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Productive, Morphological and Nutritional Indicators of Cactus Pear in a Semiarid Region

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Abstract: This study aimed to evaluate the effect of irrigation depths (IDs) with brackish water and levels of organic fertilizer (OF) on the morphological aspects, production, chemical composition and in vitro digestibility of cactus pear grown in a semiarid region. This experiment was conducted in an area already established for 2 years with cactus pear [*Opuntia stricta* (Haw.)] and started 18 months after the standardization cut. This was a 5 × 4 factorial design of five irrigation depths (0, 12.5, 25, 37.5 and 50% evapotranspiration—ETo) and four levels of organic fertilizer (0, 15, 30, and 45 megagram per hectare—Mg/ha), with four replications. The water used in the experiment was classified with high salinity and low sodium content (C3S1), and presented an electrical conductivity of 1.73 dS/m. There was no effect of the ID × OF interaction on the morphological and productive characteristics of cactus pear ($p > 0.05$); however, the ID × OF interaction promoted effects on ether extract, crude protein, neutral detergent insoluble protein, neutral detergent insoluble ash, total carbohydrates and non-fiber carbohydrates ($p < 0.05$). The ID and OF levels separately influenced the productive, morphological and nutritional characteristics of cactus pear. Under experimental conditions, we recommend the use of organic fertilizer at a level up to 45 Mg/ha, which is associated with the use of lower brackish water levels for the cultivation of cactus pear. This study's findings provide new insights into reducing the use of potable water in crop irrigation for dryland regions and other regions.

Keywords: animal manure; brackish water; crude protein; *Opuntia stricta* (Haw.) Haw

1. Introduction

The semiarid region in this study is characterized by high temperatures and low rainfall, with space–time variability. In addition, the region has a high solar incidence

(2800 h/year) and an evapotranspiration level (2000 mm/year) higher than precipitation [1–3], with shallow, stony soils, with a low water retention capacity and low levels of organic matter [4]. These characteristics promote a reduction in forage availability in periods of greater water deficit, which increases the vulnerability of agricultural production in this region [5].

The success of cactus pear in rainfed regions is related to its rusticity, productivity, nutritional value and consumption by ruminants [6]. The high productivity in these regions can be explained by their xerophytic habit and the crassulacean acid metabolism (CAM), which lead to morphophysiological changes under adverse conditions [7]. Due to CAM, their stomata open essentially at night, when ambient temperatures are mild, which reduces water loss through evapotranspiration, thus having a high water use efficiency [8].

Among cactus pear clones, the Mexican elephant ear (*Opuntia stricta* Haw.) presents good agronomic responses, being less demanding in terms of nutrients, more tolerant to water stress conditions and having a higher production of green and dry matter per unit area [9]. Its high productivity is related to its efficiency in the use of water [10] and higher forage accumulation rate [11], in addition to high values for the cladode area, which allows a large water accumulation and a larger photosynthetic area [12].

Climate change contributes to the reduction in fresh water available for watering, resulting in intense aridization. Since the demand for drinking water is intensifying due to world population growth, brackish water is a valuable resource in agriculture [13], as irrigated agriculture is responsible for the highest consumption of available drinking water in semiarid regions. Thus, problems related to water economy have increased the interest in research related to techniques to reduce the use of potable water in irrigation [14]. Therefore, the use of brackish water as a water source to meet the needs of plants is an important alternative for the development of irrigated agriculture [15]. This innovative approach needs to be developed to ensure the expansion of sustainable in the semiarid regions.

Haloculture is a term describing agricultural techniques that use salinized soils and brackish or saline water to cultivate salinity-tolerant plants [13]. It is one of the practical approaches that can contribute to mitigating the adverse effects on food security and other socioeconomic issues arising from climate change, seeking the benefits that a system can have on agricultural resilience [16].

However, irrigation with brackish water, when poorly managed, can compromise the production system. Soil salinity can limit plant growth and development, causing loss of productivity in agricultural species [17]. Most cultivated plants are sensitive to salinity caused by high concentrations of salts in the soil and may present alterations in their metabolic and biochemical activities due to osmotic and ionic effects in the root zone due to the accumulation of ions, such as sodium, chlorine and boron, inside of the plant and soil, with impacts on stomatal conductance and photosynthetic rate, reduced protein synthesis, reduced enzymatic activities and increased chlorophyll deterioration [14,18,19].

Araújo Junior et al. [20] mentioned that cactus pear does not tolerate saline stress, with an inhibition of root development and of the aerial part of plant, due to the accumulation of salts in the soil, which inhibit the absorption of CO_2. However, Farrag et al. [21] observed that irrigation with brackish water for short periods does not significantly reduce crop productivity, requiring more detailed studies on the reality of the arid and semiarid regions, seeking ways that promote better coexistence with conditions of water scarcity [22].

Thus, to minimize the toxicity of salt accumulation resulting from the use of brackish water for irrigation, and to improve soil properties, the use of economic approaches, such as the application of organic matter, particularly animal manure, is a useful and viable alternative [23]. This practice attenuates the effect of soil salinity, with the production of humic acids and organic acids, promoting an increase in the solubilization of carbonates, which delays the effect of adding salts to the soil through irrigation and leaching of these salts during the rainy season. Organic fertilizer can mitigate the harmful effects of salts on plant roots, stimulating the uptake of water and nutrients by cactus pear in the semiarid region [2,24].

The yield potential of cactus pear under irrigation conditions with brackish water in the Brazilian Semiarid region is still little known [25,26]. In addition, studies that indicate the amount of brackish water and the ideal dose of organic matter that can favor the production of cactus pear biomass are incipient, and research is needed to support this management strategy. In this sense, we hypothesized that cactus pear irrigated with brackish water and fertilized with organic fertilizer increases its production and water use efficiency, without affecting its nutritional composition.

Thus, the objective was to evaluate the effect of irrigation with brackish water and levels of organic fertilizer on the morphological aspects, production, chemical composition and in vitro digestibility of cactus pear grown in the Brazilian Semiarid region.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out in the Biosaline Agriculture Prospecting and Research Area (Figure 1), located in the Caatinga experimental field, belonging to Embrapa Semiarid, in Petrolina, state of Pernambuco, Brazil (latitude 09°8′8.9″ S, longitude 40°18′33.6″ W, 379 m altitude).

Figure 1. Geographic location of the Embrapa Semiarid experimental area.

The climate of the region is classified as semiarid BSwh′. Rainfall is concentrated between November and April, with an average annual rainfall of around 400 mm, unevenly distributed. This experiment lasted 18 months. Information regarding temperature (°C), relative humidity (%), rainfall (mm) and reference evapotranspiration (mm) during the experimental period is illustrated in Figure 2.

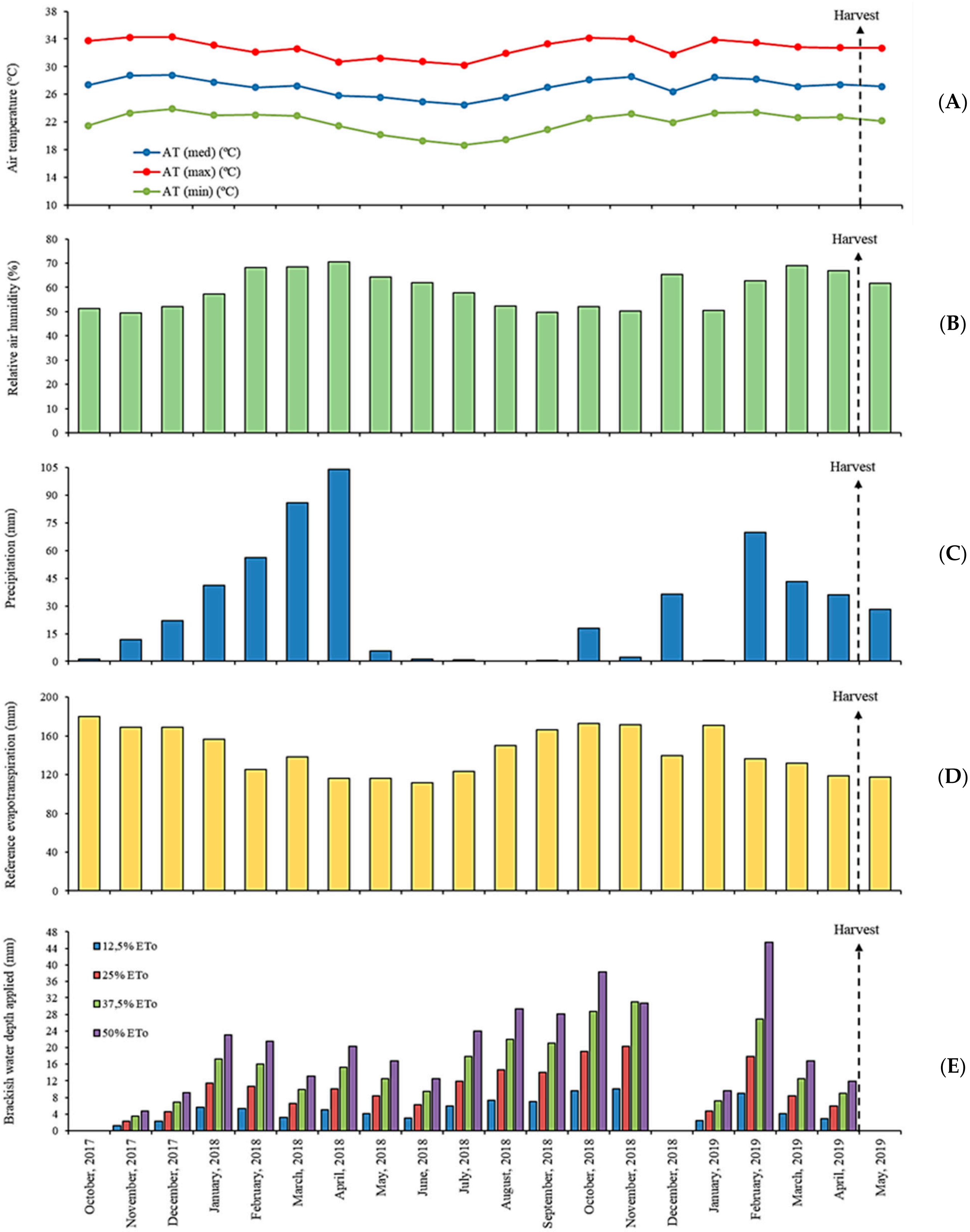

Figure 2. Air temperature (**A**), relative air humidity (**B**), precipitation (**C**), reference evapotranspiration (**D**) and brackish water depth applied (**E**) during the experimental period.

