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Chemical composition and carbohydrate fractionation of forage palm under different irrigation strategies

[Composição química e fracionamento de carboidratos da palma forrageira sob diferentes estratégias de irrigação]

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Abstract: The objective was to evaluate the chemical composition and carbohydrate fractionation of *Opuntia stricta* submitted to different irrigation strategies. A block design was adopted with a 5 x 2 x 4 factorial scheme, with 5 irrigation depths (0, 20, 40, 70 and 100 % of the real irrigation required - IRN) and 2 methods for estimating evapotranspiration (Penman-Monteith and Hargreaves Samani), with 4 repetitions. The chemical composition was quantified and carbohydrate fractionation was performed using the CNCPS model. Means and interactions were compared using the 5 % Tukey test. The fibrous components, crude protein and lignified fraction of carbohydrates showed interaction (P<0.05) between the equations and the irrigation depths. Crude protein contents were higher in lower irrigation depths. TDN values varied from 69 to 71 % in all treatments, without differing between depths. The fodder palm cultivar elephant ear has an adequate chemical composition even when grown in rainfed conditions, or in low irrigation depths. It is recommended to use an irrigation depth of 20 % of the IRN along with the model proposed by Hargreaves & Samani.

Keywords: cactaceae; evapotranspiration; *Opuntia stricta*; nutritional value.

Resumo: Objetivou-se avaliar a composição química e o fracionamento de carboidratos da palma forrageira submetida a diferentes estratégias de irrigação. Adotou-se delineamento em blocos com esquema fatorial de 5 x 2 x 4, sendo 5 lâminas de irrigação (0, 20, 40, 70 e 100 % da irrigação real necessária - IRN) e 2 métodos de estimativa da evapotranspiração (Penman-Monteith e Hargreaves Samani), com 4 repetições. Foi quantificada a composição química e realizado o fracionamento de carboidratos pelo modelo CNCPS. As médias e as interações foram comparadas pelo teste de Tukey a 5 %. Os componentes fibrosos, proteína bruta e fração lignificada dos carboidratos apresentaram interação (P<0,05) entre os modelos e as lâminas. Os teores de proteína bruta foram mais elevados em lâminas de irrigação menores. Os valores de NDT variaram de 69 a 71 % em todos os tratamentos, não diferindo entre as lâminas. A palma forrageira cultivar orelha de elefante apresenta adequada composição química mesmo quando cultivada em condições de sequeiro, ou em lâminas de irrigação baixas. Recomenda-se o uso de lâmina de irrigação de 20 % da IRN junto modelo proposto por Hargreaves & Samani.

Palavras-chave: cactáceas; evapotranspiração; *Opuntia stricta*; valor nutricional.

1. Introduction

Ruminant production systems in the Brazilian semi-arid region are mostly extensive and depend on the availability of native vegetation, which is affected by the regularity and distribution of rainfall in the region, thereby interfering with forage production and quality for most of the year [(1)]. Therefore, species adapted to the local climate and soil should be chosen to avoid decreases in nutritional quality, in addition to low production costs, which allows for greater productive efficiency during dry periods [(2)].

Among these species, forage cactus (*Opuntia stricta* (Haw.) Haw.) stands out as an excellent alternative for cultivation in semi-arid regions because it has an efficient physiological mechanism that improves water absorption and utilization [(3)], and is a valuable food source for ruminants due to its high nutritional value [(4)]. Forage palm is characterized by all plant species of the genera *Opuntia* and *Nopalea*, which are widely used in animal feed and belong to the family Cactaceae. Approximately 300 *Opuntia* species are distributed worldwide, distributed throughout the Americas [(5)]. These species have a metabolism characterized by crassulacean acid metabolism (CAM), which involves the opening of stomata predominantly at night when air temperatures are milder, promoting greater efficiency in water use by reducing losses through evapotranspiration [(6)]. However, factors such as water availability, soil fertility, planting density, and the presence of pests and diseases can interfere with its productivity and affect the quality of the cladodes [(7)].

Among these management practices, forage palm, a drought-tolerant crop, responds well to irrigation depending on its frequency and depth. For adequate irrigation management, it is important to estimate and understand the evapotranspiration of the species to define the amount of water required for replacement [(8)]. Among the models used to determine this variable, the Penman-Monteith method stands out, which requires data on maximum and minimum air temperatures, solar radiation, air humidity, and wind speed, and the one proposed by Hargreaves & Samani, which is simpler because it is based on maximum and minimum temperature data and an estimate of solar radiation from local data [(9)]. Although the Penman-Monteith method is the most widely used and standardized method in FAO Paper 56 [(10)], it requires accurate measurements and several meteorological variables. In many locations, these variables are not freely available, necessitating the use of more complete meteorological stations [(11)]. For this reason, simpler methods, such as the one proposed by Hargreaves and Samani, have been applied in various production contexts, particularly in small- and medium-sized ruminant production systems.

In addition to productivity, water availability can influence the chemical composition of palm and its development, where the frequency and intensity of water stress determine the quality of the forage offered to animals [(12)]. Water stress can affect physiological factors such as stomatal opening and closure, photosynthesis, leaf growth, and elongation, which can cause changes in secondary metabolism and nutrient deposition.

We hypothesized that different irrigation depths combined with different evapotranspiration estimation methods promote changes in the chemical composition and carbohydrate fractionation of forage palm. Thus, the objective of this study was to evaluate the chemical composition and carbohydrate fractionation of forage palm under different irrigation depths and evapotranspiration estimates.

2. Material and methods

The experiment was conducted in the experimental area of the Dom Fragoso Family Agricultural School (EFA Dom Fragoso) in the municipality of Independência, state of Ceará, Brazil (Figure 1), located at the geographic coordinates 5°20′00″ S and 40°14′21″ W. According to the Köppen climate classification, the climate of the region is BSh (tropical semi-arid), with an average annual rainfall of 760 mm during the summer.

