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Morphophysiological and Productive Responses of Forage Cactus Clones to the Water and Nutrient Use in the Brazilian Semi-Arid Region

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ABSTRACT

Crops adapted to semi-arid conditions enhance forage supply amid water scarcity. This study aimed to compare six forage cactus clones (Orelha de Elefante Mexicana [OEM, *Opuntia stricta* (Haw.) Haw.]; Orelha de Elefante Africana [OEA, *Opuntia undulata* Griffiths]; V19, *Opuntia larreyi* F.A.C. Weber ex Coult.; F8, *Opuntia atropes* Rose; MIUDA (MIU) and IPA-Sertânia (IPA), *Nopalea cochenillifera* (L.) Salm-Dyck) in terms of morphophysiological traits, forage production, nutrient and water use efficiency, and economic viability under irrigation in a semi-arid environment. The experiment was conducted from December 2016 to September 2022 in randomised blocks, with treatments of six clones: OEM, OEA, V19, F8, MIU and IPA, with three replicates. Phenology, morphophysiological rates, cutting time, productivity, water balance, water and nutrient use efficiency and crop economic indicators were determined. Plant tissue analyses were carried out to determine concentrations, coefficient of biological utilisation (CBU) and nutrient use efficiency (NUE). The OEM exhibited the highest annual average fresh matter yield (300 Mg ha^{-1} year^{-1}) and dry matter yield (24 Mg ha^{-1} year^{-1}). The efficiencies of water productivity, net and gross economic productivity of the total water applied to the system, and irrigation varied depending on the clone and cycle. The CBU of all nutrients showed an inverse relationship with cladode nutrient concentrations. This indicates that the CBU increased as the nutrient concentration in plant tissues decreased across all clones analysed. The OEM clone showed the highest NUE for all nutrients. OEM was more productive and had higher water and nutrient use efficiencies. Furthermore, the MIU clone showed superior economic efficiency in irrigation water use.

1 | Introduction

Population density and the need for food have grown exponentially in various regions of the world (Cheng et al. 2018; Cao et al. 2021; Wang et al. 2021), while water deficit and climate change are factors that aggravate the productivity of several crops, especially in semi-arid environments (Jardim et al. 2023a). Therefore, the use of agricultural practices (e.g., irrigation, adapted species, mulching, intercropping and cutting management) helps in the development of plants and allows the increase of crop productivity and greater food security (Queiroz et al. 2016; Zhang and Flottmann 2018; Jardim et al. 2021a; Salvador et al. 2021).

Crops adapted to semi-arid environments that achieve high forage accumulation are strategic for agricultural development in these regions (Araújo Júnior et al. 2021a; Jardim et al. 2023b). In this context, forage cactus stands out due to its crassulacean acid metabolism (CAM), anatomical adaptations (e.g., high chlorophyll content, photoprotective pigments, aquiferous parenchyma, modified leaves, succulent stems and specialised roots), and morphophysiological traits that confer tolerance to drought and high temperatures, enhancing its water use efficiency and productivity compared to other forages (Queiroz et al. 2015; Amorim et al. 2017; Jardim et al. 2021a; Jardim et al. 2021b). Clones of the genus *Opuntia* are particularly notable for fixing high amounts of CO_2 relative to transpiration losses, which supports their production (Araújo Júnior et al. 2021c; Neupane et al. 2021; Pastorelli et al. 2022). This efficiency is partly explained by their strategy of investing in the development of lower-order cladodes, expanding the photosynthetically active area, and accelerating forage accumulation (Santos et al. 2024). Typically, *Opuntia* produces cladodes up to the third order, while *Nopalea* extends its vegetative phase by emitting up to sixth-order cladodes, resulting in greater forage accumulation (Amorim et al. 2017; Araújo Júnior et al. 2021b).

However, even though cactus clones are adapted to the semi-arid climate, the edaphoclimatic conditions found in the region can reduce development, productivity and therefore, forage supply (Araújo Júnior et al. 2024; Gebru et al. 2021). Therefore, it is necessary to use management practices (e.g., irrigation and mineral fertilisation) capable of mitigating the effects caused by the environment (Alves et al. 2022b; Bezerra et al. 2024).

The use of complementary irrigation significantly increases forage quantity and quality. To this end, it is important to align the performance of forage plants and the availability of water with their efficiency in the use of resources to increase productive and morphophysiological responses (Araújo Júnior et al. 2024; Alves et al. 2022a; Dubeux Júnior et al. 2021; Santana et al. 2021; Salvador et al. 2024). The irrigated forage cactus, especially the most widespread clones in Brazil [i.e., Miúda (MIU), IPA-Sertânia (IPA) and Orelha de Elefante Mexicana (OEM)], presents excellent productivity (Silva et al. 2023). Among these, the clone OEM [*Opuntia stricta* (Haw.) Haw.] provides the highest yields when compared to the clones MIU and IPA, both of which belong to the same species, *Nopalea cochenillifera* (L.) Salm-Dyck (Araújo Júnior et al. 2021a).

