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Biomass components and water use efficiency in cactus pear under different irrigation systems and harvest frequencies

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ABSTRACT - The objective was to evaluate the effect of different irrigation systems and harvest frequencies on the cultivation of cactus pear. The study was conducted in the semi-arid region, in the municipality of Russas, CE, Brazil. The experiment was a split plot randomized block design, with four replications. Plots were represented by irrigation systems (surface drip, microsprinkler, Micro Spray Jet, and conventional sprinkler) and subplots by harvest frequencies (6, 9, 12, and 18 months). Cactus pear biomass production characteristics were evaluated. Most of the productive characteristics evaluated were influenced by harvest frequency and irrigation system. The harvest frequency of 12 months combined with conventional sprinkler system resulted in a total dry biomass production of 16,400 kg ha^{-1}. The conventional sprinkler system showed the highest number of second-order cladodes (4.9 cladodes plant^{-1}). The conventional sprinkler and Micro Spray Jet systems showed the highest values for various structural characteristics. For water use efficiency (WUE), the highest value was found at the frequency of six months (8.46 kg ha^{-1} mm^{-1}). Regarding the effects of irrigation system on WUE, the highest values were observed with the conventional sprinkler system (8.20 kg ha^{-1} mm^{-1}). The harvest frequency of 12 months combined with the conventional sprinkler system presents better results in the evaluated productive characteristics, mainly the cactus pear production by area.

Keywords: cladodes production, forage production, irrigation management, *Opuntia stricta*

1. Introduction

Cactus pear is one of the most strategic forage resources for ruminant production in the Brazilian semi-arid region. Its adaptability to soil and climate conditions of this region, presenting low water demand, good nutritional value, and high production potential, are attributes that make it possible not only to feed cattle, sheep, and goats, but also to provide stability and security to rural developments.

Even with adaptability to arid and semi-arid regions, the growth of cactus pear varies according to fluctuations in local climatic conditions (Pereira et al., 2015), mainly due to water availability, night temperature, and relative air humidity. Thus, irrigation has reduced the effects of adverse climatic conditions on the crop and promoted productivity gains (Cruz Neto et al., 2017), improving the efficiency of use of resources, among them, land and manpower.

The literature shows results of photosynthesis evaluations and other important characteristics of gas exchange in cactus pear under irrigation (Alves et al., 2020), as well as studies on the effects of irrigation depths and frequencies in different cactus pear varieties on growth (Pereira et al., 2015; Dantas Neto et al., 2020), soil water balance (Pereira et al., 2017), structural characteristics, and forage biomass production (Pereira et al., 2021). In addition to water availability, the way water is applied, through different irrigation systems, can influence the volume of moist soil, modifying root growth and root biomass production, which will reflect on the biomass production capacity of the forage crop, as studies (Shao et al., 2008; Edvan et al., 2013) confirm the beneficial effects of soil moisture on the development of the root system and plant productivity.

Moreover, other cultivation factors, including harvest frequency and intensity (Farias et al., 2000; Alves et al., 2007) and growing regions (Dubeux Jr. et al., 2006) influence forage production in cactus pear. In this sense, studies on cactus pear irrigation do not involve the effects of several factors, such as the morphophysiological responses of the crop under different harvest frequencies and irrigation systems.

Although most of the properties in the Northeastern semi-arid adopt low-tech cactus pear cultivation, many producers are adhering to more intensive systems, with greater plant density and the adoption of appropriate management practices, such as replenishing nutrients through fertilization and control of spontaneous plants, pests, and diseases. With the expansion of more intensive crops and areas of cactus pear under irrigation, it is important to carry out studies that allow evaluating the plant response as to productive characteristics with the use of this technology.

For this, it is necessary to understand irrigation management and know the existing irrigation methods and systems, thus allowing to use it more efficiently, by maximizing the response of cactus pear in increasing forage biomass production, seeking the lowest expenditure of water resources, and environmental benefits, such as better food security for cattle, sheep, and goats, and resulting in better sustainability for milk and meat production in the Brazilian semi-arid.

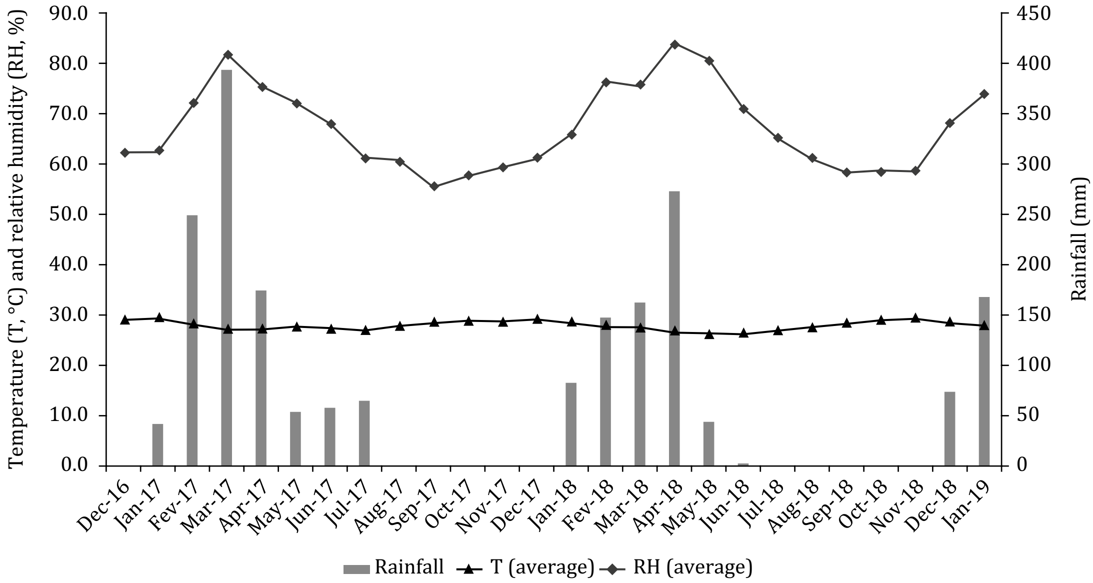
In view of this demand, the objective was to evaluate the productivity of *Opuntia stricta* (Haw.) Haw cv. Mexican Elephant Ear (IPA 200016) under different harvest frequencies and irrigation systems.