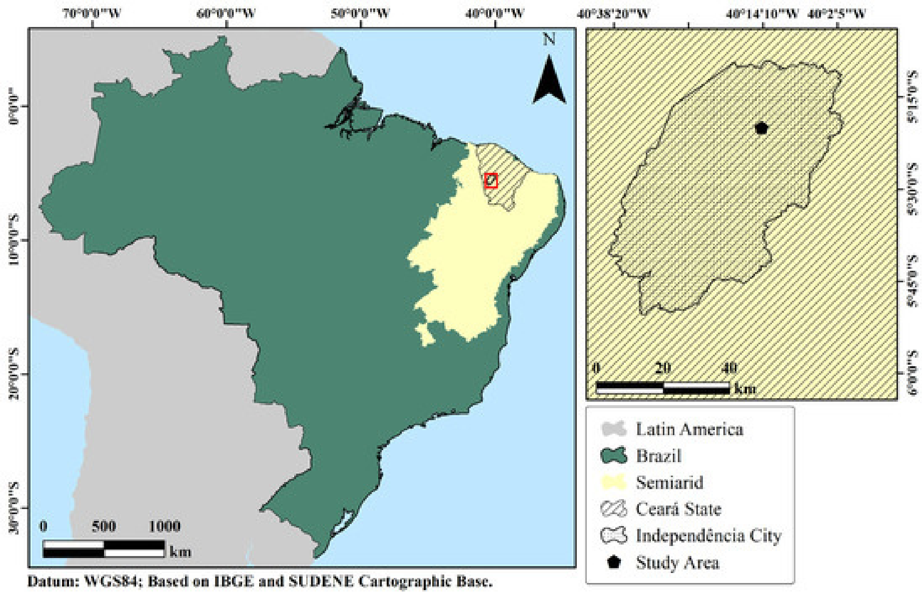

Figure 1. Location of the experimental area, highlighting the map of the Brazilian semi-arid region, the state of Ceará, the municipality of Independência, and the specific location of the EFA Dom Fragoso. Source: Bezerra et al. (2024) [13].

The crop was planted in November 2020, with treatments applied between August and December 2021. To eliminate weeds, two weedings were carried out during the rainy season and two during the dry season (during irrigation). The presence of mealybugs in numbers that would justify intervention with pesticides was not observed.

The experimental design was randomized blocks, with four repetitions in a 5 × 2 factorial scheme, relating to 5 irrigation depths (0 %, 20 %, 40 %, 70 %, and 100 % of the actual irrigation requirement - IRN) and 2 methods for estimating reference evapotranspiration (Penman-Monteith and Hargreaves Samani). Each experimental unit consisted of 5 rows, 9 m long, 0.8 m spaced apart, totaling an area of 36 m² and, therefore, a total experimental area of 1,440 m².

The soil in the experimental area presented a sandy-loam texture and the following chemical properties: pH in water of 6.0; electrical conductivity of the saturation extract (ECe) of 0.13 dS m^{-1}; exchangeable cations (cmolc kg^{-1}) Ca^{2+} = 3.10, Mg^{2+} = 0.40, Na^+ = 0.07, K^+ = 0.26, H^+ + Al^{3+} = 1.16, and Al^{3+} = 0.10; sum of bases of 3.80 cmolc kg^{-1}; cation exchange capacity of 5.00 cmolc kg^{-1}; base saturation of 77 %; aluminum saturation of 3 %; and exchangeable sodium percentage of 1 %. The carbon and nitrogen contents were 2.64 and 0.27 g kg^{-1}, respectively, resulting in a C/N ratio of 10, organic matter of 4.55 g kg^{-1}, and assimilable phosphorus of 2 mg kg^{-1}.

The irrigation water came from a tilapia farm tank supplied by a deep well with a flow rate of 1000 L h^{-1}; the water is brackish. A chemical analysis of the water revealed a pH of 7.2; an electrical conductivity (CEw) of 1.7 dS m^{-1}, and the following concentrations: Ca^{2+} = 4.5 mmolc L^{-1}, Mg^{2+} = 5.8 mmolc L^{-1}, Na^+ = 6.1 mmolc L^{-1}, K^+ = 0.3 mmolc L^{-1}; Cl^- = 15.4 mmolc L^{-1}; HCO_3^- = 1.2 mmolc L^{-1}, and phosphorus = 0.58 mg L^{-1}. The sodium adsorption ratio (SAR) was 1.91.

Five physical weedings were conducted during the rainy season, from January to June of 2021 and 2022. Irrigation was conducted during the dry periods, from July to December of 2021 and 2022, when three additional weedings were carried out. Additionally, during the rainy season of 2021, organic fertilization with cattle manure was carried out at a dose equivalent to 30 t ha^{-1}, according to recommendations for dense plantings of forage palm [14].

The Penman-Monteith equation uses a broader set of meteorological information, recorded by an agrometeorological station located in the center of the experimental area, and also considers aspects of plant physiology, described below:

$$ETo = \frac{0.408 * \Delta * (Rn - G) + \left(y * \frac{900}{Tmed + 273}\right) * v_2 * (es - ea)}{\Delta + Y * (1 + 0.34 * v_2)}$$

Where: Eto = reference evapotranspiration in mm day^{-1}; Rn = total net radiation from the sward in MJ m^{-2} day^{-1}; G = soil heat flux density in MJ m^{-2} day^{-1}; Tmed = average daily air temperature in °C; v2 = average daily wind speed at 2m height; es = saturation vapor pressure in kPa; ea = partial vapor pressure; Δ = slope of the vapor pressure curve in kPa C^{-1}, γ = psychrometric coefficient.

The equation proposed by Hargreaves Samani estimates ETo using only the maximum, minimum, and average air temperatures and radiation at the top of the atmosphere, as follows:

$$ETo = \alpha * (Tmax - Tmin)^{\beta} * (Tmed + 17.8) * Ra * 0.408$$

Where: Eto = reference evapotranspiration in mm day^{-1}; Tmax and Tmin, maximum and minimum temperature, respectively; α = 0.0023; β = 0.5; Tmed = sum of maximum and minimum divided by two; Ra = extraterrestrial radiation, expressed in MJ m^{-2} day^{-1}.

Using the estimated ETo values, we could calculate the crop evapotranspiration (ETc mm day^{-1}) by multiplying it by a value called the crop coefficient (Kc):

$$ETc = ETo * Kc$$

Where: Etc = crop evapotranspiration in mm day^{-1}; Eto = reference evapotranspiration in mm day^{-1}, and Kc = crop coefficient.

