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Management strategies for forage cactus based on cutting intensity and planting density: agronomic performance and chemical composition

Estratégias de manejo da palma forrageira em função da intensidade de corte e densidade de plantio: avaliação das características agronômicas e composição química

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Highlights

Planting density and cutting intensity affect growth and productivity of pear cactus.
Single-row produce higher dry forage yield when the primary cladode is preserved.
Single rows exhibit a higher dry matter content in the matrix cladodes.

Abstract

Growth characteristics, yield, chemical composition, and macro- and micronutrient contents of sweet forage cactus (Doce) were evaluated under three planting densities and two cutting intensities in the Brazilian Savanna. A completely randomized design was adopted in a 2 × 3 factorial arrangement with eight replications. Treatments consisted of two planting densities (single-row and double-row arrangements) and three cladode cutting intensities (matrix, primary, and secondary). Data were subjected to analysis of variance (ANOVA), and when the F-test indicated significance, means were compared using Tukey's test. Differences were considered significant at $p < 0.05$. The smallest cladode area ($p < 0.05$) and lowest

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plant height occurred under single-row planting with preservation of the matrix cladode. This treatment combination also resulted in higher dry matter content and lower mineral matter content ($p < 0.05$). Based on agronomic performance, yield, and chemical composition, forage cactus management should prioritize cutting intensities that preserve primary or secondary cladodes combined with double-row planting systems.
Key words: Cladodes. Macronutrients. Micronutrients. Green mass yield. Nopalea cochenillifera.

Resumo

Avaliou-se as características de crescimento, produção, composição química e teores de macro e micronutrientes da palma forrageira Doce em relação a três densidades de plantio e duas intensidades de corte em Savana Brasileira. Foi utilizado delineamento experimental inteiramente casualizado em esquema fatorial 2 × 3, com oito repetições. Os fatores corresponderam a duas densidades de plantio: fileira simples e fileira dupla; e três intensidades de corte do cladódio: matriz, primário e secundário. Os dados foram submetidos à análise de variância ANOVA e quando houve diferença significa pelo teste F, as médias dos tratamentos foram comparadas pelo teste de Tukey. Os valores médios foram considerados diferentes quando $p<0.05$. A menor área de cladódio ($p < 0.05$) e menor altura da planta foram observados no cultivo com fileira simples preservando o cladódio matriz. Também foi observado maior teor de matéria seca e menor teor de matéria mineral ($p< 0.05$) para essa combinação de tratamento. Considerando as características agronômicas, produtivas e de composição química, da palma forrageira, recomenda-se a intensidade de corte com preservação dos cladódios primários ou secundários, associado ao cultivo em fileiras duplas.
Palavras-chave: Cladódios. Macronutrientes. Micronutrientes. Produção de massa verde. Nopalea cochenillifera.

Introduction

The forage cactus (*Opuntia* spp. or *Nopalea* spp.) belongs to the *Cactaceae* family and represents an important feed alternative for livestock in tropical regions because of its resilience to adverse climatic conditions in arid and semiarid environments (Silva et al., 2021; Rodrigues et al., 2021). Its cladodes are widely used in animal feeding systems, supplying water and nutrients in quantities and quality sufficient to meet animal requirements during dry seasons (Oliveira et al., 2021).

Forage cactus is classified as a xerophytic and calciphytic plant and responds positively to intensive management, organic and mineral fertilization, and irrigation, exhibiting high water-use efficiency even under irrigated conditions (Dubeux et al., 2010; Nascimento et al., 2020). Optimal development occurs in soils with medium to high fertility, and the species tolerates elevated concentrations of calcium (Ca), magnesium (Mg), and potassium (K) (Voltolini et al., 2022). The sweet forage cactus variety (*Nopalea cochenillifera* Salm-Dyck) is distinguished by its high sprouting capacity (Nascimento et al., 2020), making it a suitable option for animal feeding systems (Pinos-Rodríguez et al., 2010). In addition, it provides elevated levels of water, non-fibrous carbohydrates (400–500 g kg^{-1} dry matter, DM), and metabolizable energy (2.0–2.5 Mcal kg^{-1} DM) (Rocha & Santos, 2025). However, limitations exist in its nutritional profile, particularly low concentrations of dry matter (92 g kg^{-1} DM), crude protein (63 g kg^{-1} DM), and neutral detergent fiber (217 g kg^{-1} DM) (Cardoso et al., 2019). Regarding macronutrient content (g kg^{-1} DM), forage cactus typically contains Ca (26.55), K (20.17), Mg (2.97), and phosphorus (P, 0.55) (Carvalho et al., 2020; Barros et al., 2025).