2. Material and Methods

2.1. Experimental site

The experiment was conducted in an agricultural plot located in the Irrigated Perimeter Tabuleiro de Russas, municipality of Russas, in the state of Ceará, Brazil. The experimental period was between December 26, 2016 and January 25, 2019, for a total of 25 months. The experimental area is located at an altitude of 80 m, with the rainy season from January to April and the dry season from May to December. The average annual rainfall is 857.7 mm and temperatures between 22.0 and 35.0 °C, with annual average of 28.5 °C (IPECE, 2009), at the geographical coordinates: 4°56'00.5" S, 38°01'25.3" W, with BSw’h’ climate, hot semi-arid tropical, according to Koeppen classification (1948). The soil in the experimental area is Quartzarenic Neosol, with sandy texture (Embrapa, 2013).

Throughout the experimental period, monthly averages of temperature, relative humidity, and rainfall (monthly and total) were monitored (Figure 1). Daily, monthly, and total rainfall were obtained at the experimental site, while temperature and relative humidity were obtained from FUNCEME Agroclimatological Station, located 27.2 km from the experimental area, in the municipality of Morada Nova. During the experiment (December 2016 to January 2019), the rainfall totaled 1,996 mm. The average maximum and minimum temperatures were 28.7 and 27.3 °C, respectively, presenting a general average in the period of 28.0 °C. The average maximum and minimum relative humidity (RH) were 70.5 and 64.2%, respectively, while the general average RH during the experimental period was 67.4%.



Source: rainfall data were obtained at the experimental site, while temperature and relative humidity data were obtained from FUNCEME Agroclimatological Station.

Figura 1 - Monthly averages of temperature, relative humidity, and rainfall (monthly and total) throughout the experimental period.

2.2. Treatments and experimental design

The experiment was a split plot randomized block design, with plots represented by the irrigation systems (surface drip – Netafin; microsprinkler - Implebrás irrigation; Micro Spray Jet - Implebrás irrigation; and conventional sprinkler - Naandan) and sub-plots by harvest frequencies (6, 9, 12, and 18 months), totaling 64 experimental units.

2.3. Physical and chemical characterization of the soil in the experimental area

At the experimental onset, the physicochemical characterization of soil was carried out at a depth of 0.0-20.0 cm (Table 1), with a new soil analysis made one year after the beginning of the experiment (Table 2). The soil was classified as sandy texture, with 90.8% sand in its composition (coarse and fine sand). Based on the results obtained, the need for liming and fertilization of the experimental area was calculated.

Table 1 - Physicochemical characteristics of the soil in the experimental area in the municipality of Russas, CE, Brazil, before implementing the experiment

Coarse sand		Fine sand		Silt	Clay		PD		Texture classification	
---------------------------- g kg^{-1} ------------------------------							g cm^{-3}			
648		260		16	76		2.73		Sand	
P	K	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	SB	ECEC	pH	OM
mg dm^{-3}	-- $cmol_c$ dm^{-3} --								H_2O	g kg^{-1}
1.0	0.15	0.18	0.6	0.4	0.2	1.29	1.3	2.82	4.3	10.45

PD - particle density; SB - sum of bases; ECEC - effective cation exchange capacity; OM - organic matter.

Table 2 - Soil chemical characteristics of the experimental area in the municipality of Russas, CE, Brazil, after one year of cultivation of cactus pear

P	K	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	SB	ECEC	pH	OM
mg dm^{-3}	-- $cmol_c\ dm^{-3}$ --								H_2O	g kg^{-1}
9.0	0.08	0.21	0.7	0.5	0.3	0.86	1.5	2.65	5.5	6.41

SB - sum of bases; ECEC - effective cation exchange capacity; OM - organic matter.

2.4. Implementation and conduction of the experiment

The experimental area was prepared in late November 2016, with soil plowing and harrowing, in addition to liming with lime incorporation. The liming requirement was calculated using the base saturation method, according to Lopes et al. (1990). In the experimental area, the goal was to increase the soil base saturation to 80%, which resulted in the need to apply 1,200 kg ha^{-1} $year^{-1}$ during the implementation of the experiment. Due to the fact that magnesium is below 20% in the CEC of soil, dolomitic limestone was used to correct soil acidity.

After preparing the area, the experiment was installed, starting with the demarcation of plots and subplots. The spacing used was 1.60 × 0.40 × 0.14 m, planting 14 seedlings per linear meter in the double row (seven seedlings in each row), resulting in a density of 70,000 plants ha^{-1}, which was defined based on the results obtained by Cavalcante et al. (2014), when evaluating productive response of cactus pear at different planting densities. Furrows for planting cactus pear were made manually, with a hoe, obeying the average depth of 30 cm.