In a cropping system with limited available resources, soil fertility is a key factor in plant yield. This is because cacti respond differently to soil fertility, varying according to each clone. Plants of the *Nopalea* genus have greater nutritional demands compared to plants of the *Opuntia* genus. This is because of the concentration of soluble carbohydrates and greater nutritional value (Inácio et al. 2020). However, it is worth noting that the concentrations present in plants will vary depending on the efficiency in incorporating and applying fertiliser management to the soil (Moreira et al. 2020). When well-managed, forage cactus can contribute significantly to animal production, increasing the quality of animal protein and maximising savings in the livestock sector (Dubeux Júnior et al. 2021). Therefore, it is important to consider the economic impact that the use of these inputs (water and fertilisers) may have on the socioeconomic development of a region.

To determine water and nutrient use efficiency, there are analyses capable of assessing how much nutrient and water were needed to produce biomass, and which clone is most economically efficient in using nutrients from fertilisers. For example, irrigation water productivity (WPi), crop water productivity (WPc) and water use efficiency (WUE) are widely applied to assess agronomic and environmental responses in forage systems (Bezerra et al. 2024; Nunes et al. 2024; Araújo Júnior et al. 2025; Hoover et al. 2023; Drastig et al. 2023). The coefficient of biological utilisation (CBU) and nutrient use efficiency (NUE) have also been reported as important indicators for evaluating nutrient dynamics and fertilisation efficiency (Govindasamy et al. 2023; Ali et al. 2025). Additionally, gross economic irrigation water productivity (GEWPi) and economic crop water productivity (EWPc) allow integrating agronomic and economic perspectives into water management strategies (Bezerra et al. 2024; Silva et al. 2024). These parameters, when combined, provide a comprehensive framework for understanding the agronomic performance and sustainability of plant production systems under semi-arid conditions.

In this context, although it is known that the OEM, IPA-Sertânia and Miúda clones have distinct canopy architectures and productivities (Amorim et al. 2017), there is still a lack of studies quantifying how these morphophysiological differences translate into efficiency in the use of critical resources, such as water and nutrients, under the same irrigated regime. Management recommendations still address the crop in a generalized manner, without distinguishing the water and nutritional requirements of each genetic material. Therefore, comparing the capacity of these specific clones to convert water and fertilizers into biomass is essential for generating precise applied knowledge.

In the present study, we tested the hypothesis that the water and nutrient conversion capacity of forage cactus changes between clones as a function of their morphophysiological and productive responses. Therefore, this study aimed to evaluate the morphophysiological traits, forage accumulation, water and nutrient use efficiencies and economic performance of six forage cactus clones cultivated under irrigation in a Brazilian semi-arid environment.

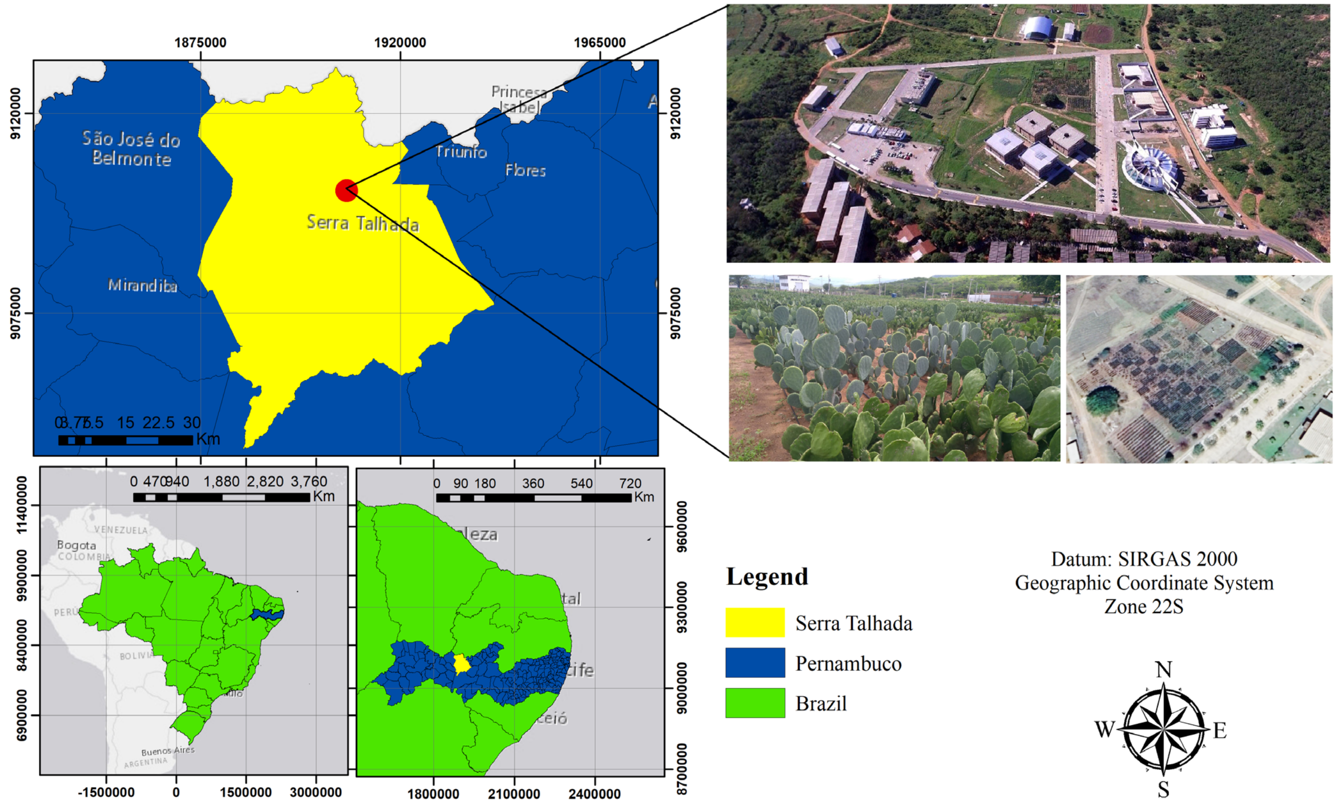

FIGURE 1 | Location map of the experimental area.

