

Article

Agronomic Performance and Grain Quality of Green Maize as Affected by Cover Crops and No-Till System Stages

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Abstract

This study evaluated the agronomic and bromatological characteristics of green maize grown under different cover crops and developmental stages of the no-till system (NTS) in the Brazilian Cerrado. A randomized block design with a 6×3 factorial arrangement and four replications was used. Six cover crops were evaluated: *Brachiaria* (B), Pearl millet (PM), Sunn hemp (SH), and mixtures B + SH, B + PM, and PM + SH. Three NTS stages were assessed: initial (1 year, NTS1), transition (8 years, NTS8), and consolidation (20 years, NTS20). Evaluated variables included cover crop dry matter (DM), green maize ear yield with husk (EYH), shucked ear yield (SEY), straw yield (SY), grain yield per ear (GYE), and grain bromatological characteristics: pH, moisture (HU), ash (AS), lipids (LIP), protein (PTN), carbohydrates (CHE), total titratable acidity (TTA), total soluble solids (TSS), and ascorbic acid (AA). SH and the PM + SH mixture produced the highest DM across the NTS stages. Cover crop residues did not affect green maize yield attributes, whereas progression through NTS stages increased SEY, EYH, and GYE. Bromatological quality was mostly unaffected by cover crops, except for moisture and TSS, while NTS stages influenced pH, moisture, LIP, PTN, TTA, TSS, and AA. The integrated use of cover crops, either as sole crops or intercropping systems, associated with long-term no-till adoption, contributes to increased biomass production and improved grain quality attributes of green maize under Cerrado conditions.

Keywords: intercropping; tropical agroecosystems; cerrado soils; biomass accumulation; kernel composition



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1. Introduction

Maize (*Zea mays* L.) is one of the most important crops in Brazilian agriculture due to its economic significance and strategic role in global grain markets. Maize production in Brazil is estimated at 138.0 million tons for the 2025/26 season, representing approximately 40% of the total national grain production of 341.2 million tons and consolidating the country as one of the world's largest grain producers [1,2]. In addition to its importance for international trade, maize plays a fundamental role in food security and animal feed production.

Although most maize production in Brazil is intended for dry grain harvest, part of the crop is marketed as green maize, which offers higher added value and faster economic returns to producers. Green maize is harvested at the milk stage, approximately 70 to 90 days after planting, when the ears have 70–80% moisture content, maintaining desirable physicochemical characteristics for consumption [3,4]. Green maize production has expanded in Brazil, particularly in the Southeast, Northeast, and Midwest regions [1,5].

Due to its short production cycle, green maize is often cultivated under intensive production systems. In many cases, these systems still rely on conventional tillage, which involves repeated soil disturbance and may result in erosion, compaction, and nutrient losses through leaching [6]. In contrast, the no-tillage system (NTS) has been widely adopted in grain production because it reduces soil degradation, increases soil organic matter, and improves water and nutrient use efficiency [7,8].

The benefits of NTS are associated with the absence of soil disturbance, the retention of crop residues on the soil surface, and crop rotation practices, which gradually improve soil physical, chemical, and biological properties [9,10]. Currently, approximately 33 million hectares of grain crops in Brazil are managed under NTS [11]. However, the efficiency of this system largely depends on the use of cover crops capable of producing high biomass and promoting nutrient cycling.

In the Brazilian Cerrado, pearl millet (*Pennisetum glaucum*), brachiaria (*Urochloa* spp.), and sunn hemp (*Crotalaria* spp.) are among the most commonly used cover crops, grown either as sole crops or in intercropping systems. These species are well adapted to the region's edaphoclimatic conditions and contribute to soil protection, moisture conservation, and gradual nutrient cycling through nutrient uptake from deeper soil layers and their subsequent release during residue decomposition, benefiting subsequent crops [7,12].

Some studies report yield increases, whereas others indicate limited effects, suggesting that system performance depends on cover crop species, residue production, and soil management history [13–16]. This variability is associated with the different phases of NTS establishment—initial, transitional, and consolidated—which present distinct soil responses [17,18]. Although the effects of cover crops on crop productivity are well documented, gaps remain regarding the interaction between different species and NTS developmental stages, particularly under Cerrado conditions [6,19].

In addition to agronomic performance, soil management practices may also influence the chemical quality of green maize, including protein and lipid content, moisture, soluble solids, and ascorbic acid. Residues from cover crops can release nutrients and organic compounds into the soil, influencing nutrient availability and crop performance [15,20]. Although some studies have reported effects of crop residues on the chemical composition of maize and other vegetables [9,21], information regarding the interaction between cover crop species and NTS developmental stages and their influence on the bromatological quality of green maize remains limited, particularly under Cerrado conditions. Furthermore, most studies have focused primarily on ear yield with husk, whereas the effects of these management practices on the chemical quality of green maize have received comparatively little attention. Understanding these interactions is essential for developing production systems capable of improving both productivity and nutritional quality.

Given this context, this study hypothesized that systems with longer consolidation times and greater functional diversity of cover crops promote improvements in the edaphic environment, which are reflected in both the agronomic performance and chemical composition of green maize. Thus, the objective of this study was to evaluate the agronomic and bromatological attributes of green maize grown under different cover crops and at different stages of no-till system (NTS) development in the Cerrado.

