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RESEARCH ARTICLE

Morphological and productive responses of cactus pear cv. Mexican elephant ear under different planting densities

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ABSTRACT

The aim was to evaluate the morphological and productive responses of cactus cv. Mexican elephant ear (*Opuntia stricta* Haw.) under different crop densities and days after planting. This was a randomised block design consisting of four treatments of planting densities (30.000; 45.000; 60.000 and 75.000 plants/ha) with four replications. Morphological characteristics, phenology, growth and production rates were evaluated, such as: total number of cladodes (TNC), primary cladode length (PCL), secondary cladode width (SCW), cladode area index (CAI), net assimilation rates (NAR) and the productive characteristics of fresh matter (FMP) and dry matter (DMP). There was an effect of densities ($P < 0.001$) at 120 DAP on TNC. At 240 DAP, there was an effect ($P < 0.05$) of densities on PCL and SCW. There was a quadratic effect ($P < 0.05$) on plant height at 360 DAP. A quadratic model was fit ($P < 0.05$) for data of SCW at 240 DAP. The densities of 30.000; 45.000 and 75.000 plants/ha showed three phenophases. Densities of 75.000 plants/ha showed higher CAI, while net assimimilation rates was similar for densities of 60.000 and 75.000 plants/ha. The increase in planting density shortens the cactus pear phenophase and alters the morphological characteristics, however its production increases.

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KEYWORDS
Assimilation rate; cladode; *Opuntia stricta* Haw; phenology; arid land

Introduction

Cactus pear is considered essential in the strategic planning of food production, nutritional plans and livestock development in dry lands. In this way, cactus pear assumes the role of nourishing and hydrating the herds in periods of water déficit. In this production scenario, the Brazilian Northeast has a cultivation area between 500 and 600 thousand hectares (Dubeux Júnior et al. 2013; Dubeux Júnior 2016).

This cactus allows the continuity of the production process, during the lack of water for animal watering, making production systems more competitive, resulting in the

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revitalisation of rural areas and a reduction in rural exodus. Taking into account the social role of cactus pear in a production system, several studies report the effect of planting density (Silva et al. 2014; Cavalcante et al. 2014; Lemos et al. 2021), irrigation (Freire et al. 2018; Nadaf et al. 2018; Castro et al. 2020) and fertilisation (Donato et al. 2017; Dantas Neto et al. 2020) on the morphological and productive characteristics of cactus pear.

High yields are usually associated with large tracts of land. However, livestock in semiarid regions is mainly developed by family farming (Silva et al. 2018). This, in turn, does not have large amounts of land. In this way, the low availability of arable land for family farmers is not a limiting factor for achieving productive efficiency. In this sense, the increase in planting density aims to optimise production (Ramos et al. 2011) by promoting an increase in the support capacity of the production system.

One of the factors that justifies the low productivity of cactus pear crops with lower densities is the loss of energy (solar radiation) that is reflected by bare soil, which reduces the conversion of light energy into phytomass (Santos et al. 2006). Nevertheless, when an area of cladodes is made available and efficiently uses light energy, productivity increases (Nobel et al. 1995). However, the planting density of cactus pear alters the light interception dynamics, consequently the photosynthetic efficiency, which can reduce productivity (Fonseca et al. 2020). In this sense, some studies have demonstrated the effect of spacing/density on the vegetative and productive characteristics, in order to determine the number of plants per hectare for the maximum production for each productive model.

Effects of dense planting go beyond productivity, for instance, Silva et al. (2014) evaluated different densities (10; 20; 40; 60 and 80 thousand plants ha^{-1}) and observed that the increase in production is due to the number of plants in the cactus pear crop. However, the same authors observed alterations in morphogenetic characteristics with increasing density, with the reduction in cladode length and plant height. In this sense, the objective was to evaluate the morphological and productive characteristics in the establishment of a cactus pear crop.

Material and methods

Area description

The study was carried out in the caatinga experimental field, belonging to Embrapa Semiarid, Petrolina, state of Pernambuco (09°04'16.4"S, 40°19'5.37"W and 379 metres altitude). According to the Köppen (2015) classification, the climate is BSwh'. The soil of the experimental area is classified as Acrissols (WRB/FAO 2015), flat relief, with medium texture.

At the onset of experimental implementation, soils were sampled in the 0-0.10 m; 0.10-0.20 m; 0.20-0.30 m and 0.30-0.40 m depth to determine the physical chemical properties of the soil (Table 1) at the Laboratory of Soils and Plant Tissues of Embrapa Semiarid. Soil samples were evaluated for electrical conductivity using a conductivity metre (AZ, model 6505) (AOAC 2016), pH, using a previously calibrated potentiometer (Digimed, model dmph-2). The levels of phosphorus (P), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) were quantified using the methodology

Table 1. Chemical and physical characterisation of the soil at the onset of the experiment implementation.

	Chemical analysis															
	EC	pH	P	Cu2+	Fe2+	Mn2+	Zn2+	K+	Na+	Ca2+	Mg2+	Al	H + Al	SB	CEC	V
Depth (m)	dS cm−1	–		– – – – mg dm − 3 – – – -					– – – – cmolc dm − 3 – – – –							%
0-0.10	3.90	7.10	18.00	0.77	23.56	13.98	2.33	0.16	0.71	2.68	1.28	0.00	0.13	3.95	4.08	97.60
0.10-0.20	3.71	7.15	18.72	0.75	23.52	23.04	2.46	0.16	0.71	2.73	1.33	0.00	0.23	4.05	4.28	95.13
0.20-0.30	3.38	6.20	3.53	1.13	28.65	20.44	0.98	0.11	0.73	1.90	0.93	0.00	1.15	2.83	3.98	74.78
0.30-0.40	3.30	6.23	3.82	1.17	29.42	15.99	0.99	0.12	0.74	1.90	1.18	0.00	1.53	3.08	4.60	69.43

	Physical analysis					
	Soil density			Particle size		
	Soil	Particles		Sand	Silt	Clay
Depth (m)	– – kg dm − 3 – –		Total porosity (%)	– – – – g kg − 1 – – – – 0		
0-0.10	1.52	2.56	40.80	575.75	353.29	70.96
0.10-0.20	1.53	2.54	39.74	616.52	300.15	83.33
0.20-0.30	1.51	2.54	40.52	568.04	312.51	119.47
0.30-0.40	1.45	2.55	43.08	476.01	267.34	256.68

EC = Electrical conductivity; pH = Potential of hydrogen; *P* = phosphorus; Cu^{2+} = copper; Zn^{2+} = zinc; K^{+} = potassium; Na^{+} = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Al = aluminium; H + Al = Potential acidity; SB = Sum of Bases; CEC = Cation Exchange Capacity; V = Base saturation.

of Holanda Filho *et al.* (2011). Copper (Cu^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}) were determined according to Claessen (1997). Exchangeable acidity (H + Al), sum of bases (SB), cation exchange capacity (CEC) and base saturation (V) were obtained according to Coldebella et al. (2018). Total porosity was obtained according to Claessen (1997) and the particle density, according to EMBRAPA (1997), while the fractions of sand, silt and clay were quantified using the methodology of Donagema et al. (2011).