2 | Material and Methods

2.1 | Characterisation of the Area

The study was carried out in the Centro-REF (International Reference Centre for Agrometeorological Studies of the Cactus and other Forage Plants), in the Federal Rural University of Pernambuco, Academic Unit of Serra Talhada, municipality of Serra Talhada, Pernambuco, Brazil (7°59′S, 38°15′W and 431 m of altitude) (Figure 1). The city is located in the Sertão Pernambucano micro-region. It has, according to the Köppen classification, a BShw type climate, with an average rainfall of 667.2 mm, humidity of 62.3%, average temperature of 25.9°C, and reference evapotranspiration greater than 1800 mm year^{-1} (Alvares et al. 2013; Nunes et al. 2020a; Araújo Júnior et al. 2021b).

The soil in the experimental area is classified as a typical Eutrophic Ta Haplic Cambisol according to the Brazilian Soil Classification System, with flat relief, and with physical and chemical attributes measured at a depth of 0.0–0.20 m (Table S1). Mineral fertilisation was carried out after planting the forage cactus (top dressing) and at each cycle, equally for all clones, based on the recommendation of the Agronomic Institute of Pernambuco (Cavalcanti 2008), applying 200 kg N ha^{-1}, 80 kg P ha^{-1}, 130 kg K ha^{-1}.

For planting, the area received soil preparation with ploughing, harrowing and furrowing. The cladodes were planted, leaving 50% of their length buried in the soil. The experimental area remained unassessed in two different periods (August 2018 to January 2019 and March 2020 to August 2020). However, all plots were cut at the beginning of the second and third cycles, leaving only the first-order cladodes present in the plants. The first experimental cycle was carried out from December 2016 to July 2018 (585 days), the second from February 2019 to February 2020 (388 days), the third from September 2020 to August 2021 (344 days) and the fourth cycle from August 2021 to September 2022 (383 days). The discrepancy between the cycles occurred due to the ideal harvest timing, where, in the succeeding cycles, the forage cactus reached the maximum forage accumulation in advance.

2.2 | Experimental Design, Culture Used and Treatments

The present study was conducted in randomised blocks with three replications (Figure 2). Six forage cactus clones comprised the treatments, namely: Orelha de Elefante Mexicana (OEM, *Opuntia stricta* (Haw.) Haw.), Orelha de Elefante Africana (OEA, *Opuntia undulata* Griffiths), V19 (*Opuntia larreyi* F.A.C. Weber ex Coult.), F8 (*Opuntia atropes* Rose), Miúda (MIU, *Nopalea cochenillifera* (L.) Salm-Dyck) and IPA-Sertânia (IPA, *Nopalea cochenillifera* (L.) Salm-Dyck). Each clone corresponded to treatment. The experimental area had dimensions of 18 m × 9 m, with a spacing of 1.2 m between rows and 0.2 m between plants (41,667 plants ha^{-1}), and was divided into 3 blocks. Treatment combinations were randomly allocated to each block. Each block covered six plots, with 3 lines, each line with 15 plants, totaling 45 plants per plot, each plot measuring 10.8 m^2. It was considered the working plot, the central row, except for one plant at each end, totaling 13 plants per working plot in an area of 4.48 m^2.