Planting was carried out at the end of December 2016, in the dry season of the year, using whole cladodes of the cactus pear *Opuntia stricta* (Haw.) Haw cv. Mexican Elephant Ear (IPA 200016), aged 110 to 120 days, with 15-20 cm wide and 20-25 cm long, and planted after 10 days of harvest (period for healing the cut site made at harvesting), arranged one after the other in the east-west direction and coverage of 2/3 of their length. The plant material used for planting was supplied by a company accredited by the Ministry of Agriculture (MAPA), which garanteed the quality and health of cladodes, which were thus free from pests and diseases.

Each plot was formed by an area of 8.4 × 19 m, resulting in an area of 159.6 m^2, with 1,120 plants per plot. Each subplot was formed by 4.0 × 8.4 m, 1 m apart, resulting in an area of 33.6 m^2, containing 280 plants, distributed in five double rows 4.0 m long, each with 56 plants (28 in each single row), with 20 plants in the middle of the central row intended for measurements and the others, as borders. The total useful area of the experiment was 2,553.6 m^2. Adding the area equivalent to the borders (between plots and subplots), the total experimental area was 6,150 m^2.

Soil correction and fertilization were carried out to guarantee the levels of macro- (N, P, K, Ca, Mg, and S) and micronutrients (B, Fe, Mn, and Zn) necessary for the full development of the crop (Dubeux Júnior et al., 2010; Donato et al., 2017). The amounts of mineral fertilizers were calculated based on the results of soil analyses (Tables 1 and 2) carried out before the implementation of the experimental area and after the first year of cultivation, with the expectation of a dry biomass production of 40,000 kg ha^{-1} $year^{-1}$.

Fertilization consisted of the application equivalent to 50 kg ha^{-1} $year^{-1}$ FTE BR 12 (micronutrients: 9.0% Zn, 1.8% B, 0.8% Cu, 3.0% Fe, 2.0% Mn, and 0.1% Mo), 185.0 kg ha^{-1} $year^{-1}$ P_2O_5, using the single superphosphate (18.0% P_2O_5; 720.0 kg) and monoammonium phosphate-MAP (50.0% P_2O_5; 111.0 kg), 188.0 kg ha^{-1} $year^{-1}$ nitrogen, using urea (45.0% N, 200.0 kg) as a source, ammonium sulphate (20.0% N; 429.0 kg), and monoammonium phosphate-MAP (11.0% N; 111.0 kg) and 742.8 kg ha^{-1} $year^{-1}$ K_2O, with potassium chloride (1,238 kg) as a source. The area also received organic fertilization, with proportional application of 20,000 kg^{-1} ha^{-1} $year^{-1}$ chicken litter, a material that, by means of an analysis, presented in its composition 1.43% N, 2.27% P_2O_5, and 0.9% K_2O.

Initial fertilizations of phosphorus and micronutrients were carried out at the center of the double row, 15 days after planting, at once. Organic fertilization was carried out 30 days after planting, in the center of the double rows of cactus pear.

Thirty days after planting, we began production fertilization (Lemos et al., 2018) using nitrogen and potassium fertilizers, which was carried out weekly through fertigation, throughout the year. After a year of experiment, a new soil analysis was performed; however, in view of the results obtained, it was not necessary to make changes in fertilization with phosphorus (P_2O_5) and micronutrients, as well as nitrogen and potassium fertilizers, keeping similar amounts to those applied in the first year of cultivation.

At the beginning of the second year of cultivation, both phosphate and micronutrient fertilizations, as well as organic fertilization, this time applied only to the sides of the rows of cactus pear, were carried out at once, in January 2017.

After one year of the experiment, lime was applied again, this time as broadcast, in the proportion of 780 kg ha^{-1} year^{-1}, an amount defined based on the results of soil analysis carried out twelve months after implementing the experimental area, once again using the base saturation method, aiming to increase it to 80%. In the same way that the first application, due to the magnesium being below 20% in the CEC of the soil, dolomitic limestone was used to correct soil acidity.

The irrigation equipment was installed in the experimental area immediately after planting cactus pear, with the implementation of the four different irrigation systems: surface drip, microsprinkler, Micro Spray Jet, and conventional sprinkler. Among the irrigation systems evaluated, three are characterized by the localized irrigation method (surface drip, microsprinkler, and Micro Spray Jet) and one by sprinkler (conventional sprinkler).

For irrigation management, as the soil in the experimental area is classified as sandy texture, with low water holding capacity, and while cactus pear has a shallow root system (Santos et al., 2017), we used a higher frequency of irrigation, with application interval of two days. The established irrigation depth was 2.5 mm day^{-1}, defined based on the replacement of 33% average reference evapotranspiration (ETo) from September to December (7.48 mm day^{-1}), corresponding to the highest indices for the region (Cabral, 2000). Thus, total depth of 5 mm was applied every two days.

Because the flow rate is different for each irrigation system used, the volume of water applied was determined by the system operating time in each plot (Table 3), thus guaranteeing the same water depth used in all of them.

To obtain the proper irrigation management, all the equipment was automated, following previously established programming to turn on and off each irrigation system, respecting the pre-established operating time in each of them. To minimize the interference of wind with the applied water depth, the period between 05:00 and 07:00 h was defined as the time of irrigation, which has the lowest incidence of wind at the site of the experiment.

Therefore, as irrigation was carried out throughout the year, also comprising the rainy season, at every 10 mm or more of rainfall occurring in one day, irrigation was interrupted, returning on the fourth day after their occurrence.