Several studies conducted in Caatinga ecosystems have evaluated planting density of forage cactus in the Brazilian semiarid region, reporting increased forage mass production under higher planting densities. These responses are often associated with high-density systems, adoption of double-row arrangements (0.20 × 0.20 × 0.20 × 1.5 m), and increased rates of organic and/or mineral fertilization (Voltolini et al., 2016; Lucena et al., 2020; Teles et al., 2024).

In contrast, information on management strategies for forage cactus under Brazilian Savanna (Cerrado) conditions remains limited. Evaluation of management practices, particularly planting density and cutting intensity, is essential because these factors directly influence cladode area, cladode weight, plant physiological responses, and overall productivity (Nascimento et al., 2020; Lucena et al., 2020). Moreover, planting density and cutting intensity are strongly associated with growth characteristics, yield, and chemical composition of forage cactus, indicating that appropriate management strategies can substantially improve crop performance (Dubeux et al., 2021).

Based on these considerations, it was hypothesized that an intermediate cutting intensity of the sweet forage cactus variety, combined with higher planting density, would enhance yield, and improve chemical composition. Therefore, this study aimed to evaluate growth characteristics, yield, chemical composition, and macronutrient content of sweet forage cactus (*Nopalea cochenillifera* Salm-Dyck) under two planting densities and three cutting intensities in the Brazilian Savanna.

Materials and Methods

Site and experimental design

The experiment was conducted in the municipality of Bom Jesus, Piauí, Brazil (09°04′28″ S, 44°21′31″ W; altitude 277 m). According to the Köppen climate classification, the region has a tropical climate with a dry winter season. Native vegetation is classified as Cerrado, corresponding to the Brazilian Savanna (Costa-Coutinho et al., 2019). Rainfall, air temperature, and relative humidity recorded during the experimental period from 2020 to 2022 are presented in Figure 1.

