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Effect of Different Irrigation Programs on Structural Characteristics, Productivity and Water Use Efficiency of *Opuntia* and *Nopalea* Forage Cactus Clones

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Citation: Araujo, J.F.N.d.; Santos, J.P.A.d.S.; Souza, L.S.B.d.; Souza, C.A.A.d.; Alves, C.P.; Jardim, A.M.d.R.F.; Eugênio, D.d.S.; Souza, L.F.d.; Morais, J.E.F.d.; Santos, W.R.d.; et al. Effect of Different Irrigation Programs on Structural Characteristics, Productivity and Water Use Efficiency of *Opuntia* and *Nopalea* Forage Cactus Clones. *Grasses* **2024**, *3*, 307–319. https://doi.org/10.3390/grasses3040023

Academic Editor: Mario Licata

Received: 24 September 2024
Revised: 29 October 2024
Accepted: 4 November 2024
Published: 11 November 2024

Abstract: The objective of this study was to evaluate the structural characteristics, yield and water use efficiency of forage cactus under daytime and nighttime irrigation in a Brazilian semiarid region. The experiment followed a completely randomized design in a 3 × 2 factorial scheme, with ten replications: three clones of forage cactus ("IPA Sertânia"—IPA, "Miúda"—MIU, "Orelha de Elefante Mexicana"—OEM) and two irrigation schedules (daytime and nighttime). Irrigation was applied once a week using a graduated cylinder. The structural characteristics (i.e., plant height and width, total number of cladode—TNC; cladode number per emergence order—CN1, CN2 and CN3; cladode area—CA; cladode area index—CAI), productive characteristics (fresh mass production per plant—FM and dry mass—DM) and water use efficiency (WUE_{FM} and WUE_{DM}) were obtained from the plant harvests. Our results showed that the irrigation schedules did not lead to significant differences in most of the response variables ($p > 0.05$), except for the TNC (13.2 und), CN2 (7.4 und) and CAI (1.58 $m^2\ m^{-2}$) of MIU. It was observed that OEM presented the highest yield, WUE_{FM} and WUE_{DM} ($p < 0.05$). Adopting the OEM clone, regardless of the irrigation schedule, is the strategy that achieves the best production.

Keywords: irrigation schedule; cacti; Cactaceae; semiarid

1. Introduction

Agricultural activity is recognized as one of the major sources of income for populations living in semiarid climate regions [1]. Due to its importance, it must rely on efficient strategies for utilizing natural resources, especially water [2–4]. Severe climates can lead to prolonged periods of drought with high temperatures, making it challenging to provide quality water for plant and animal production [5,6]. Such strategies must yield results capable of supplying livestock with forage [7], promoting socioeconomic development and, consequently, improving the human development index (HDI) in these regions [3,8].

The scientific community, in collaboration with governments, has been working to mitigate the effects of climate on economic activities in highly vulnerable regions [9]. The United Nations (UN) has set goals to improve people's quality of life by 2030 [10], establishing the Sustainable Development Goals (SDGs), a set of 17 objectives focused on enhancing human well-being and conserving and restoring ecosystems [11,12]. Some of these SDGs address sustainable agriculture and the development of sustainable cities and communities [13].

Achieving success in sustainable agriculture requires the implementation of efficient technologies that optimize natural resource use without compromising environmental conservation [14]. In agricultural activity, the main challenge is to reduce the impact of management practices, while in semiarid regions, the priority is efficient water use in plant production for animal feed [15].

In Brazil, agricultural activity has grown significantly, registering an increase of 15.1% between 2022 and 2023. This growth has directly impacted the Gross Domestic Product (GDP), providing greater economic stability for the population, especially in the semiarid region of the country [16,17]. In this region, the primary economic activities are agriculture and livestock, with a focus on beef and dairy cattle production [18,19]. In the semiarid region, the success of farming activities is directly linked to people's knowledge of environmental conditions, such as the influence of irregular rainfall [20]. When neglected and associated with the inadequate use of water resources, these conditions can cause significant losses in agricultural production, resulting in a reduction in the supply and availability of forage for livestock [6,21].