2.2. Characterization of Water, Soil and Organic Fertilizer Used in the Experiment

Water used in irrigation came from an underground well, with an approximate flow of 1500 L/h. Water samples were collected monthly for analysis (Table 1) in bottles with a capacity of 500 mL. Water analyses were performed at the Water Analysis Laboratory of Embrapa Semiárido, Petrolina, PE, Brazil. Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}), chlorides (Cl^{-}), bicarbonate ($CO_3{}^{2-}$) and sulfate ($SO_4{}^{2-}$), pH, electrical conductivity (EC) and sodicity were analyzed according to Parron et al. [27].

Table 1. Chemical composition of the water used for irrigation over the 18 months.

	Description	Unit	Values
Cations	Calcium (Ca^{2+})	mmol/L	15.14
	Magnesium (Mg^{2+})	mmol/L	6.89
	Sodium (Na^{+})	mmol/L	3.72
	Potassium (K^{+})	mmol/L	0.29
	Sum	mmol/L	30.84
Anions	Bicarbonates ($CO_3{}^{2-}$)	mmol/L	3.70
	Sulfates ($SO_4{}^{2-}$)	mmol/L	2.63
	Chlorides (Cl^{-})	mmol/L	22.40
	Sum	mmol/L	35.62
	Potential hydrogenionic (pH)	-	7.38
	Electrical conductivity (EC)	dS/m	1.73
	Sodicity	-	Low

The water used in the experiment was classified as C3S1, i.e., with high salinity, low sodium content, and moderate hardness (75–150 mg/L) based on calcium carbonate [28].

The soil in the experimental area was classified as Acrisols [29], located on a flat relief, with medium texture. Soil samples from 0–0.10, 0.10–0.20, and 0.20–0.30 m depth profiles were collected during the implementation of the experiment to determine the physical and chemical properties of the soil (Table 2). To evaluate the physical properties, undisturbed soil samples were collected using volumetric cores (0.03 × 0.05 m) to preserve the soil structure. Soil bulk density was assessed after weighing the soil, when the core volume was already known (0.03 × 0.05 m). Total porosity was determined from the ratio between soil bulk density and particle density [30]. Particle density was determined by the volumetric balloon method and alcohol as liquid penetrant [30]. Sand, silt, and clay fractions were quantified using the methodology described by Teixeira et al. [31].

The pH and electrical conductivity (EC) were measured according to the AOAC [32]. The nitrogen (N) content was quantified by the Kjeldahl method [33]. The phosphorus (P), potassium (K^{+}), sodium (Na^{+}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) contents were quantified according to the methodology described by Holanda Filho et al. [34]. Copper (Cu^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}) were evaluated according to the methodology of Claessen [30]. The potential acidity (H + Al) was quantified by extraction, following the methodology described by Coldebella et al. [35]. The sum of bases (SB), cation exchange capacity (CEC) and base saturation (V) were calculated with the equations below [36]:

$$SB = Ca^{2+} + Mg^{2+} + Na^{2+} + K^{+}$$

$$CEC = SB + H + Al$$

$$V\% = 100 \times SB\ /\ CEC$$

The determination of the organic matter (OM) content was carried out following the method established by Goldin [37], through total combustion. The determination of the total carbon content of the soil was carried out according to the EMBRAPA [36].

Table 2. Chemical composition of the soil in the experimental area before the installation of the experiment.

Items	Unit	Layer (cm)		
		0–10	**10–20**	**20–40**
Electrical conductivity	mS/cm	1.06	0.30	0.24
Potential hydrogeologic	-	6.10	6.00	5.50
Organic Matter	g/kg	4.6	4.1	3.7
Total carbon	g/kg	5.20	4.90	3.70
Nitrogen	mg/dm^3	0.43	0.43	0.38
Phosphorus	mg/dm^3	2.97	2.50	0.61
Potassium	cmol/dm^3	0.34	0.30	0.18
Sodium	cmol/dm^3	0.24	0.21	0.03
Calcium	cmol/dm^3	1.50	1.20	1.60
Magnesium	cmol/dm^3	0.60	0.70	0.60
Potential acidity	cmol/dm^3	2.10	2.70	3.00
Sum of bases	cmol/dm^3	2.70	2.40	2.40
Cation exchange capacity	cmol/dm^3	4.80	5.10	5.50
Base saturation	%	56.30	47.00	44.20
Copper	mg/dm^3	0.54	0.50	1.06
Iron	mg/dm^3	12.90	6.20	7.90
Manganese	mg/dm^3	9.60	20.00	8.90
Zinc	mg/dm^3	15.38	3.66	22.34
Density (Soil)	kg/dm^3	1.47	1.41	1.44
Density (Particles)	kg/dm^3	2.58	2.58	2.58
Porosity	%	43.2	45.23	44.02
Granulometry (Sand)	%	83.4	80.6	71.64
Granulometry (Silt)	%	10.49	13.53	11.47
Granulometry (Clay)	%	6.11	5.87	16.89

2.3. Planting System and Irrigation Management

The cactus pear variety used in the experiment was the Orelha de elefante mexicana (*Opuntia stricta* Haw.). The cladodes were from the experimental field of the Universidade Federal Rural de Pernambuco, Academic Unit of Serra Talhada—PE. After being cut, the cladodes were stored in a shed with open sides and covered with zinc tiles. The cladodes underwent a rest period of fifteen days before planting so that healing could occur. After this period, they were planted using one cladode per hole in a vertical position.

The cactus pear was planted in the experimental field at a spacing of 1.6 × 0.4 m, totaling 15.625 plants per hectare and managed in rainfed conditions for one year, until the establishment of the crop. For two years, the cactus pear area received 700 mm irrigation and, after two years, a standardization cut was made to start the experimental test. Throughout the crop cycle, the necessary cultural treatments were carried out to reduce the incidence of spontaneous weeds and pests.

The experimental design adopted was a factorial arrangement 5 (irrigation depths; ID) × 4 (organic fertilizer levels; OF), with 4 replications, totaling 80 subplots, each containing 50 plants, with 32 plants referring to borders, and the remaining 18 plants per plot (Figure 3).

Among the 18 plants, 6 central plants were used for evaluations. Each experimental unit subjected to water depth treatments and organic fertilizer levels had 32 m^2 (8 × 4 m^2), of which 15.36 m^2 (4.8 × 3.2 m^2) referred to as the useful area.

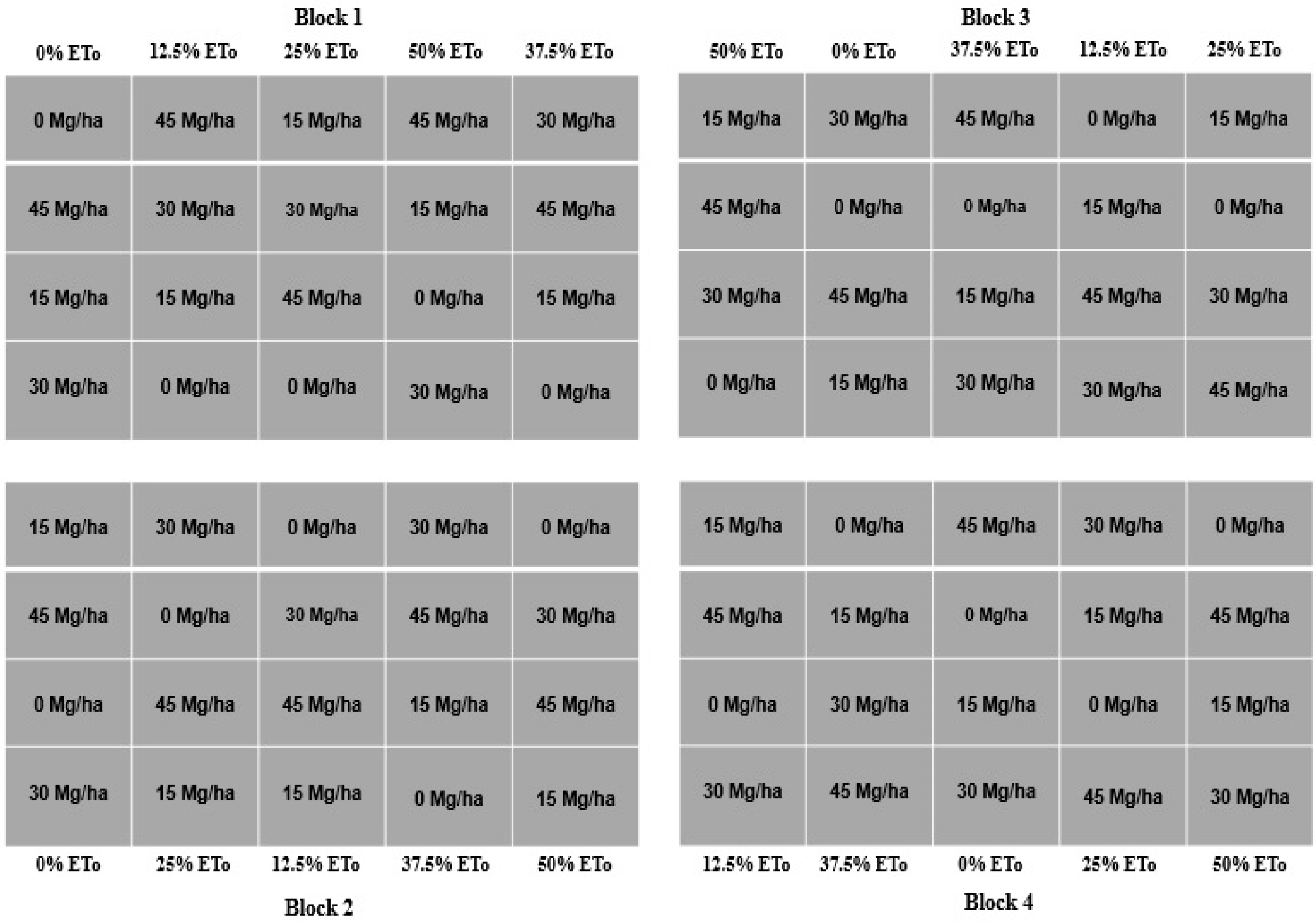

Figure 3. Schematic representation of the experimental design.