Table 3 - Technical characteristics of the different irrigation systems and operating time for irrigation of cactus pear cv. Mexican Elephant Ear in the experimental area, in the municipality of Russas, CE, Brazil

Irrigation system	Spacing (rows/emitter)	Flow (L h^{-1})	Number of emitters ha^{-1}	Flow (L ha^{-1} h^{-1})	Operating time (min./watering)
Surface drip	2.0 m/0.2 m	2	25,000	50,000	60
Microsprinkler	4.0 m/4.0 m	60	625	37,500	80
Micro Spray Jet	2.0 m/1.0 m	20	5,000	100,000	30
Conventional sprinkler	12.0 m/12.0 m	510	69	35,190	55[1]

[1] The irrigation time of the conventional sprinkler was adjusted due to the use of sectored emitters/sprinklers (90° and 180°), which reduced the necessary irrigation time.

As a standard procedure to suspend irrigation, we established three days before the beginning of the morphological survey of the plants, only to irrigate again after harvesting the cactus pear for weighing. This management was defined to avoid interference of water via irrigation in the composition of cactus pear at the time of harvesting.

After implementation of the plantation and throughout the experimental period, the necessary crop treatments were carried out routinely to promote the full development of the crop, such as control of undesirable plants, by means of cleaning and chemical weeding (use of herbicide as a test: hexazinona, diuron, and metrimex). Pest controls were also performed whenever necessary, especially caterpillars, fungi, and cochineal (*Diaspis echinocacti*), which were controlled using specific agrochemicals: lannate, kocide, and evidence/imidagold, respectively.

Evaluations were made when the material was collected, according to the harvest frequency set (6, 9, 12, and 18 months). Cactus pear was cut on the secondary cladode, 5 cm above the intersection between the primary and secondary cladodes, according to the methodology used by Carneiro et al. (1989). This harvest strategy aimed to maintain the longevity of the crop and better plant regrowth capacity by means of a higher remaining cladode area index (remaining CAI).

During the experiment (24 months), four harvests were performed every six months, two harvests at the harvest frequencies of 9 and 12 months, and one harvest at the frequency of 18 months. Analyses were performed using the averages of the measurements obtained at the respective harvest frequencies.

At the end of each growth cycle, for the harvest frequencies of 6, 9, 12, and 18 months, the plants in the useful area of each treatment (sample row; composed of 20 plants) were harvested and weighed on a digital scale accurate to 0.05 g, per order of cladodes (second, third, fourth, and fifth), allowing the estimate of production of fresh forage biomass per order of cladode and total per plant.

A sample of the harvested material were taken at random from each treatment and sent to the laboratory and weighed. Then, the cladodes were cut to 1-2 cm and dried in a forced-air oven at 55 °C to constant weight, with pre-drying. Then, this material was ground in a Wiley mill with a 1.0-mm sieve and taken to the oven at 105 °C for 16 h, weighed to determine the dry matter content of the sample for later estimation of dry biomass, according to the methodology described by Silva and Queiroz (2006). With these data, dry biomass production was determined for each treatment and for each harvest, allowing to estimate production per ha^{-1}.

With the measurements described, the following production variables were determined in the cactus pear cv. Mexican Elephant Ear: number of cladodes in each order; total number of cladodes per plant (TNC); total number of harvestable cladodes per plant (TNHC), determined from the sum of all cladodes per plant, from the second order onwards; total fresh biomass production (TFBP); dry forage biomass per hectare; and water use efficiency (WUE).

Water use efficiency was calculated considering the volume of water from rainfall, together with water via irrigation (Aujla et al., 2005). It was estimated by the ratio of the production of harvestable dry biomass (PHDB, kg ha^{-1}) of cactus pear to the volume of water accumulated in the growth cycle (R = rainfall + I = irrigation), in mm, according to the formula:

$$\text{WUE (kg ha}^{-1}\text{ mm}^{-1}) = \text{PHDB (kg ha}^{-1})/\text{R + I (mm)}$$

2.5. Statistical analysis

Data were analyzed according to their nature, testing by analysis of variance, test of comparison of means, and descriptive analysis. To compare the different harvest frequencies and irrigation methods, analysis of variance was applied, compared by Tukey's test, at the level of 1 and 5% probability. All statistical analyses were performed using the software SAS (2002). The following statistical model (01) was used:

$$Yijk = \mu + Bk + SIi + \alpha ik + FCj + (SI \times FCij) + \varepsilon ijk, \quad (1)$$

in which Yijk is the dependent variable; μ is the overall costant; Bk is the random effect of block; SIi is the effect of the irrigation system; αik is the effect of the plot error; FCj is the effect of the harvest frequency; (SI × FCij) is the fixed effect of the interaction between irrigation system and harvest frequency; and εijk is the effect of random error.

For variables with no significant interaction (P>0.05) between harvest frequencies and irrigation systems, regression analysis was performed on the main effect, with discussion of the linear and quadratic effects that marked the relationships between variables.

3. Results

Differences were detected (P<0.05) for number of second- (NSOC) and third-order (NTOC) cladodes, TNC, and TNHC, considering both the harvest frequency and irrigation system (Tables 4 and 5). Number of first-order cladodes (NFOC) had an effect (P<0.05) only in relation to irrigation system (Table 5). No differences were detected (P>0.05) for the number of fourth- and fifth-order cladodes in the two factors evaluated.