2. Materials and Methods

The study was conducted in an experimental area located in the municipality of Uberaba, Minas Gerais, Brazil (19°39'19" S; 47°57'27" W; 795 m elevation), during the 2019/2020 growing season. Prior to the establishment of the experiment, all areas had been cultivated under a conventional tillage system, with soil preparation involving two harrow operations (a heavy disk harrow and a leveling harrow), in rotation with maize, soybean, sorghum, and beans in an annual cropping system, without a second crop.

The soil in the area was classified as an Oxisol [22] or Typic Hapludox [23], with a sandy loam texture, containing 220 g kg⁻¹ clay, 720 g kg⁻¹ sand, and 60 g kg⁻¹ silt in the 0–0.40 m layer. The initial soil chemical characteristics at depths of 0–0.10, 0.10–0.20, and 0.20–0.40 m are presented in Table 1, considering the three no-till system phases: initial, transition, and consolidation.

Table 1. Initial soil chemical properties at different soil depths under no-till system phases (SP), initial (NTS1), transition (NTS8), and consolidation (NTS20) in Uberaba, Minas Gerais, Brazil, before the 2019/2020 growing season.

System	pH	P (Mehl-1)	K ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	Al ³⁺	H + Al	MO
	H ₂ O	mg kg ^{−1}	Cmolc dm ^{−3}						g kg ^{−1}
0.00–0.10 m									
NTS1	5.00	27.43	0.18	1.64	1.40	0.03	0.27	3.49	12.66
NTS8	4.85	18.35	0.18	1.19	1.29	0.03	0.43	4.81	12.98
NTS20	4.85	14.85	0.22	1.37	1.05	0.04	0.35	4.91	14.23
0.10–0.20 m									
NTS1	4.90	9.31	0.07	1.32	0.97	0.03	0.32	3.46	10.38
NTS8	4.50	9.52	0.12	0.65	1.22	0.03	0.50	4.54	11.71
NTS20	4.60	9.29	0.14	0.87	1.25	0.04	0.27	5.16	10.64
0.20–0.40 m									
NTS1	5.00	27.43	0.06	1.22	1.15	0.03	0.40	3.39	8.45
NTS8	4.70	14.97	0.10	0.42	0.97	0.04	0.27	3.72	7.93
NTS20	4.70	12.09	0.11	0.62	0.97	0.03	0.43	4.70	7.76

Note: Soil chemical properties were used only for initial characterization of the experimental areas. Values refer to soil chemical characterization at each depth and no-till system phase; therefore, standard deviations are not presented for this table. NTS1: no-till system for one year (initial phase); NTS8: no-till system for eight years (transition phase); NTS20: no-till system for 20 years (consolidation phase); P: available phosphorus (Mehlich-1).

Sixty days before sowing, soil acidity was corrected by applying 1200 kg ha⁻¹ of limestone containing 36.4% CaO, 14% MgO, 99.87% neutralizing power, and 90.28% effective calcium carbonate equivalent, uniformly distributed across all experimental plots.

The region's climate is classified as Aw (tropical savanna) according to the updated Köppen classification, characterized by hot, rainy summers and dry, mild winters, with an average annual precipitation of 1600 mm and an average annual temperature of 22.6 °C [24,25]. During the green maize growing season (February to May 2020), cumulative precipitation was 463.5 mm, distributed as follows: February (232 mm), March (100.5 mm), April (106 mm), and May (25 mm).

During the experimental period, rainfall was concentrated mainly between November and March, corresponding to the rainy season in the Brazilian Cerrado. Green maize culti-

vation occurred from February to May 2020 under supplemental irrigation provided by a conventional sprinkler system. Irrigation was scheduled according to reference evapotranspiration requirements, ensuring adequate water availability throughout crop development despite the progressive reduction in rainfall toward the end of the growing season.

The experiment was conducted in a randomized block design, arranged in a 6×3 factorial scheme with four replicates. The first factor consisted of six cover crop systems: brachiaria (B) (*Urochloa brizantha* cv. *Marandu*), pearl millet (PM) (*Pennisetum glaucum* L.), sunn hemp (SH) (*Crotalaria spectabilis*), and the mixtures B + SH, B + PM, and PM + SH. The second factor corresponded to three stages of no-till system (NTS) development: initial (NTS1, 1 year), transition (NTS8, 8 years), and consolidation (NTS20, 20 years). The NTS stages were represented by adjacent areas with different histories of system adoption, while cover crop treatments were randomly assigned within each area.

Because the NTS stages were represented by adjacent areas with different durations of no-till adoption rather than by randomized assignment, the comparison among NTS phases should be interpreted as a chronosequence approach. Therefore, although management history was the primary distinguishing factor among areas, part of the observed variation may also be associated with pre-existing site heterogeneity.

Each experimental plot received uniform management for green maize cultivation, with 0.50 m row spacing and three seeds per meter, resulting in a plant density of 60,000 plants ha^{-1} , along with standardized fertilization, irrigation, and phytosanitary management.

Maize was sown mechanically across the entire experimental area without considering the position of the previous cover crop rows. Sowing followed the contour lines of the terrain, as previously adopted for cover crop establishment, resulting in a uniform distribution of maize plants over the residue-covered soil surface.

Irrigation was supplied by a conventional sprinkler system throughout the crop cycle. Water applications were performed daily and scheduled according to reference evapotranspiration requirements, with an average irrigation duration of approximately 20 min per day to maintain adequate soil moisture for crop development.