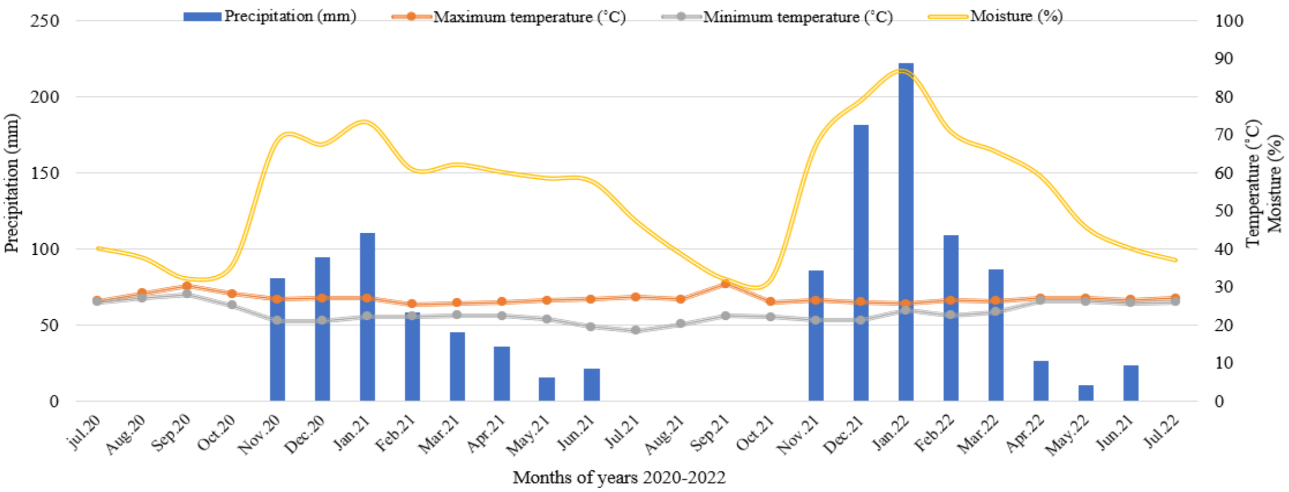

Figure 1. Cumulative monthly averages of rainfall, maximum and minimum temperatures, and relative humidity throughout the experiment in Bom Jesus, Piauí, Brazil.

A completely randomized design was adopted in a 2 × 3 factorial arrangement with eight replications, resulting in 48 experimental units. The first factor consisted of two planting densities (single-row and double-row arrangements). The second factor comprised three cutting intensities: matrix (matrix cladode preserved), primary (matrix and primary cladodes preserved), and secondary (matrix, primary, and secondary cladodes preserved) (Figure 2).

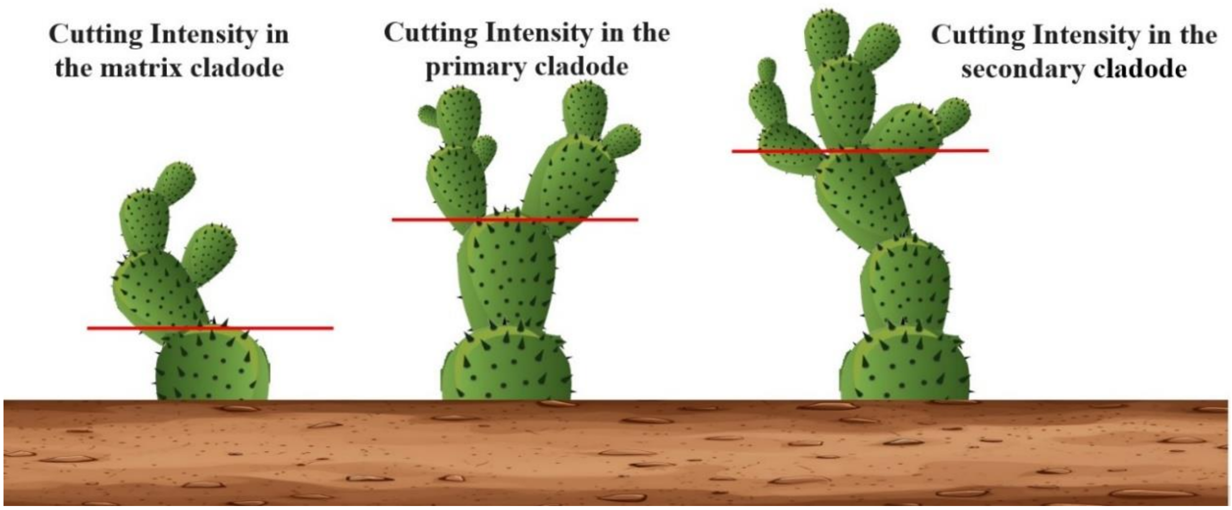

Figure 2. Preservation scheme for cladodes of the 'Doce' variety of forage cactus according to cutting intensity.

Cultivation of sweet forage cactus

Planting of the sweet forage cactus variety was conducted using single-row and double-row arrangements. Single-row planting was established at a spacing of 1.5 m between rows and 0.10 m between plants, resulting in a density of 66,667 plants ha^{-1}. Double-row planting followed a spacing of 0.10 × 0.10 × 1.5 m, corresponding to 125,000 plants ha^{-1}. In both systems, cladodes were planted vertically with approximately 50% of their length buried in soil (Figure 3).