Throughout the experimental period (October 2020 to October 2021) rainfall, evapotranspiration, temperature, wind speed, relative humidity and global radiation (monthly averages) were monitored through the Embrapa Semiarid Agrometeorological Station (Figure 1).

Treatments and management of the experimental area.

In this experiment, an area of 2.560m² was planted with the clone IPA-2000116/ Mexican elephant ear, with a row spacing of 2.00 m, of which 15.36 m² (4.8 × 3.2 m) refer to the useful area. These units are made up of four double rows of cactus pear cultivation, of which two were useful and the other two were considered as borders. A randomised block design was used, consisting of four treatments represented by planting densities (30.000; 45.000; 60.000 and 75.000 plants ha^{-1}) with four replications (Figure 2).

During the 12 months of cultivation, three harvests were made at 120, 240 and 360 days after planting (DAP). Fertilisation and irrigation were not carried out during the experimental period. Weed control was carried out with a herbicide based on isoxaflutol and applied at a dosage of 1.5%, and for the control of carmine cochineal (*Dactylopius coccus*), mineral oil at 1% was used.

Morphogenesis and morphological indices

Morphogenetic characteristics from day 30 of the productive cycle, in intervals of 120 DAP, were registered for plant height (PH; cm), plant width (PW; cm), total number of cladodes (TNC; n), length of primary and secondary cladodes (PC and SC; cm), width of primary and secondary cladodes (PCW and SCW; cm), cladode perimeter (CP; cm), cladode thickness (CT; mm). To obtain these variables, sixteen plants were selected per treatment to be monitored throughout the cycle. Measurements of lengths and widths were obtained using a millimeter tape. CT was measured using a digital calipre.

The cladode area index (CAI) was obtained through the ratio of the total cladode area and the spacing used for planting (Pinheiro et al. 2014). Cladode areas (CA) were calculated in order of emergence according to the methodology of Silva *et al.* (2014). Daily rates of dry matter accumulation (DRDMA; Mg ha^{-1} °C day); absolute growth rate of the crop (AGRC, Mg ha^{-1} °C day); net assimilation rates (NAR, Mg ha^{-1} °C day); relative growth rates (RGR, Mg Mg^{-1} °C day) and specific cladode area (SCA, Mg ha^{-1}) were obtained according to the methodology of Santos et al. (2024).

$$CA = 0.7086 * \frac{(1\text{- exp (-0.000 plants ha-1045765 * CC * LC)})}{0.000 \text{ plants ha-1045765}} \quad (1)$$

$$NAR = \frac{\text{Absolute growth rate of the crop}}{\text{Cladode area indices}} \quad (2)$$

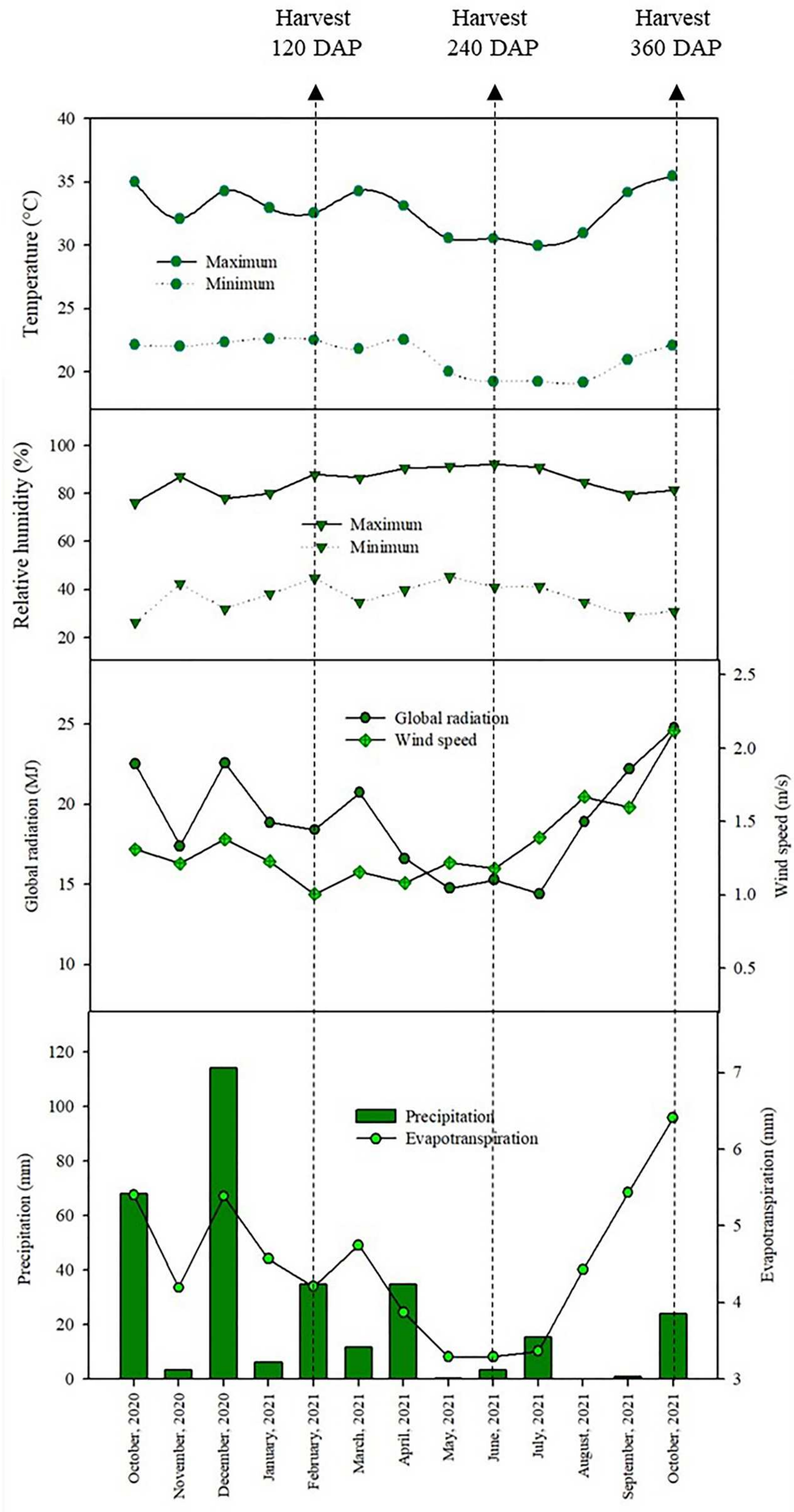

Figure 1. Meteorological data during the experimental cultivation period.