During the experimental period, the average maximum and minimum temperatures were 34.43 and 22.51 °C, respectively; the average relative humidity was 67.41 %, and the average wind speed was 1.44 m s^{-1}. The Penman-Monteith method estimated the average reference evapotranspiration at 6.32 mm day^{-1}, with a corresponding crop evapotranspiration of 3.21 mm day^{-1}. Using the Hargreaves-Samani method, the average reference evapotranspiration was 5.61 mm day^{-1}, with an average crop evapotranspiration of 2.89 mm day^{-1}. Figure 2 illustrates the variation in crop evapotranspiration (ETc), reference evapotranspiration (ET_0), and meteorological conditions, including rainfall and air temperature, throughout the study period.

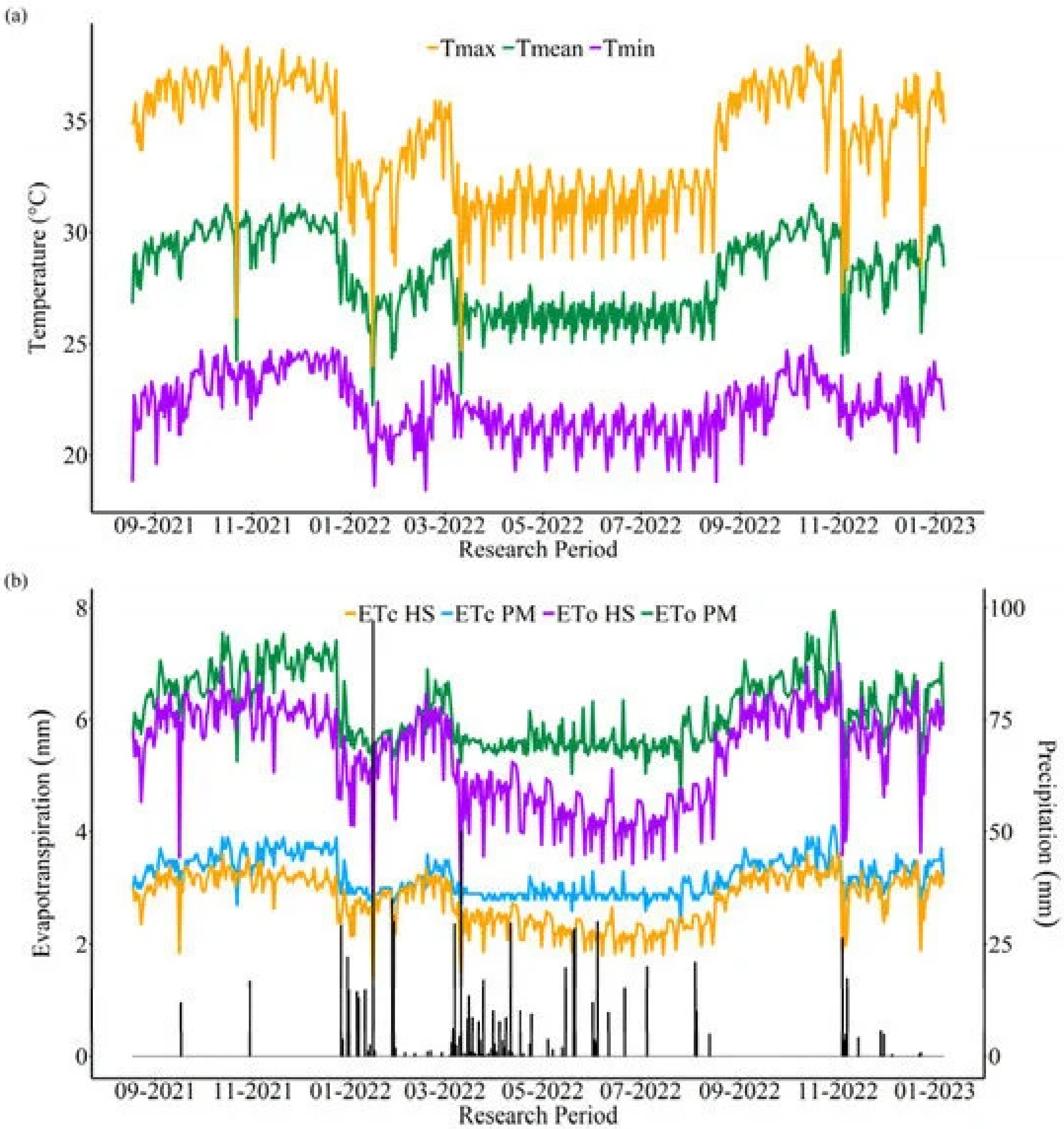

Figure 2. Variation in the average daily values of minimum temperature (Tmin), maximum temperature (Tmax) and average temperature (Tmean) (a); rainfall (P), reference evapotranspiration estimated by the Penman-Monteith (ET_0 PM) and Hargreaves-Samani (ET_0 HS) methods, and crop evapotranspiration estimated by the respective methods (ETc PM and ETc HS) (b), throughout the experimental period, conducted at the Dom Fragoso Family Agricultural School (EFA Dom Fragoso), located in the municipality of Independência, CE. Source: Bezerra et al. (2024) [13].

The volume of replenishment water (in millimeters) effectively estimated by the evapotranspiration equations, as a function of the irrigation depth percentages, and the difference in the amount of water used in each treatment through the two equations is described in Table 1.

Table 1. Cumulative water (in millimeters) effectively applied in the equations as a function of irrigation percentages.

Depths	**Equations**		**Difference (%)**
(%)	Penman-Monteith	Hargreaves Samani	
0	46.48 mm*	46.48 mm*	-
20	84.78 mm	65.94 mm	22.22
40	196.56 mm	131.88 mm	32.91
70	296.73 mm	230.79 mm	22.22
100	423.92 mm	329.70 mm	22.23

*Effective rainfall between August and December of 2021.

Forage palm samples were collected in the morning from different plots, selecting the first-order cladodes. Samples were collected using a combination of the following experimental treatments: 2 evapotranspiration estimation equations × 5 irrigation depths × 4 repetitions, for a total of 40 samples sent to the laboratory in each collection. The cladodes had their spines removed, were identified, and were dehydrated under ambient conditions. Then, they were placed in paper bags and dried in a forced-air oven at 55°C for 72 hours.