The NFOC showed a positive linear effect with increasing harvest interval, with values observed between 3.58 and 3.81 cladodes plant^{-1} (Table 4). Regarding the effects of irrigation system on NFOC,

Table 4 - Mean values of number of cladodes of cactus pear cv. Mexican Elephant Ear as a function of different harvest frequencies

Variable	Harvest frequency (months)				SEM	P-value	Equation
	6	9	12	18			
NFOC	3.58	3.65	3.71	3.81	0.09	0.3577	Y = 3.67
NSOC	3.64b	3.51b	4.53a	5.08a	0.18	<0.0001	$Y = 2.66643 + 0.1356x$, $R^2 = 33$
NTOC	1.38ab	1.13b	1.86ab	2.26a	0.25	0.0106	$Y = 1.1836 - 0.0091x + 0.0039x^2$, $R^2 = 10$
NFoOC	0.11	0.09	0.17	0.09	0.58	0.6706	Y = 0.12
NFiOC	0.002	0.002	0.02	-	0.007	0.3214	Y = 0.005
TNC	8.72bc	8.37c	10.28ab	11.24a	0.45	<0.0001	$Y = 6.9429 + 0.2409x$, $R^2 = 18$
TNHC	5.14bc	4.72c	6.58ab	7.43a	0.41	<0.0001	$Y = 3.47 + 0.222x$, $R^2 = 71$

SEM - standard error of the mean; R^2 - coefficient of determination; NFOC - number of first-order cladodes (cladodes plant^{-1}); NSOC - number of second-order cladodes (cladodes plant^{-1}); NTOC - number of third-order cladodes (cladodes plant^{-1}); NFoOC - number of fourth-order cladodes (cladodes plant^{-1}); NFiOC - number of fifth-order cladodes (cladodes plant^{-1}); TNC - total number of cladodes (cladodes plant^{-1}); TNHC - total number of harvestable cladodes (cladodes plant^{-1}).
Means followed by different letters, in the same row, are significantly different by Tukey's test at 5% probability (P<0.05).

Table 5 - Mean number of cladodes of cactus pear cv. Mexican Elephant Ear according to different irrigation systems

Variable	Irrigation system				SEM	P-value
	Surface drip	Microsprinkler	Micro Spray Jet	Conventional sprinkler		
NFOC	3.51b	3.54b	3.73ab	3.95a	0.09	0.0041
NSOC	3.61b	4.01b	4.22b	4.92a	0.18	<0.0001
NTOC	0.59b	1.76a	1.91a	2.38a	0.25	<0.0001
NFoOC	0.02	0.09	0.16	0.20	0.58	0.1468
NFiOC	-	-	0.01	0.02	0.007	0.3786
TNC	7.37c	9.39bc	10.02ab	11.46a	0.45	<0.0001
TNHC	4.22c	5.85b	6.28ab	7.51a	0.41	<0.0001

SEM - standard error of the mean; NFOC - number of first-order cladodes (cladodes plant^{-1}); NSOC - number of second-order cladodes (cladodes plant^{-1}); NTOC - number of third-order cladodes (cladodes plant^{-1}); NFoOC - number of fourth-order cladodes (cladodes plant^{-1}); NFiOC - number of fifth-order cladodes (cladodes plant^{-1}); TNC - total number of cladodes (cladodes plant^{-1}); TNHC - total number of harvestable cladodes (cladodes plant^{-1}).
Means followed by different letters, in the same row, are significantly different by Tukey's test at 5% probability (P<0.05).

there was no difference (P>0.05) between the results obtained in the conventional sprinkler system and Micro Spray Jet (Table 5), which presented the highest values, 3.95 and 3.73 cladodes plant^{-1}, respectively. In the Micro Spray Jet, values were similar to those observed in the microsprinkler (3.54 cladodes plant^{-1}) and surface drip (3.51 cladodes plant^{-1}) systems.

The number of second order cladodes, TNC, and TNHC adjusted in a positive linear way to the increase in the harvest interval of cactus pear (Table 4). The NTOC responded quadratically to the reduction in harvest frequency (Table 4), which was estimated through the adjusted model that the minimum value for this variable reached 1.18 cladodes plant^{-1} at 2.47 months.

Regarding the effect of the irrigation system on NSOC, the highest value was found for conventional sprinkling (4.92 cladodes plant^{-1}), while the other systems showed similar results (P<0.01) to each other (Table 5). With respect to the effect of the irrigation system on TNC, the highest values were obtained in the conventional sprinkler system (11.46 cladodes plant^{-1}), and in the Micro Spray Jet (10.02 cladodes plant^{-1}), there was no difference (P>0.05) from each other (Table 5). The microsprinkler system showed 9.39 cladodes plant^{-1}, while surface dripping obtained 7.37 cladodes plant^{-1}, results that were similar.

Considering the different irrigation systems, the greatest TNHC occurred with the use of conventional sprinkler (7.51 cladodes plant^{-1}), followed by the Micro Spray Jet system (6.28 cladodes plant^{-1}), values that were not different from each other (P>0.05). On the other hand, the observed TNHC in the Micro Spray Jet was not different from the value obtained in the microsprinkler system (5.85 cladodes plant^{-1}). The surface drip showed the lowest TNHC (4.22 cladodes plant^{-1}), result that differed (P<0.01) from those observed in the other irrigation systems evaluated (Table 5).

For TFBP, there was an interaction (P<0.05) between irrigation systems and harvest frequencies. An increasing linear response was observed in the surface drip, microsprinkler, and Micro Spray Jet systems (Table 6). The conventional sprinkler system presented a quadratic behavior (Table 6), reaching a maximum value of 242,390 kg ha^{-1} fresh biomass at 15.2 months.

For the total dry biomass production (TDBP), the conventional sprinkler system showed a quadratic behavior, reaching maximum values of 16,350 kg ha^{-1} at 16.98 months (Table 7). For interaction between irrigation system and harvest frequency, there was significance (P<0.05) only for the harvest frequency of 12 months, whose highest TDBP was verified when associated with the conventional sprinkler system, showing a difference (P<0.05) for the values obtained in the other irrigation systems (Table 7).