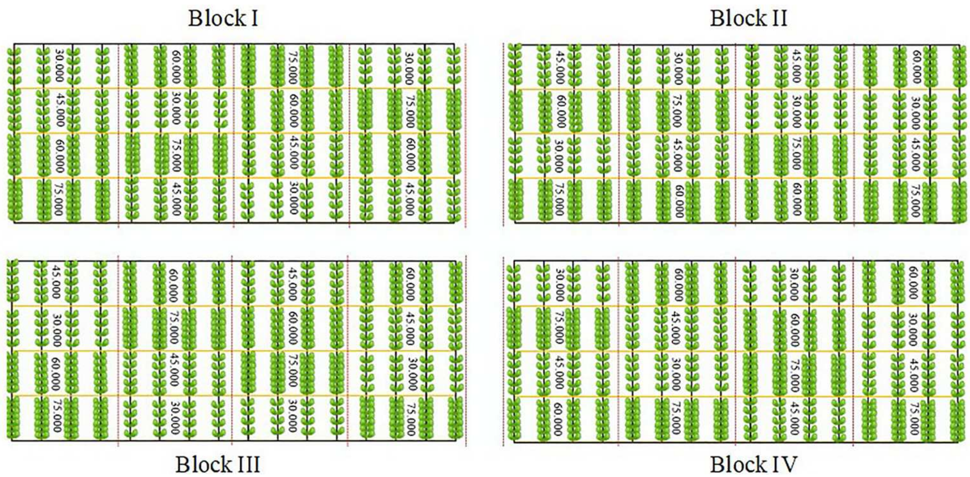

Figure 2. Schematic representation of the experimental design.

$$RGR = \frac{\text{Absolute growth rate of the crop}}{\text{Dry matter}} \quad (3)$$

$$SCA = \frac{\text{Cladode area indices}}{\text{Dry matter}} \quad (4)$$

Phenology

The phenological evaluation was carried out by regression analyses, using sigmoid models with the use of three parameters, in order to test the association between the number of cladodes per order and the accumulated degree days (GAD, °C day). GAD was obtained by adding the values of the degree days (GD °C day), obtained by the difference between the average daily air temperature (°C) and the basal temperature of the lower region of the crop (°C), considered 22°C according to Araújo Junior et al. (2017).

Thus, equations with coefficients of determination equal to or greater than 0.85, which present significance ($P < 0.05$), by t-test, were derived for calculation of the daily cladode production rates (DCPR). A new vegetative phase was considered when the cladode emergence rate of an order surpassed the emergence rate of the subsequent order (Amorim et al. 2017).

Production

Cactus pear production was obtained at intervals of 120 days by sampling the aerial part of cactus pear from eight plants per treatment, preserving the basal cladode, to determine the yield of fresh and dry biomass. After harvesting, cladodes were weighed on a digital electronic precision scale (Toledo Prix, model 3400, Capacity 30 kg, São Paulo – SP, Brazil) to obtain the fresh weight per plant (PFP, kg/plant) to determine the fresh weight per plant (FWP, kg plant^{-1}) and then, the production of fresh matter (PFM t ha^{-1}) by the product between FWP and the equivalent density of plants per hectare.

Then, cladodes were fragmented and placed in aluminium containers, duly identified and taken to a forced ventilation oven (Tecnal, TE-394/2-MP, Piracicaba – SP, Brazil) at 55° C, to a constant dry weight (dry mass). The DM/FWP ratio resulted in the dry matter content (DM, g kg^{-1}). From the product between PFM and DM, the dry matter productivity (DMP t ha^{-1}) was obtained.

Statistical analysis

The results were evaluated for normality (Shapiro–Wilk at 5% probability) using the UNIVARIATE procedure (PROC UNIVARIATE) of the Software Statistical Analysis System University (SAS 2015). After the analysis of normality, analysis of variance and regression at 5% probability for type I error were run using the PROC REG procedure from the SAS (2015) for the crop density factor. The statistical analysis was analysed according to the following statistical model: The following statistical model was used:

$$Y = \mu + Bi + Tj + Dl + Tj * Dl + eijl \quad (5)$$

where: Y = observed value of the variable; μ = overall average; Bi = block effect; Tj = effect of different cultivation densities; Dl = effect of days after planting; Tj*Dl = interaction between densities and days after planting; eijl = random error associated with each repetition.

The data was subjected to analysis of variance and regression at α = 0.05 for the crop density factor. The significance of the parameters estimated by the models and the values of the coefficients of determination.

For the effect of days after planting (DAP), the study carried out repeated measurements over time, with evaluations at 120, 240 and 360 days after planting (DAP). The effects of time were statistically evaluated, considering the influence of the days after planting on the morphological and productive response of the plants. The Tukey test was performed at 5% probability for type I error, to verify differences between the measurement times.

The standard error of the mean was obtained from the original data. To create the figures, the SigmaPlot (2014) software version was used.

Results

There was an effect of densities ($P < 0.001$) at 120 days after planting (DAP) on the total number of cladodes (TNC), with a higher number in the density of 30.000 plants ha^{-1} (Table 2). At 240 DAP, there was an effect ($P < 0.05$) on TNC, secondary cladode length (SCL) and secondary cladode width (SCW), resulting in higher TNC for the density of 45.000 plants $ha^{-1.}$ and higher PCL and SCW for the density of 75.000 plants ha^{-1} (Table 2). There was an effect at 360 DAP ($P < 0.05$) on plant height (PH), TNC and secondary cladode perimeter (SCP). Higher values were found for PH in crops with 60.000 plants $ha^{-1.}$ with 48.60 cm, while TNC showed higher values at lower densities (30.000 plants ha^{-1} and 45.000 plants ha^{-1}). The densities of 45.000 and 75.000 plants ha^{-1} showed thicker cladodes (Table 2).

There was a quadratic effect ($P < 0.05$) on plant height (PH) at 360 DAP (Figure 3A) with a maximum point of 48.12 cm for a density of 54,000 plants ha^{-1}. TNC showed a

Table 2. Effect of planting densities and days after planting on the morphological characteristics of cactus pear.

Density (thousand plants ha^{-1})	PH	PW	TNC	PCL	SCL	PCW	SCW	PCP	SCP	PCT	SCT
120 days after planting											
30	38.78	37.09	4.34^{a}	24.81	14.93	17.17	12.31	61.83	40.58	5.53	3.56
45	40.20	40.36	4.00^{ab}	25.11	16.21	16.43	12.56	62.26	41.94	6.69	4.09
60	38.01	32.86	3.13b^{c}	25.14	17.16	16.10	12.97	62.28	45.56	6.21	4.17
75	39.09	35.72	2.91^{c}	26.19	12.56	16.26	9.87	65.58	34.19	6.73	3.76
SEM	0.63	2.22	0.58	0.44	1.47	0.34	1.03	1.30	3.19	0.42	0.24
p-value	0.566	0.084	<0.001	0.541	0.240	0.753	0.293	0.352	0.311	0.272	0.649
240 days after planting											
30	44.84	49.91	4.94^{ab}	26.94	23.39^{ab}	17.62	19.57^{ab}	68.09	64.19	9.31	9.73
45	46.28	52.28	5.59^{a}	27.59	23.59^{ab}	19.69	19.89^{ab}	67.23	63.05	10.51	9.03
60	44.27	45.55	3.88b^{c}	28.98	21.73^{b}	19.56	18.20^{b}	69.87	60.72	10.02	8.73
75	43.26	48.28	3.81^{c}	27.98	25.96^{a}	18.56	21.06^{a}	70.94	69.09	10.42	8.80
SEM	0.90	2.09	0.71	0.61	1.15	0.77	0.80	1.37	2.41	0.40	0.33
p − value	0.552	0.258	<0.001	0.679	0.006	0.435	0.014	0.578	0.077	0.637	0.344
360 days after planting											
30	43.14^{b}	53.16	5.47^{a}	26.56	23.85	17.84	20.27	64.54	63.76	6.00	4.47^{b}
45	47.84^{ab}	55.63	5.38^{a}	27.75	23.14	18.00	19.77	68.53	62.66	7.22	6.97^{a}
60	48.60^{a}	50.95	4.53^{ab}	27.30	24.54	18.75	20.39	69.11	66.48	8.23	5.82^{ab}
75	45.40^{ab}	51.37	4.25^{b}	27.20	23.35	19.95	19.51	69.14	65.22	8.50	6.95^{a}
SEM	1.98	1.62	0.52	0.32	0.48	0.72	0.35	1.65	1.32	0.88	0.91
p − value	0.031	0.472	0.038	0.887	0.277	0.105	0.583	0.219	0.430	0.150	<0.001

