.73 ± 0.81	0.532
ADF	24.31 ± 0.91	26.77 ± 0.75	25.85 ± 0.74	0.338
Lignin	2.22 ± 0.23	2.25 ± 0.09	2.50 ± 0.18	0.227
NFC	41.47 ± 1.06	39.56 ± 0.92	40.88 ± 0.87	0.729
Starch	26.82 ± 2.13	20.26 ± 2.14	26.58 ± 1.84	0.343
Ash	4.62 ± 0.12	4.80 ± 0.09	4.64 ± 0.12	0.474
Calcium	0.21 ± 0.01	0.20 ± 0.01	0.20 ± 0.01	0.935
Phosphorus	0.19 ± 0.01 ab	0.20 ± 0.01 a	0.18 ± 0.01 b	0.079
Potassium	1.37 ± 0.08	1.42 ± 0.03	1.22 ± 0.04	0.125
Magnesium	0.19 ± 0.01	0.20 ± 0.01	0.20 ± 0.01	0.893
TDN	70.82 ± 1.19 a	66.33 ± 1.11 b	70.67 ± 1.09 a	0.099

[I]Values expressed as mean ± standard error; NDF: neutral detergent fiber; ADF: acid detergent fiber; NFC: non-fiber carbohydrates; TDN: total digestible nutrients. Different lowercase letters, in the same row, indicate significant differences by the Tukey-Kramer test (p < 0.10).

The TDN content also differed (P = 0.099) between ensiling years (Table 4), with higher values in 2020 and 2022, which were similar to each other and had an average value of 70.74%, and a lower value in 2021, which had an average of 66.33%. This variation in the energy content of silages may be related to the variation in grain production between the years of production, which may have been affected by rainfall and the occurrence of frost.

Corn is a very water-demanding crop, consuming 400 to 700 mm of water during its production cycle (Andrade et al., 2006; Martin et al., 2012b). Water demand is high at three times: during flower initiation and inflorescence development (V_{10} to V_{17} stages) – when the potential number of grains is determined; during the fertilization period (V_T to R_1 stages) – when the production potential is fixed; and during grain filling (R_1 to R_5 stages), when there is greater accumulation of DM, which is closely related to photosynthesis (Magalhães et al., 2002). The most critical time for water stress is close to the R_1 stage. Water deficits before, during, and after this stage can cause losses of up to 30, 50, and 20% in productivity, respectively (Andrade et al., 2006). Among the production years evaluated, 2022 was the year with adequate rainfall levels (Table 2) to meet the requirements of the corn crop. In 2020 and 2021, there was lower rainfall, and a high incidence of leafhoppers in the corn crop, as previously mentioned. The lowest rainfall rates were recorded in 2021, which contributed to a reduction in the energy content of the silage produced this year (Table 4).

In 2021 there was a higher occurrence of frost (Table 2), which may also have caused lower grain production and a reduction in the TDN content of silage (Table 4). Frost is an atmospheric phenomenon that causes the freezing of plant tissues due to low air temperatures, with or without ice formation, and which can cause plant death (Pereira et al., 2007; Taiz & Zaiger, 2016). In this condition, plants change metabolism due to the freezing of their internal structures. According to Larcher (2004), the peripheral vascular bundles freeze and then the protoplast dehydrates, releasing ions of salts and organic acids that inactivate enzymes and have a toxic effect on the plant cell, resulting in the destruction of the cytoplasm.

The physicochemical process of frost begins when the plant reaches its lethal temperature, which in corn is -2°C in the leaf at the time of germination (V_E stage) and flowering (V_T stage), and -3°C at fertilization and grain filling (R_1 to R_5 stages) (Pereira et al., 2007). Frost causes great damage at these times due to the loss of leaf area, which reduces photosynthesis in plant establishment and at the time of accumulation of carbohydrates (starch) in the grains. Ximenes et al. (2004) evaluated the effect of frost on corn productive attributes (grain/ear mass, grain mass in 20 ears, and apparent specific weight) and concluded that the accumulation of DM in the grains was inversely proportional to the damage caused in the leaf area of the plants. However, until the growing point is below the soil (V_6 stage) and from the moment the grain dent forms (R_5 stage), the damage caused by frost is almost imperceptible (Cruz et al., 2011). Therefore, the reduction in TDN content in silages produced in 2021 suggests that corn crops were exposed to frost from the emergence of growing point above the ground, during the vegetative phase, to the grain filling stage, causing a decrease in carbohydrate accumulation in the grains. The lower starch content of silages produced in 2021 (20.3%) compared to those produced in 2020 and 2022 (average of 26.7%; Table 4) reinforces this hypothesis, even though the starch content did not differ (P = 0.343) between the production years evaluated.

Technical considerations

This study demonstrated that the nutritional composition of whole-plant corn silage is affected by the meso-regions/sub-regions of Paraná where the properties assisted by COOPERMAIS are located. The differences in silage quality are possibly related to the corn harvest point and the occurrence of leafhopper infestation. Among the regions evaluated, the Northwest produced the best quality silage between 2020 and 2022, probably due to the later harvest point and the low leafhopper infestation in the corn crop. The later harvest and greater plant integrity result in higher grain production, increasing the quality of the ensiled mass and the silage produced. Climatic factors such as rainfall and the occurrence of frost mainly affect the energy content of the silages. In this case, the energy content of whole-plant corn silage increases when corn cultivation occurs under adequate rainfall and with a lower incidence of frost.

The results and information generated here can be used as a reference to assess the quality of whole-plant corn silages produced in Paraná. Furthermore, based on the causes of variation in the nutritional composition of the silages evaluated, more assertive decisions can be made such as defining the best time to harvest corn for ensiling and controlling leafhopper infestations more effectively. Understanding how rainfall and frost affect corn crops allows us to estimate the quality of silage that will be produced under suitable and harsh weather conditions.

Conclusion

Whole-plant corn silage produced in the Northwest of Paraná has a better nutritional composition, which may be related to the higher proportion of grains in the ensiled mass and better health condition of the plants at the time of harvest. Rainfall and the occurrence of frost are climatic factors that vary annually and mainly affect the energy content of silage produced in Paraná.

Data availability

Not applicable.

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