The main plot consisted of five irrigation depths: 0, 12.5, 25, 37.5 and 50% ETo. ETo is the reference evapotranspiration, and was quantified using the Penman-Monteith method, parameterized according to FAO Bulletin 56 [38], considering a Kc of 0.52 during the 18 months. The accumulated precipitation during the 18 experimental months (535 mm) was added to the irrigation depths: 0% (0 + 535, equivalent to 535 mm), 12.5% (88.9 + 535, equivalent to 623.9 mm), 25% (117.8 + 535, equivalent to 652.8 mm), 37.5% (266.7 + 535, equivalent to 801.7 mm) and 50% (355.6 + 535, equivalent to 890.6 mm).

Irrigation was performed with fixed depth twice a week, according to each treatment (equal to 5, 10, 15 and 20 mm per week). The five irrigation depths were calculated based on the Kc value recommended by Queiroz et al. [39], in which the maximum evapotranspiration of cactus pear occurs around 50% of the ETo. Therefore, depths below 50% ETo represent deficient irrigation conditions. Irrigation was performed by surface dripping, using a drip tube with emitters at a flow rate of 1.5 L/h, nominal diameter (ND) of 16 mm and spacing 0.20 m between them, with a uniformity coefficient of 93% and flow of 0.9 L/h. Water was applied according to crop evapotranspiration (ETc), obtained by multiplying ETo and crop coefficient (Kc).

The subplots were composed of four levels of organic matter (0, 15, 30 and 45 Mg/ha). The tanned cattle and goat manure was used as organic fertilizer (OF). The manure had the following characteristics: electrical conductivity = 12.27 mS/cm; pH = 8.3; total nitrogen = 9.3 g/kg; total phosphorus = 355.39 mg/dm^3; total potassium = 243.5 cmolc/dm^3; total calcium = 6.4 cmolc/dm^3; total magnesium = 2.5 cmolc/dm^3; copper = 1.45 mg/dm^3; iron = 5.36 mg/dm^3; manganese = 58.13 mg/dm^3; zinc = 2.43 mg/dm^3. Fertilization management was carried out only once during the implementation of the experiment, in which each treatment received its respective level of fertilization.

2.4. Morphological and Productive Responses of Cactus Pear with an Eighteen-Month Cycle

Morphological characteristics were collected in all experimental treatments from 18 months after the beginning of the productive cycle. Values of plant height (PH), plant width (PW) total number of cladodes (TNC), number of primary cladodes (NPC1), number of secondary cladodes (NSC2), number of tertiary cladodes (NTC3), length (LC), width (WC), perimeter (PC) and thickness (TC) of primary (P), secondary (S) and tertiary (T) cladodes and mother (M) cladode.

For production data, three plants from the useful area of each plot were sampled and weighed on a precision scale to obtain fresh weight. The average fresh weight per plant (FWP, kg/plant) was obtained and then the green matter production (GMP, Mg/ha) estimated from the product of the FWP and the equivalent density of plants per hectare (DPH). From the product of GMP and % dry matter (% DM), the dry matter production (DMP, Mg/ha) was obtained. The water accumulation of in the crop (WA, m^3/ha) was estimated by calculating the difference between GMP and DMP, according to Perazzo et al. [40]. With the ratio of DMP values to total water depths received by each treatment, the water use efficiency based on dry matter (WUE_DM, g DM/ha/mm) was calculated, in kg/ha/mm, according to Silva et al. [41].

2.5. Chemical Composition

Samples were ground in a knife mill (Wiley, Marconi, MA-580, Piracicaba, Brazil), using 2 mm sieves for in vitro digestibility and 1 mm for chemical composition analysis. Laboratory analyses were performed using the methods described by AOAC [33] for dry matter (DM; method 967.03), mineral matter (MM; method 942.05), crude protein (CP; method 981.10), ether extract (EE; method 920.29) and acid detergent fiber (ADF; Method 973.18). Neutral detergent fiber (NDF) content was determined as described by Van Soest et al. [42]. Neutral detergent fiber corrected for ash and protein (using thermostable alpha-amylase) was determined according to Mertens [43]. The content of neutral detergent insoluble protein (NDIP) was determined according to Detman et al. [44]. Neutral insoluble ash (NIA) was determined according to procedures described by Silva and Queiroz [45].

Lignin (LIG) was determined by treating the acid detergent fiber residue with 72% sulfuric acid [46] and the fractions of hemicellulose (HEM) and cellulose (CEL) were estimated by the following equations:

$$HEM = NDF - ADF$$

$$CEL = ADF - LIG$$

Total carbohydrates (TC) were estimated according to Sniffen et al. [47]:

$$TC = 100 - (\%\,CP + \%\,EE + \%\,MM)$$

Non-fiber carbohydrates (NFC) were calculated as proposed by Hall [48]:

$$NFC = \%TC - \%NDF$$

2.6. In Vitro Dry Matter Digestibility

In vitro dry matter digestibility (IVDMD) analysis was performed according to the methodology described by Tilley and Terry [49], with modifications proposed by Holden [50]. One gram of sample was incubated in 160 mL glass vials, with 80 mL buffer solution (nutrient medium composed of buffer solution, pH indicator solution, macro- and micro-mineral solution, sodium hydroxide solution (1 Molar) and reducing solution; with pH 6.8) and 20 mL ruminal fluid.

Rumen fluid used as inoculum was obtained from a cow fistulated in the rumen, kept confined and fed with corn silage. The ruminal fluid was collected through the cannula and stored in an anaerobic environment in a thermos bottle, and sent to the laboratory.

Ruminal contents were collected after the morning meal. The solid part was collected from the rumen through the cannula and manually pressed to separate the solid part from the liquid part. The ruminal inoculum was filtered through 4 layers of cheesecloth, constantly injecting CO_2 to maintain the anaerobic environment and kept in a water bath (TECNAL, Piracicaba, SP, Brazil) at 39 °C.

After 48 h of incubation in an oven at 39 °C, 2 mL hydrochloric acid (6 Molar) and 1 mL pepsin (0.4 g pepsin/mL solution) were added to each flask. The same procedure was applied to blanks (flasks containing inoculum and medium, without samples). Two bottles were used as a blank. In total, 82 flasks were incubated. After 24 h of incubation, vacuum filtering procedures were carried out in filtering crucibles, residues were dried and weighed for later calculation of IVDMD.

2.7. Statistical Analysis

Variables were subjected to analysis of variance to test the significance of interactions between the factors by F-test, at 5% probability. When there was only an isolated effect of the factors, a regression analysis was performed. Significant interactions were broken down into a response surface and the averages of the response variables were compared by Tukey's test at 5% probability. All statistical analyzes were performed using the statistical software R version 4.1.2 using statistical packages (ExpDes) [51]. The following statistical model was used:

$$Yij = \mu + IDi + OFj + Bl + (ID \times OF)ij + eij$$

where Yij = observed value for the response variable obtained for the i-th treatment in its j-th repetition; μ = overall mean; Idi = effect of the ith irrigation depth; OFj = effect of the j-th organic fertilizer; Bl = effect of the l-th block; (ID × OF)ij = interaction between irrigation depth and organic fertilizer; and ϵij = experimental error associated with each observation.

3. Results

3.1. Morphological Responses of Cactus Pear with an Eighteen-Month Cycle

The results obtained for the morphological characteristics of cactus pear as a function of the application of brackish water levels and organic fertilization doses show that the tested factors influence the characteristics evaluated in isolation, with no interaction effect between the factors ($p > 0.05$; Table 3).

Brackish water depths applied in cactus pear provided a quadratic effect for LMC, with greater length (26.63 cm) obtained with the application of 37.5% ETo ($p = 0.025$; Table 3; Figure 4). The other morphological characteristics evaluated in cactus pear were not influenced by the applied brackish water depths ($p > 0.05$; Table 3).

The application of organic fertilizer doses improved the morphological characteristics of cactus pear ($p < 0.05$; Table 3). Increases were observed in the height and width of cactus pear ($p < 0.001$; Table 3), with an increase of 53.68–89.92 cm for PH ($p < 0.001$; Figure 5A) and of 55.12–133.67 cm for PW ($p < 0.001$; Figure 5B), as the doses of organic fertilizer applied increased.