To overcome losses and increase the efficiency of production systems, a viable alternative is to adopt the cultivation of species that are tolerant and/or adapted to water deficits [22,23]. In this context, forage cactus (*Opuntia* sp. and *Nopalea* sp.) plays an important role in the semiarid environment due to its anatomical and morpho-physiological aspects that highlight its adaptation [17]. These characteristics are associated with its crassulacean acid metabolism (CAM), which gives it high water use efficiency, radiation use efficiency, stomatal opening and CO_2 fixation at night, i.e., greater efficiency than C3 and C4 plants [24,25].

Forage cactus is traditionally cultivated under dryland conditions and is rarely irrigated, hardly receiving adequate management to enhance its growth and productive performance [26]. In semiarid regions, the use of management practices such as irrigation becomes crucial, especially when rainfall does not replenish the crop's water demand [27,28]. In commercial cultivation, supplementary irrigation in forage cactus can promote greater development and, consequently, increase crop productivity [29]. When considering the adoption of irrigation management, it is important to emphasize the timing of water application, as it can directly influence the growth dynamics and productive characteristics of the crop. Nighttime irrigation management provides a different dynamic of water flow in the soil, allowing for storage and utilization by the crop at dawn, thereby reducing evaporation as the water is applied [30].

Soil heating is also an aggravating factor in reducing crop yields, as it causes thermal stress that affects the root system and limits the availability of water and nutrients [31]. Therefore, nighttime irrigation helps lower soil temperature during the night, enhancing crop development, especially in regions where irrigation is essential for agricultural production [32].

In this context, it was hypothesized that nighttime irrigation management in plants with CAM physiological mechanism enables the better utilization of water resources, reducing water losses, increasing water use efficiency, and lowering electricity costs. Therefore, the objective was to evaluate the structural characteristics, yield and water use efficiency of forage cactus under daytime and nighttime irrigation in a semiarid environment.

2. Materials and Methods

2.1. Characterization of the Study Area

This study was conducted at the International Reference Center for Agrometeorological Studies of Forage Cactus and Other Forage Plants at the Federal Rural University of Pernambuco, Academic Unit of Serra Talhada, in the semiarid region of Pernambuco, Brazil (7°57′20″ S; 38°17′31″ W, at an altitude of 499 m) (Figure 1).

Figure 1. Location of the experiment, with forage cactus cultivated at the International Reference Center for Agrometeorological Studies of Forage Cactus and Other Forage Plants—CentroRef, in the semiarid municipality of Serra Talhada, Pernambuco, Brazil.

According to the Köppen classification, the climate of the region is type BSh, which means hot semiarid, with higher rainfall indices in the summer [33]. The average annual rainfall is 642 mm, with mean temperatures ranging from 20.1 to 32.9 °C, and an average atmospheric water demand of 1800 mm per year, resulting in an annual water deficit of 1158 mm [34].

Throughout the experimental period from December 2017 to September 2018, the accumulated rainfall was 382 mm, representing 59.5% of the historical average. The reference evapotranspiration (ET_0) reached its highest and lowest magnitudes in January and April, with values of 5.55 and 1.63 mm per day, respectively. However, this behavior resulted in an average of 4.46 mm per day throughout the experimental period (Figure 2).

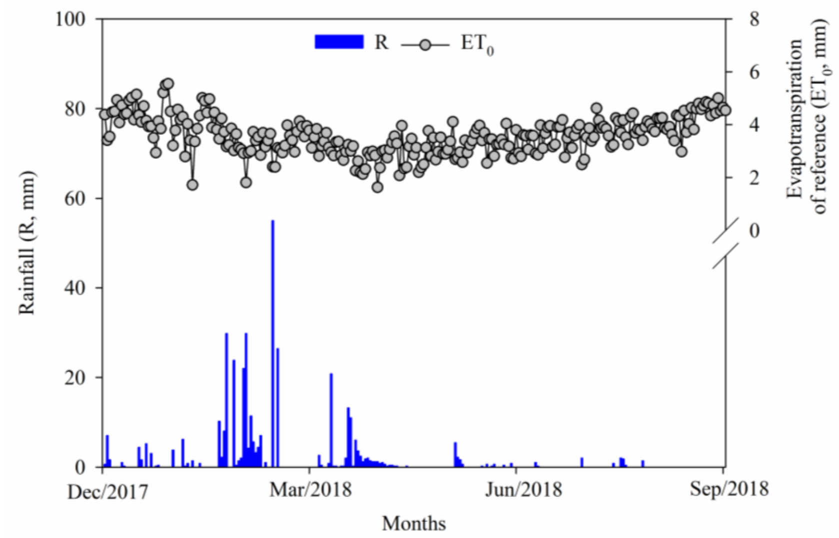

Figure 2. Meteorological variables throughout the experimental period (December 2017 to September 2018) in an area cultivated with forage cactus in the semiarid municipality of Serra Talhada, Pernambuco, Brazil.