Then, the samples were ground into 2 mm particles using a Wiley knife mill, and, according to the methodologies described [15], the contents of dry matter (DM), mineral matter (MM), organic matter (OM), ether extract (EE), and crude protein (CP) were determined. The contents of neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin (LIG) were obtained according to the methodologies described [16], adapted for use in an autoclave (105°C/60 min) [17]. The contents of hemicellulose (HEM) and cellulose (CEL) were obtained using the following equations: %HEM = %NDF - %ADF and %CEL = %ADF - %LIG, respectively. The estimate of total digestible nutrients (TDN) was obtained by the equation [18]: TDN = 74.49 - 0.5635 * ADF.

Total carbohydrates (CHO) were estimated based on the equation CHO = 100 – (% CP + % EE + % MM) [19] and non-fiber carbohydrates (NFC) by the equation NFC = 100 – (% NDFcp + % CP + % EE + % MM) [20]. After quantifying the chemical composition, the carbohydrates were fractionated according to the methodology [19] into: Fraction A = Soluble and rapidly fermentable carbohydrates; Fraction B1 (starch and pectin) + B2 (cellulose and hemicellulose) = Rapidly degradable fraction, and Fraction C = Lignified and unavailable fraction.

The means were subjected to a normality analysis using the Shapiro-Wilk test and a homogeneity of variances analysis using Levene's test. An analysis of variance was performed to determine the significance of the interactions between the irrigation depths and the reference equations. When significant, the means were compared using Tukey's test at a 5 % probability level. Statistical analyses were performed using the PROC ANOVA procedure in SAS software [21].

Although irrigation depths are a quantitative variable, analysis of variance (ANOVA) was chosen over regression analysis to address the objective of comparing the two methods of estimating evapotranspiration (Penman-Monteith and Hargreaves-Samani). ANOVA allowed for the breakdown of interactions and comparison of means between methods at specific irrigation depths (0, 20, 40, 70, and 100 % of IRN). This approach identified specific differences between the methods in each water supply scenario, which is fundamental to determining the technical feasibility of using simplified models in different water management strategies in the semi-arid region.

3. Results and discussion

The results of the analysis of variance (ANOVA) revealed significant effects of the isolated factors (irrigation depths and models) and their interactions on most of the studied variables (Table 2). There was a main effect of irrigation depth ($P < 0.05$) for all chemical composition parameters. The evapotranspiration estimation model had a significant effect on crude protein content and cell wall components. The subsequent tables (Tables 3 and 4) present the breakdown of the significant interactions between the factors (irrigation depths × models).

Regarding NDF levels, a reduction was observed as irrigation increased. Higher values were found in the 0 % treatment for both the Penman-Monteith (21.17 %) and Hargreaves-Samani (18.02 %) equations. The opposite was observed for ADF: an average increase of 27.11 % in the 100 % irrigation depth compared to the 0 % treatment. There was no interaction between the equations for either parameter, and no statistical difference was detected between depths of 0 %, 40 %, 70 %, and 100 %, indicating that the equation proposed by Hargreaves Samani would be more advantageous for management in a semi-arid region, as it requires fewer meteorological variables than the Penman-Monteith equation.

The fiber fraction of forage palm is usually low, and therefore, it should always be combined with sources of physically effective fiber in the diet. The values closest to those recommended by the NRC (22), 25 to 33 % NDF, were observed in the 0 % depth (21.17 and 21.81 %). Alves et al. (23) state that adequate fiber content in the diet of ruminants is essential for the proper rumen function and helps maintain rumen microorganisms and their fermentative processes, even when supplied in small quantities. It also establishes homeostasis in the digestive systems of these animals.

Table 2. Summary of significance (*P*-values) and Coefficients of Variation (CV) for chemical components and carbohydrate fractionation of forage palm (*Opuntia stricta* (Haw.) Haw.).

Variable	Depths (D)	Models (M)	Interaction (D × M)	CV (%)
Dry matter (DM)	0.001*	0.154 ns	0.089 ns	2.25
Crupe protein (CP)	0.004*	0.012*	0.002*	8.49
NDF	0.001*	0.067 ns	0.121 ns	7.37
ADF	0.002*	0.321 ns	0.245 ns	9.44
TDN	0.015*	0.451 ns	0.312 ns	2.78
Hemicellulose (HEM)	0.001*	0.003*	0.001*	4.63
Cellulose (CEL)	0.001*	0.001*	0.001*	5.18
Lignin (LIG)	0.001*	0.002*	0.001*	9.43
Fraction A	0.010*	0.211 ns	0.078 ns	6.21
Fraction B1+B2	0.008*	0.189 ns	0.154 ns	8.34
Fraction C	0.001*	0.001*	0.001*	9.18

*Significant (*P*<0.05); ns: non-significant; CV: coefficient of variation.

Table 3 presents the chemical composition values of forage palm (*Opuntia stricta* (Haw.) Haw.) when irrigated with different irrigation depths and evapotranspiration estimated using two reference equations.

Table 3. Chemical composition of forage palm (*Opuntia stricta* (Haw.) Haw.) under different irrigation depths and evapotranspiration using two reference equations.