The organic fertilizer applied benefited the total number of cladodes, with an increase of 355.92% in the TNC in relation to the control treatment, without fertilization ($p < 0.001$; Figure 5C). Likewise, increases were observed for NPC1, NSC2 and NTC3, with an increase of 130.03%, 355.32% and 1590% for NPC1, NSC2 and NTC3, respectively, according to the increase in the doses of organic fertilizer applied in the cactus pear ($p < 0.001$; Figure 5C).

Table 3. Effect of irrigation depths with brackish water and organic fertilizer doses on morphological characteristics of cactus pear in the semiarid region.

Items	Irrigation Depths (% ETo)					SEM	Organic Fertilizer Levels (Mg/ha)				SEM	*p*-Value		
	0.0	12.5	25.0	37.5	50.0		0	15	30	45		ID	OF	ID × OF
PH	79.29	77.85	73.54	74.7	69.93	3.708	53.68	75.26	81.43	89.92	2.585	0.253	0.000	0.786
PW	107.04	102.42	96.88	99.25	93.85	7.454	55.12	100.23	110.54	133.67	4.915	0.438	0.000	0.326
Number of cladodes (unit)														
TNC	16.81	16.81	17.44	15.41	15.33	2.180	5.74	14.78	18.76	26.17	0.798	0.786	0.000	0.839
NPC1	5.11	6.40	6.08	5.61	5.34	0.328	3.23	5.94	6.23	7.43	0.299	0.262	0.000	0.465
NSC2	8.31	7.79	9.36	7.97	7.66	0.979	2.82	7.71	9.51	12.84	0.473	0.448	0.000	0.504
NTC3	4.10	3.53	3.68	2.90	2.61	0.944	0.40	1.81	4.51	6.76	0.266	0.629	0.000	0.194
Length of cladodes (cm)														
LMC	18.45	23.17	21.80	23.63	21.00	0.842	20.78	22.10	21.10	22.46	1.181	0.025	0.525	0.699
LPC1	26.05	27.44	27.58	27.67	27.51	1.160	22.27	27.94	29.27	29.51	0.913	0.787	0.000	0.485
LSC2	31.21	29.91	29.46	31.81	28.94	0.733	25.28	30.92	31.74	33.14	1.711	0.455	0.000	0.463
LTC3	25.00	18.14	23.19	23.49	16.71	3.185	4.74	21.51	29.97	28.99	2.598	0.191	0.000	0.559
Width of cladodes (cm)														
WMC	25.91	28.30	30.89	27.83	28.13	1.119	22.96	28.95	29.08	31.85	1.059	0.085	0.000	0.168
WPC1	22.26	23.53	22.96	23.57	23.59	0.458	19.16	24.45	24.57	24.55	0.836	0.591	0.000	0.348
WSC2	24.51	24.79	24.51	25.61	23.44	0.531	20.82	25.72	25.52	26.24	1.414	0.698	0.000	0.307
WTC3	20.53	14.97	19.76	19.58	14.63	2.701	3.90	18.55	24.89	24.23	2.152	0.214	0.000	0.531
Thickness of cladodes (cm)														
TMC	4.69	4.26	4.88	4.66	4.65	0.323	3.07	4.60	5.33	5.51	0.208	0.195	0.000	0.162
TPC1	2.13	2.17	2.21	2.27	2.24	0.122	1.70	2.31	2.39	2.42	0.082	0.714	0.000	0.559
TSC2	1.34	1.49	1.61	1.56	1.46	0.068	1.16	1.56	1.63	1.64	0.084	0.155	0.000	0.391
TTC3	0.91	0.70	1.01	0.95	0.68	0.135	0.16	0.87	1.24	1.13	0.088	0.146	0.000	0.535
Perimeter of cladodes (cm)														
PMC	54.61	62.94	63.06	62.04	59.06	1.936	53.57	63.21	60.45	64.13	2.455	0.184	0.004	0.543
PPC1	71.18	76.15	74.21	74.05	74.37	2.159	59.94	77.78	79.50	78.75	2.412	0.773	0.000	0.274
PSC2	83.95	82.16	80.54	85.33	78.09	1.905	68.60	84.87	85.74	88.85	4.676	0.621	0.000	0.451
PTC3	67.69	49.91	64.57	64.68	46.92	8.687	12.70	60.25	82.78	79.29	6.962	0.167	0.000	0.578

PH = plant height; PW = plant width; TNC = total number of cladodes; NPC1 = number of primary cladodes; NSC2 = number of secondary cladodes; NTC3 = number of tertiary cladodes; LMC = length of mother cladodes; LPC1 = length of primary cladodes; LSC2 = length of secondary cladodes; LTC3 = length of tertiary cladodes; WMC = width of mother cladodes; WPC1 = width of primary cladodes; WSC2 = width of secondary cladodes; WTC3 = width of tertiary cladodes; TMC = thickness of mother cladodes; TPC1 = thickness of primary cladodes; TSC2 = thickness of secondary cladodes; TTC3 = thickness of tertiary cladodes; PMC = perimeter of mother cladodes; PPC1 = perimeter of primary cladodes; PSC2 = perimeter of secondary cladodes; PTC3 = perimeter of tertiary cladodes; SEM = standard error of the mean; ID = irrigation depth; OF = organic fertilizer; ID × OF = interaction effect between irrigation depth and organic fertilizer; significant at the 5% probability level by Tukey's test.

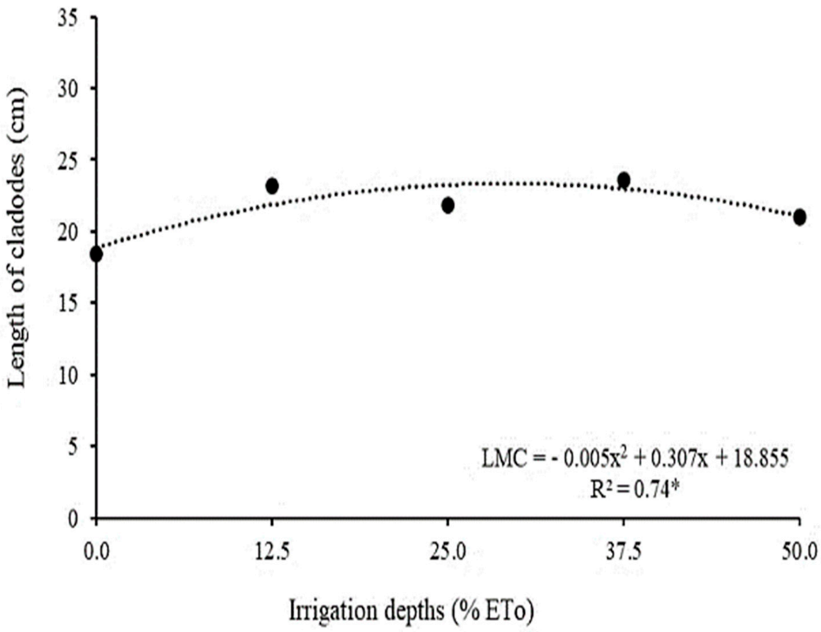

Figure 4. Effect of irrigation depths on the length of mother cladodes of cactus pear in a semiarid region (* indicates the determination coefficient).