2.2. Experimental Design, Plant Material, and Irrigation Management

The experiment followed a completely randomized design (CRD) in a 3 × 2 factorial system, consisting of three forage cactus clones [IPA Sertânia—IPA (*Nopalea cochenillifera* (L.) Salm-Dyck); Miúda—MIU (*Nopalea cochenillifera* (L.) Salm-Dyck); and Orelha de Elefante Mexicana—OEM (*Opuntia stricta* (Haw.) Haw.)] and two irrigation schedules (daytime and nighttime), with ten replications.

The experiment was conducted in 60 pots (each with a total volume of 21 L and a radius of 0.28 m, i.e., area equal to 0.25 m^2), arranged in a spacing of 1.0 × 0.5 m between rows and plants, respectively. The soil in the experimental area is classified as typic Eutrophic Ta Haplic Cambisol [35], with a flat relief the following physical and chemical characteristics at a depth of 0.00–0.20 m: bulk density of 1.45 g cm^{-3}, sand content of 828.6 g kg^{-1}, silt content of 148.25 g kg^{-1}, clay content of 23.15 g kg^{-1}, electrical conductivity of saturated soil extract (EC) of 0.32 dS m^{-1}, pH (water) of 5.95, P (Mehlich-1) of 168.96 mg dm^{-3}, K^+ of 13.8 $cmol_c$ dm^{-3}, Ca^{2+} of 3.45 $cmol_c$ dm^{-3}, Mg^{2+} of 1.90 $cmol_c$ dm^{-3}, Na^+ of 1.09 $cmol_c$ dm^{-3}, H + Al of 0.6 $cmol_c$ dm^{-3}, cation exchange capacity (CEC) of 20.85 $cmol_c$ dm^{-3}, base saturation (V%) of 97.15%, sum of bases (SB) of 20.25 $cmol_c$ dm^{-3}, soil organic carbon of 4.6 g kg^{-1}, and organic matter of 7.93 g kg^{-1}. The soil was sieved and used to fill the pots. Subsequently, the forage cactus clones were planted, inserting one cladode per container, with 50% of the cladode length buried in the soil.

Irrigation events were performed manually with the aid of a graduated cylinder. A fixed volume of 2 L per pot was applied once a week. This volume was calculated based on the average reference evapotranspiration (ET_0) of the region during the experimental period (i.e., 4.5 mm day^{-1}), calculated with the Penman–Monteith method [36], and on the average value of the forage cactus crop coefficient in the initial development phase (i.e., 0.26) according to Silva et al. [37]. Therefore, 5.5 mm day^{-1} was multiplied by 7 days and by 0.26, resulting in a depth of 8 mm per week. Considering that the pots had an area of 0.25 m^2, the volume applied per week corresponded to 2 L. However, when rainfall events occurred, 0.1 L was deducted from the pre-established volume for every 1 mm, that is, 2 minus 0.1 = 1.9 L.

The irrigation, both daytime and nighttime, was carried out once a week (on Thursdays) at 7:00 a.m. and 7:00 p.m.; the total water applied through the irrigation depth was 306.4 mm. The water used had an average electrical conductivity of 1.62 dS m^{-1}, classified as C3 (high salinity) according to Richards' classification [38], a pH of 6.84, and sodium and potassium concentrations of 168.66 mg L^{-1} and 28.17 mg L^{-1}, respectively, originating from a groundwater well.

2.3. Structural Characteristics, Biomass Yield and Water Use Efficiency

The structural characteristics of the crop were obtained from monthly biometric campaigns. During these campaigns, three representative plants (one from each clone) were monitored to obtain the following variables: plant height (PH), plant width (PW), total number of cladodes (TNC), and cladode emergence order (CN1, CN2, and CN3). On each plant, a representative branch was chosen to measure the cladode length (CL), cladode width (CW), cladode perimeter (CP) and cladode thickness (CT).