Different letters, in the same column, indicate significant difference by Tukey's test at 5% probability for type I error; *p*-value = statistical probability; SEM = Standard error of the mean; PH = plant height (cm); PW = plant width (cm); TNC = total number of cladodes (units); PCL = primary cladode length (cm); SCL = secondary cladode length (cm); PCW = primary cladode width (cm); SCW = secondary cladode width (cm); PC*P* = primary cladode perimeter (cm); SC*P* = secondary cladode perimeter (cm); PCT = primary cladode thickness (cm); SCT = secondary cladode thickness (cm).

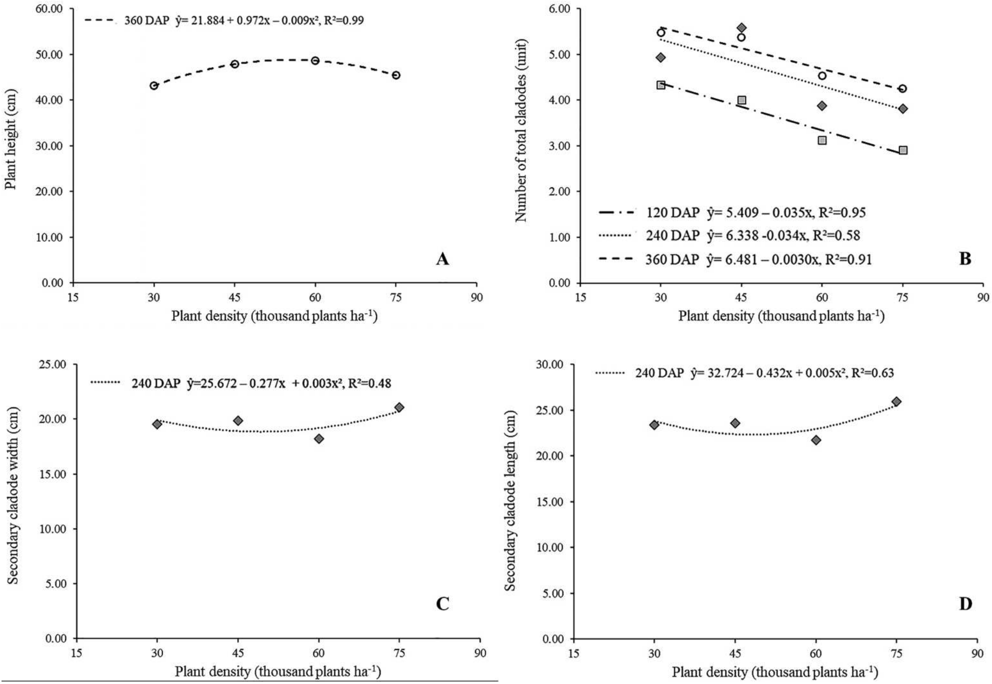

Figure 3. Effect of planting densities on morphological characteristics and total number of cladodes of cactus pear.

decreasing linear effect ($P < 0.05$), a reduction of 0.035, 0.034 and 0.030 cladodes with the population increase of a thousand plants, respectively for 120, 240 and 360 DAP (Figure 3B). A quadratic model was fit ($P < 0.05$) for secondary cladode width (SCW) at 240 DAP (Figure 3C), with a minimum point of 19.27 cm for a density of 46,160 plants ha^{-1}. There was a quadratic behaviour ($P < 0.05$) for the secondary cladode length (SCL) at 240 DAP (Figure 3D) with a minimum point of 23.39 cm for the density of 43.20 thousand plants per ha^{-1}.

The dynamics and duration of phenophases varied according to planting densities (Figure 4). The densities of 30.000, 45.000 and 75.000 plants ha^{-1} showed three phenophases. Phenophase 2 (F2) started at 779.2 and 796 °C DAP for densities of 30.000 and 45.000 plants ha$^{-1.}$ respectively (Figure 4A and 4B). Phenophase 3 (F3) started when the emergence rate of the third order cladode stood out, thus F3 started at 1670.8 and 1154 °C DAP for densities of 30.000 and 45.000 plants ha^{-1} (Figure 4A and 4B), regarding the F3 of the densities of 60.000 and 75.000 plants ha$^{-1.}$ peaks of this phenophase were not observed (Figure 4C and 4D).

Morphological indices were influenced by density (Figure 5A), so that up to 1.000 GAD the treatment with 75.000 plants ha^{-1} showed higher cladode area indices (CAI). At 500 GAD the densities of 30.000, 45.000 and 60.000 plants ha^{-1} showed similar CAI. However, at 1.859 GAD, the lowest densities (30.000 and 45.000 plants ha^{-1}) presented higher CAI values (Figure 5A). As for the cladode area index rate (CAIR), the density of 75.000 plants ha^{-1} peaked at 525 GAD (0.0011 ha^{-1} ha^{-1} °C day^{-1}), followed by the density of 60.000 plants ha^{-1} at 698 GAD, with 0.0016 ha^{-1} ha^{-1} °C day$^{-1.}$ and