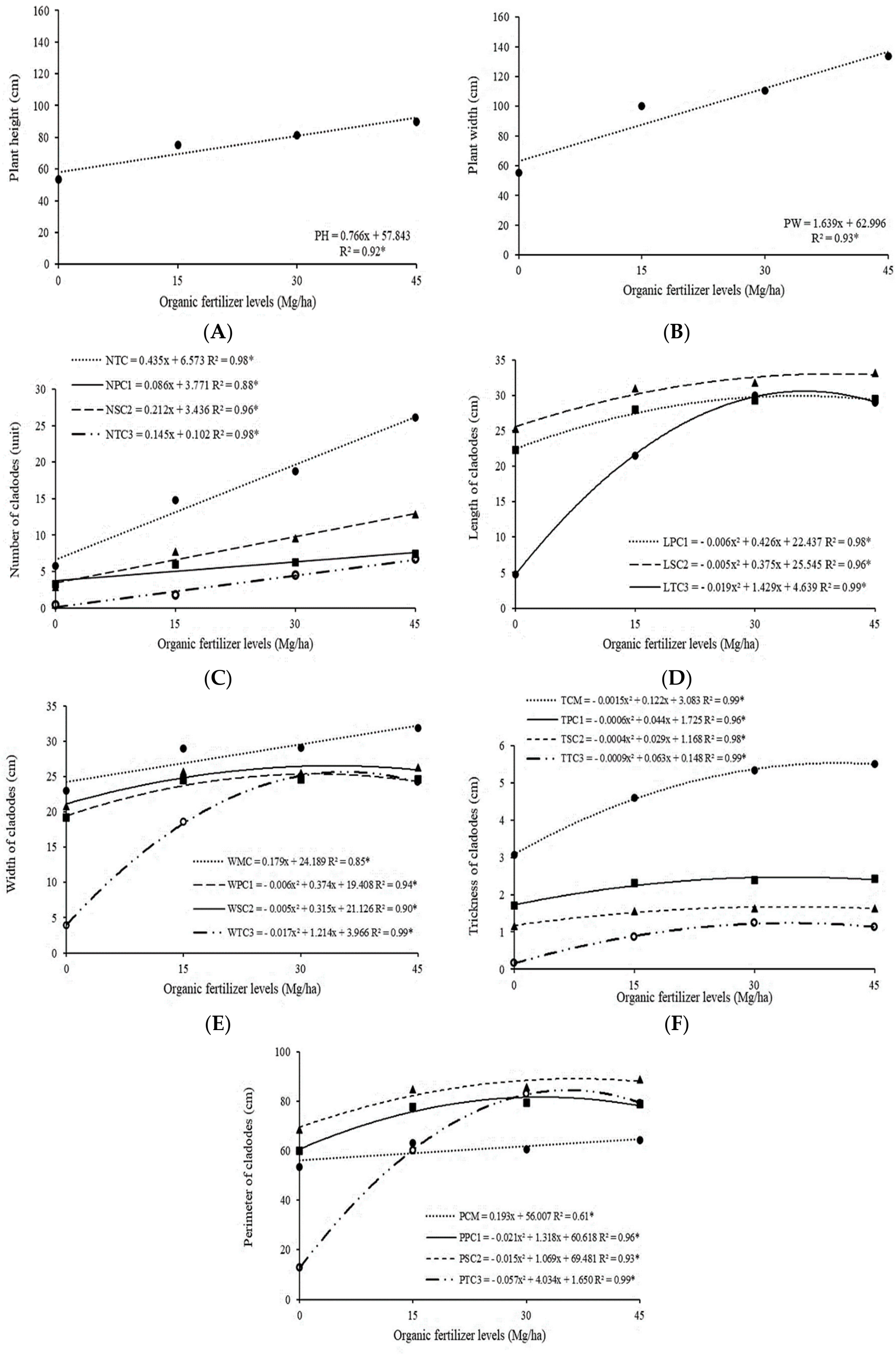

Figure 5. Effect of organic fertilizer doses on plant height (**A**), plant width (**B**), number of cladodes (total—NTC; primary—NPC1; secondary—NSC2 and tertiary—NTC3) (**C**), length of cladodes (primary—LPC1; secondary—LSC2; tertiary—LTC3) (**D**), width of cladodes (mother—WMC; primary—WPC1; secondary—WSC2; tertiary—WTC3) (**E**), thickness of cladodes (primary—TPC1; secondary—TSC2; tertiary—TTC3) (**F**) and perimeter of cladodes (mother—PMC; primary—PPC1; secondary—PSC2; tertiary—PTC3) (**G**) of cactus pear in a semiarid region (* indicates the determination coefficient).

3.2. Productive Responses of Cactus Pear with an Eighteen-Month Cycle

The productive responses of cactus pear with an eighteen-month cycle as a function of the application of brackish water depths and organic fertilizer doses are presented in Table 4. It was possible to observe that, when evaluated together, the irrigation depths and the doses of organic fertilizer tested do not influence the productive responses of cactus pear ($p > 0.05$; Table 4). However, when evaluated in isolation, there is an effect of the tested factors.

Table 4. Effect of irrigation depths and organic fertilizer doses on the characteristics of green matter production (GMP), dry matter production (DMP), water accumulation (WA) and water use efficiency based on dry matter (WUE_DM) of cactus pear in the semiarid region.

Items	Irrigation Depths (% ETo)					SEM	Organic Fertilizer Levels (Mg/ha)				SEM	*p*-Value		
	0.0	12.5	25.0	37.5	50.0		0	15	30	45		ID	OF	ID × OF
GMP	216.26	255.07	308.09	227.54	240.48	30.295	58.49	238.39	291.21	409.85	9.999	0.174	0.000	0.474
DMP	19.78	20.56	25.33	18.38	19.71	2.825	4.89	19.41	23.94	34.76	0.789	0.293	0.000	0.531
WA	196.46	234.51	282.77	209.15	220.77	27.501	53.60	218.98	267.26	375.09	9.218	0.164	0.000	0.469
WUE_DM	36.99	32.96	38.80	22.93	22.13	5.281	7.64	29.06	34.47	51.87	1.476	0.013	0.000	0.367

SEM = standard error of the mean; ID = irrigation depth; OF = organic fertilizer; ID × OF = interaction effect between irrigation depth and organic fertilizer; significant at the 5% probability level by Tukey's test.

The increase in brackish water levels applied to cactus pear influenced only the WUE_DM, reducing from 36.99 DM/ha (Control treatment; 0% ETo) to 22.13 DM/ha (50% ETo) ($p = 0.013$; Table 4; Figure 6).

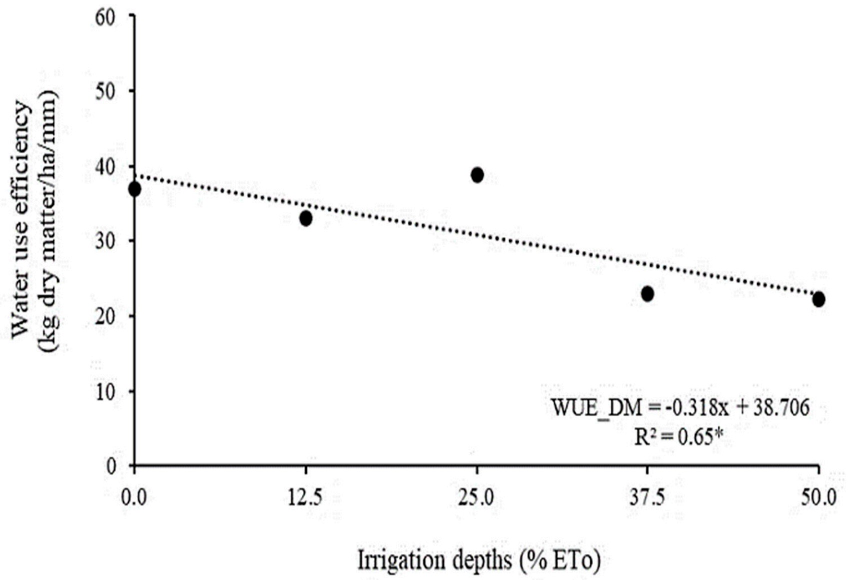

Figure 6. Effects of irrigation depths on water use efficiency of cactus pear in a semiarid region (* indicates the determination coefficient).

The organic fertilizer applied increased GMP ($p < 0.001$) and DMP ($p < 0.001$), with GMP from 58.49 to 409.85 Mg/ha and DMP from 4.89 to 34.76 Mg/ha (Table 4). According to Figure 5A,B, it was possible to observe an increase of 7.81 Mg/ha of green matter (Figure 7A) and 0.664 Mg/ha of dry matter (Figure 7B) for each Mg/ha of OF applied.

The organic fertilizer applied increased the water accumulation ($p < 0.001$; Table 4) in cactus pear to 375.09 m^3/ha at the level of 45 Mg/ha, with a relative increase of 7.144 m^3/ha for each Mg/ha of organic fertilizer applied, according to Figure 7C. An increase was also observed for WUE_DM (51.87 g DM/ha/mm) with the use of 45 Mg/ha organic fertilizer, with an increment of 0.983 kg DM/ha/mm for each Mg/ha of OF applied, according to Figure 7D.

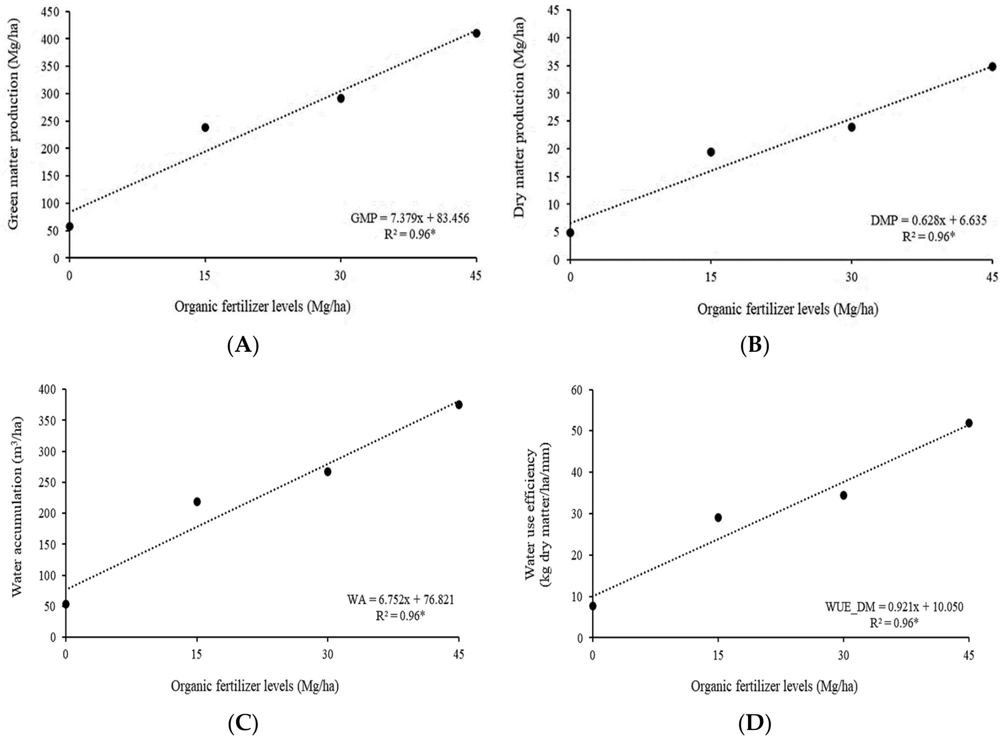

Figure 7. Effect of organic fertilizer doses on green matter production (GMP) (**A**), dry matter production (DMP) (**B**), water accumulation (WA) (**C**) and water use efficiency (WUE) (**D**) of cactus pear in a semiarid region (* indicates the determination coefficient).

3.3. Chemical Composition and In Vitro Digestibility of Dry Matter

As shown in Table 5, the brackish water depths, organic fertilizer and the interaction between these factors influence the nutritional composition of cactus pear ($p < 0.05$). The interaction of brackish water depths x organic fertilizer doses influenced the EE ($p < 0.001$), CP ($p = 0.043$) NDIP ($p = 0.001$), NIA ($p = 0.041$), TC ($p = 0.032$) and NFC ($p = 0.015$) contents (Table 5).