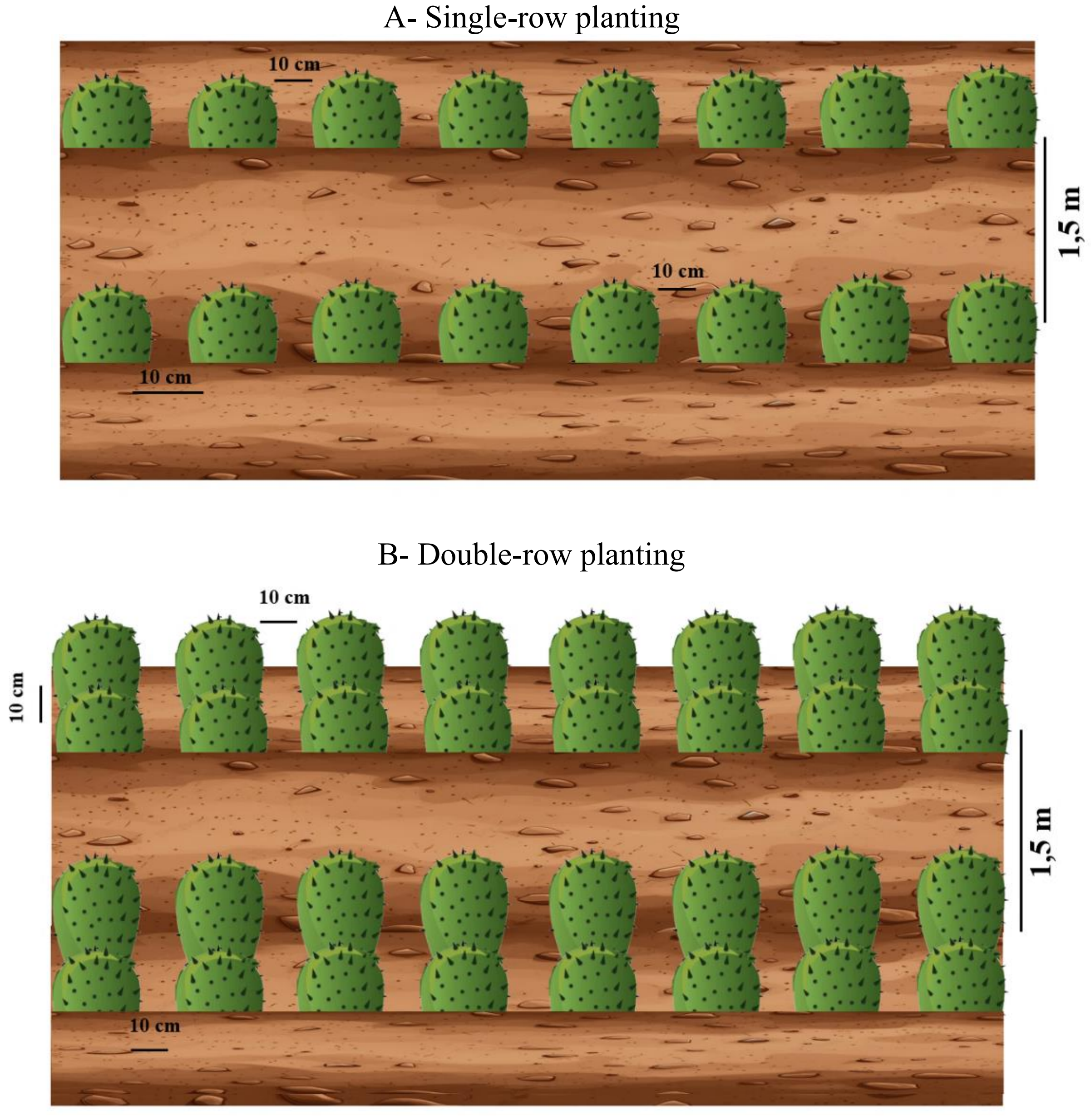

Figure 3. Diagram illustrating planting density of the 'Doce' variety of forage cactus under single-row (A) and double-row (B) arrangements.