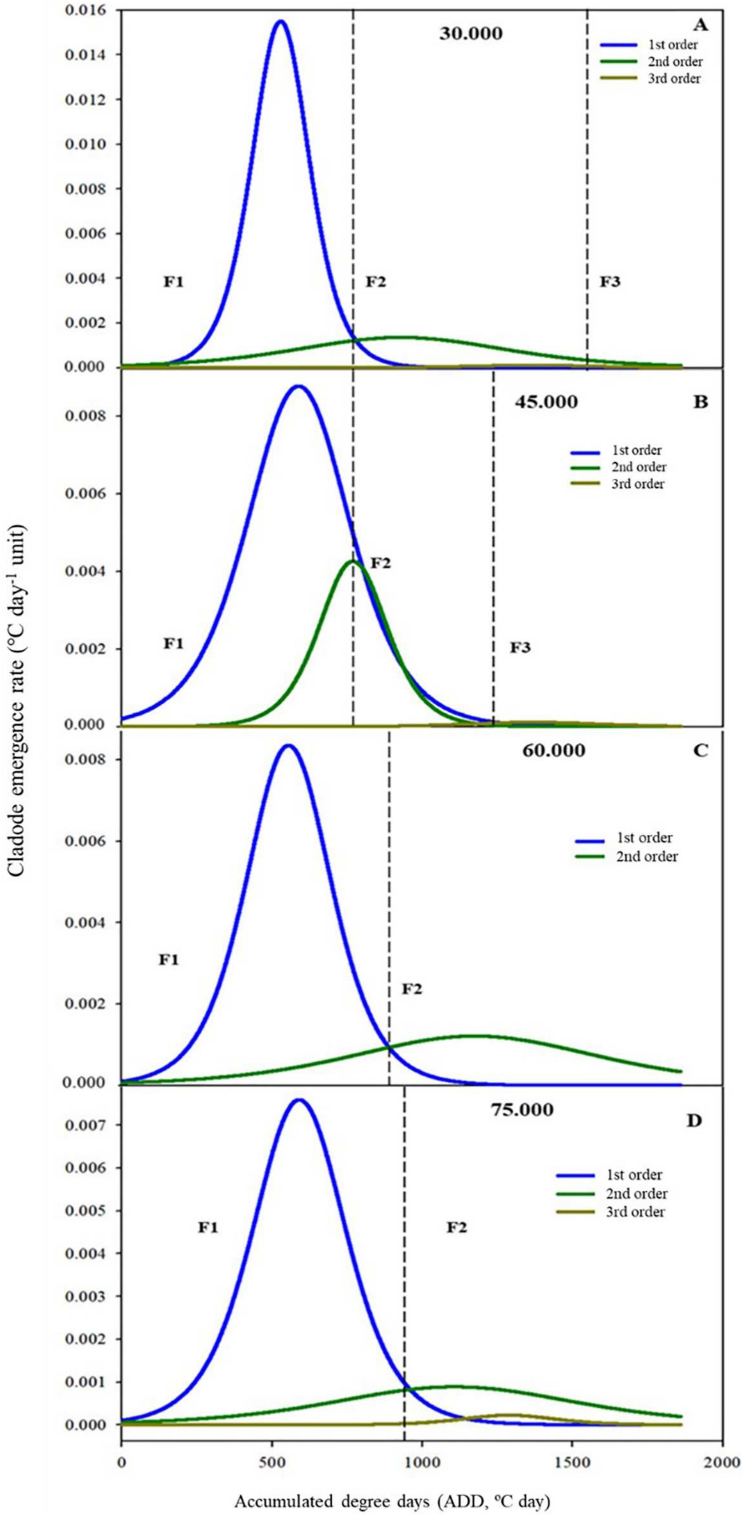

Figure 4. Phenophases of cactus pear grown under different planting densities: **A** 30.000 plants ha^{-1}; **B** 45.000 plants ha^{-1}; **C** 60.000 plants ha^{-1}; **D** 75.000 plants ha^{-1}.

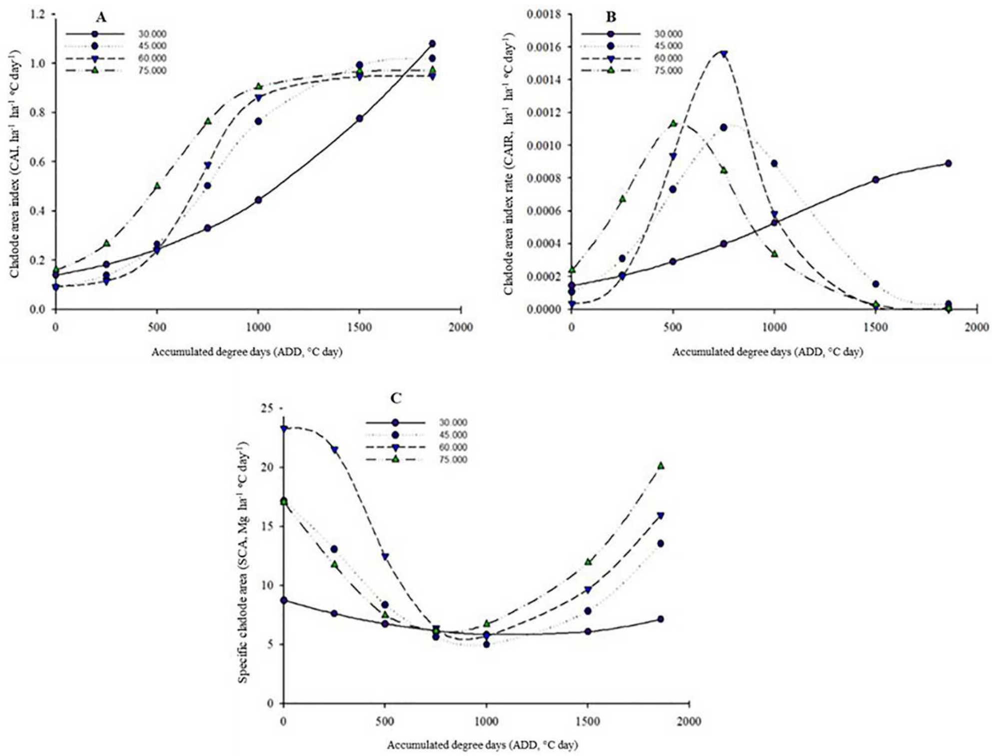

Figure 5. Morphophysiological indices of cactus pear growth cultivated under different planting densities. **A** Cladode area index (CAI, ha^{-1} ha^{-1} °C day^{-1}); **B** Cladode area index rate (CAIR, ha^{-1} ha^{-1} °C day^{-1}); **C** Cladode area (CA, Mg ha^{-1} °C day^{-1}).

45.000 plants ha^{-1} at 779.9 GAD with 0.0011 ha^{-1} ha^{-1} °C day^{-1} (Figure 5B). In turn, the density of 30.000 plants ha^{-1} failed to express the CAIR peak in the one-year cultivation period (Figure 5B).

The specific cladode area (SCA) was higher for the density of 60.000 plants ha$^{-1.}$ followed by the densities of 45.000 and 75.000 plants ha^{-1} (Figure 5C). At 801 GAD, all densities showed similar SCA, with 0.0060 Mg ha^{-1} °C day, completing the cycle with higher SCA for densities of 75.000, 60.000, 45.000 and 30.000 plants ha$^{-1.}$ with 20.09; 15.96; 13.51 and 7.11 Mg ha^{-1} °C day, respectively (Figure 5C).

The net assimilation rate (NAR) was similar for the densities of 60.000 plants ha^{-1} and 75.000 plants ha^{-1} up to 490 GDA, being higher than the other densities (Figure 6A). The density of 75.000 plants ha^{-1} completed the cycle with the highest NAR (0.030 Mg ha^{-1} °C) followed by densities of 60.000, 45.000 and 30.000 plants ha$^{-1.}$ with 0.023; 0.022 and 0.010 Mg ha^{-1} °C (Figure 6A).