Reference Evapotranspiration Equation (ETo mm day^{-1})	Irrigation depth (% IRN)²	Parameters¹												
		DM (%)	MM (%)	OM (%)	NDF (%)	ADF (%)	HEM (%)	CEL (%)	LIG (%)	TC (%)	NFC (%)	CP(%)	EE (%)	TDN (%)
Penman-Monteith	0	28.32	12.32^{c}	81.97^{a}	21.17^{a}	5.67^{b}	69.64^{aA}	28.91^{Cc}	1.45^{b}	75.31^{a}	54.13^{b}	8.77^{aB}	1.54	71.29^{a}
	20	27.15	16.66^{b}	72.82^{b}	18.39^{a}	8.79^{a}	61.47^{abA}	33.21^{bcC}	5.32^{aA}	67.17^{b}	48.78^{c}	9.18^{aA}	1.17	69.67^{b}
	40	20.29	18.22^{b}	72.57^{bc}	15.07^{ab}	8.99^{a}	58.18^{b}	36.44^{b}	5.38^{aA}	68.48^{b}	53.41^{b}	8.93^{aB}	1.66	69.42^{b}
	70	28.76	20.04^{a}	71.85^{bc}	14.44^{b}	8.54^{a}	55.06^{b}	40.09^{b}	4.85^{a}	72.01^{a}	57.57^{a}	7.81^{bC}	1.13	69.67^{b}
	100	29.43	20.05^{a}	70.97^{bc}	16.28^{b}	7.91^{a}	45.56^{c}	50.33^{a}	4.11^{a}	73.42^{a}	57.14^{a}	8.36^{a}	1.41	70.08^{b}
Hargreaves Samani	0	29.15	11.63^{c}	80.52^{a}	21.81^{a}	5.71^{b}	55.49^{abA}	42.65^{Ba}	1.86^{c}	76.97^{a}	55.17^{a}	9.32^{aA}	1.87	71.27^{a}
	20	28.35	18.41^{b}	72.48^{b}	18.02^{b}	8.54^{a}	47.7^{bC}	48.71^{Ab}	3.58^{bB}	69.71^{b}	49.69^{b}	6.84^{bC}	1.32	69.67^{b}
	40	29.08	16.98^{b}	72.1^{b}	17.94^{bc}	8.31^{a}	59.28^{aA}	35.79^{c}	4.93^{aA}	68.26^{b}	53.32^{ab}	7.12^{bC}	1.12	69.95^{b}
	70	30.27	23.11^{a}	69.16^{b}	17.18^{bc}	8.37^{a}	50.65^{bB}	44.29^{b}	5.06^{a}	71.91^{b}	55.46^{a}	8.24^{abB}	1.35	69.77^{b}
	100	29.21	23.41^{a}	68.08^{bc}	18.26^{b}	7.64^{a}	45.67^{cC}	49.09^{a}	5.24^{a}	75.99 ^{a}	57.72^{a}	7.48^{bC}	1.14	70.46^{ab}
Equation × Depth		ns	ns	ns	ns	ns	**	**	**	ns	ns	**	ns	ns
Coefficient of variation		2.25	7.36	4.11	7.37	9.44	4.63	5.18	9.43	3.21	6.21	8.49	3.12	2.78

¹DM = Dry matter; MM = Mineral matter; OM = Organic matter; NDF = Neutral detergent fiber; ADF = Acid detergent fiber; HEM = Hemicellulose; CEL = Cellulose; LIG = Lignin; TC = Total carbohydrates; NFC = Non-fiber carbohydrates; CP = Crude protein; EE = Ether extract; TDN = Total digestible nutrients. ²Means followed by the same uppercase letter in the same column do not differ from each other by Tukey's test at 5% significance. Lowercase letters for irrigation depths and uppercase letters for evapotranspiration equations.

In a study on the effects of replacing sorghum silage with forage palm at levels ranging from 0 to 800g/kg/day, Rezende et al. [24] observed an improvement in the apparent digestibility of dry matter (4.86 %), crude protein (3.93 %) and non-fiber carbohydrates (9.58 %), with a 27.66 % decrease in NDF intake. This demonstrates that lower fiber intake may have improved the supply of protein and energy.

The CHO levels also did not differ (*P*<0.05) between the 0 % and 100 % treatments. From a physiological and biochemical perspective, water volume affects plant photosynthesis through stomatal and non-stomatal effects [25]. Under water stress, plants close their stomata to avoid water loss through evapotranspiration. Under favorable conditions, they use the supply of molecular hydrogen to synthesize carbohydrates from the reduction of carbon dioxide (CO^2) and to hydrolyze starch into soluble sugars [12], increasing the CHO increment in the plant. No interaction between the equations was observed for NFC either.

According to Magalhães et al. [26], high levels of non-fiber carbohydrates associated with low cell wall lignification in forage species can stimulate ruminal degradation and enhance the utilization of the slower degradable fractions of DM, since NFCs are readily available to be fermented by rumen microorganisms, favoring their growth and improving energy supply, and may also increase the total digestibility of DM and OM [27].

The highest values for CEL (50.33 and 49.09 % for Penman-Monteith and Hargreaves Samani equations, respectively) and the lowest values for HEM (45.56 and 45.67 %) were obtained in the 100 % depth, differing (P>0.05) from the other treatments. Regarding LIG, the lowest values (1.45 and 1.86 %) were observed in the control depth. However, when the water supply increased above 40 %, LIG increased by over 4 %. According to Valente et al. [28], each plant tissue has a chemical composition related to the plant's structure, and among these, the supporting tissues must be densely packed, thick, and lignified. In this sense, the increase in CEL and LIG levels and the reduction in HEM with increased water supply may be related to crop development investing more in supporting tissues and less in specialized tissues, which justifies the increase in ADF levels observed.

CP showed an interaction between the equations (*P* < 0.05). In the first equation (Penman-Monteith), the 70 % water depth (7.81 % CP) was the only value that differed statistically from the others (*P* < 0.05), with the highest value (9.18 %) observed in the 20 % irrigation depth. In the second equation (Hargreaves Samani), the highest value (9.32 %) was found in the 0 % treatment, with mean values of 6.84, 7.17, and 7.48 % for irrigation depths of 20, 40, and 100 %, respectively. Because crude protein is estimated from the total nitrogen (N) value, and this nutrient has high mobility in the soil [29], it may not be uniformly available for plant absorption, which influences CP levels and explains the difference obtained between the equations.

Low crude protein content is a common characteristic of cactus species, presenting an average of 7.4 % in the genus *Opuntia* [26]. However, this protein deficit can be addressed by combining it with concentrated ingredients that have a higher protein content, as well as non-protein nitrogen (NPN) sources, such as urea. Management strategies, such as split nitrogen fertilization, can also be employed to add this nutrient to the composition of forage species.

Regarding mineral matter (MM) content, an increase of approximately 9.20 % was observed with each increase in the water supply compared to the control depth (0 %), which may be related to the composition of the water used for crop irrigation, which comes from reused water. However, regardless of the genus, forage palm contains high amounts of minerals. According to

Silva et al. [30], this is due to the high concentration of macrominerals, mainly calcium, potassium, and magnesium. These macrominerals vary according to species, cultivation, cladode age, and time of year. Similar results were reported by DuToit, Wit and Hugo [31] when analyzing the nutrients of different forage palm cultivars of the genus *Opuntia*; they found 16.8 to 18.8 % MM.