There was no interaction (P>0.05) between harvest frequencies and irrigation systems for WUE. Isolated effects (P<0.05) of the evaluated factors on the WUE of cactus pear cv. Mexican Elephant Ear (Table 8). A decreasing linear response (P<0.01) was found for WUE as a function of harvest frequencies (Table 8). This shows that shorter crop cycles (higher cutting frequency) resulted in increased WUE

Table 6 - Mean values of total fresh biomass production (kg ha^{-1}) of cactus pear cv. Mexican Elephant Ear, due to the interaction between harvest frequency and irrigation systems

Irrigation system (IS)	Harvest frequency (HF; months)				Equation
	6	9	12	18	
Surface drip	73393b	89161ab	115516Bab	165106a	$Y = 22911.50 + 7811.77x, R^2 = 82$
Microsprinkler	103120	100498	158440B	188190	$Y = 48760.79 + 7893.47x, R^2 = 58$
Micro Spray Jet	88498b	113542ab	142279Bab	192232a	$Y = 36387.07 + 8688.75x, R^2 = 51$
Conventional spraying	114782b	116372b	267795Aa	221417a	$Y = -165452.41 + 53657.15x - 1764.47x^2, R^2 = 53$

SEM	P-value		
	IS	FC	IS × HF
17433	<0.0001	<0.0001	0.026

SEM - standard error of the mean; R^2 - coefficient of determination.
Means followed by different letters, in the same column or row, are significantly different by Tukey's test at 5% probability (P<0.05).

Table 7 - Mean values of total dry biomass production (kg ha^{-1}) of cactus pear cv. Mexican Elephant Ear, due to the interaction between harvest frequency and irrigation systems

Irrigation system (IS)	Harvest frequency (HF; months)				Equation
	6	9	12	18	
Surface drip	4987b	6381b	8389Bab	12963a	Y = 572.79 + 676.22x, R^2 = 85
Microsprinkler	6322b	6739b	9761Bab	14568a	Y = 1161.11 + 727.67x, R^2 = 76
Micro Spray Jet	6158b	8508b	9886Bb	15320a	Y = 1488.46 + 753.74x, R^2 = 76
Conventional spraying	6945b	7898b	16373Aa	15901a	Y = −8757.32 + 2957.19x − 87.06x^2, R^2 = 69

SEM	P-value		
	IS	FC	IS × HF
961.65	<0.0001	<0.0001	0.0179

SEM - standard error of the mean; R^2 - coefficient of determination.
Means followed by different letters, in the same column or row, are significantly different by Tukey's test at 5% probability (P<0.05).

Table 8 - Water use efficiency (kg ha^{-1} mm^{-1}) in cactus pear cv. Mexican Elephant Ear as a function of different harvest frequencies and irrigation systems

Harvest frequency (months)				SEM	P-value	Equation
6	9	12	18			
8.46a	6.03b	7.05b	5.71b	0.37	<0.0001	Y = 8.83 − 0.18x, R^2 = 15
Irrigation system						
Surface drip	Microsprinkler	Micro Spray Jet	Conventional spraying	SEM	P-value	-
5.50b	6.65b	6.89ab	8.20a	0.37	<0.0001	-

SEM - standard error of the mean; R^2 - coefficient of determination.
Means followed by different letters, in the same row, are significantly different by Tukey's test at 5% probability (P<0.05).

of cactus pear. As for the effect of irrigation systems, higher values were observed for WUE in the conventional sprinkler system (8.20 kg ha^{-1} mm^{-1}) and in the Micro Spray Jet (6.89 kg ha^{-1} mm^{-1}), which did not differ (P>0.05) from each other (Table 8). There was no difference (P>0.05) in WUE between the Micro Spray Jet, drip (5.50 kg ha^{-1} mm^{-1}), and microsprinkler (6.65 kg ha^{-1} mm^{-1}) systems.

4. Discussion

Whether analyzing the effects of harvest frequency (Table 4) or the irrigation system (Table 5), NFOC was always lower than NSOC, except for that obtained at the harvest frequency of nine months, in which NFOC was superior to NSOC. These numbers reflect the probable stabilization of the plant as to the emergence of first-order cladodes, which, from this moment onwards, the plant prioritizes the emergence of upper cladodes (Ramos et al., 2011). In addition, this order of cladodes may be receiving less active photosynthetically radiation, which may inhibit the development of buds in the primary cladodes, affected by the development of upper cladodes, reducing the penetration of solar radiation in the lower cladode order, inhibiting the emergence of new shoots in this part of the plant. For Silva et al. (2010), this is also due to the fact that the primary cladodes originate from a single cladode (base or mother cladode), different from the secondary cladodes, which arise through new buds of several cladodes, in this case, of the first order.

The largest number of primary cladodes is important, since it is related to the cladode area index (CAI), mainly the remaining CAI after harvesting, which makes it possible to enlarge the photosynthetically active area and, consequently, greater production of total harvestable biomass. In addition, first-order cladodes provide the plant with better structure, which is desirable, since it is this part that will support all biomass produced through the orders of upper cladodes (Pinheiro et al., 2014), also presenting an important function in the distribution of nutrients and water to the other organs of the plant (Pereira et al., 2015).

The results observed for NSOC, TNC, and TNHC show the positive effect of the longer time between harvests for the production of total number of cladodes in the plant, since the longer period between harvests allows the emergence of new shoots by the plant, especially in intensive cultivations with continuous supply of water and nutrients, which occurred in the experimental area of the present study.