With these data, the cladode area of the MIU, OEM and IPA clones (CA_{MIU}, CA_{OEM} and CA_{IPA}, respectively) was calculated according to the emergence order and the forage cactus clone, as described by Silva et al. [39], using Equations (1)–(3).

$$CA_{MIU} = 0.7198 \times CL \times CW \quad (1)$$

$$CA_{OEM} = 0.7086 \times (1 - \exp(-0.000045765 \times CL \times CW))/0.000045765 \quad (2)$$

$$CA_{IPA} = 1.6691 \times (1 - \exp(0.0243 \times CP))/-0.0243 \quad (3)$$

where CL: cladode length (cm); CW: cladode width (cm); and CP: cladode perimeter (cm).

The cladode area index (CAI) was calculated by the ratio of the total cladode area to the spacing used, as described in Equation (4) [40]:

$$CAI = (\sum CA)/10{,}000/(S1 \times S2) \quad (4)$$

where CAI: observed cladode area index ($m^2\ m^{-2}$); 10,000: conversion factor from cm^2 to m^2; and S1 × S2: spacing between the rows and plants of each clone, respectively.

At the end of the cycle, the fresh biomass productivity (FM, Mg ha^{-1}) was determined by harvesting and weighing the plants (5 plants per treatment). Subsequently, two cladodes from the middle third of each plant were selected for weighing to obtain the fresh weight, followed by drying in a forced air circulation oven at 55 °C to obtain the dry weight. The dry mass productivity (DM, Mg ha^{-1}) was estimated based on the dry matter content of the cladodes and the estimated FM values of the plants. The dry mass content of the cladodes was obtained from the ratio of dry weight to fresh weight.

In addition to the mentioned analyses, the applied water use efficiency (WUE) was also calculated, which represents the relationship between the biomass produced by the crop (in terms of fresh or dry mass) and the amount of water received (rainfall and irrigation, in 688.4 mm), as described in Equation (5):

$$WUE(R + I) = Y/(R + I) \quad (5)$$

where Y represents the productivity achieved in each treatment (kg $plant^{-1}$), and R + I represents the rainfall + irrigation.

2.4. Statistical Analysis

The data were subjected to normality and homogeneity analysis. Upon meeting the assumptions, analysis of variance (ANOVA) was performed, and when significant, means were compared using Tukey's test at a 5% probability level. All statistical procedures were conducted using R software, version 4.3.3 [41].

3. Results

In Table 1, the *p*-values for all studied variables are presented, considering each factor individually and their interaction.

Table 1. *p*-Value for all determined variables, for each factor, as well as their interaction.

Source of Variation	PH	PW	TNC	CN1	CN2	CN3	CA1	CA2	CA3	CAI	PFM	PDM	WUE_{FM}	WUE_{DM}
Clone	0.270	0.008	<0.001	0.401	<0.001	0.075	<0.001	<0.001	0.131	0.042	<0.001	0.001	<0.001	0.005
Irrigation schedule (IS)	0.986	0.707	0.323	0.267	0.056	0.237	0.264	0.567	0.297	0.147	0.929	0.788	0.922	0.856
Clone × IS	0.421	0.282	0.026	0.900	0.014	0.249	0.696	0.356	0.337	0.049	0.085	0.153	0.0769	0.159

In Table 2, the structural variables of the forage cactus are presented. Upon analyzing the mean values, it was found that the variables did not show interaction between the studied factors ($p > 0.05$). However, for PW and CA1, a significant difference was observed ($p < 0.05$) for the clone factor.

Table 2. Average values of growth variables of forage cactus clones (IPA: IPA Sertânia, MIU: Miúda, OEM: Orelha de Elefante Mexicana) subjected to two irrigation schedules in a semiarid environment.

Clone	PH	PW	CN1	CN3	CA1	CA2	CA3
	----------cm----------		------unit-------		-------------cm²----------		
OEM	41.9 a	33.0 b	3.7 a	0.0 a	293.1 a	15.0 b	0.0 a
IPA	44.0 a	38.3 ab	4.3 a	0.0 a	212.8 b	0.0 b	0.0 a
MIU	45.8 a	43.4 a	3.7 a	0.7 a	120.9 c	106.0 a	15.3 a
Mean	43.9	38.2	3.9	0.23	208.9	40.3	5.1
CV%	11.8	17.6	28.9	322.6	25.02	81.1	368.5
Irrigation schedule	PH	PW	CN1	CN3	CA1	CA2	CA3
Daytime	43.8	37.7	4.1	0.06	198.0	44.0	1.4
Nighttime	43.9	38.7	3.6	0.4	219.8	37.1	8.7
Mean	43.85	38.2	3.85	0.2	208.9	40.55	5.05
CV%	11.8	17.6	28.9	322.6	25.02	81.1	368.5

PH—plant height; PW—plant width; CN—cladode number (in respective orders); CA—cladode area (in respective orders); CV—coefficient of variation. Means followed by the same letters vertically do not differ statistically from each other.