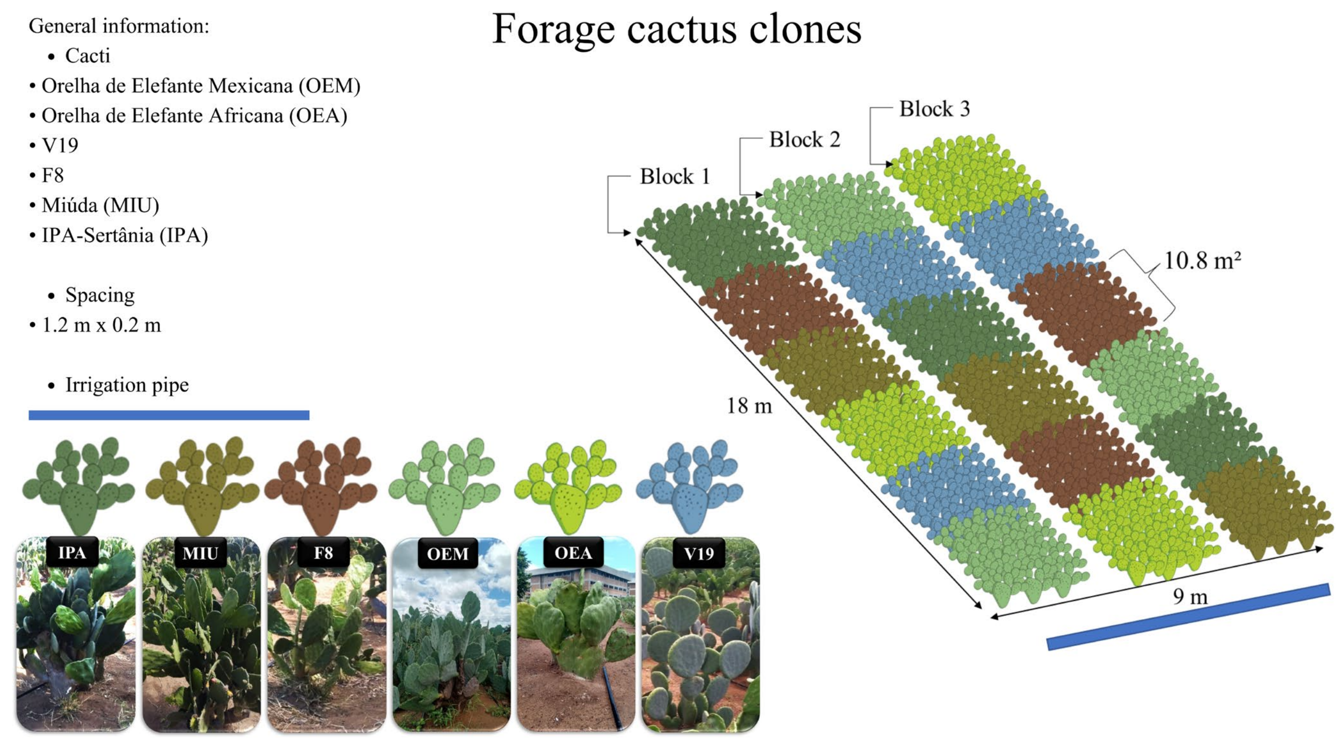

FIGURE 2 | Arrangement of the cultivated area with different forage cactus clones.

2.3 | Irrigation

The irrigation depth was applied uniformly across all clones. Total irrigation in the 1st, 2nd, 3rd and 4th cycles was 1127.9 mm, 673.6 mm, 155.3 mm and 101.3 mm, respectively. Using a drip system with uniformity above 90%, a flow rate of 1.62 L h^{-1}, and a pressure of 100 kPa, the application of irrigation depth was based on 120% of the crop evapotranspiration (ET_c) obtained from the product between the reference evapotranspiration (ET_0) and the crop coefficient (K_c). The reference evapotranspiration was determined based on the Penman–Monteith equation according to FAO Bulletin-56 (Allen et al. 1998). K_c of 0.52 was used (Queiroz et al. 2016). The average electrical conductivity of the water used was 1.51 dS m^{-1} and a pH of 6.84, classifying it as C3 (high salinity) according to Richards (1954).

2.3.1 | Meteorological Variables

Meteorological data on wind speed (m s^{-1}), maximum, average and minimum air temperature (°C); maximum, average and minimum relative air humidity (%); maximum, mean and minimum atmospheric pressure (hPa); global radiation (MJ m^{-2} day^{-1}) and rainfall (mm) were collected from the National Institute of Meteorology (INMET).

2.4 | Analysis of the Morphological and Productive Characteristics of Forage Cactus Clones

Biometric analyses were performed at 30-day intervals, where variables such as plant height (HP, cm), plant width (WP, cm), the total number of cladodes per plant (TNC, units), and the number of cladodes per order by emergence (NC1: first order; NC2: second order; NC3: third order and so forth) were recorded (Silva et al. 2015a; Santos et al. 2024).

To measure cladode dimensions, data on cladode length (CL, cm), cladode width (CW, cm), cladode perimeter (CP, cm) and cladode thickness (CT, mm) were collected (Silva et al. 2015a). In addition, the cladode area (CA, cm^2) was calculated by order of appearance and by forage cactus clone (Equations S1–S6) (Silva et al. 2014b). The cladode area index (CAI, $m^2\,m^{-2}$) was determined by the ratio of the total area of cladodes and the area spacing (Santos et al. 2024).

Forage mass samplings (fresh and dry weight) were carried out every 3 months. At the time of cutting, an entire plant was weighed using an electronic scale to obtain the fresh weight. For the determination of dry weight and nutrient concentrations in plant tissue, two cladodes from the middle third of the plant were selected. This was done by the criteria of representativeness in relation to the other cladodes. The cladodes were then fractionated and packed in paper bags and placed in a forced air circulation oven at 55°C until reaching a constant dry matter weight. The relationship between the fresh weight and the cladode's dry weight resulted in the cladode's dry matter content (DMC). From the final density of the plants and the total weight of the plant, without the basal cladode, the fresh matter forage mass (YFM, Mg ha^{-1}) was estimated. To estimate the dry matter forage mass (YDM, Mg ha^{-1}), the DMC and the YDM values were considered.

From a sigmoid regression analysis, with data from CAI, YDM and accumulated degree days (ADD), the morphophysiological indices were determined. The ADD was obtained through the accumulated difference between the mean air temperature values (°C) and the base temperature of the crop (Tb, °C) (Souza

TABLE 1 | Start and end dates of the 7 periods in which the soil water balance components were accumulated, during the period from February 20, 2017 to September 12, 2022, Serra Talhada-PE, Brazil.