Cover crops were sown using a Semina 2 (SB Agricultural Machinery, Cambé, Paraná, Brazil) seeder with five rows spaced 0.20 m apart, in 30 m^2 plots (6×5 m). The effective plot area consisted of the four central rows, excluding 0.5 m at both ends.

Sowing densities were 20, 50, and 50 seeds per meter for sunn hemp (SH), *brachiaria* (B), and pearl millet (PM), respectively, according to regional agronomic recommendations. In the mixtures (B + SH, PM + B, and PM + SH), half the recommended seed rate of each species was used, with seeds pre-mixed prior to sowing. No fertilizers or phytosanitary treatments were applied to the cover crops.

Cover crops were sown on 10 November 2019 and grown until 8 February 2020, when they were desiccated for residue formation. Green maize was subsequently sown on 15 February 2020 and harvested at the R3 stage, approximately 80 days after sowing, on 5 May 2020.

At 90 days after sowing, when approximately 50% of the species had reached maximum flowering, samples were collected from an area of 1.6 m^2 per plot, covering the four central rows. All fresh plant material within the delimited area was harvested and weighed to determine fresh mass (FM), and then oven-dried at 65 °C until constant weight to determine dry mass (DM), with results expressed in kg ha^{-1} [26].

Immediately after sampling, the cover crops were desiccated with 1440 g ha^{-1} of glyphosate acid equivalent (approximately 2 kg ha^{-1} of the commercial product Roundup WG® (Monsanto do Brasil Ltda, São José dos Campos, São Paulo, Brazil)), applied using a tractor-mounted boom sprayer with a spray volume of 250 L ha^{-1} .

After cover crop desiccation, the AG7098PRO2 maize hybrid (Agrocere/Bayer, Cachoeira Dourada, Minas Gerais, Brazil) was mechanically sown over the residues, with 0.50 m row spacing and three seeds per meter, resulting in a plant population of 60,000 plants ha⁻¹. This hybrid is genetically modified, resistant to major maize pests and glyphosate, with an early maturity cycle of 90 to 105 days. The four central rows were used for evaluations.

Basal fertilization was performed according to soil analysis and technical recommendations, applying 32, 112, and 64 kg ha⁻¹ of N, P₂O₅, and K₂O, respectively, using the 4-14-8 + Zn formulation, following [27]. Two topdressings were applied: the first at 20 days after sowing, with 70 kg ha⁻¹ of N and 70 kg ha⁻¹ of K₂O (20-00-20 formulation); the second at 40 days after sowing, with 70 kg ha⁻¹ of N as urea. Basal fertilization was mechanized, whereas topdressing was applied manually.

Pest and disease monitoring was conducted weekly throughout the crop cycle. Chemical control was applied when necessary, using recommended insecticides and fungicides, with a Jacto 2000 (Jacto Agricultural Machinery S.A., Pompeia, São Paulo, Brazil) boom sprayer calibrated to deliver 200 L ha⁻¹ of spray solution.

Green maize was harvested manually starting at 80 days after sowing (R3 stage), when kernels had approximately 75% moisture and ears were about 15 cm long and 3 cm in diameter, meeting commercial standards [4]. Twenty-four ears were randomly harvested from the central rows of each plot and transported to the laboratory, where they were weighed to determine shucked ear yield, husk/straw yield, and ear yield with husk, which were then extrapolated to Mg ha⁻¹.

Husk mass was determined after removing the leaves from the ears, and grain yield was obtained after manual shelling, with values expressed in kg ha⁻¹ and percentage.

Part of the harvested material (ears) was sent to the IFTM Food Analysis Laboratory for the determination of moisture (HU), ash (AS), lipids (LIP), proteins (PTN), carbohydrates (CHE), total soluble solids (TSS), total titratable acidity (TTA), pH, and ascorbic acid (AA). Analyses followed standard methodologies: moisture by the gravimetric method; protein by the Kjeldahl method (conversion factor 6.25); lipids by the Soxhlet method; and ascorbic acid by the Tillmans method, according to [28].

Ash content was determined by muffle furnace calcination at 550 °C until constant weight. Total titratable acidity and predominant acid content were determined according to [29], while pH was measured using a pH meter at 25 °C.

Total soluble solids were measured by electronic refractometry. Total energy value was calculated based on macronutrient composition. Dried samples were used for nitrogen, lipid, moisture, and ash analyses, whereas the remaining analyses were performed on fresh samples collected within 24 h after harvest, stored under refrigeration in plastic bags, according to [28].

The data were subjected to normality analysis using the Lilliefors test and homogeneity of variances using the Cochran test. After verifying these assumptions, data were analyzed by analysis of variance (ANOVA). When significant interactions were observed, means were compared using Tukey's test at a 5% significance level ($p \leq 0.05$). Statistical analyses were performed using AgroEstat software, version 1.1.

3. Results

3.1. Dry Matter Production

Analysis of dry matter (DM) production showed that sunn hemp (11.15 Mg ha⁻¹) stood out among the cover crops grown as sole crops, while the pearl millet + sunn hemp (PM + SH) mixture (9.11 Mg ha⁻¹) showed the highest DM production among intercropping

systems. In contrast, brachiaria (B) (6.35 Mg ha^{-1}) produced the lowest DM among all evaluated treatments (Table 2).

Table 2. Dry matter (DM) production of cover crops as affected by cover crop systems (CC) and no-till system phases (SP), initial (NTS1), transition (NTS8), and consolidation (NTS20) in Uberaba, Minas Gerais, Brazil, during the 2019/2020 growing season.