The absolute growth rate (AGR) increased with the advance in GAD, with the density of 75.000 plants ha^{-1} achieving the highest rate with 0.029 Mg ha^{-1} °C day (Figure 6B), while the densities of 60.000, 45.000 and 30.000 plants ha^{-1} showed rates of 0.021; 0.022 and 0.010 Mg ha^{-1} °C day, respectively at 1.859 GDA (Figure 6B). With respect to the relative growth rate (RGR), the density of 45.000 plants ha^{-1} presented the highest RGR from 200 GDA, followed by the density of 75.000

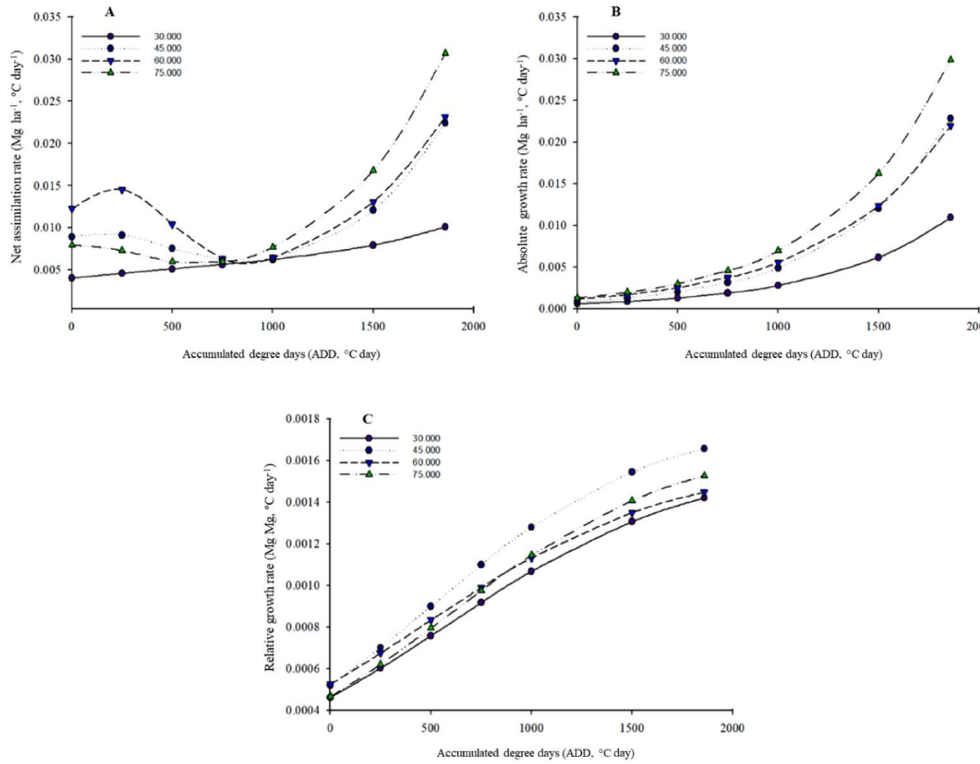

Figure 6. Effect of planting densities on growth rates: **A** net assimilation rate (NAR, Mg ha^{-1} °C day); **B** absolute growth rate (AGR, Mg ha^{-1} °C day); **C** Relative growth rate (RGR, Mg ha^{-1} °C day).

Table 3. Effect of planting densities and days after planting on production.

	Fresh matter production (t ha^{-1})			Dry matter production (t ha^{-1})		
Density (thousand plants ha^{-1})	120 DAP	240 DAP	360 DAP	120 DAP	240 DAP	360 DAP
30	20.01 b	38.88 c	36.54 c	2.44 b	3.69 c	6.43 c
45	32.77 b	66.21 bc	67.82 b	3.40 b	5.95 bc	11.47 ab
60	34.35 b	82.85 ab	75.92 ab	3.79 b	7.65 ab	12.77 a
75	55.22 a	103.83 a	101.40 a	5.30 a	9.04 a	16.90 a
SEM	9.82	20.40	18.24	0.81	1.76	2.94
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

DAP = days after planting; SEM = Standard error of the mean.

plants ha^{-1} (Figure 6C), completing the cycle with rates of 0.0014; 0.0016; 0.0014 and 0.0015 Mg Mg °C day, respectively, for densities of 30.000, 45.000, 60.000 and 75.000 plants ha^{-1} (Figure 6C).

The fresh matter production was higher ($P < 0.001$) for the density of 75.000 plants ha^{-1} in the three harvest periods (120; 240 and 360 DAP). However, dry matter production showed the same behaviour up to 240 DAP, with higher values for the density of 75.000 plants ha^{-1} at 360 DAP; the density of 60.000 and 75.000 showed statistically similar production (Table 3).

There was a decreasing linear model fit ($P < 0.05$) for the fresh matter production for the three harvests (Figure 7A). Showing an increase of 0.17; 1.41 and 1.35 t ha^{-1}

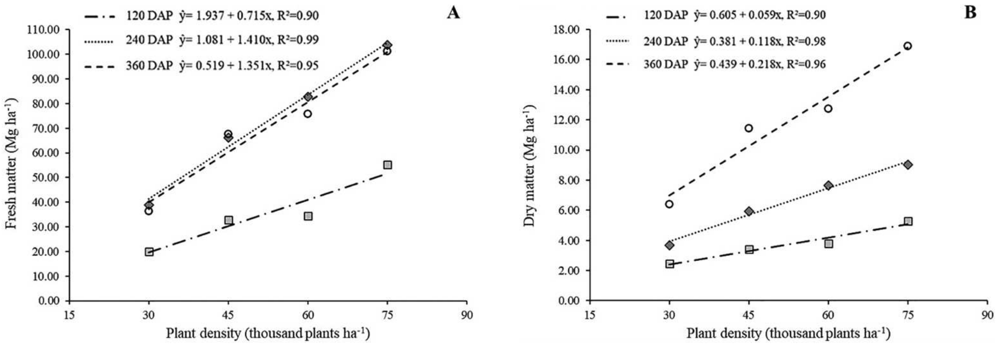

Figure 7. Effect of cactus pear planting densities on fresh matter **A** and dry matter **B** production.

respectively for 120; 240 and 360 DAP for every thousand plants added to the population. Dry matter production also showed an increasing linear effect ($P < 0.05$) for the three harvests, with a greater increase at 360 DAP, with 0.218 t ha^{-1} more, for every thousand plants included in the density (Figure 7B).

The accumulation of dry matter showed a similar behaviour between the four densities up to 1.000 plants ha^{-1} GAD (Figure 8), even with similar behaviours, the highest densities showed a higher accumulation. From 1.000 plants ha^{-1} GDA, the density of 30.000 plants ha^{-1} showed a more subtle inflection point (Figure 8).

When the days after planting (DAP) was evaluated separately, it was observed that DAP influenced plant height and width (Figure 9), total number, length, width (Figure 10) and perimeter of cladodes (Figure 11A), so that the 240 and 360 DAP showed similar values (Table 4).

Regarding cladode thickness, greater values were found at 240 DAP, followed by 360 and 120 DAP (Figure 11B). There were higher fresh matter productions at 240 and 360 DAP (Table 5; Figure 12A). However, greater DMP was achieved as DAP advanced (Figure 12B).

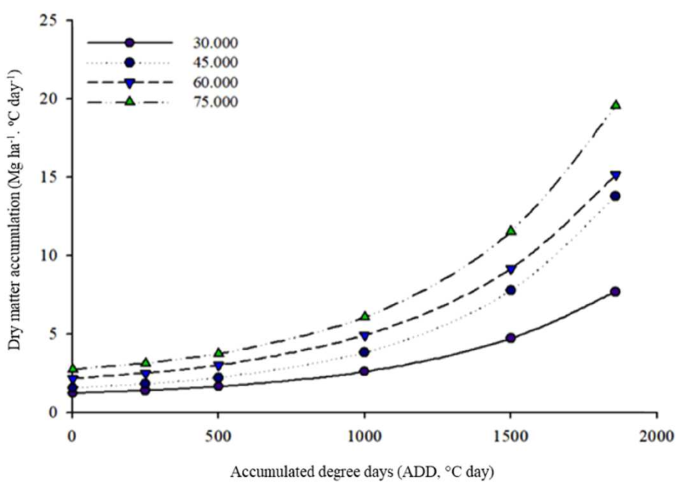

Figure 8. Dry matter accumulation of cactus pear under different planting densities.