	Season 1		Season 2		Season 3		Season 4	
Period	**Start**	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
1	20/02/2017	8/05/2017	16/01/2019	20/03/2019	21/10/2020	25/11/2020	03/09/2022	22/10/2021
2	15/05/2017	31/07/2017	27/03/2019	29/05/2019	02/12/2020	06/1/2021	29/10/2021	17/12/2021
3	07/8/2017	23/10/2017	05/06/2019	07/8/2019	13/01/2021	17/02/2021	24/12/2021	11/02/2022
4	30/10/2017	15/01/2017	14/08/2019	16/10/2019	24/02/2021	31/03/2021	18/02/2022	08/04/2022
5	22/01/2018	09/04/2018	23/10/2019	25/12/2019	07/04/2021	12/05/2021	15/04/2022	03/06/2022
6	16/04/2018	02/07/2018	01/01/2020	05/03/2020	19/05/2021	07/07/2021	11/06/2022	29/07/2022
7	09/7/2018	24/09/2018	13/03/2020	06/05/2020	14/07/2021	25/08/2021	05/08/2022	12/09/2022

Note: The date is in the format of DD/MM/YYYY.

et al. 2021), adopting the Tb value of 22°C, according to Araújo Júnior et al. (2017). Through sigmoidal regressions, the three parameters (a, b and x0) were derived to calculate the dry forage accumulation, resulting in the absolute crop growth rate (AGR, $Mg\,ha^{-1}$ ADD), and from that, it was calculated specific cladode area (SCA, $ha\,Mg^{-1}$), relative growth rate (RGR, $Mg\,Mg^{-1}$ ADD) and net assimilation rate (NAR, $Mg\,ha^{-1}$ ADD) (Jardim et al. 2023c). These rates were calculated according to the following expressions: RGR = AGR/DM, SCA = CAI/DM and NAR = AGR/CAI. The cutting moment for the forage cactus was defined as 25% after the peak (AGR).

Based on regression analysis, the vegetative phenology of the clones was defined according to Santos et al. (2024). To calculate the cladode emission rate, equations with significant parameters and R^2 superior to 0.85 ($p < 0.05$) were used by the t-test (Araújo Júnior et al. 2021b). In this study, a new phenological phase was considered when the cladode emission rate of one order was surpassed by the cladode emission rate of a new order (Amorim et al. 2017).

2.5 | Water Balance

The soil water balance (SWB) was determined according to the model by Libardi (2005), which consists of the conservation of the water mass in a given volume of soil, described by Equation (1).

$$\text{ETa} = R + \text{ID} \pm \text{SR} \pm Q_z \pm \Delta S \tag{1}$$

where ETa is the actual evapotranspiration (mm), R is the rainfall (mm), ID is the irrigation depth (mm), SR is the surface runoff (mm), Q_z is the vertical soil water flow (mm) and ΔS is the variation in soil water storage in the root zone (mm).

The ΔS was obtained through readings using a capacitance probe. The R was monitored from an automatic rain gauge installed in the experimental area. The ID was obtained from the water depth values during the experimental period. The SR was obtained from the adjustment of second-degree polynomial regression models between the R and SR data, using 1 m^2 gutters to determine runoff through rainwater collection. The Qz was calculated based on the flux density (q), which was quantified from the equation proposed by Darcy-Buckingham (Libardi 2005).

ETa was determined from the residual of the soil water balance equation (Equation 1). The SWB components were calculated in non-equidistant intervals of days due to the non-uniform evaluation period, resulting in seven periods per experimental time (Table 1).

2.6 | Water Efficiency Indices

Yield data (YDM—dry matter forage mass, biomass—total forage accumulation, $kg\,ha^{-1}$), ETa, R, ID, obtained throughout the cycles, was used to determine the water indices (Santos et al. 2024). The indices included crop water use efficiency (WUEc, *WUEc, kg m^3), crop water productivity (WPc, *WPc, kg m^3), and irrigation water productivity (WPi, kg m^3) (Fernández et al. 2020). The water indices were obtained using the following equations:

$$\text{WUEc} = \frac{\Sigma(\text{ETa})}{\Sigma(R + \text{ID})} \tag{2}$$

$$*\text{WUEc} = \frac{\text{Biomass}}{\Sigma(\text{ETa})} \tag{3}$$

$$\text{WPc} = \frac{\text{YDM}}{\Sigma(\text{ETa})} \tag{4}$$

$$*\text{WPc} = \frac{\text{YDM}}{R + \text{ID}} \tag{5}$$

$$\text{WPi} = \frac{\text{YDM}}{\Sigma(\text{ID})} \tag{6}$$

Economic efficiency indices included gross and net economic productivity of irrigation water (GEWPi, NEWPi, US$ m^3), crop and irrigation water economic productivity (EWPc, EWPi, US$ m^3) (Fernández et al. 2020). To prepare the indices, the following data were used: gross margin (US$ ha^{-1}) = revenue—variable costs, net margin (US\$ ha^{-1}) = revenue—fixed and variable costs, profit = opportunity cost profit (US\$), ΣID and R. For the revenue, the value of US\$ 28.79 (1 US\$ = 5.21 BRL) was considered for Mg ha^{-1} of fresh matter. For the opportunity cost, the value of the cladode unit (0.03 US\$) was considered, according to Santos et al. (2024).