Regarding plant height, it was evidenced that the studied forage cactus clones and irrigation schedules did not significantly influence their values, with average values of 43.9 and 43.85 cm, respectively. On the other hand, when evaluating the width variable, it was found that there was a difference among the forage cactus clones, with higher values for the MIU (43.4 cm) and IPA (38.3 cm) clones. These results were 31.5% and 16% higher, respectively, than the OEM clone (33 cm), differing only from the MIU clone.

Observing the performance of the first and third-order cladodes (CN1 and CN3), it was demonstrated that the factors studied did not significantly affect their results. The average values for the clone and irrigation schedule were 3.9 and 3.85 units for CN1, respectively. For CN3, the average values obtained were 0.23 and 0.2 units, in that order. However, for the cladode area (Table 2), only the clone factor showed a significant difference ($p < 0.05$) for the first-order cladode area (CA1), where the OEM clone (293.1 cm^2) demonstrated a result 37.7% higher than the IPA clone (212.8 cm^2) and 142.4% higher compared to the MIU clone (120.9 cm^2). However, when observing the irrigation schedule factor, it was found that CA1 did not show significant results, with an average value of 208.9 cm^2.

The same behavior was observed for forage cactus clones and irrigation schedules when analyzing the second-order cladode area (CA2). It was proven that these factors significantly influenced their values ($p < 0.05$), with the MIU clone (106 cm^2) achieving the best results compared to the other studied clones, showing a 606.6% superiority when compared to the OEM clone (15 cm^2). The third-order cladode area (CA3) had average values of 5.1 cm^2 and 5.05 cm^2 for the clones and irrigation schedules.

The results presented in Table 3 pertain to the growth variables (TNC, CN2, and CAI) and demonstrate a significant interaction between the evaluated factors ($p < 0.05$).

Table 3. Average values of growth variables of forage cactus clones (IPA Sertânia—IPA, Miúda—MIU, Orelha de Elefante Mexicana—OEM) subjected to two irrigation regimes in a semiarid environment.

Variable	Irrigation	Clone		
		OEM	IPA	MIU
TNC (Unit)	Daytime	5.2 Ba	5.6 Ba	9.8 Ab
	Nighttime	4.4 Ba	5.0 Ba	13.2 Aa
CN2 (Unit)	Daytime	0.2 Ba	0.0 Ba	4.8 Ab
	Nighttime	0.0 Ba	0.0 Ba	7.4 Aa
CAI (m^2 m^{-2})	Daytime	1.45 Aa	1.20 Ba	1.11 Bb
	Nighttime	1.46 ABa	1.13 Ba	1.58 Aa

TNC—Total number of cladodes; CN2—Number of second-order cladodes; CAI—Cladode area index. Values with the same uppercase letters do not differ among rows, while values with the same lowercase letters do not differ among columns.

When observing the total number of cladodes (TNC), it was found that the condition resulting in the highest TNC was for the MIU clone under nighttime irrigation, with an average value of 13.2 units. However, it was noted that the same irrigation schedule for the OEM and IPA clones did not show a significant difference. However, the IPA clone under different irrigation schedules and the OEM clone under nighttime irrigation did not show any significant difference between them, with an average value close to 0 units.

Regarding the cladode area index (CAI), it was found that the highest results are associated with the nighttime condition for the MIU clone, with an average value of 1.58 m^2 m^{-2}. Additionally, the response to both daytime and nighttime irrigation for the OEM clone showed average values of 1.45 m^2 m^{-2} and 1.46 m^2 m^{-2}, respectively. For the MIU clone under daytime irrigation, the average value of the cladode area index (CAI) was 1.11 m^2 m^{-2}, which is 29.74% lower compared to the nighttime condition for MIU, which was the most efficient, with an average of 1.58 m^2 m^{-2}.