At planting, phosphorus was applied at 48 kg ha^{-1} as single superphosphate (18% P_2O_5), and potassium at 107 kg ha^{-1} as potassium chloride (60% K_2O). Nitrogen fertilization was performed at a rate of 100 kg N ha^{-1} using conventional urea (CH_4N_2O; 45% N). To reduce nitrogen losses due to volatilization, applications were split into three doses applied during the rainy season, following recommendations proposed by Edvan and Carneiro (2019).

Growth and production evaluation

A uniformity cut was performed at the onset of the rainy season (day zero), followed by application of experimental treatments. Growth and production evaluations were conducted 720 days after the uniformity cut. Each experimental unit consisted of eight plants, which were assessed once at the end of the second cultivation year.

Non-destructive morphometric variables included plant height (PH), number of cladodes (NC), and cladode length and width. Plant height was measured vertically from the base of the plant to the highest point, whereas plant width was measured horizontally across the widest plant section using a graduated measuring tape (cm). Cladode number was determined by direct counting. Individual cladode area (CA) was estimated according to Cortázar and Nobel (1991) using the equation: CA = length × width × 0.632.

Forage yield was determined from total cladode harvest of all plants within each experimental unit. Green forage mass yield (GFMY) production was recorded at harvest and expressed as Mg ha^{-1}. A subsample of approximately 500 g of fresh material was collected for determination of dry matter content. Samples were sliced to facilitate drying and pre-dried in a forced-air oven at 65°C until constant weight was achieved (Detmann et al., 2021).

Chemical analyses and determination of macro- and micronutrients

After pre-drying, samples were ground using a Wiley-type mill equipped with a 1-mm sieve and stored in airtight plastic containers. Dry matter content was used to calculate forage dry matter yield (FDMY), expressed as Mg ha^{-1}. Chemical analyses followed procedures recommended by the Association of Official Analytical Chemists [AOAC] (1998), including determination of dry matter (DM) at 105°C, crude protein (CP; method 988.05), and mineral matter (MM; method 942.05).

Neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents were determined according to Mertens (2002), using an autoclave-adapted procedure (105°C for 60 min) as described by Barbosa et al. (2015). Analyses employed nonwoven fabric bags (TNT, 100 g m^{-2}) measuring 4 × 5 cm with a porosity of 100 μm, following Valente et al. (2011).

Macronutrient concentrations were determined after nitric–perchloric digestion. Phosphorus content was measured by UV–Vis spectrophotometry at 660 nm based on the intensity of the blue phosphor-molybdenum complex formed by molybdate reduction with ascorbic acid, using an IL-592 EVEN® spectrophotometer. Potassium, calcium, and magnesium contents were quantified by atomic absorption spectrophotometry (AAS) using an AA240FS VARIAN® instrument, following methodologies described by Silva (2009). Analyses were conducted at the Soil Analysis Center of CPCE/UFPI.

Statistical analysis

Data were subjected to analysis of variance (ANOVA), and residual normality was assessed using the Shapiro–Wilk test at a 5% probability level. The statistical model was defined as: Yijk = μ + Ai + Ij + AIij + εijk, where Y_{ijk} represents the observed value for cutting intensity i and planting density j; μ is the overall mean; A_i is the effect of cutting intensity (i = matrix, primary, or secondary); D_j is the effect of planting density (j = single row or double row); AD_{ij} represents the interaction between cutting intensity and planting density; and ε_{ijk} denotes random error. When significance was detected by the F test, treatment means were compared using Tukey's test. Differences were considered significant at $p < 0.05$. Statistical analyses were performed using SISVAR software, version 5.0 (D. F. Ferreira, 2011).

Results

There was a significant interaction ($p < 0.05$) between planting density and cutting intensity for number of cladodes (NC), cladode area (CA), plant height (PH), green forage mass yield (GFMY), and forage dry matter yield (FDMY) (Table 1).