$$\text{GEWPi} = \frac{\text{Gross margin}}{\Sigma\text{ID}} \quad (7)$$

$$\text{NEWPi} = \frac{\text{Net margin}}{\Sigma\text{ID}} \quad (8)$$

$$\text{EWPc} = \frac{\text{Profit}}{\Sigma(R + \text{ID})} \quad (9)$$

$$\text{EWPi} = \frac{\text{Profit}}{\Sigma\text{ID}} \quad (10)$$

2.7 | Nutritional Efficiency of the Crop

The biological utilisation coefficient (CBU, $kg\,kg^{-1}$) was determined using data on dry matter production, nutrient concentration (CN, $kg\,kg^{-1}$) and nutrient accumulation (AC, $kg\,ha^{-1}$) in cladodes, according to the method of Lédo et al. (2020) (Equations 11 and 12).

$$\text{CBU} = \frac{\text{YDM}}{A_{(i)}} \quad (11)$$

$$A_{(i)} = CN_{(i)} \times \text{YDM} \quad (12)$$

To obtain nutrient concentrations, the dry plant material was processed in a Wiley-type mill with a 2-mm sieve and subsequently packed in labeled plastic bags. The nitrogen concentration was determined by the Kjeldahl method. The plasma induction atomic emission spectrometry method was used to determine P, K^+, Ca^{2+} and Mg^{2+} (EMBRAPA 2000).

The values of YMD, ΣETa and nutrient concentration in the plant (Nu, $g\,kg^{-1}$) were used to calculate the nutrient use efficiency (NUE, $g\,ha^{-1}\,mm^{-1}$) (Silva et al. 2014a).

$$\text{NUE}(w) = \frac{\text{YDM} \times [\text{Nu}]}{\Sigma\text{ETa}} \quad (13)$$

where (w)—refers to the nutrient under analysis (N, P, K, Ca and Mg).

2.8 | Statistical Analysis

The data of variables on yield, biometrics, concentrations of N, P, K^+, Ca^{2+} and Mg^{2+}, NUE and CBU were submitted, separately, to analysis of variance by F test ($p < 0.05$), normality (Shapiro–Wilk test at 5% significance) and homogeneity of variances (Oneillmathews test at 5% significance). If significant, the averages were submitted to the Tukey test at 5% probability. All statistical analyses were performed in the R software version 4.4.0 (R CORE TEAM 2019). The experimental design was a randomised block design with three replications. The statistical model adopted was:

$$\text{Yij} = \mu + \tau\text{i} + \beta\text{j} + \varepsilon\text{ij} \quad (14)$$

where μ is the overall mean. τi is represents the fixed effect of the treatments, βj is represents the random effect of the blocks and εij – is the random error, assumed as $\varepsilon ij \sim N(0,\sigma^2)$.

The adjustment of the morphophysiological and phenology indices' regression curves and the graphs was carried out in SigmaPlot version 14.0 (Systat Software Inc., San Jose, CA, USA).

3 | Results

3.1 | Morphophysiological Indices of Different Forage Cactus Clones

Figure 3 shows the growth rates for all cacti. Firstly, the different durations between cycles are highlighted, which provide different accumulations of heat energy. In the first cycle (585 days), the accumulated degree days reached 2574 ADD; the second (388 days), 2204 ADD; the third (344 days), 1404 ADD; and the fourth (383 days), 1686 ADD. The specific cladode area is shown in Figure 3A–D for each forage cactus production cycle. In the first cycle (585 days), the behaviour of the curve showed a downward trend for V19, OEM and IPA, with the maximum specific cladode area (SCA) at the beginning of the cycle. V19 obtained the highest value (1.72 $ha\,Mg^{-1}$) among all clones, followed by IPA, F8, MIU, OEM and OEA, with maximum values of 0.82, 0.61, 0.46, 0.25 and 0.15 $ha\,Mg^{-1}$, respectively. The high value for the V19 clone, observed only at the beginning of the first cycle, was atypical and did not recur in subsequent cycles. This initial peak likely results from the combination of its high production of fresh and dry matter, typical of the *Opuntia* genus, with the still small cladodes characteristic of the early cultivation stage. Note that the SCA curve showed an increasing behaviour for clone F8. Except for MIU and OEA in the first cycle, the other clones had the opposite effect, with the maximum value at the beginning and decreasing at the end of the cycle.

The net assimilation rate (NAR) performed differently during the cactus cycles. Clone F8 behaved the most differently, reaching the highest values in the first and second cycles (1.61 and 1.68 $Mg\,ha^{-1}$ ADD, respectively). For the other cycles, the behavior was subtly decreasing, without showing major differences between the clones.

The absolute growth rate (AGR) for the six different forage cactus clones in four consecutive cultivation cycles is shown in Figure 3I–L. The OEM clone had the highest values in the first 3 cycles (0.018, 0.030 and 0.031 $Mg\,ha^{-1}$ ADD respectively). In the last cycle, which was just below the IPA, the clone obtained 0.017 $Mg\,ha^{-1}$ ADD. IPA, which had the highest value only in the last cycle, showed a gradual increase, going from 0.002 to 0.029 $Mg\,ha^{-1}$ ADD in the first cycle. The MIU clone had a good result only in the third cycle; however, the value was much lower than the OEM. In the other cycles, it always registered relatively low growth. V19 and F8 basically followed the same behaviour. The F8 clone showed low fresh and dry matter forage accumulation due to its high mortality rate, which resulted in the lowest absolute growth rate among all clones.