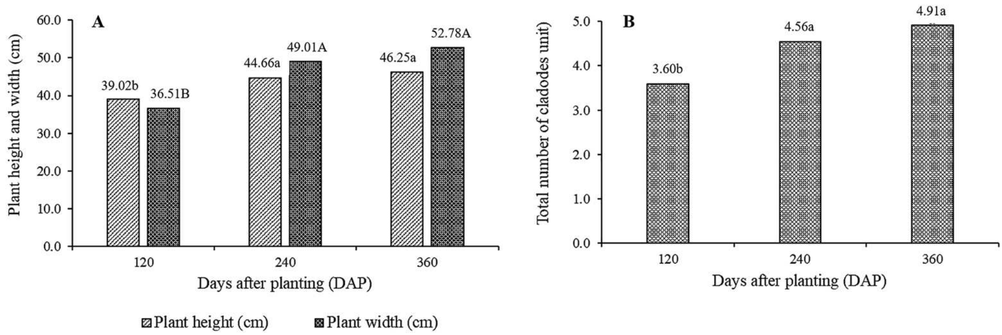

Figure 9. Effect of days after planting on plant height and width **A** and total number of cladodes **B** of cactus pear. [a,b] different lowercase letters in columns, differ statistically for plant height and and total number of cladodes; [A,B] different uppercase letters in columns, differ statistically for plant width. Significant by Tukey's test at 5% probability.

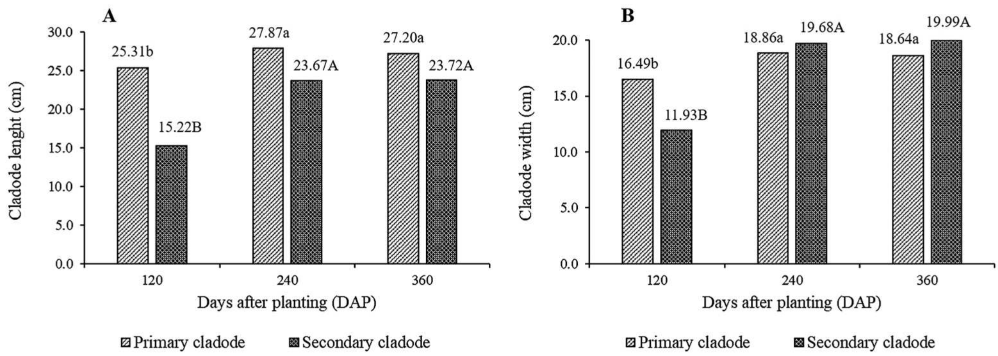

Figure 10. Effect of days after planting on cactus pear cladode length (A) and width (B). [a,b] different lowercase letters in columns, differ statistically for primary cladodes; [A,B]different uppercase letters in columns, differ statistically for secondary cladodes. Significant by Tukey's test at 5% probability.

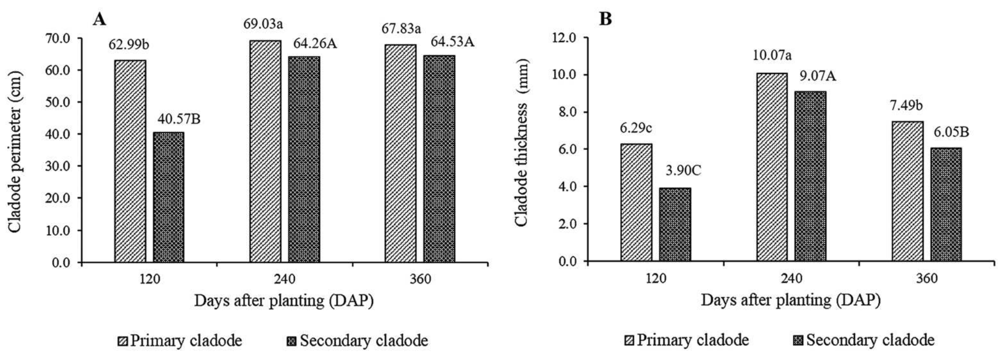

Figure 11. Effect of days after planting on cladode perimeter (A) and cladode thickness (B) production of cactus pear. [a,b]different lowercase letters in columns, differ statistically for primary cladodes; [A,B]different uppercase letters in columns, differ statistically for secondary cladodes. Significant by Tukey's test at 5% probability.

Table 4. Effect of days after planting (DAP) regardless of densities on morphological characteristics.

DAP	PH	LAR	TNC	PCL	SCL	PCW	SCL	PCP	SCP	PCT	SCT
120	39.02^{b}	36.51^{b}	3.59^{b}	25.31^{b}	15.22^{b}	16.49^{b}	11.93^{b}	62.99^{b}	40.57^{b}	6.29^{c}	3.89^{c}
240	44.66^{a}	49.00^{a}	4.55^{a}	27.87^{a}	23.67^{a}	18.86^{a}	19.68^{a}	69.03^{a}	64.26^{a}	10.07^{a}	9.07^{a}
360	46.24^{a}	52.78^{a}	4.91^{a}	27.20^{a}	23.72^{a}	18.63^{a}	19.98^{a}	67.83^{a}	64.53^{a}	7.49^{b}	6.05^{b}
SEM	2.86	6.39	0.51	0.99	3.77	1.00	3.51	2.42	10.59	1.41	1.82
p-value	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Different letters, in the same column, indicate significant difference by Tukey's test at 5% probability for type I error; *p*-value = statistical probability; SEM = Standard error of the mean; PH = plant height (cm); PW = plant width (cm); TNC = total number of cladodes (units); PCL = primary cladode length (cm); SCL = secondary cladode length (cm); PCW = primary cladode width (cm); SCL = secondary cladode width (cm); PC*P* = primary cladode perimeter (cm); SC*P* = secondary cladode perimeter (cm); PCT = primary cladode thickness (cm); SCT = secondary cladode thickness (cm).

Table 5. Effect of days after planting (DAP) regardless of densities on fresh matter and dry matter production.

DAP	Fresh matter production (t ha^{-1})	Dry matter production (t ha^{-1})
120	35.59^{b}	3.73^{c}
240	72.94^{a}	6.58^{b}
360	70.42^{a}	11.89^{a}
SEM	16.04	2.99
p-value	<0.001	<0.001

Different letters, in the same column, indicate significant difference by Tukey's test at 5% probability for type I error; *p*-value = statistical probability; SEM = Standard error of the mean.