Treatment	Dry Matter (Mg ha^{-1})
Cover crops (CC)	
Brachiaria (B)	$6.35 \pm 2.83 \text{ d}$
Pearl millet (PM)	$7.30 \pm 1.32 \text{ c}$
Sunn hemp (SH)	$11.15 \pm 3.72 \text{ a}$
B + SH	$7.93 \pm 2.23 \text{ c}$
B + PM	$7.38 \pm 1.34 \text{ c}$
PM + SH	$9.11 \pm 3.10 \text{ b}$
System phases (SP)	
NTS1	$7.14 \pm 1.58 \text{ b}$
NTS8	$10.97 \pm 3.12 \text{ a}$
NTS20	$6.50 \pm 1.49 \text{ b}$
CC F-test	20.93 **
F-test SP	84.60 **
CC $\times$ SP interaction	4.28 **
CV (%)	15.69

Note: Values are presented as mean $\pm$ standard deviation. Means followed by the same lowercase letter within each factor do not differ according to Tukey's test at $p \leq 0.05$. ** indicates significance at $p \leq 0.05$. NTS1: no-till system for one year; NTS8: no-till system for eight years; NTS20: no-till system for 20 years; CV: coefficient of variation.

Regarding the system phases, the NTS8 area (transition phase) showed significantly higher DM production compared to NTS1 (initial phase) and NTS20 (consolidation phase), which did not differ statistically.

The analysis of the significant interaction between cover crops and system phases (SP) showed that sunn hemp (SH) presented the highest DM values in all three phases of the no-till system: initial (9.39 Mg ha^{-1}), transition (15.32 Mg ha^{-1}), and consolidation (8.72 Mg ha^{-1}). In contrast, brachiaria (B) showed the lowest DM values in the same phases: 4.81 , 10.07 , and 4.17 Mg ha^{-1} , respectively (Table 3).

Table 3. Interaction between cover crop systems (CC) and no-till system phases (SP) for dry matter (DM) production of cover crops in Uberaba, Minas Gerais, Brazil, during the 2019/2020 growing season.

Cover Crops	NTS1	NTS8	NTS20
	Dry Matter (Mg ha^{-1})		
Brachiaria (B)	$4.81 \pm 0.64 \text{ bC}$	$10.07 \pm 1.02 \text{ aC}$	$4.17 \pm 0.25 \text{ bC}$
Pearl millet (PM)	$7.41 \pm 1.36 \text{ aD}$	$7.72 \pm 1.90 \text{ aD}$	$6.77 \pm 0.60 \text{ aB}$
Sunn hemp (SH)	$9.39 \pm 0.86 \text{ bA}$	$15.32 \pm 3.81 \text{ aA}$	$8.72 \pm 0.45 \text{ bA}$
B + SH	$6.76 \pm 0.67 \text{ bB}$	$10.75 \pm 1.16 \text{ aC}$	$6.30 \pm 0.65 \text{ bB}$
B + PM	$6.64 \pm 0.49 \text{ bB}$	$8.87 \pm 0.95 \text{ aD}$	$6.40 \pm 0.97 \text{ bB}$
PM + SH	$7.85 \pm 0.51 \text{ bB}$	$13.07 \pm 1.08 \text{ aB}$	$6.62 \pm 1.00 \text{ bB}$
CV (%)	7.15		

Note: Values are presented as mean $\pm$ standard deviation. Lowercase letters compare means within rows, and uppercase letters compare means within columns. Means followed by the same letter do not differ according to Tukey's test at $p \leq 0.05$. NTS1: no-till system for one year; NTS8: no-till system for eight years; NTS20: no-till system for 20 years; CV: coefficient of variation.

Among the intercropping systems, significant differences were observed only during the transition phase (NTS8), in which PM + SH showed the highest DM production (13.07 Mg ha^{-1}), followed by B + SH (10.75 Mg ha^{-1}) and B + PM (8.87 Mg ha^{-1}).

The transition phase (NTS8) resulted in the highest DM values for most species. Pearl millet did not differ between the initial and transition phases, whereas the other species showed no significant differences between the initial and consolidation phases.

3.2. Agronomic Attributes of Green Maize

The agronomic traits of green maize, including Shucked Ear Yield (SEY), straw yield (SY), ear yield with husk (EYH), and grain yield per ear (GYE), were not significantly influenced by the residues of the different cover crops used. No significant interaction was observed between cover crops and system phases (Table 4).

Table 4. Agronomic performance of green maize as affected by cover crop systems (CC) and no-till system phases (SP), initial (NTS1), transition (NTS8), and consolidation (NTS20) in Uberaba, Minas Gerais, Brazil, during the 2019/2020 growing season.