The highest TDN values (71.28 %) were observed in the control treatment. However, values above 69 % were also obtained in the other irrigation depths, characterizing forage palm as an important source of roughage. This is especially significant because its energy levels are close to those found in concentrate feeds, such as wheat bran (74.28 %) and cottonseed meal (67.75 %) [32]. This makes forage palm a potential alternative for reducing production costs. No interaction was identified between the irrigation equations for this parameter.

The high TDN levels can also be explained by the values obtained for ADF, as they were estimated based on this nutrient (TDN = 99.39 - 0.7641 * ADF). Therefore, the lower the ADF content, the higher the estimated TDN proportion. This increases the digestibility of the forage, resulting in a greater potential energy supply. Furthermore, TDN values correlate with carbohydrates present in the plant, especially non-fiber carbohydrates, which are rapidly digestible and mainly composed of starch and pectin.

Table 4 lists the values of fractions A, B1+B2, and C, referring to the fractionation of total carbohydrates in forage palm (*Opuntia stricta* (Haw.) Haw.) under different irrigation depths and estimated evapotranspiration using two reference equations. More than 85 % of total carbohydrates are present in fractions A and B1+B2, indicating that most are readily available for use by ruminal microorganisms, reducing them to simple sugars and short-chain fatty acids, generating ATP for microbial growth. This process may increase the utilization of the structural fiber fraction [33].

Table 4. Carbohydrate fractionation (%NDF) of forage cactus (*Opuntia stricta* (Haw.) Haw.) under different irrigation depths and evapotranspiration estimated by two reference equations.

Reference Evapotranspiration Equation (ETo mm day^{-1})	Irrigation depth (% IRN)²	Carbohydrate fractionation ¹		
		Fraction A	Fraction B1+B2	Fraction C
Penman-Monteith	0	55.14^{a}	41.31^{ab}	3.55^{cC}
	20	45.27^{b}	45.92^{a}	8.81^{bB}
	40	50.16^{ab}	39.41^{b}	10.43^{aAB}
	70	55.57^{a}	33.82^{c}	10.61^{aAB}
	100	55.14^{a}	34.98^{c}	9.88^{abB}
Hargreaves Samani	0	55.17^{a}	40.42^{ab}	4.41^{cC}
	20	49.69^{b}	41.82^{a}	8.49^{bB}
	40	53.32^{ab}	35.07^{bc}	11.61^{aA}
	70	55.76^{a}	32.08^{c}	12.16^{aA}
	100	57.62^{a}	31.02^{c}	11.36^{aA}
Equation × Depth		ns	ns	**
Coefficient of variation		6.21	8.34	9.18

¹Fraction A = Soluble and rapidly fermentable carbohydrates; Fraction B1+B2 = Rapidly degradable fraction; Fraction C = Lignified and unavailable fraction. ²Means followed by the same letter in the same column do not differ from each other by Tukey's test at 5 % significance. Lowercase letters for depths and uppercase letters for reference evapotranspiration equations.

For fraction A, no difference (*P*>0.05) was observed in the values corresponding to 0, 40, 70, and 100 % irrigation, with levels above 50 % in all treatments. This indicates its suitability for inclusion in diets, as the carbohydrates in this fraction are soluble sugars with simpler structures. These sugars are degraded more rapidly by rumen microorganisms and utilized more efficiently to meet energy demands. Thus, the need for large amounts of concentrates can be reduced.

Fractions B1 and B2 decreased with increased irrigation volume, and no interaction was detected between the evapotranspiration equations, as well as in fraction A. This demonstrates that replacing the Penman-Monteith equation with the Hargreaves-Samani equation does not affect the levels of rapidly and potentially digestible carbohydrate fractions.

Fraction B1 contains greater quantities of starch and pectin, while fraction B2 corresponds to the fibrous part that is degraded more slowly by microorganisms than fractions A and B1. This helps maintain the rate of passage and, consequently, food digestibility. For this reason, the components of fraction B are important because they indicate the quality of the carbohydrates present in forage plants. The results corroborate those of Magalhães et al. [(26)], who analyzed the carbohydrate fractionation of forage palm genotypes and found levels of 79.54 %, 13.79 %, and 6.67 % in fractions A + B1, B2, and C, respectively, in the Mexican elephant ear cultivar.

The different estimates of the irrigation equations influenced the C fraction of carbohydrates, representing approximately 15 % of the total carbohydrates. The lowest contents were observed in the 0 % (3.55 % and 4.41 %) and 20 % (8.81 % and 8.49 %) irrigation depths, for the Penman-Monteith and Hargreaves Samani equations, respectively. This effect may be related to the lignin content of the forage (Table 2), because the C fraction is estimated based on it. It may also be related to the greater water supply available to the plants, which need to invest in structural components as water accumulates inside them. The C fraction is indigestible because it consists of tannin-protein complexes and lignin associated with protein, which are generally not degraded in the rumen.

The results obtained for the C fraction align with those of Pessoa et al. [(34)], who analyzed the nutritional value of the *Opuntia* palm in different phenological phases, and observed for the elephant ear cultivar levels of 5.46 %, 6.41 %, and 11.65 %, in the young, intermediate, and mature phases, respectively. Valente et al. [(28)] report that, as plants age, supporting tissues become thicker and more lignified, resulting in lower soluble carbohydrate content.

In semi-arid regions with high temperatures throughout the year, forage crops are expected to have lower soluble carbohydrate content due to a greater proportion of protective structures (cell walls), which is a defense mechanism against pests and radiation that increases lignification. C3, C4, and CAM plants respond differently to this mechanism because they perform photosynthesis differently, using carbon dioxide and water to synthesize carbohydrates. Therefore, the amount of water supplied to the plants can influence the amount of carbohydrates in their cell walls.

4. Conclusion

The chemical composition and carbohydrate fractionation of forage palm (*Opuntia stricta*) are influenced by the interaction between irrigation depths and evapotranspiration estimation models, particularly with regard to fiber components and crude protein. Cultivation under rainfed conditions or with reduced irrigation depths does not compromise the crop's nutritional value. In fact, it favors crude protein concentration while maintaining a high total digestible nutrients (TDN) content.