Table 1
Productivity evaluation of the 'Doce' forage cactus variety under different cutting intensities and planting densities

Planting density	Cutting intensity				*p-value			
	Matrix	Primary	Secondary	Average	PD	CI	PD×CI	SEM
				Nº of Cladodes				
Single row	5.37aB	13.12aA	8.75aAB	9.08	0.12	0.93	0.03	1.00
Double row	8.75aA	7.87bA	11.0aA	9.20				
Average	7.06	10.50	9.87					
				Cladode Area (cm²)				
Single row	56.86aB	88.02aA	96.90aA	80.59	<0.01	0.55	<0.01	2.94
Double row	83.16bA	85.17aA	80.95bA	83.09				
Average	70.01	86.60	88.92					
				Plant Height (cm²)				
Single row	44.50bC	74.25aA	61.62bB	60.12	<0.01	<0.01	<0.01	1.86
Double row	69.25aA	76.50aA	73.0aA	72.91				
Average	56,87	75,37	67,31					
				GFMY[1] (Mg ha^{-1} $year^{-1}$)				
Single row	30.48bB	112.38aA	54.40bB	72.82	<0.01	0.02	0.02	10.22
Double row	79.27aA	133.59aA	133.33aA	108.34				
Average	54.87	122.92	93.89					
				FDMY[2] (Mg ha^{-1} $year^{-1}$)				
Single row	3.11bB	12.66aA	5.00bB	6.92	<0.01	0.07	0.01	0.89
Double row	6.65aA	9.66aA	11.53aA	9.25				
Average	4.88	11.11	8.27					

* p-value: PD: planting density; CI: cutting intensity; PD × CI: planting density × cutting intensity; SEM: standard error of the mean. GFMY: green forage mass yield. FDMY: forage dry matter yield. When a significant effect was detected by the F-test, treatment means were compared using Tukey's test. Means followed by the same lowercase letters within columns and uppercase letters within rows do not differ ($p < 0.05$).

The highest NC ($p < 0.05$) was observed under primary cutting intensity combined with single-row planting, reaching 13.1 cladodes per plant. The smallest CA occurred under matrix cutting intensity associated with single-row planting, with a mean value of 56.86 cm². Lower PH ($p < 0.05$) was also recorded in single-row planting when the primary cladode was preserved.

Higher GFMY and FDMY were obtained under single-row planting when the primary cladode was preserved. In contrast, under double-row planting, no differences in GFMY or FDMY were detected among cutting intensities ($p > 0.05$). However, double-row planting resulted in greater GFMY and FDMY than single-row planting ($p < 0.05$) when either the matrix or secondary cladodes were preserved.

An interaction (p < 0.05) between planting density and cutting intensity for dry matter (DM) and mineral matter (MM) contents (Table 2); however, no effect (p > 0.05) was observed for crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiver (ADF) contents.

Table 2
Chemical composition of the 'Doce' forage palm variety as affected by cutting intensity and planting density

Planting density	Cutting intensity				*p-value			
	Matrix	Primary	Secondary	Average	PD	CI	PD×CI	SEM
				Dry matter (DM g kg^{-1})				
Single row	110.0aA	103.0aB	93.0aC	102.0	<0.01	<0.01	<0.01	0.01
Double row	86.3bB	83.6bC	88.0bA	86.0				
Average	98.1	933.3	90.5					
				Crude protein (CP g kg^{-1})				
Single row	59.72	57.75	62.68	60.05a	0.36	0.10	0.38	0.32
Double row	50.84	52.32	66.63	56.60a				
Average	55.28A	55.04A	64.65A					
				Neutral Detergent Fiber (NDF g kg^{-1})				
Single row	277.4	232.8	292.9	267.7a	0.96	0.11	0.14	0.95
Double row	291.7	260.5	252.7	268.3a				
Average	284.5A	246.6A	272.8A					
				Acid Detergent Fiber (ADF g kg^{-1})				
Single row	186.2	173.1	146.5	168.6a	0.69	0.28	0.76	1.01
Double row	165.2	171.3	150.4	162.3a				
Average	175.7A	172.1A	148.4A					
				Mineral matter (MM g kg^{-1})				
Single row	22.3bB	48.4aA	54.7aA	41.8	0.44	<0.01	<0.01	0.24
Double row	51.0aA	55.0aA	27.5bB	44.5				
Average	36.6	51.7	41.1					

*p-value: PD: planting density; CI: cutting intensity; PD × CI: planting density × cutting intensity; SEM: standard error of the mean. When a significant effect was detected by the F-test, treatment means were compared using Tukey's test. Means followed by the same lowercase letters within columns and uppercase letters within rows do not differ (p < 0.05).