Treatments	Agronomic Attributes of Green Maize			
	SEY	SY	EYH	GYE
	Mg ha ^{−1}			%
Cover crops (CC)				
Brachiaria (B)	7.52 ± 0.52	3.67 ± 0.23	11.18 ± 0.50	56.60 ± 16.72
Pearl millet (PM)	7.53 ± 0.53	3.63 ± 0.28	11.15 ± 0.65	56.73 ± 16.90
Sunn hemp (SH)	7.59 ± 0.75	3.69 ± 0.49	11.28 ± 1.20	56.21 ± 17.27
B + SH	7.42 ± 0.61	3.69 ± 0.44	11.11 ± 0.96	56.13 ± 17.07
B + PM	7.35 ± 0.49	3.59 ± 0.42	10.87 ± 0.79	56.72 ± 16.46
PM + SH	7.44 ± 0.70	3.83 ± 0.94	11.27 ± 0.91	57.88 ± 14.65
System phases (SP)				
NTS1	6.95 ± 0.61 b	3.69 ± 0.77 a	10.60 ± 0.79 b	34.57 ± 5.05 b
NTS8	7.82 ± 0.48 a	3.79 ± 0.35 a	11.62 ± 0.78 a	67.35 ± 1.46 a
NTS20	7.65 ± 0.44 a	3.57 ± 0.35 a	11.22 ± 0.61 a	68.21 ± 1.94 a
CC F-test	0.40 ^{ns}	0.28 ^{ns}	0.47 ^{ns}	0.47 ^{ns}
F-test SP	22.17 ^{**}	1.02 ^{ns}	10.95 ^{**}	881.48 ^{**}
CC × SP interaction	0.95 ^{ns}	0.621 ^{ns}	0.89 ^{ns}	0.39 ^{ns}
CV (%)	6.41	14.87	6.78	5.58

Note: Values are presented as mean ± standard deviation. Means followed by the same lowercase letter in the column, within each factor, do not differ according to Tukey's test at $p \leq 0.05$. ns: not significant; ** significant at $p \leq 0.05$. SEY: shucked ear yield; SY: straw yield; EYH: ear yield with husk (EYH); GYE: grain yield per ear; NTS1: no-till system for one year; NTS8: no-till system for eight years; NTS20: no-till system for 20 years; CV: coefficient of variation.

The agronomic attributes of green maize, with SEY ranging from 7.35 to 7.59 Mg ha^{−1}, SY from 3.59 to 3.83 Mg ha^{−1}, EYH from 10.87 to 11.28 Mg ha^{−1}, and GYE from 56.13 to 57.88%, were not significantly influenced by the residues of the different cover crops used. These values remained within the commercial standards required by the consumer market.

With regard to the system phases, SEY, EYH, and GYE were significantly higher in the transition and consolidation phases—with no significant differences between them—compared to the initial phase, while SY remained constant across the phases. There was no significant interaction between cover crops and system phases for the evaluated attributes.

3.3. Physicochemical Attributes of Green Maize

Regarding the physicochemical attributes of green maize kernels grown under different cover crops, in general, most of these parameters showed no significant influence of the cover crop used, including pH, AS, PTN, CHE, TTA, and AA ($p > 0.05$). However, moisture was significantly higher in grains grown on pearl millet residues (85%), while the other cover crops showed statistically similar values among themselves (Table 5).

Table 5. Physicochemical attributes of green maize kernels as affected by cover crop systems (CC) and no-till system phases (SP), initial (NTS1), transition (NTS8), and consolidation (NTS20) in Uberaba, Minas Gerais, Brazil, during the 2019/2020 growing season.

Treatments	Parameters Evaluated in Green Maize Kernels								
	pH	HU	AS	LIP	PTN	CHE	TTA	TSS	AA
	H ₂ O			%			Meq L ⁻¹	Brix	Mg 100 g ⁻¹
Cover crops (CC)									
Brachiaria (B)	6.79 ± 0.38	65.93 ± 11.73 b	2.53 ± 0.22	2.33 ± 0.16	11.36 ± 1.32	77.23 ± 0.93	2.31 ± 0.50	10.43 ± 2.54 a	11.64 ± 1.07
Pearl millet (PM)	6.94 ± 0.32	85.00 ± 6.11 a	2.36 ± 0.22	2.69 ± 0.99	10.75 ± 0.81	76.03 ± 1.86	2.09 ± 0.46	9.26 ± 1.38 b	9.96 ± 1.75
Sunn hemp (SH)	6.89 ± 0.31	72.40 ± 6.68 b	2.83 ± 0.40	2.44 ± 0.47	11.04 ± 0.59	76.66 ± 1.35	2.47 ± 0.36	9.51 ± 1.99 b	11.33 ± 0.88
B + SH	7.04 ± 0.36	70.42 ± 12.69 b	2.41 ± 0.32	2.47 ± 0.53	11.44 ± 1.76	76.37 ± 2.17	2.29 ± 0.84	10.96 ± 1.30 a	10.45 ± 2.65
B + PM	6.76 ± 0.45	65.75 ± 17.77 b	2.81 ± 0.19	2.52 ± 0.36	10.95 ± 0.98	77.07 ± 1.51	2.69 ± 0.84	10.00 ± 2.18 a	10.38 ± 1.21
PM + SH	6.84 ± 0.45	73.60 ± 10.81 b	2.45 ± 0.16	2.47 ± 0.72	11.39 ± 1.13	76.45 ± 1.24	2.34 ± 0.16	8.91 ± 1.48 b	9.80 ± 1.46
System phases (SP)									
NTS1	6.90 ± 0.44 b	59.40 ± 14.24 b	2.38 ± 0.23	2.94 ± 0.46 a	12.18 ± 1.25 a	76.74 ± 2.34	2.58 ± 0.78 a	11.16 ± 1.99 a	10.67 ± 0.90 a
NTS8	6.60 ± 0.19 c	76.99 ± 4.99 a	2.56 ± 0.27	2.46 ± 0.25 b	10.41 ± 0.36 b	76.75 ± 1.01	2.55 ± 0.33 a	8.10 ± 1.20 c	9.34 ± 1.34 b
NTS20	7.13 ± 0.08 a	80.13 ± 4.41 a	2.76 ± 0.27	2.05 ± 0.44 c	10.87 ± 0.57 b	76.61 ± 0.79	1.97 ± 0.23 b	10.27 ± 0.78 b	11.77 ± 1.59 a
CC F-test	1.09 ^{ns}	3.09 ^{**}	1.36 ^{ns}	1.08 ^{ns}	0.70 ^{ns}	0.54 ^{ns}	2.36 ^{ns}	4.18 ^{**}	1.70 ^{ns}
F-test SP	14.66 [*]	15.50 [*]	2.43 ^{ns}	30.79 ^{**}	14.48 ^{**}	0.05 ^{ns}	13.84 ^{**}	35.00 ^{**}	9.21 ^{**}
CC × SP interaction	0.55 ^{ns}	1.45 ^{ns}	1.28 ^{ns}	1.09 ^{ns}	1.40 ^{ns}	0.66 ^{ns}	3.81 ^{**}	2.29 [*]	1.45 ^{ns}
CV (%)	4.93	19.26	23.43	15.74	10.65	2.78	18.98	13.21	18.58