The use of brackish water depths of 37.5% ETo associated with doses of 30 and 45 Mg/ha, raised the EE content to 20 g/kg DM (Figure 8A). The absence of irrigation depths (0% ETo), regardless of the organic fertilizer load applied, maintained CP values above 50 g/kg DM. However, when the applied brackish water depths were increased, the CP content was reduced (Figure 8B).

The highest concentrations of NDIP (Figure 8C) and NIA (Figure 8D) were obtained with the application of a 50% ETo brackish water depth associated with doses of 0, 15 and 30 Mg/ha of organic fertilizer. Despite the joint effect of brackish water and organic fertilizer levels on TC (Figure 8E) and NFC (Figure 8F) levels, the greatest influence was exerted by the levels of organic fertilizer applied, in which these variables reached concentrations greater than 760 g/kg TC and 560 g/kg NFC, respectively, when 45 Mg/ha of organic fertilizer was applied without irrigation (0% ETo).

The irrigation of brackish water depths resulted in a quadratic effect for MM ($p < 0.001$; Table 5), with the 25% ETo depth promoting the highest MM content (211.99 g/kg DM), with an increase of 25.64% MM in this treatment compared to the control depth (0% ETo) (Figure 9A). A quadratic effect was also observed for the contents of NDF ($p < 0.001$), NDFap ($p < 0.001$), HEM ($p < 0.001$), and FC ($p < 0.001$), with higher values of these components in the with the use of the 37.5% ETo brackish water depth, with 264.65 g/kg for NDF ($p = 0.001$; Figure 9B), 239.28 g/kg MS for NDFap ($p = 0.001$; Figure 9C), 172.15 g/kg for HEM ($p = 0.001$; Figure 9D) and 238.58 g/kg for FC ($p = 0.001$; Figure 9E).

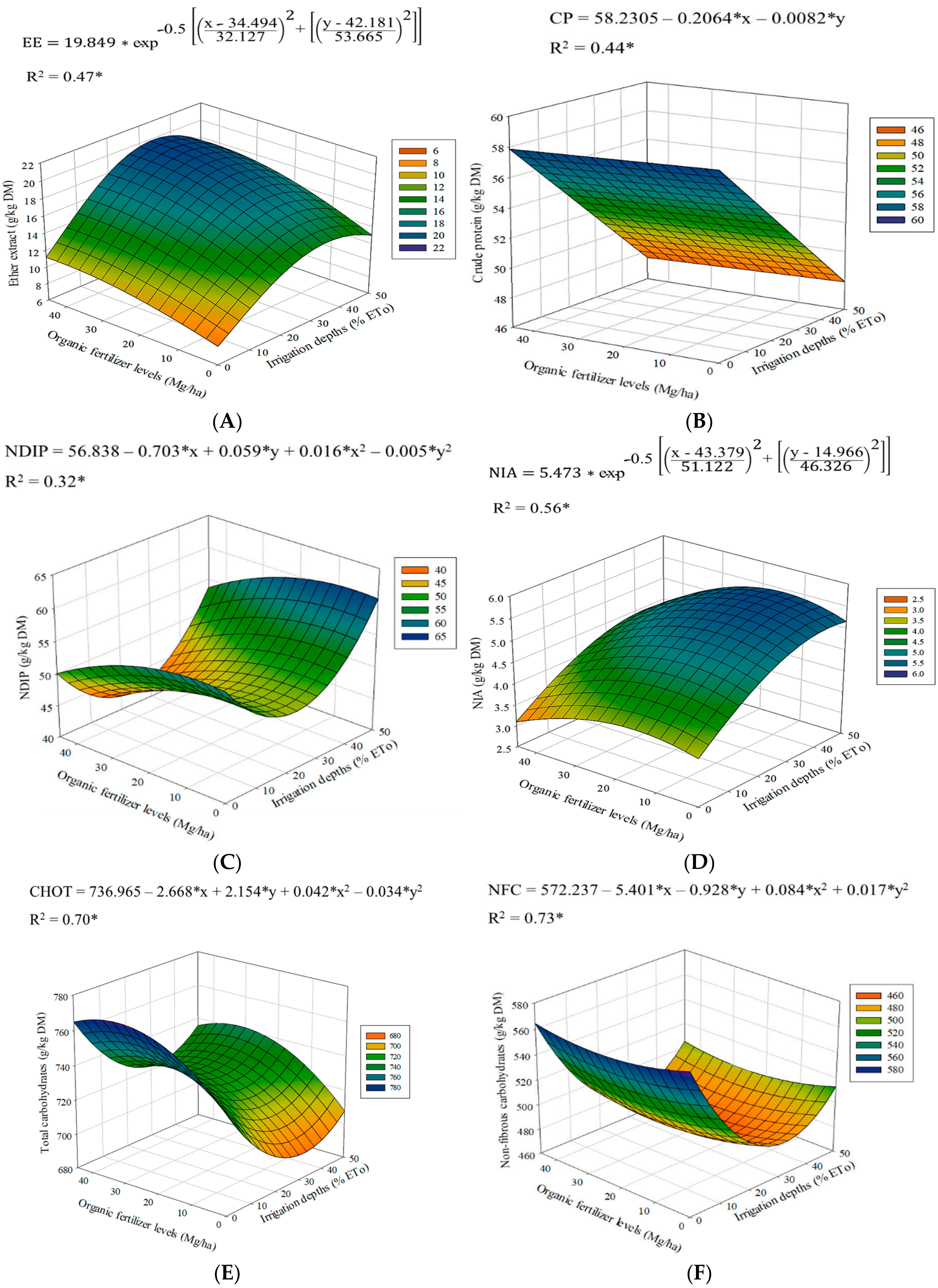

Figure 8. Interaction effect between irrigation depths and organic fertilizer levels on ether extract (EE) (**A**), crude protein (CP) (**B**), neutral detergent insoluble protein (NDIP) (**C**), neutral insoluble ash (NIA) (**D**) total carbohydrates (CHOT) (**E**) and non-fibrous carbohydrates (NFC) (**F**) of cactus pear in a semiarid region (* indicates the determination coefficient).

Regarding in vitro dry matter digestibility, a quadratic effect of brackish water depth was observed (Table 5), with higher values observed for the treatment without irrigation (0% ETo; 886.75 g/kg DM) and according to the irrigation was applied, the IVDMD decreased by 3.19% when 50% ETo was applied, compared to the treatment without irrigation (0% ETo) (Figure 9F).

The organic fertilizer doses applied to cactus pear provided a quadratic effect on the MM content (Table 5), with a 17.74% reduction in MM, going from 225.18 g/kg DM (0 Mg/ha) to 159.9 g/kg DM (45 Mg/ha) (Figure 10A). Quadratic effects were also observed for NDF (Figure 10B), HEM (Figure 10C), LIG (Figure 10D) and FC (Figure 10E), with the highest concentrations of these components for the application of 30 Mg/ha of organic fertilizer, with increases of 21.05% NDF, 25.97% HEM, 29.90% LIG and 23.07% FC in this treatment compared to the control treatment (0% ETo).

For the variables NDFap, ADF and CEL, the application of 45 Mg/ha of organic fertilizer increased the NDFap (Figure 10F), ADF (Figure 10G) and CEL (Figure 10H) by 23.07%, 15.30% and 15.19%, in relation to the treatment without application of organic fertilizer.