They found that different water availability conditions did not promote significant differences in CAI, with average values around 1.14 m^2 m^{-2}. The magnitude of the cladode area index is associated with the total number of cladodes present on the plant and the growth habit of the crop. Thus, the results obtained for OEM may be associated with the greater development of CA1, while the MIU clone is influenced by TNC.

For the fresh and dry mass production of the presented forage cactus clones (Figure 3), it was observed that there was no interaction between the factors studied ($p > 0.05$). However, there was a significant difference ($p < 0.05$) for the individual factor of clone. When evaluating the fresh mass production data of the forage cactus, it was shown that the Orelha de Elefante Mexicana clone had the highest production among the clones studied, with an average production value of 3.20 kg $plant^{-1}$. On the other hand, the MIU clone had the lowest fresh mass production (1.8 kg $plant^{-1}$), which was 43.75% lower compared to the OEM clone.

For the dry mass production of the forage cactus, the OEM and IPA clones provided better results, with average values of 0.30 kg $plant^{-1}$ and 0.23 kg $plant^{-1}$, respectively. However, in terms of dry mass production, the MIU clone showed the lowest value (0.18 kg $plant^{-1}$) compared to the OEM and IPA clones, which were 40% and 21.73% lower, respectively.

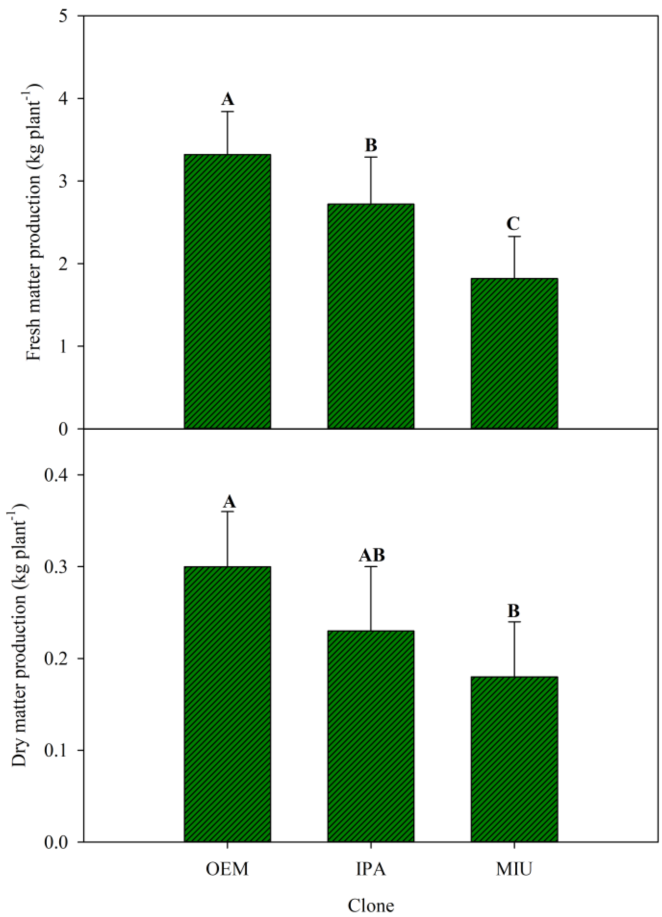

Figure 3. Productivity of fresh and dry mass (kg plant^{-1}) of forage cactus clones (IPA: IPA Sertânia, MIU: Miúda, OEM: Orelha de Elefante Mexicana) irrigated in a semiarid environment. The same capital letters do not differ significantly ($p < 0.05$), as judged by the Tukey test. Error bars represent the standard deviation.

When analyzing the effect of irrigation schedules on fresh and dry mass production, no significant difference was observed ($p > 0.05$) (Table 4). The fresh mass production averaged 2.62 kg plant^{-1}, and for dry mass production, the schedules yielded an average of 0.235 kg plant^{-1}.

Table 4. Productivity of fresh and dry mass (kg plant^{-1}) of forage cactus clones (IPA: IPA Sertânia, MIU: Miúda, OEM: Orelha de Elefante Mexicana) subjected to two irrigation regimes in a semiarid environment.