Dry matter (DM) content was higher ($p < 0.05$) in single-row plantings across all cutting intensities when compared with double-row plantings. Lower MM content was observed in single-row plantings under primary cladode cutting intensity (22.3 g kg^{-1}) and in double-row plantings under secondary cladode cutting intensity (27.5 g kg^{-1}). In contrast, no differences ($p > 0.05$) were observed for crude protein (CP; ranging from 55.04 to 60.05 g kg^{-1}), neutral detergent fiber (NDF; ranging from 246.6 to 284.5 g kg^{-1}), or acid detergent fiber (ADF; ranging from 148.4 to 175.7 g kg^{-1}) across planting densities or cutting intensities.

An interaction ($p < 0.05$) between cutting intensity and planting density was detected for calcium (Ca) and phosphorus (P) concentrations. In contrast, forage cactus cultivated in double rows showed higher magnesium (Mg) and potassium (K) accumulation compared with single-row plantings (Table 3).

Table 3
Contents of macronutrients in the 'Doce' variety of forage cactus as affected by cutting intensity and planting density

Planting density	Cutting intensity				*p-value			
	Matrix	Primary	Secondary	Average	PD	CI	PD×CI	SEM
Macronutrient (g kg⁻¹)								
Calcium (Ca)								
Single row	23.91aA	20.14bA	22.04bA	22.03	<0.01	<0.01	<0.01	0.93
Double row	19.20aB	30.78aA	34.52aA	28.17				
Average	21.56	25.46	28.28					
Magnesium (Mg)								
Single row	8.69	7.76	10.29	8.91b	<0.01	<0.01	0.08	0.26
Double row	8.89	10.29	11.51	10.23a				
Average	8.79B	9.03B	10.90A					
Phosphorus (P)								
Single row	5.60bB	15.73aA	1.35aA	1.16	0.03	<0.01	<0.01	0.03
Double row	1.59aA	1.47aA	0.84bB	1.30				
Average	1.07	1.52	1.09					
Potassium (K)								
Single row	1.59	2.32	3.21	2.37b	<0.01	0.05	0.38	0.34
Double row	7.28	9.53	8.9	8.57a				
Average	4.44A	5.93A	6.05A					

* p-value: PD: planting density; CI: cutting intensity; PD × CI: planting density × cutting intensity; SEM: standard error of the mean. When a significant effect was detected by the F-test, treatment means were compared using Tukey's test. Means followed by the same lowercase letters within columns and uppercase letters within rows do not differ ($p < 0.05$).

Discussion

The intermediate cutting intensity, characterized by preservation of the primary cladode, promoted greater growth, productivity, and improved chemical composition of the 'Doce' forage cactus when associated with single-row planting. In contrast, preservation of secondary cladodes combined with double-row planting also resulted in enhanced growth, productivity, and chemical composition.

Cutting at the matrix (mother) cladode combined with single-row planting density negatively affected forage cactus performance. This management reduced the number of areoles, which are responsible for cladode sprouting, limited the photosynthetic area, and decreased reserves of water-soluble carbohydrates stored in the cladode, directly impairing plant regrowth. Similar results were reported by C. M. Ferreira et al. (2024), who observed lower values for number of cladodes per plant (13.12), plant height (63.28 cm), cladode area (407.57 cm^2), green forage mass yield (130.1 Mg ha^{-1} $year^{-1}$), and forage dry matter yield (11.5 Mg ha^{-1} $year^{-1}$) when the matrix cladode was preserved. In contrast, cutting intensities that preserve primary and secondary cladodes maintain higher levels of organic reserves, which enhances cladode production per plant (Pereira et al., 2022), promotes greater vegetative growth, and does not compromise forage mass yield (Araújo et al., 2025).