Note: Values are presented as mean ± standard deviation. Means followed by the same lowercase letter in the column, within each factor, do not differ according to Tukey's test at $p \leq 0.05$. ns: not significant; * and ** indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively. HU: moisture; AS: ash; LIP: lipids; PTN: protein; CHE: carbohydrates; TTA: total titratable acidity; TSS: total soluble solids; AA: ascorbic acid. NTS1: no-till system for one year; NTS8: no-till system for eight years; NTS20: no-till system for 20 years; CV: coefficient of variation.

Total soluble solids (TSS) also varied according to cover crop, with higher values observed under brachiaria, B + SH, and B + PM compared with pearl millet, sunn hemp, and PM + SH.

The system phases also affected the evaluated attributes: pH was highest in the consolidation phase; HU was higher in the transition and consolidation phases; AA was higher in the initial and consolidation phases; TTA was higher in the initial and transition phases; and PTN and LIP showed the highest values in the initial phase of the system. These results indicate that, although cover crops have limited influence on most bromatological characteristics, they affect important attributes such as moisture and total soluble solids, which directly influence the postharvest quality and commercial value of green maize.

The breakdown of the significant interaction between cover crops and no-till system phases for total titratable acidity (TTA) and total soluble solids (TSS) is presented in Table 6.

For TTA, differences were observed among the cover crops in the initial phase of the system (NTS1), with the B + PM mixture standing out with the highest value (3.55 Meq L⁻¹), followed by the B + SH and PM + SH mixtures. The lowest values were observed in brachiaria and pearl millet grown as sole crops. In the transition (NTS8) and consolidation (NTS20) phases, no significant differences were observed among the cover crops.

Considering the behavior of the cover crops within each phase of the system, a reduction in TTA was observed for the B + PM and B + SH mixtures as the NTS progressed, with higher values in the initial phase.

For TSS, in the initial phase of the system (NTS1), the highest values were observed in treatments involving brachiaria, especially the B + SH and B + PM mixtures, as well as brachiaria grown as a sole crop. The lowest values were observed in pearl millet, sunn hemp, and in the PM + SH mixture.

In the transition phase (NTS8), no differences were observed among the cover crops. Similarly, in the consolidation phase (NTS20), the cover crops showed no statistically significant differences.

When evaluating the behavior of the cover crops across the system phases, most treatments showed a reduction in TSS values during the transition phase, followed by an increase or stabilization in the consolidation phase.

Table 6. Interaction between cover crop systems and no-till system phases (SP) for total titratable acidity (TTA) and total soluble solids (TSS) of green maize kernels in Uberaba, Minas Gerais, Brazil, during the 2019/2020 growing season.

Cover Crops	Stages of the No-Till Farming System					
	NTS1	NTS8	NTS20	NTS1	NTS8	NTS20
	TTA			TSS		
	Meq L ⁻¹			°Brix		
Brachiaria (B)	1.92 ± 0.13 cB	2.48 ± 0.22 Aa	2.07 ± 0.13 aB	12.40 ± 0.04 aA	8.22 ± 0.50 aB	10.66 ± 0.52 aA
Pearl millet (PM)	1.78 ± 0.16 cA	2.51 ± 0.40 aA	1.99 ± 0.18 aA	9.88 ± 0.46 bA	8.11 ± 0.20 aA	9.77 ± 0.53 aA
Sunn hemp (SH)	2.80 ± 0.24 bA	2.95 ± 0.22 aA	2.14 ± 0.10 aA	9.95 ± 0.57 bA	7.39 ± 0.25 aB	11.19 ± 1.21 aA
B + SH	2.75 ± 0.17 bA	2.40 ± 0.21 aA	1.72 ± 0.17 aB	13.23 ± 0.42 aA	9.55 ± 0.49 aB	10.10 ± 1.06 aB
B + PM	3.55 ± 0.24 aA	2.73 ± 0.13 aB	1.78 ± 0.34 aC	12.18 ± 0.32 aA	8.17 ± 0.46 aB	9.66 ± 0.89 aB
PM + SH	2.51 ± 0.19 bA	2.38 ± 0.22 aA	2.14 ± 0.13 aA	9.30 ± 0.25 bA	7.19 ± 0.30 aB	10.24 ± 0.37 aA
CV (%)	22.18			23.09		

Note: Values are presented as mean ± standard deviation. Lowercase letters compare cover crops within each no-till system phase, in the columns. Uppercase letters compare no-till system phases within each cover crop, in the rows. Means followed by the same letter do not differ according to Tukey's test at $p \leq 0.05$. TTA: total titratable acidity; TSS: total soluble solids. For TSS, the values from the spreadsheet were divided by 10 and are expressed as °Brix. NTS1: no-till system for one year; NTS8: no-till system for eight years; NTS20: no-till system for 20 years.