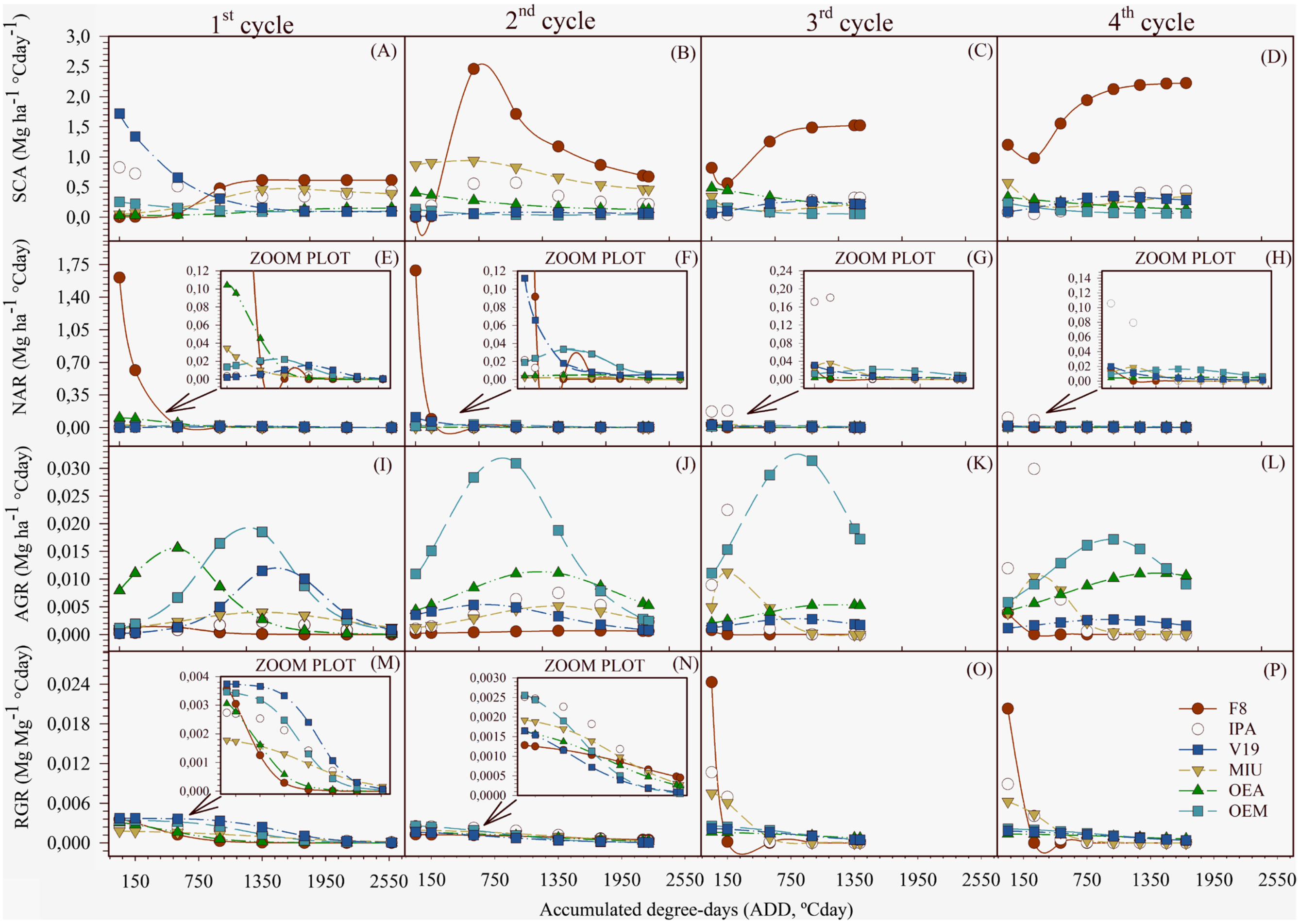

FIGURE 3 | Specific cladode area – SCA (Mg ha^{-1} ADD), net assimilation rate – NAR (Mg ha^{-1} ADD), absolute growth rate – AGR (Mg ha^{-1} °ADD), and relative growth rate – RGR (Mg Mg^{-1} ADD) of forage cactus clones.

The relative growth rate (RGR) has been depicted in Figure 3M–P. In the first 2 cycles, the behaviour of the six clones is highlighted in the zoom of each figure (see inset in Figure 3). In the first cycle, clone V19 obtained 0.0037 Mg Mg^{-1} ADD, configuring the highest RGR. Notably, the first four clones with the highest RGR belong to the genus *Opuntia* (F8, OEM and OEA, in that order). The other clones, both of the genus *Nopalea*, showed lower values, with MIU having the lowest relative growth rate (0.0017 Mg Mg^{-1} ADD). However, in subsequent cycles, the two clones (IPA and MIU, in that order) occupied the second and third-best RGR, surpassed by OEM (0.0025 Mg Mg^{-1} ADD) in the second cycle and the last 2 cycles by F8 (0.024 and 0.020 Mg Mg^{-1} ADD, respectively).

3.2 | Phenological Phases and Harvest Timing

The clones that reached the highest number of phenological phases were V19 and MIU. V19, in the first cycle (Figure 4F), emitted cladodes of up to 5th order, characterising that the plants reached phenophase 5 (Ph5), but did not obtain the same result in the second cycle (Figure 4L), with emission of cladodes of up to 2nd order. The MIU (Figure 4E,K) showed evolution between cycles. In the first cycle, it emitted 4th-order cladodes, configuring phenophase 4 (Ph4) and in the second cycle, it emitted cladodes of up to 6th order, reaching the largest number of phenophases (Ph6). Except for the OEA and IPA clones in the first cycle, which emitted second-order cladodes, characterising phenophase 2 (Ph2), the others emitted 3rd-order clones and ended the cultivation cycles in phenophase 3 (Ph3).