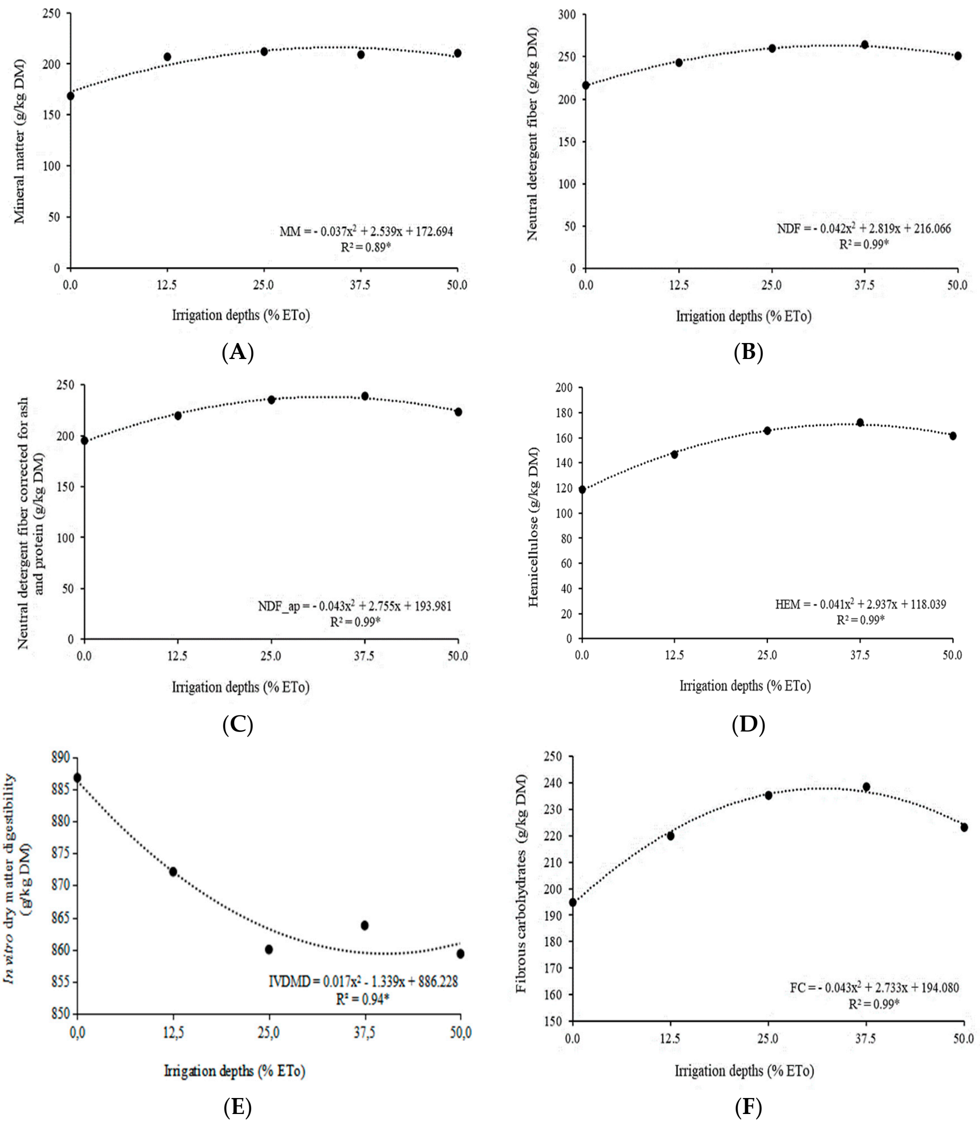

Figure 9. Effect of irrigation depths on mineral matter (**A**), neutral detergent fiber (**B**), neutral detergent fiber corrected for ash and protein (**C**), hemicellulose (**D**), fibrous carbohydrates (**E**) and in vitro dry matter digestibility (**F**) of cactus pear in a semiarid region (* indicates the determination coefficient).

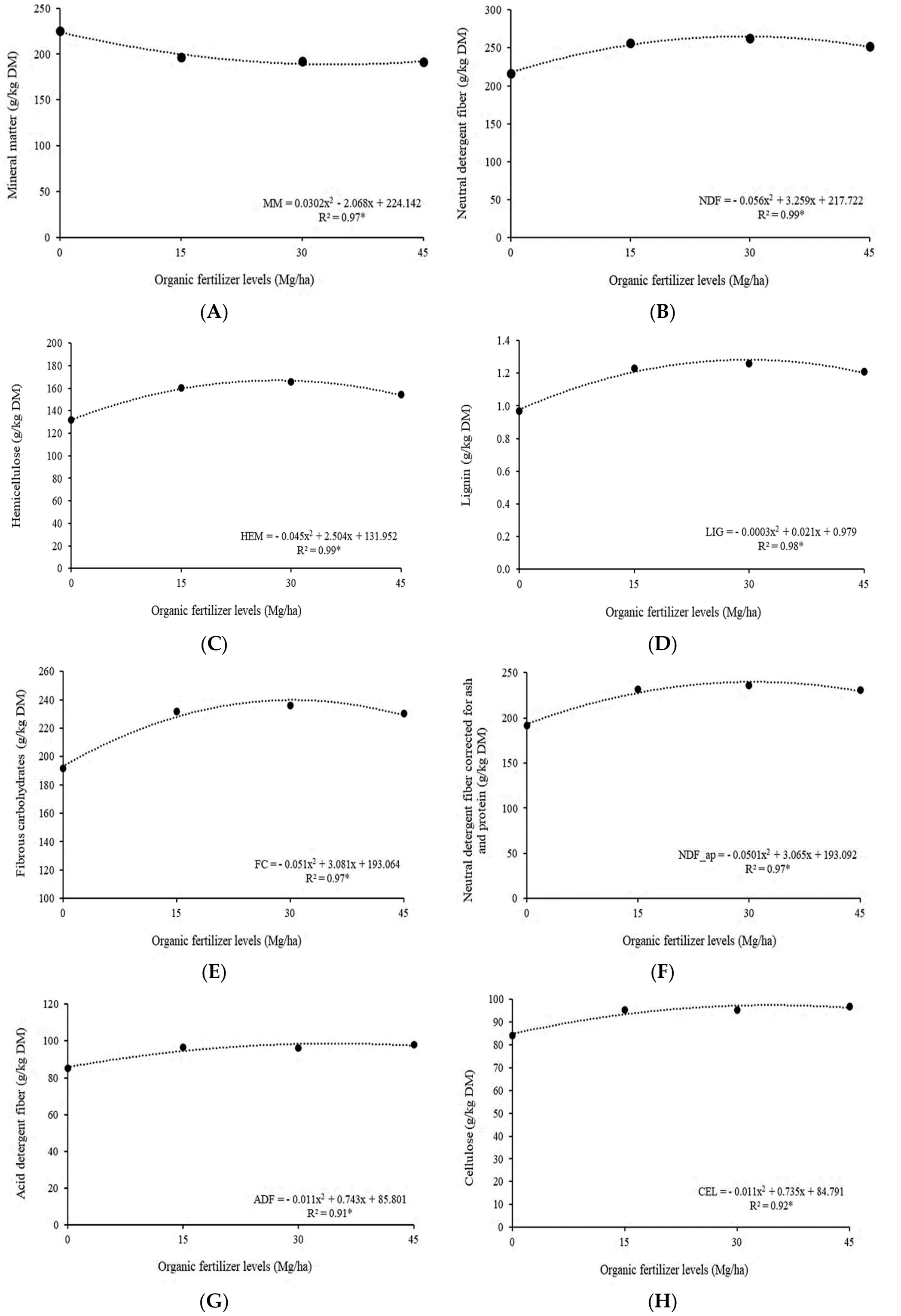

Figure 10. Effect of organic fertilizer levels on mineral matter (MM) (**A**), neutral detergent fiber (NDF) (**B**), hemicellulose (HEM) (**C**), lignin (LIG) (**D**), fibrous carbohydrates (FC) (**E**), neutral detergent fiber corrected for ash and protein (NDFap) (**F**), acid detergent fiber (ADF) (**G**) and cellulose (CEL) (**H**) from cactus pear in a semiarid region (* indicates the determination coefficient).

Table 5. Effect of irrigation depths and organic fertilizer doses on the chemical composition and in vitro digestibility of cactus pear in the semiarid region.

Items (g/kg DM)	Irrigation Depths (% ETo)					SEM	Organic Fertilizer Levels (Mg/ha)				SEM	*p*-Value		
	0.0	12.5	25.0	37.5	50.0		0	15	30	45		ID	OF	ID × OF
DM *	91.42	79.31	83.19	81.97	86.79	2.182	87.78	81.41	84.04	84.91	2.340	0.054	0.088	0.086
MM	168.73	206.88	211.99	208.87	210.61	4.143	225.18	196.81	192.43	191.25	6.901	0.000	0.000	0.141
EE	10.86	14.33	13.25	22.48	13.83	0.884	12.23	14.51	16.30	16.76	1.157	0.000	0.000	0.000
CP	57.30	58.01	50.91	49.58	48.62	2.738	54.63	50.58	52.87	53.46	2.223	0.045	0.254	0.043
NDF	216.88	243.25	259.79	264.65	250.82	5.284	216.77	256.88	262.40	252.26	7.062	0.000	0.000	0.146
NDFap	194.89	220.06	235.38	239.28	223.16	4.639	191.79	231.67	236.00	230.75	5.695	0.000	0.000	0.271
ADF	98.11	96.03	94.22	92.50	89.35	2.674	85.11	96.59	96.34	98.13	3.544	0.190	0.001	0.162
CEL	96.95	95.09	93.03	91.39	88.16	2.617	84.14	95.37	95.28	96.92	3.471	0.179	0.001	0.171
HEM	118.78	146.95	165.56	172.15	161.47	4.628	131.66	160.29	165.85	154.13	6.323	0.000	0.001	0.402
LIG	1.16	1.19	1.19	1.11	1.18	0.075	0.97	1.23	1.26	1.21	0.097	0.943	0.032	0.308
NDIP	53.18	50.86	46.53	47.48	59.52	3.668	54.44	51.88	53.24	46.47	2.785	0.091	0.044	0.000
NIA	3.45	4.31	5.01	4.70	5.13	0.270	4.55	4.93	4.59	3.99	0.349	0.002	0.038	0.041
TC	762.92	720.77	724.49	719.06	726.97	5.007	707.80	738.21	738.83	738.54	6.776	0.000	0.000	0.032
NFC	568.02	500.71	489.11	480.48	503.81	6.578	516.01	506.53	502.83	508.34	9.927	0.000	0.545	0.015
FC	194.89	220.06	235.38	238.58	223.16	4.639	191.79	231.67	236.00	230.20	5.695	0.000	0.000	0.246
IVDMD	886.75	872.11	859.93	863.74	859.33	3.104	864.67	868.21	870.15	870.45	5.765	0.001	0.708	0.404

DM = dry matter; MM = mineral matter; EE = ether extract; CP = crude protein; NDF = neutral detergent fiber; NDFap = neutral detergent fiber corrected for ash and protein; ADF = acid detergent fiber; CEL = cellulose; HEM = hemicellulose; LIG = lignin; NDIP = neutral detergent insoluble protein; NIA = neutral insoluble ash; TC = total carbohydrates; NFC = non-fiber carbohydrates; FC = fibrous carbohydrates; IVDMD = in vitro dry matter digestibility; SEM = standard error of the mean; ID = irrigation depth; OF = organic fertilizer; ID × OF = interaction effect between irrigation depth and organic fertilizer; significant at the 5% probability level by Tukey's test; * in g/kg green matter.

4. Discussion

Most previous studies on the production of cactus pear irrigated with brackish water and fertilized with doses of organic matter focus on shorter production cycles, not representing the effects of irrigation with brackish water on cactus pear in longer production cycles (18–24 months), such as those used by rural producers in semiarid regions. Just as previous studies use lower doses of organic matter to remedy the effects of using smaller depths of brackish water. Given the above, we observed that the increase in organic matter by up to 45 ton/ha increases production and water use efficiency and improves the chemical-bromatological composition of cactus pear cultivated in the semiarid region in an eighteen-month production cycle.