4. Discussion

The superior performance of sunn hemp (9.39–15.32 Mg ha⁻¹) observed across the three phases of the NTS (Table 2) is related to its taproot system, which exhibits rapid growth and the ability to fix nitrogen biologically (BNF) through symbiosis with *Rhizobium* spp. [30,31]. These DM values are above the range reported by [5,13], which ranged from 4.0 to 9.0 Mg ha⁻¹, and are comparable to the 7.0–12 Mg ha⁻¹ described for *Crotalaria* under NTS in different tropical regions [32], indicating that the management adopted in this study favored biomass accumulation, especially during the transition phase (15.32 Mg ha⁻¹).

Brachiaria, with DM ranging from 4.17 to 10.07 Mg ha⁻¹, presented the lowest values, consistent with the 6.0–13.0 Mg ha⁻¹ reported in regional and international studies [7]. The lower production can be explained by the species' longer vegetative cycle and its early phenological stage at evaluation, as also observed by [33,34] for tropical grasses in intercropping systems.

The lower dry matter production observed in Brachiaria should also be interpreted considering its longer vegetative cycle compared with pearl millet and sunn hemp. Because biomass sampling was performed when approximately 50% flowering was reached, differences in phenological development among species may have influenced biomass accumulation, particularly for brachiaria, which may not have reached its maximum dry matter production at the sampling date.

The PM + SH intercropping system showed intermediate to high DM (6.62–13.07 Mg ha⁻¹), higher than that observed for intercrops with brachiaria (B + SH: 6.30–10.75 Mg ha⁻¹ and B + PM: 6.40–8.87 Mg ha⁻¹). These results suggest a potential benefit from combining Poaceae and Fabaceae species. However, because sunn hemp also showed the highest dry matter production when grown alone, part of the response observed in the mixtures may be associated with the strong biomass production capacity of this species rather than exclusively with interspecific complementarity. These results corroborate studies by [13,35], which reported that the association of millet with sunn hemp can increase biomass production by 20–30% compared to brachiaria or millet monocultures. In the international literature, [36,37] reported that grass–legume mixtures increase cover crop biomass production by 20–35% compared to monocultures.

The higher DM production observed for sunn hemp and for mixtures involving legumes can be attributed to the high efficiency of biological nitrogen fixation and the

vigorous early growth of these species, characteristics widely described for tropical systems [10,26].

The mixture of Fabaceae and Poaceae species aims to combine the individual benefits of each group and can mitigate problems such as low yield, reduced persistence of residues on the soil surface, soil compaction, and nitrogen deficiency during the early stages of the subsequent crop, as well as enhance nutrient cycling [7,11].

The transition phase showed the highest DM values for all species, reflecting the cumulative effect of improved soil physical properties, aggregate stabilization, and organic matter addition [31,35]. In this study, sunn hemp reached 15.32 Mg ha⁻¹ in this phase, compared to 11.5 Mg ha⁻¹ reported by [5] under similar conditions in the same region, and values between 11 and 13 Mg ha⁻¹ observed in tropical no-till systems in Africa and Asia [32,38].

The reduction in DM during the consolidation phase (sunn hemp: 8.72 Mg ha⁻¹; brachiaria: 4.17 Mg ha⁻¹) may be associated with factors such as soil compaction caused by machinery traffic and successive cropping cycles, although no direct measurements of soil physical properties were performed in the present study to confirm this mechanism, corroborating reports by [7,37]. The use of Fabaceae × Poaceae intercrops is an effective strategy to mitigate compaction effects and increase residue persistence on the soil surface, favoring nutrient cycling and subsequent crop production [30,36].

The results showed that the agronomic attributes of green maize (SEY, SY, EYH, and GYE) were not significantly influenced by the different cover crops used, corroborating previous findings [5,13]. This behavior can be explained by the crop's harvest stage (R3–milky), with approximately 75% moisture content, when maximum DM accumulation has not yet occurred.

Although cover crops often increase maize yield under NTS [39,40], these effects depend on the phenological stage of the subsequent crop, which explains the absence of a significant influence in this study. In maize grown for dry grain, the presence of Fabaceae or intercrops typically increases productivity, especially in later stages of the crop cycle [15,31].

The lack of a significant response of green maize to cover crops may also indicate that, in systems with adequate fertilization, the effect of mulch on immediate nutrient availability is limited, especially in short-cycle crops. Similar results were reported by [13], who observed stable green maize yields regardless of the cover crop species, suggesting that the main benefit of NTS occurs through gradual improvement of the soil environment rather than direct nutrient supply.

Analysis of the NTS phases showed that SEY, EYH, and GYE were higher during the transition and consolidation phases compared to the initial phase, while SY remained constant. This pattern indicates progressive improvement of soil physical, chemical, and biological attributes as the NTS consolidates, due to continuous organic matter input via plant residues and root systems, as well as soil restructuring over time [5,17].