The results obtained in this study were inferior to those observed by Rocha et al. (2017), in which at 4, 8, 12, and 16 months of harvest interval, they obtained a total of cladodes per plant of 8.2, 14.0, 14.9, and 19.7, respectively. Both studies adopted the irrigated cultivation system, but differed in the number of plants per hectare, 70,000 in the present study and 50,000 in the research carried out by the authors. In this case, it is likely that the lower density used may have positively influenced the number of cladodes per plant, a behavior that was confirmed by Silva et al. (2014a), who evaluated the effects on productive characteristics of cactus pear palm at different densities (10,000, 20,000, 40,000, and 80,000) and found a linear reduction in the number of cladodes per plant in the Redonda and Gigante varieties due to the increase in plant density.

When evaluating the morphometric characteristics of the cactus pear cv. Gigante (*Opuntia ficus-indica* Mill) under different water depths and irrigation intervals with saline water, Fonseca et al. (2019) obtained, in the first growing cycle (365 days), an average of 9.9 total cladodes per plant, with values varying, depending on the treatments, between 8.6 and 11.3 cladodes plant^{-1}. These results were close to those verified in the present study; however, considering the values obtained in the second cultivation cycle, the study carried out by those authors showed a higher number of cladodes per plant, varying from 9.6 to 15.9. The difference in results between the studies can be because the present study used data referring to the average number of cladodes obtained from all cycles (in the respective harvest frequencies), with no evaluation per cultivation cycle, in which, notably, there is an evolution not only in the number of cladodes in the plant in the cycles subsequent to the first harvest, but also in other morphological characteristics, such as CAI, a result found in the research carried out by the aforementioned authors.

The variable TNHC is perhaps the most important in relation to the quantification of the produced cladodes, since it refers to the biomass component of the plant that is actually harvested, that is, that represents the final biomass produced, which will be supplied to the animals, or even, as genetic material to be used in new plantings.

According to the results observed for NFOC, NSOC, NTOC, TNC, and TNHC, for the purpose of the irrigation system, there was a positive correlation between these variables. The sequence from the highest to the lowest value obtained for NFOC in the respective irrigation system was repeated in the other orders of cladodes, in the TNC and TNHC of the plant (Table 5). The values for these five variables were obtained, in decreasing order, by conventional sprinkler, Micro Spray Jet, microsprinkler, and surface drip.

This is relevant, as it indicates the importance of providing adequate conditions for the cultivation of cactus pear right after planting, at the initial stage of development, thus enabling greater vigor of sprouting and, therefore, a greater number of first-order cladodes, and subsequently, higher NSOC, NTOC, and TNC and TNHC per plant. As there is a positive correlation between the number of cladodes and CAI, and this morphological characteristic has a positive influence on fresh and dry biomass productivity (Silva et al., 2020), higher productivity is to be expected at the end of the productive cycle.

The fresh biomass production of cactus pear cv. Mexican Elephant Ear in this study (Table 6) was inferior to that reported by Rocha et al. (2017), who, at 12 months, in an irrigated system, found a fresh biomass production of 566,000 kg ha^{-1}. This difference can be explained by the adopted harvesting frequency, which, in that study, the harvest was carried out from the first-order cladodes, while in the present study, the cladodes of this order were preserved in the plant after the cut. Considering that, in the present study, these represented 30.82 to 56.61% cladodes existing in the plant, according to the results observed in the different harvest frequencies and irrigation system, it is likely that, if the primary cladodes were harvested, TFBP would reach values close to those observed by those authors.

When evaluating the morphometric and physiological characteristics of the cactus pear cv. Gigante under different depth and frequency of irrigation with saline water, Fonseca et al. (2019) obtained yields between 103,750 and 218,200 kg ha^{-1} fresh biomass in the second cultivation cycle (365 days after harvest). These values were close to those obtained in this study, but with a significant difference detected only in the results of the interaction between the conventional sprinkler system and the 12-month harvest frequency, which is higher than those observed in the study carried out in the semi-arid region of the state of Bahia.

The results observed herein were close to those obtained by Fonseca et al. (2019), who evaluated the productivity of the cactus pear cv. Gigante, using different water depths and irrigation frequencies in the semi-arid region of the state of Bahia, and obtained values between 5,340 kg DM ha^{-1} (5 L water/linear meter every 15 days) and 10,570 kg DM ha^{-1} (100% ETo, with daily irrigation). There was a difference only in the result obtained from the conventional sprinkler system and harvest frequency of 12 months (16,373 kg DM ha^{-1}), and the values observed in the frequency of 18 months in the four irrigation systems evaluated, which varied between 12,963 and 15,901 kg DM ha^{-1} (Table 7).

As reported by Shao et al. (2008), the activity of the root system, both in expansion and in depth, undergoes oscillations depending on the amount of moisture in the soil. This hypothesis is reinforced by the results obtained by Edvan et al. (2013), who assessed the accumulation of biomass and the root growth of cactus pear at different harvest times and found that the presence of moisture in the soil has a direct relationship with root development. According to the results obtained, the authors concluded that the root dry biomass had an increase in weight due to the occurrence of rainfall and its development over time, and the opposite effect with absence of rainfall. Thus, unlike surface dripping, which limits the moist area close to the plant, irrigation using conventional sprinkling may have had a positive impact on the formation and maintenance, throughout the experimental period, of a more structured cactus pear root system, with higher root density and distribution in the soil profile, all of this permanently reflecting in the greater capacity of uptake of water and nutrients, thus resulting in greater cactus pear biomass production.