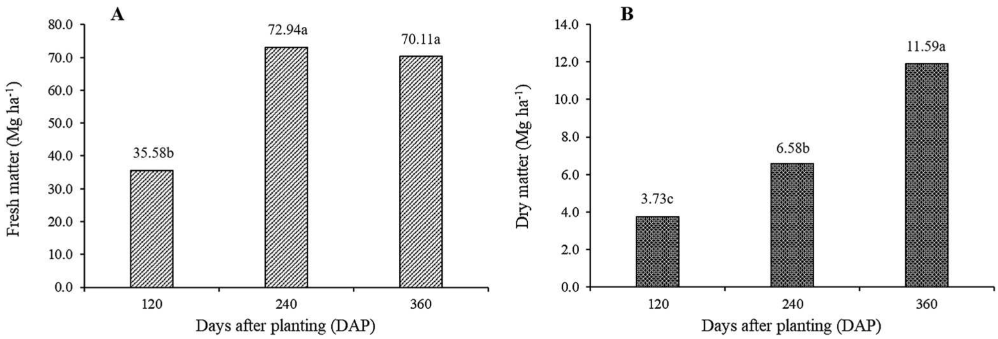

Figure 12. Effect of days after planting on fresh matter (A) and dry matter (A) production of cactus pear. [a,b]different lowercase letters in columns, differ statistically by Tukey's test at 5% probability.

4 Discussion

The height and width of the plant are considered productivity indicators, as depending on the management used, they influence production (Arantes et al. 2010), however in this study, the planting density of 60.000 plants ha^{-1} resulted in the highest height at 360 DAP, the highest productivity found was at the density of 75.000 plants ha^{-1}.

Plant height is a result of the number of cladodes. As DAP increases, the number of cladodes tends to increase. However, competition between plants can lead to a reduction in cladode emergence. Lemos et al. (2021) observed that the DAP increased the TNC, being 80.7% higher in irrigated plants compared to plants grown in rainfed conditions. Cladode emergence can be influenced by the planting method, density and genotype. Silva et al. (2015) reports that the Mexican elephant ear has erect growth, low emission of cladodes on the side of the mother plant. Thus, the reduction in TNC with increasing density may be a reflection of competition for space and light, also reflected in greater cladode lengths, evidencing a phototropism effect caused by increasing plant population. Nascimento et al. (2011) and Cavalcante et al. (2014) report that TNC decreases as the crop density increases, due to overlapping cladodes. Lemos et al. (2021) report higher TNC for the density of 33,333 thousand plants with 24.71 cladodes at 375 DAP.

The cladode emergence rate characterises its phenology, so that when the cladode emergence rate exceeds the other, a new phenophase begins, considered a tool for decision-making on the most appropriate management for the crop (Amorim et al. 2017).

The emergence of a new order of cladodes does not completely stop the emercenge of cladodes from the previous order; Amorim et al. (2017) state that new cladodes are indicative of energy losses, due to their small size and the ability to act as a pathway for the elimination of photoassimilates. Thus, the vegetative growth of cactus pear is characterised by the development of primary cladodes, given that densities with faster emergence of a new order of cladodes achieved smaller heights.

According to Dubeux Júnior and Santos (2005), the frequency of cactus pear harvesting depends on the planting density, since under adequate fertilisation conditions, a higher plant density provides an optimal CAI quickly, which requires more frequent harvests, aiming to reduce the negative effects of shading. Light is a factor that assumes great importance, considering the almost perpendicular arrangement of the cladodes in relation to the soil, making it difficult to intercept the incident light, which results in slow initial growth, due to the low photosynthetic area (Menor 2018). Therefore, for future research, it is necessary and pertinent to analyse light interception in the area of cactus pear cultivated at different densities in the semiarid region.

Therefore, identifying the ideal harvest time is a prerequisite for better production efficiency, given that the adaptation of the plant to cultivation conditions is its growth. In this context, the density of 30.000 plants ha^{-1} takes longer to express the highest cladode area index (CAI), cladode area index rate (CAIR) and specific cladode area (SCA), an effect associated with the greater energy loss attributed to the emergence of young cladodes (Amorim et al. 2017), which reduces their net assimilation rate (NAR), as it reflects the relationship between leaf area and dry matter production (Queiroz et al. 2015) demonstrating that low densities have low photosynthetic efficiencies, a factor also associated with loss of light energy, as the photosynthetic process depends on the interception of photosynthetically active radiation and its conversion capacity into chemical energy (Pinheiro et al. 2015).

The density of 30.000 plants ha^{-1} presented the third phenophase close to 1.500 GAD, a period in which there was low rainfall, which led to alterations in morphological indices, as new cladodes carried out the C3 photosynthetic metabolism during the day (Acevedo et al. 1983), which requires water availability from older cladodes (Wang et al. 1997) and reduces the net daily absorption of CO_2 (Pimienta-Barrios et al. 2005).

The increase in fresh and dry matter production (FMP and DMP) is due to the number of plants in the palm crop (Silva et al. 2014). Even if the plant has smaller heights, fewer cladodes and consequently lower weight per plant at higher densities, the plant population per hectare will excel in production. Thus, in studies carried out by Donato et al. (2013) evaluating a density of 20.000 plants ha^{-1} observed DMP at 600 DAP of 18.2 t ha^{-1} (without the use of organic matter – OM). Cortázar et al. (2001) observed that palm crops with 60.000 plants ha^{-1} after 450 DAP with 60.0 t ha^{-1} year^{-1} of biofertiliser achieve yields of 19.9 t ha^{-1}. Higher densities were evaluated by Lemos *et al.* (2021) with 66,667 plants ha$^{-1.}$ resulting in higher FMP (956,508.3 t ha-1 yr – 1) and DMP (71.240.7 t ha^{-1} year^{-1}).

Regarding the thickness, width and length of cladodes, greater values of thickness were verified at 240 DAP, and lengths and widths equal to 240 and 360 DAP, close to 240 DAP there was an increase in the volume of rainfall, compared to 360 DAP. Thus, the emergence of cladodes is associated with the stage of growth and vegetative development (Pinheiro et al. 2014; Silva et al. 2015), as well as the ability of cactus pear to quickly absorb moisture by absorbing roots (Prat and Franck 2017), in addition to the fact that the epidermis presents a folded and non-smooth surface, which favours its flexibility in the accumulation of water, causing the volume of the vein to increase as the water is absorbed without affecting the epidermis surface (Mauseth 2006), just as the cladode has the ability to absorb the moisture present in the soil in a few hours, the same when it is found in periods of low water availability, the internal recycling of water begins between the parenchyma and chlorenchyma, a mechanism that seeks to maintain the photosynthetic process of the tissue (Inglese et al. 2017).

Under the experimental conditions, the increase in planting density promotes an increase in production and changes the morphological characteristics and phenophases. Thus, the increase in density makes it possible to anticipate the harvest, and it is recommended planting densities of 60.000 and 75.000 plants per hectare.

The study on cactus pear (*Opuntia stricta* Haw.) reveals significant implications, especially for pasture management in semiarid regions. The research highlights how different planting densities impact morphological, phenological and productive characteristics of cactus pear, such as the total number of cladodes, cladode area index and net assimilation rates. These findings help to elucidate physiological mechanisms that can be optimised to increase photosynthetic efficiency and water use in systems with low water availability, promoting advances in knowledge about the physiology and ecophysiology of crops adapted to semiarid regions.

The results reinforce the importance of higher planting densities (such as 75.000 plants ha^{-1}), which promote greater productivity of fresh and dry matter, essential for feeding livestock during periods of drought.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data will be made available on request.

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