Using an irrigation strategy with a depth of 20 % of the IRN combined with the Hargreaves-Samani model is an efficient management practice for this crop. This strategy optimizes the use of water, a scarce resource in the region, while ensuring a consistent supply of high-quality forage for ruminant production systems and mitigating the impacts of prolonged droughts. Thus, in the face of climatic irregularity and water scarcity, which are characteristic of the semi-arid region, the forage palm consolidates its position as a highly resilient strategic resource capable of maintaining its nutritional integrity with minimal water.

Conflict of interest statement

The authors declare no conflicts of interest.

Data availability statement

The dataset supporting the results of this study is published in the article itself.

Author contributions

Conceptualization: Bezerra, F.M.S. and Lacerda, C.F. Data curation: Garcez, B.S.; Bezerra, F.M.S. and Lacerda, C.F. Formal analysis: Garcez, B.S.; Bezerra, F.M.S., Lacerda, C.F. and Costa, P.C.A. Methodology: Bezerra, F.M.S. and Lacerda, C.F. Supervision: Garcez, B.S.; Bezerra, F.M.S. and Lacerda, C.F. Validation: Garcez, B.S.; Costa, P.C.A.; Macedo, K.D.A.; Sousa, D.A.M.; Sérvulo, A.A. and Caetano, M.A. Writing (original draft): Garcez, B.S.; Costa, P.C.A.; Macedo, K.D.A.; Sousa, D.A.M.; Sérvulo, A.A. and Caetano, M.A. Writing (revision and editing): Caetano, M.A.

Generative AI use statement

The authors did not use generative artificial intelligence tools or technologies in the production or editing of any part of this manuscript.

References

1. Cândido MJD, Gomes GMF, Lopes MN, Ximenes LJF. Cultivo de palma forrageira para mitigar a escassez de forragem em regiões semiáridas. Informe Rural ETENE, Fortaleza: Banco do Nordeste do Brasil/ETENE; 2013;7(3):1-7. Available from: https://www.bnb.gov.br/s482-dspace/handle/123456789/922

2. Souza RA, Carvalho RG, Pimentel AJB, Inácio JG, Lima Silva J. Desempenho produtivo e qualidade nutricional de forrageiras do gênero Urochloa no Oeste da Bahia. Agrarian. 2021 Dec 15;14(54):392-403. Available from: https://doi.org/10.30612/agrarian.v14i54.14841

3. Silva LM, Fagundes JL, Viegas PAA, Muniz EN, Albuquerque Rangel JH, Moreira AL, et al. Produtividade da palma forrageira cultivada em diferentes densidades de plantio. Ciência Rural. 2014 Nov;44(11):2064-2071. Available from: https://doi.org/10.1590/0103-8478cr20131305

4. Tosto MSL, Araújo GGLD, Oliveira RL, Bagaldo AR, Dantas FR, Menezes DR, et al. Composição química e estimativa de energia da palma forrageira e do resíduo desidratado de vitivinícolas. Revista Brasileira de Saúde e Produção Animal. 2007 Jul-Sep;8(3):239-249. Available from: https://revbaianaenferm.ufba.br/index.php/rbspa/article/view/39527

5. Valdez CAF. Produccion industrializacion y comercialización del nopal como verdura en México. 18th ed. Chapingo: Violeta Hernández Quintero; 1994. 23 p.

6. Ferreira MA, Pessoa RAS, Silva FM. Utilização da palma forrageira na alimentação de ruminantes. In: I Congresso Brasileiro de Nutrição Animal; 2008; Anais. https://dialnet.unirioja.es/descarga/articulo/8630807.pdf

7. Matos LV, Donato SLR, Kondo MK, Lani JL. Sistemas tradicionais de produção de palma forrageira ‘Gigante’ em agroecossistemas do Semiárido Baiano. Revista Brasileira de Geografia Física. 2021;14(2):554-590. Available from: https://doi.org/10.26848/rbgf.v14.2.p554-590

8. Cascone S, Coma J, Gagliano A, Pérez G. The evapotranspiration process in green roofs: a review. Building and Environment. 2019 Jan;147:337-355. Available from: https://doi.org/10.1016/j.buildenv.2018.10.024

9. Fernandes DS, Heinemann AB, Paz RL, Amorim AO. Evapotranspiração: uma revisão sobre os métodos empíricos. Santo Antônio de Goiás: Embrapa Arroz e Feijão; 2010 Dec. 44 p. (Documentos, 263). Available from: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/879913

10. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration: guidelines for computing crop water requirements. Rome: FAO; 1998. 300 p. (FAO Irrigation and Drainage Paper, 56).

11. Paredes P, Pereira LS, Almorox J, Darouich H. Reference grass evapotranspiration with reduced data sets: parameterization of the FAO Penman–Monteith temperature approach and the Hargreaves–Samani equation using local climatic variables. Agricultural Water Management. 2020 Oct;240:106210. Available from: https://doi.org/10.1016/j.agwat.2020.106210

12. Araújo Júnior GDN, Gomes FT, Silva MJ, Jardim AMFR, Simões VJLP, Izidro JLPS, et al. Estresse hídrico em plantas forrageiras: uma revisão. Pubvet. 2019 Jan;13(1):1-10. Available from: https://doi.org/10.31533/pubvet.v13n01a241.1-10

13. Bezerra FMS, Lacerda CF, Giroldo AB, Cavalcante ES, Michelon N, Pennisi G, et al. Deficit irrigation of forage cactus (*Opuntia stricta*) with brackish water: impacts on growth, productivity, and economic viability under evapotranspiration-based management. Agronomy. 2024;14(7):1445. Available from: https://doi.org/10.3390/agronomy14071445

14. Saraiva FM. Desenvolvimento e acúmulo de nutrientes de palma forrageira (*Nopalea*) em diferentes sistemas de cultivo [dissertação]. Recife: Universidade Federal Rural de Pernambuco; 2014. 104 f. Available from: http://www.tede2.ufrpe.br:8080/tede2/handle/tede2/7023

15. Association of Analytical Communities (AOAC) International. Official methods of analysis of AOAC International. 19th ed. Gaithersburg (MD): Association of Analytical Communities; 2012. 2610 p.