The increase in yield during the transition and consolidation phases reinforces the importance of long-term NTS adoption for improving the edaphic environment. Older systems exhibit greater aggregate stability, higher water infiltration, and increased biological activity, favoring root development and resource use efficiency [19,20].

Maintaining soil cover during the transition and consolidation phases promotes moisture retention and straw quality, as reflected in the observed values of SY (3.59 to 3.83 Mg ha⁻¹) and SEY (7.35 to 7.59 Mg ha⁻¹), which fall within commercial standards. Similar results were reported by [13], who observed SEY between 6.9 and 7.8 Mg ha⁻¹, SY between 3.7 and 3.8 Mg ha⁻¹, and GYE from 56.6 to 68.2% in green maize grown on residues from different cover crops.

International studies also confirm these patterns [41,42], which demonstrated that green maize grown on legume residues under NTS exhibits SEY between 7.0 and 8.0 Mg ha⁻¹ and GYE of 55–60%, values similar to those obtained in this study.

The role of legumes as nitrogen sources, such as sunn hemp in this study, is well documented [43], which showed that legumes used as cover crops provide residual N to maize, potentially improving growth and productivity under NTS. However, the benefits associated with this additional N supply may become more evident in crops harvested at physiological maturity, whereas green maize harvested at the R3 stage may not fully express these responses, reinforcing the interpretation discussed previously, as also reported by [5,13].

Differences in productivity reported by [44] (13.3 Mg ha⁻¹) and [45] (15.45 Mg ha⁻¹) reflect variations in cultivars, planting density, and soil management, reinforcing that green maize productivity is influenced by environmental and management factors beyond the type of cover crop. Overall, these results indicate that, although soil cover is essential for maintaining and improving soil attributes in no-till systems, its effect on green maize yield depends on the crop's phenological stage.

The pH values of green maize kernels ranged from 6.76 to 7.04, remaining within the slightly neutral range expected for fresh consumption and consistent with ideal values reported for green maize [46]. These results agree with [47,48], who reported similar ranges. Maintaining near-neutral pH contributes to microbiological stability and shelf life.

Moisture content (HU) showed significant differences among treatments, being higher in pearl millet and lower in the other treatments. Grain moisture is a critical attribute for texture and sensory quality, ideally between 70 and 78% at harvest [4]. This parameter directly influences postharvest quality and product value [49].

Management practices such as NTS can increase grain moisture due to reduced evapotranspiration and greater water availability in the soil surface layer [5,13,16], especially when residues with longer persistence are present.

Total soluble solids (TSS), an indirect indicator of soluble sugars, were higher in treatments with brachiaria and intercrops compared to sole sunn hemp and pearl millet. These results are consistent with studies linking higher soluble sugars to better sensory quality [4,46].

Protein (PTN) and lipid (LIP) contents were not influenced by cover crops but were higher in the initial NTS phase, suggesting greater initial N availability and lower dilution by carbohydrates, as also observed by [44].

Total titratable acidity (TTA) varied across NTS phases, with higher values in earlier stages. This parameter influences organoleptic characteristics and reflects changes in grain composition over time.

Ascorbic acid (AA) ranged from 9.80 to 11.77 mg 100 g⁻¹, with higher values in the initial and consolidation phases. These values are consistent with those reported in the literature and indicate the influence of edaphoclimatic conditions and management on vitamin preservation.

The significant interaction between cover crops and NTS phases for TTA and TSS indicates that these attributes are influenced by both cover type and system maturity. The higher TTA values in the initial phase may be associated with more intense residue decomposition, while the stability observed in later phases reflects greater soil equilibrium [50].

For TSS, higher values in treatments with brachiaria suggest an influence on carbohydrate accumulation in kernels. Overall, the results indicate that the diversity of cover crops and the duration of NTS influence the chemical quality of green maize.

In general, the relative stability of grain composition suggests that nutritional quality is less sensitive to cover crop type and more dependent on genetic and management factors.

However, variations in TTA and TSS indicate the influence of soil microclimate provided by mulch [51,52].

In summary, although most bromatological attributes were not significantly affected by cover crops, parameters such as moisture, soluble solids, and vitamin C were influenced by both cover crops and NTS phases, directly affecting quality, shelf life, and commercial value of green maize.

This study was based on a chronosequence approach using adjacent areas representing different stages of no-till system development. Consequently, although the observed differences among NTS phases are consistent with the expected effects of long-term no-till adoption, some responses may also reflect inherent site variability. In addition, the results were obtained during a single growing season under specific environmental conditions. Therefore, caution is recommended when extrapolating these findings to other regions and years.

5. Conclusions

Sunn hemp and the pearl millet + sunn hemp intercrop produced the highest dry matter yields across the evaluated no-till system phases, demonstrating their potential for biomass production in the Brazilian Cerrado.

Cover crop residues did not significantly affect green maize yield. However, the transition and consolidation phases of the no-till system increased shucked ear yield, ear yield with husk, and grain yield per ear without affecting straw yield.

The bromatological quality of green maize grains was only slightly influenced by cover crops, with significant effects observed mainly for moisture content and total soluble solids. In contrast, the no-till system phases affected most bromatological attributes, except ash and carbohydrate contents.

The integrated use of cover crops, either in sole cropping or intercropping systems, associated with long-term no-till adoption, contributes to increased biomass production and improved grain quality attributes of green maize under Cerrado conditions.

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