In this context, it is noteworthy that in cactus pear, the better response in growth and development through optimization of the photosynthetic process and, consequently, greater biomass, is a function of the adequate balance of factors such as photosynthetically active radiation, mean night-time temperature, water availability, and nutrient supply (Nobel and Hartsock, 1986; Nobel and Israel, 1994; Israel and Nobel, 1995). It can, therefore, be inferred that the differences in production, with better results in the conventional sprinkler system, can be explained by the better balance of soil and climate factors, especially more favorable water availability together with the best availability of nutrients for plants and possible improvement in the microclimate with a reduction in air temperature, favoring carbon assimilation and optimizing productivity in the conventional sprinkler system.

Although the moisture content in cactus pear is relevant, both in the physiological aspect of the plant (water reserve) and as a source of quality water for animals, the amount of dry biomass and nutrients define its inclusion in diets for ruminants, including their percentage of participation.

Dry biomass production per area is an important variable for agronomically comparing forage species, mainly under similar conditions of environment and cultivation. In addition, knowledge of the forage dry biomass production is the most accurate way to calculate the forage carrying capacity in the rural property, since the formulations of the diets are carried out based on the dry matter of the food, as concentrate or roughage. In this way, it is possible to define the size of the forage cultivation areas on the farm, according to the needs of cattle, goats, or sheep.

Dry biomass production in cactus pear can vary depending on several factors, including soil and climatic conditions, genotype, crop management, crop treatments, plant health, among others. In turn, dry matter content, in spite of presenting differences between genotypes, is more influenced by water supply, accumulating more water according to its availability in the soil (Edvan et al., 2013).

The results observed for WUE at the six- and nine-month sampling frequencies in the present study (Table 8) were close to those reported by Cruz Neto et al. (2017), who obtained mean WUE values of 7.25 kg ha^{-1} mm^{-1}, in irrigated cultivation of cactus pear cv. Miúda at 523 days. However, they were lower when compared with those observed by Lédo et al. (2019), who, evaluating different organomineral fertilization in cactus pear cv. Gigante in an rainfed system and with preservation of primary cladodes after harvest, obtained rainwater use efficiency of 18.1 and 20.8 kg ha^{-1} mm^{-1} in the second and third cultivation cycles (cutting interval of 330 days), respectively. Even comparing the values obtained in one of the treatments with fertilizations close to the present study (30,000 kg manure and 150-300-300 NPK), there were great differences between the results.

The plausible explanation lies in the difference in water volume between these studies. While the research carried out by Lédo et al. (2019) took place in rainfed conditions, with rainfall of 853.90 and 879.60 mm rainwater in cycles I and II, respectively, the present study was conducted under an irrigated regime, with practically twice as much water volume over the experimental period. It should also be noted that the authors performed the standardization cut of the cactus pear, leaving the primary cladodes, starting from that moment on the cultivation cycles; therefore, the water used was totally directed to the production of superior-order cladodes. In the present study, there was also the preservation of the primary cladodes at the time of harvest, but the crop standardization cut was not performed. In this case, there was consumption of water for the formation of primary cladodes during the experimental period, but as they were preserved in the plant, they did not contribute to biomass production, resulting in lower WUE.

The results observed for WUE for the different irrigation systems were inferior to those obtained by Silva et al. (2014b), who obtained 10.0 kg ha^{-1} mm^{-1} for cactus pear cv. Mexican Elephant Ear. Probably, the results differed according to the cultivation system used in the studies, being in rainfed conditions in that study versus irrigation in ours.

It is noteworthy that results similar to the present study were reported by Edvan et al. (2020), with three genotypes of cactus pear (Miúda, Baiana, and Orelha de Elefante Mexicana), under rainfed conditions, harvested 365 days after planting and in seven different locations of the tropical semi-arid region. The authors observed WUE values in the variety Orelha de Elefante Mexicana between 1.0 and 20.0 kg ha^{-1} mm^{-1}, in which the lowest WUE occurred in regions with lower relative humidity. Importantly, the highest values observed in the study conducted in semiarid region were higher than those observed in the present study, probably because they considered the biomass production of first-order cladodes in the WUE calculation, while the present study considered the biomass harvested from the second-order cladodes. Another factor that may have influenced was the cultivation system used in these studies, which, despite presenting approximate planting density (66,133 and 70,000 $plants^{-1}$ ha^{-1}), differed in terms of water availability, since the research in the state of Piauí was carried out in rainfed conditions. The difference between these production regimes resulted in very different percentages of dry matter in cactus pear, a result that indirectly influences the WUE values. While in that study, the values obtained were in the range of 9.76 to 13.9% DM, in the present study, these percentages were between 6.62 and 7.49%.

The results observed here, in a way, contradict statements that the surface drip system is the most suitable for the cultivation of cactus pear. In general, these recommendations are based on the argument that localized irrigation presents greater efficiency in the distribution and use of water, in addition to lower drift losses when compared with sprinkler irrigation (Mantovani et al., 2009).

Nevertheless, given the results obtained in this study, in which conventional sprinkler showed higher efficiency in water use when compared with those observed in surface dripping, the positive effect of the interrelationship between plant and irrigation system was evidenced, indicating the importance of knowing and evaluating all the factors involved in the process, as well as the responses arising from the interaction between them. Therefore, as reported by Eloi et al. (2007), the irrigation management of a crop is carried out through knowledge of the root system and the interrelationships with water and soil. Of course, this concept also serves to define the irrigation methods and systems to be used in each crop.

5. Conclusions

The harvest frequency of 12 months combined with the conventional sprinkler system shows better results in the evaluated productive characteristics, with emphasis on the forage biomass production per area. Irrigation by conventional sprinkler and Micro Spray Jet provide greater efficiency in the use of water by cactus pear cv. Mexican Elephant Ear.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

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