16. Mertens DR. Análise da fibra e sua utilização na avaliação de alimentos e formulação de rações. In: Simpósio Internacional de Ruminantes; 1992; Lavras. Anais. Lavras: SBZ-ESAL; 1992. p. 188 -219. https://www.redalyc.org/pdf/636/63612750006.pdf

17. Barbosa MM, Detmann E, Rocha GC, Franco MDO, Filho SDCV. Evaluation of laboratory procedures to quantify the neutral detergent fiber content in forage, concentrate, and ruminant feces. Journal of AOAC International. 2015;98(4):883-889. Available from: https://doi.org/10.5740/jaoacint.14-156

18. Cappelle ER, Valadares Filho SDC, Silva JFCD, Cecon PR. Estimativas do valor energético a partir de características químicas e bromatológicas dos alimentos. Revista Brasileira de Zootecnia. 2001;30(6):1837-1856. Available from: https://doi.org/10.1590/S1516-35982001000700022

19. Sniffen CJ, O'Connor JD, Van Soest PJ, Fox DG, Russell JB. A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. Journal of Animal Science. 1992 Nov 1;70(11):3562-3577. Available from: https://doi.org/10.2527/1992.70113562x

20. Hall MB. Calculation of non-structural carbohydrate content of feeds that contain non-protein nitrogen. Gainesville: University of Florida; 2000. 25 p. (Bulletin 339). Available from: https://ufdcimages.uflib.ufl.edu/IR/00/00/16/13/00001/AN08700.pdf

21. SAS, Statistical Analysis System. Software, version 9.0. Cary: SAS Institute, 2000.

22. National Research Council (NRC). Nutrient requirements of beef cattle. Washington (DC): National Academy Press; 2001.

23. Alves AR, Pascoal LAF, Cambuí GB, Silva Trajano J, Silva CM, Gois GC. Fibra para ruminantes: aspecto nutricional, metodológico e funcional. Pubvet. 2016 Jul;10(7):568-579. Available from: https://doi.org/10.22256/pubvet.v10n7.568-579

24. Rezende FM, Véras ASC, Siqueira MCB, Conceição MG, Lima CL, Almeida MP, et al. Nutritional effects of using cactus cladodes (*Opuntia stricta* Haw.) to replace sorghum silage in sheep diet. Tropical Animal Health and Production. 2020 Jan 18;52(4):1875-1880. Available from: https://doi.org/10.1007/s11250-020-02213-w

25. Araújo SAC, Vasquez HM, Campostrini E, Netto AT, Deminicis BB, Lima ESL. Características fotossintéticas de genótipos de capim-elefante anão (*Pennisetum purpureum* Schum.) em estresse hídrico. Acta Scientiarum. Animal Sciences. 2010 Mar 31;32(1):1-7. Available from: https://doi.org/10.4025/actascianimsci.v32i1.8961

26. Magalhães ALR, Teodoro ALT, Oliveira LP, Gois GC, Campos FS, Andrade AP, et al. Chemical composition, fractionation of carbohydrates and nitrogen compounds, ruminal degradation kinetics, and in vitro gas production of cactus pear genotypes. Ciência Animal Brasileira. 2021 Oct 25;22:e69338. Available from: https://doi.org/10.1590/1809-6891v22e-69338

27. Munhame JA, Batista ÂMV, Monnerat JPIS, Maciel MV, Lopes LA, Silva TGP, et al. Intake, digestibility, ingestive behavior and performance of goats fed spineless cactus genotypes resistant to carmine cochineal. Arquivo Brasileiro de Medicina Veterinária e Zootecnia. 2021 Oct;73(5):1209-1216. Available from: https://doi.org/10.1590/1678-4162-12381

28. Valente TNP, Lima EDS, Henriques LTD, Machado Neto OR, Gomes DÍ, Sampaio CB, Costa VAC. Anatomia de plantas forrageiras e a disponibilidade de nutrientes para ruminantes. Veterinária e Zootecnia. 2011;18(3):347-358. Available from: http://hdl.handle.net/11449/141104

29. Palhares JCP, Roman ADJ. Balanço de nitrogênio e fósforo de propriedades pecuárias de uma microbacia hidrográfica. Revista em Agronegócio e Meio Ambiente. 2021 Dec 1;14(2):1-13. Available from: https://doi.org/10.17765/2176-9168.2021v14supl.2.e8860

30. Silva APG, Souza CCE, Ribeiro JES, Santos MCG, Souza Pontes AL, Madruga MS. Características físicas, químicas e bromatológicas de palma gigante (*Opuntia ficus-indica*) e miúda (*Nopalea cochenillifera*) oriundas do estado da Paraíba. Revista Brasileira de Tecnologia Agroindustrial. 2015 Dec 10;9(2):1810-1820. Available from: https://doi.org/10.3895/rbta.v9n2.1616

31. Du Toit A, Wit M, Hugo A. Cultivar and harvest month influence the nutrient content of *Opuntia* spp. cactus pear cladode mucilage extracts. Molecules. 2018 Apr 16;23(4):916. Available from: https://doi.org/10.3390/molecules23040916

32. Rocha Júnior VR, Valadares Filho SDC, Borges ÁM, Magalhães KA, Ferreira CCB, Valadares RFD, et al. Determinação do valor energético de alimentos para ruminantes pelo sistema de equações. Revista Brasileira de Zootecnia. 2003 Apr;32(2):473-479. Available from: https://doi.org/10.1590/S1516-35982003000200028

33. Silva AL, Sousa DB, Amorim DS, Santos MS, Silva KB, Nascimento RR. Carboidratos de plantas forrageiras para ruminantes: uma revisão. Nucleus Animalium. 2019 May 30;11(1):1-12. Available from: https://doi.org/10.3738/21751463.2945

34. Pessoa DV, Andrade AP, Magalhães ALR, Teodoro AL, Santos DC, Araujo GGL, et al. Forage nutritional differences within the genus *Opuntia*. Journal of Arid Environments. 2020 Oct;181:104243. Available from: https://doi.org/10.1016/j.jaridenv.2020.104243