Irrigation Schedule	Production (kg planta^{-1})	
	Fresh Mass	**Dry Mass**
Daytime	2.61	0.23
Nighttime	2.63	0.24
Mean	2.62	0.235
CV%	19.5	25.7

The data regarding water use efficiency (WUE) did not show a significant interaction between the studied factors. However, when each forage cactus clone was observed individually (Table 5), significant differences ($p < 0.05$) were observed for the variables WUE_{FM} and WUE_{DM}. When analyzing the water use efficiency expressed in fresh mass, the OEM forage cactus clone achieved a production of 0.0048 kg plant^{-1} mm^{-1}, a value superior to those found for IPA and MIU, which were inferior by 18.75% and 45.83%, respectively, when compared to OEM. A similar result was observed for dry mass, with the OEM clone achieving a production of 0.0004 kg plant^{-1} mm^{-1}, maintaining its position as the highest producer of dry mass, with a superiority of 100% over MIU and 33.33% over IPA in terms of productivity.

Table 5. Water use efficiency (WUE) in different forage cactus clones irrigated in a semiarid environment. Means followed by the same small letter in the column did not differ significantly ($p < 0.05$; Tukey's test).

Clone	**WUE (kg plant^{-1} mm^{-1})**	
	Fresh Mass	**Dry Mass**
OEM	0.0048 a	0.0004 a
MIU	0.0026 c	0.0002 b
IPA	0.0039 b	0.0003 ab
Mean	0.0038	0.0003
CV%	19.5	29.7

Upon observing the irrigation schedule results, it was found that there was no significant difference ($p > 0.05$) between the daytime and nighttime periods (Table 6). Therefore, the choice of irrigation schedule will depend on logistical considerations and the irrigator's needs, as it does not influence the efficiency of the system. Regarding the average values of WUE throughout the crop cycle, these were 0.0038 kg plant^{-1} mm^{-1} for fresh mass and 0.0003 kg plant^{-1} mm^{-1} for dry mass.

Table 6. Water use efficiency (WUE) in different forage cactus clones subjected to two irrigation schedules in a semiarid environment.

Irrigation Schedule	**WUE (kg plant^{-1} mm^{-1})**	
	Fresh Mass	**Dry Mass**
Daytime	0.0037	0.00033
Nighttime	0.0038	0.00034
Mean	0.0038	0.0003
CV%	19.5	29.7

4. Discussion

The behavior of the PH and PW values obtained in this study is consistent with the results found in the literature [42–44]. This difference is related to the morphological structure of each clone, where the OEM exhibits semi-open growth, which favors the emission of primary cladodes, while the MIU and IPA clones show greater height development. In addition, the *Nopalea* genus (IPA and MIU) has more cladodes of a higher order when compared to the *Opuntia* genus [24], a fact that promotes the opening of the canopy, increasing the plant's PW values. The analysis of these variables is especially important when it comes to carrying out cactus management practices [44].

The CA1 value found in this study for the OEM clone, 293.1 cm^2, is higher than that found by Pereira et al. [43], with an average value of 285 cm^2 for the same clone under an irrigation frequency of every 7 days. The *Opuntia* genus of forage cactus clones has a higher emission of primary cladodes and tends to concentrate more assimilates, thereby increasing its leaf area. Elevated values of CA1 are physiologically important because, at the beginning of each cycle, they are responsible for intercepting the radiation used in photosynthesis, influencing biomass accumulation [45].

The highest cladode emission for the MIU clone is reported in the literature [43,46]. For the variable number of second-order cladodes (CN2), the MIU clone with nighttime irrigation achieved the best result, with an average value of 7.4 units. This result is higher than that reported by Silva et al. [47], who evaluated the morphological characteristics of cactus clones and obtained an average value of 6.8 units. Studies indicate that the cladode emission rate of the MIU clone is superior to other clones, potentially reaching up to the 5th order, which directly influences the TNC [46]. Thus, the association of night irrigation, which reduces the amount of water lost to the atmosphere and increases water availability for the crop, together with the MIU clone, which has, due to its morphophysiological characteristics, greater cladode emission, may have led to the maximization of the production of new cladodes [45]. These results are consistent with those found by Silva et al. [47], who investigated the effect of supplementary irrigation on forage cactus productivity. However, the MIU clone experiences a negative effect when subjected to daytime irrigation [40]. Similar behavior was evidenced in a study by Silva et al. [39], reinforcing that the MIU clone shows lower productivity compared to other clones in terms of both fresh and dry mass. The superiority of the OEM clone in fresh and dry matter productivity [48] may be attributed to its hardiness and adaptability to imposed conditions. Additionally, its growth variables (e.g., PH, PW, TNC, CA, cladode emission rate, among others) favor this achievement, even under limiting conditions [49].