The contribution of organic fertilizer to the morphological and productive characteristics of cactus pear resides in the fact that the doses of organic fertilizer provide greater accumulation of nutrients and, consequently, in the occurrence of taller and more developed plants. According to Lédo et al. [52], fertilization with a higher supply of nutrients, mainly N, promotes better plant growth. The slow availability of nutrients applied via manure to the soil is sufficient to meet the needs of the plant throughout its development [53].

The greater PW compared to PH observed here is due to the structure of the cladodes, as plants with larger cladodes can invest in lateral growth, due to their structural shape [7]. Cactus pear genotypes that have larger plant width, as is the case in the studied genotype, cultivation using larger spacing between plants is recommended, due to competition for water, light and nutrients, in addition to facilitating crop treatment and harvesting [54].

Plants that received 45 Mg/ha of OF developed a greater number of total cladodes, as well as among the orders, which may be associated with the composition of the applied organic fertilizer, which has nitrogen and phosphorus contents of 9.3 g/kg and 355.39 mg/dm^3), respectively. N favors the emergence of cladodes because it is a nutrient that stimulates plant cell division [55] and P accelerates root formation and plant growth [56]. Second-order cladodes were found in greater numbers in this study. This higher number possibly occurred due to the increase in the number of halos in the plant with the emergence of primary cladodes. These structures are equivalent to axillary buds, and under appropriate environmental conditions they can give rise to new cladodes [57,58].

Corroborating our findings, Barbosa et al. [59] also found a higher number of second-order cladodes for the Orelha de elefante mexicana. The authors mention that second-order cladodes are those in greater number in the OEM clone, contributing to the final crop yield, given that the higher number of cladodes per unit area tends to increase CO_2 uptake and maximize productivity [60].

Both the knowledge of the total number of cladodes in cactus pear and the number of cladodes per order are of great morphophysiological importance. According to Pinheiro et al. [61], studies on correlations between the cladode area index and morphogenic and productive characteristics of cactus pear, TNC is the characteristic with the highest correlation with cactus pear yield, followed by the height and width of the plant.

Another important point of the TNC, from a technical point of view, is the fact that cactus pear is normally propagated by vegetative parts (whole cladodes) [58]. Varieties with a higher number of cladodes would be easier to replicate in the process of multiplying seedlings of varieties and/or clones produced by breeding programs [62].

Greater lengths obtained in first- and second-order cladodes with the use of 45 Mg/ha OF were due to the greater accumulation of water in this treatment because, according to Pereira et al. [63], cladode growth is more related to the water status of the plant, and organic fertilization promotes soil improvements, such as water retention [64]; thus, under ideal soil moisture conditions, cactus pear stores more water in the parenchymal tissue [2,65].

Cladode thickness was reduced according to the order of emergence. This was also reported by Pereira et al. [63], who state that the more advanced the maturity stage of the cladodes, the greater their thickness. Older cladodes have the function of supplying and transporting water, nutrients and organic substances required for plant maintenance [66,67]. According to Silva et al. [68], characteristics such as the number and thickness of cladodes can serve as a basis for selecting accessions with good productive characteristics, according to the management adopted.

The improvements in the physical and chemical properties of the soil, promoted by organic fertilization, in addition to the greater availability of nutrients for the plants, resulted in an increase in GMP and DMP. This is a reflection of the greater responses obtained for PH, PH, number, width and length of cladodes according to the levels of OF applied, considering that these variables presented better results with the use of 45 Mg/ha OF. According to Edvan et al. [7], the characteristics of plant height and width, as well as the number, length, width and thickness of cladodes, directly influence GMP and DMP.

Cactus pear has an efficient and specific physiological mechanism in the uptake of nutrients and water use. As a result, when there is abundant water and nutrient availability, associated with fertilization, it may contribute to the growth and development of cladodes [69,70], increasing the productivity of green and dry matter.

WUE_DM for cactus pear decreased with increasing levels of ID applied, possibly due to its age, since according to Snyman [71], WUE is higher in longer cycles (third and fourth years), in relation to shorter cycles, as the cycle of the present study (18 months). So, possibly because cactus pear is highly efficient in water use, the available water volume, when irrigated at the highest frequencies, was above the necessary level for maximum dry matter fixation.

Another speculative fact that may have reduced the WUE_DM of cactus pear with increasing ID may be due to changes in the metabolism of cactus pear because, when cactus pear is under adequate water supply, its crassulacean acid metabolism (CAM) becomes facultative, and the plant starts to have a photosynthetic metabolism similar to C3 plants, managing to fix CO_2 during the day, thus reducing its efficiency in water use. Nevertheless, the potential of CAM on cactus pear WUE has not yet been sufficiently explored, requiring further studies [72].

The WUE of cactus pear is up to 11 times higher than that observed in C3 plants, showing its prominence in relation to any other forage [73]. According to Sá et al. [74], irrigation management can be an important strategy for greater production during dry periods; however, low amounts of water, uniformly distributed as in this experiment, are sufficient to keep the cladodes turgid. Besides that, cactus pear Orelha de elefante mexicana is a variety that stands out in terms of WUE, considering the GMP, as it is more efficient in the use of water retained in the plant [10]. As a result, the Mexican elephant ear cultivar has a greater ability to adapt to water deficit conditions [63].

The increase in the WUE_DM of cactus pear according to OF levels is linked to the ability of OF to increase soil water retention, resulting in less evaporation and better water use in the system [4]. This also justifies the behavior of the plant GMP, since the greater the biomass production, the more efficient the cladodes were in terms of their ability to store water.

The highest content of MM in the treatments that received water via irrigation, compared to ID 0% ETo, demonstrates the uptake and accumulation of minerals by cactus pear, according to the concentration of salts in water applied. Thus, the application of OF levels combined with irrigation with brackish water could reduce the load of salts present in the water, which the plants could absorb. The results observed for mineral content in this study are above the findings by Araújo Junior et al. [20], for Orelha de elefante Mexicana grown under irrigation with saline water (150 g/kg).

Higher percentages of NDF, NDFap, HEM and FC observed in the ID 37.5% ETo and with the use of 30 Mg/ha OF can be attributed to a greater allocation and uptake of nutrients and minerals by the plants, since they are cofactors of growth and differentiation of plant cells [75]. The highest concentration of ADF with the application of 45 Mg/ha organic fertilizer is possibly related to greater plant development, since the higher the levels of organic fertilizer applied, the greater the mean values for plant height, and consequently the greater development of structural tissues in lower cladodes, thus providing better support for the following orders of cladodes [76] and thereby avoiding possible problems with plant bedding.

Despite the increase in CEL and LIG, their concentrations were low compared to the values found by Pessoa et al. [77], with an average of 143.13 and 4.91 g/kg DM, for CEL and LIG, respectively, among the cladodes of the cactus pear Orelha de Elefante Mexicana without application of fertilization. This result may possibly be related to fertilization, given that organic fertilization induces plant growth, promoting the emergence of new cladodes [78], which are more tender, with a lower concentration of lignin [79]. This is beneficial for ruminant feeding, as lignin is a constituent of the plant cell with low or no digestibility, acting as a physical barrier to microbial enzymes [80].

The reduction in the CP content with increasing ID can be explained by the fact that forage plants, in general, under saline stress, suffer declines in gas exchange, photosynthetic efficiency, carbohydrate and protein production. Under conditions of salt stress, the processes of uptake, transport, assimilation and distribution of nutrients, in plants, can be negatively affected [81], including nitrogen.

Under saline stress, the activity of nitrate reductase may decrease [82] and, as this enzyme is responsible for catalyzing the first step of nitrate assimilation, a reduction in its activity implies less assimilation of nitrogen by the plant [83] and consequently lower CP content. Araújo Junior et al. [20] applied different irrigation depths using saline water in cactus pear, and reported CP values ranging from 35.8 to 42.1 g/kg DM, lower than our findings (48.62–58.1 g/kg DM).

Crude protein values were below the minimum required to ensure adequate ruminal fermentation, which is 70 g/kg according to Van Soest [84], requiring nutritional supplementation when cactus pear is used in ruminant diets.

As irrigation was used, the content of TC and NFC decreased, thus reflecting on the digestibility result, which also decreased with increasing irrigation depths. According to Sapes et al. [85], plants under stress conditions present a reduction in carbohydrate content due to lower CO_2 assimilation and greater mobilization of reserves directed towards growth and maintenance.

The decrease in IVDMS with increasing ID is a result of the increase in NDF content and the decrease in TC and NFC with increasing irrigation depths. According to Cavalcante et al. [86], the high proportions of carbohydrates, mainly non-fiber carbohydrates, in general, increase the digestibility of cactus pear. This is because they are readily degraded in the rumen, quickly disappearing, and increase energy supply, favoring microbial growth and, consequently, digestion.

5. Conclusions

The morphological characteristics of cactus pear are increased with the use of organic fertilizer, in which the application of organic fertilizer by up to 45 Mg/ha increases the production and efficiency of water use in cactus pear grown in the semiarid region. The content of CP, TC, NFC, as well as the IVDMD are favored by the application of lower depths of brackish water and levels of organic fertilizer in the semiarid region. The increment of organic fertilizer of up to 45 Mg/ha associated with the use of lower brackish water levels are recommended for the cultivation of Orelha de elefante mexicana cultivated in the semiarid region.

Further studies evaluating the morphological, productive, nutritional characteristics and water use efficiency with organic fertilizer doses and reduced brackish water levels are necessary and pertinent to the maximization of forage production and efficient use of natural resources in the semiarid region.

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