Management strategies that preserve the primary cladodes, under both single- and double-row planting, as well as preservation of secondary cladodes under double-row planting, resulted in higher CA and PH compared with management preserving only the matrix cladode. These results indicate that the Doce forage cactus variety adapts well to different planting densities. Donato et al. (2020) reported that the number of cladodes per linear meter increases with planting density and is associated with a higher CAI after cutting.

Management preserving only the matrix cladode is not recommended for the Doce variety, as this strategy resulted in lower productive performance regardless of planting density. In addition, positive phototropism should be considered, as higher planting densities promote vertical elongation of cladodes in response to light competition, resulting in greater plant height. Pereira et al. (2022) evaluated forage cactus under different planting densities and observed greater plant height when secondary cladodes were preserved (94.5 cm) compared with primary cladode preservation (88.37 cm) under higher density conditions. According to Edvan et al. (2020), increased plant height at higher densities does not compromise neighboring plant growth and contributes to greater productivity per unit area.

The highest GFMY and FDMY were observed under double-row planting. This response was associated with a greater number of cladodes and larger cladode area, which promoted increased plant height. These results demonstrate that forage cactus responds positively to densification when adequate fertilization is provided. Similar findings were reported by C. M. Ferreira et al. (2024), who observed that wider spacing favored cladode number, plant height, and plant width, resulting in higher green and dry matter yields.

Chemical composition of sweet forage cactus is strongly influenced by management practices, particularly planting density and cutting intensity. As highlighted by Dubeux et al. (2021), these factors directly affect nutrient composition and dry matter accumulation. Higher planting densities tend to increase dry matter production; however, this response is also modulated by cutting intensity, especially when primary and secondary cladodes are preserved (Dubeux et al., 2010).

In double-row plantings, greater mutual shading likely reduced solar radiation exposure, favoring water conservation in plant tissues. This condition may explain the lower DM content observed in these treatments compared with single-row plantings. In addition, a DM content of 110.0 g kg^{-1} was recorded, corresponding to approximately 89% water content in the matrix cladode under single-row planting (Table 2). Because the matrix cladode is the oldest, it tends to accumulate more dry matter than primary and secondary cladodes, a pattern also reported by Teles et al. (2024).

CP content did not differ among treatments, confirming that forage cactus is inherently low in CP and that management practices did not influence this component. The values observed fall within the range reported in the literature, from 13 to 86.16 g kg^{-1} (Gomes et al., 2018; Barros et al., 2025).

NDF and ADF contents typically increase as cladodes mature, reflecting complete structural development (Pessoa et al., 2020). In the present study, NDF and ADF contents were not affected by treatments, averaging 268.3 and 168.6 g kg^{-1}, respectively, likely because all cladodes were harvested at the same physiological age. Lower NDF values (196.3 g kg^{-1}) and higher ADF values (571.4 g kg^{-1}) were reported by Edvan et al. (2020).

The lower MM content observed in double-row plantings with preservation of the secondary cladode (Table 2) is associated with the higher forage dry matter yield (11.53 Mg ha^{-1} $year^{-1}$) obtained under this management. This response reflects a dilution effect, in which increased biomass production reduces mineral concentration in plant tissues during intense vegetative growth (Barros et al., 2025).

Lower Mg and K concentrations were observed in single-row plantings compared with double rows. Moreover, the highest Mg concentration occurred in double-row plantings with preservation of the secondary cladode (Table 3). Higher planting density may reduce individual plant growth rate, leading to greater nutrient concentration in cladodes (Mello et al., 2019).

In double-row plantings with preservation of the secondary cladode, Ca and P accumulation was lower than in single-row systems. This response is also attributed to the dilution effect, as increased green and dry forage mass yields reduce Ca and P concentrations in plant tissues (Carvalho et al., 2020; Ferraz et al., 2020; Barros et al., 2025).

Conclusion

Considering agronomic performance, productivity, and chemical composition of forage cactus, a cutting intensity that preserves primary or secondary cladodes combined with double-row planting is recommended. Alternatively, traditional single-row cultivation preserving only the primary cladode represents a viable management option.

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