Forage cactus is a plant that is resistant to conditions of low water availability and high temperatures. It has the ability to store water in its cladodes and, as a CAM plant, reduces water loss by using a characteristic mechanism of opening the stomata at night. These factors help the plant maintain stable productivity and good water use efficiency, even with changes in the irrigation schedule, as long as the quantity and quality of water are adequate for the plant's development [3,8,27].

Studies conducted on forage cacti cultivation under irrigated conditions have revealed that the addition of irrigation water does not lead to increased productivity in this crop [32,50,51]. Since the irrigation depth applied was the same for both irrigation periods (daytime and nighttime), water did not lead to the difference in productivity. Furthermore, lower transpiration during the day may weaken the effects of the irrigation time [32,50,51]. According to Silva et al. [47], considering WUE, the choice of cultivation system depends on the higher conversion of water into productivity. Therefore, this statement supports the selection of the OEM clone for a more efficient cultivation system compared to other clones.

A study conducted by Silva et al. [39], evaluating water use efficiency indicators for dryland-cultivated forage cactus, found a higher water use efficiency in the OEM clone, a result consistent with the findings of the current study. According to the authors, the average data obtained for the clones were 0.0028 kg FM plant^{-1} mm^{-1} and 0.00026 kg DM plant^{-1} mm^{-1} (assuming the volume of rainfall), values lower than those obtained in the present study, which were 0.0038 kg FM plant^{-1} mm^{-1} and 0.0003 kg DM plant^{-1} mm^{-1} for fresh and dry mass, respectively. The difference in WUE values between these studies can be attributed to the difference in plant density between the experiments. However, it is observed that in both studies, the highest WUE was obtained when using the OEM clone. These results are associated with the characteristics of this clone, such as greater adaptability and higher forage production compared to the IPA and MIU clones [51].

Consoli et al. [52], in a study on *Opuntia ficus-indica* L. (Mill.) plants ten years old and approximately three meters tall in the Mediterranean climate conditions of Sicily, Italy, obtained WUE values of 0.14 kg DM plant^{-1} mm^{-1} for the year 2009 and 0.17 kg DM plant^{-1} mm^{-1} for the year 2010. These values are higher than those found in this study, highlighting the influence of different climatic conditions, the age of the crop, and the duration of the experiment. Therefore, the choice of the forage cactus clone used in cultivation and the duration of the crop cycle are crucial factors influencing the efficiency of the system. However, interdisciplinary knowledge is essential for irrigated agriculture when aiming to increase the WUE in crops, which is quite complex. Nevertheless, certain agronomic practices can favor the elevation of these values, including water management, adapted species, spacing, fertilization and climatic factors [53–55].

5. Conclusions

The growth variables TNC, CN2, and CAI of the forage cactus clones were influenced by nighttime irrigation, with higher values observed for the MIU clone. In terms of production per plant, the OEM clone showed the best WUE based on fresh and dry mass, as well as the highest fresh mass productivity. The clones demonstrating better performance regarding dry mass production were OEM and IPA. The adoption of the OEM clone, regardless of the irrigation schedule, is the strategy that should be used to achieve the best production system, aiming to increase the productivity and efficiency of the natural resources used. However, there is a need for further field studies that evaluate changes in the development and productivity of forage cactus clones subjected to different irrigation schedules and low irrigation frequencies.

Author Contributions: Conceptualization, J.F.N.d.A. and J.P.A.d.S.S.; methodology, C.A.A.d.S.; C.P.A.; validation, A.M.d.R.F.J. and D.d.S.E.; formal analysis, L.F.d.S.; investigation, W.R.d.S.; resources, G.C.G.; data curation, M.V.d.S.; writing—original draft preparation, J.F.N.d.A.; writing—review and editing, F.S.C.; visualization, A.A.d.A.M.; supervision, T.G.F.d.S.; L.S.B.d.S. and J.E.F.d.M.; project administration, T.G.F.d.S.; funding acquisition, T.G.F.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: We thank the Pernambuco Science and Technology Foundation—FACEPE (APQ-0639-5.01/21), the São Paulo Research Foundation—FAPESP (grant number 2023/05323-4), and National Council for Scientific and Technological Development—CNPq (421003/2018-9, 309421/2018-7, 402622/2021-9, 309558/2021-2) for fellowships and financial support for this study.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the last author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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