In the first cycle, only the MIU clone had the off-cycle harvest timing. This indicates that the plants maintained AGR close to the peak (0.0042 Mg ha^{-1} ADD) for a longer time than the others. In the second cycle, this behaviour was observed among clones F8, OEA, MIU and IPA. Notably, the IPA clone showed the highest emission rate (0.15 units ADD) during phase 2, emitting a third-order cladode at a level designated as Ph3. This gradual increase in IPA AGR affected the harvest timing. As the plants would still be accumulating forage in large proportions, close to the peak (0.008 Mg ha^{-1} ADD), the cutting would be estimated beyond the end of the cycle. Unlike what happened with this clone in the first cycle (Figure 4D), where the rate of cladode emission and AGR was lower, determining the harvest timing within the cultivation cycle.

The clone that presented the earliest cut was F8 (Figure 4A), which occurred at 944 ADD, even before forming the third phenophase (Ph3), indicating that the cladodes emitted in Ph3 did not have a great influence on forage accumulation. In other situations, it is noted that the harvest timing occurred when the

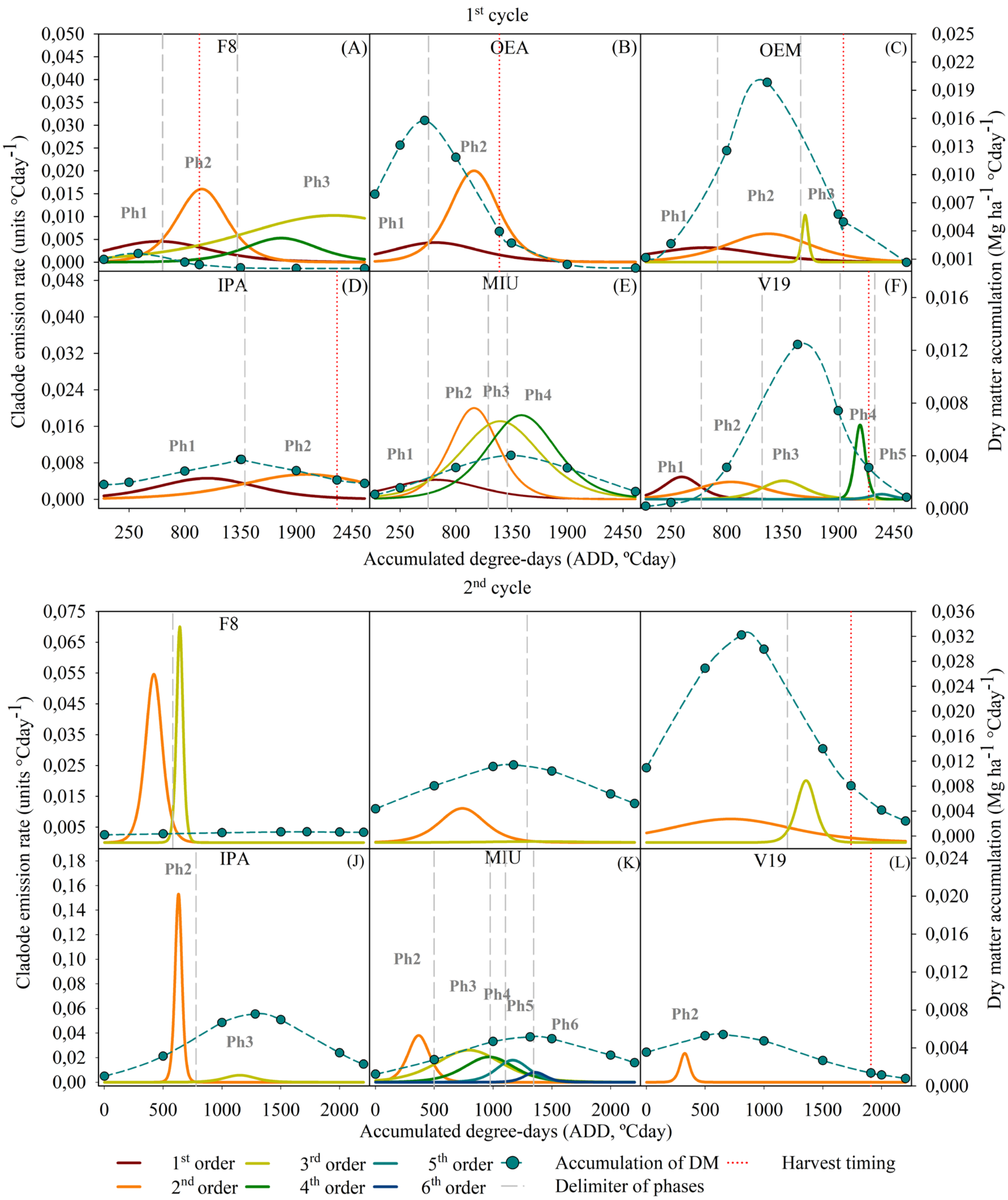

FIGURE 4 | Cladode emission rate, AGR, and ideal harvest timing of forage cactus clones in the first and second cropping cycle.

plants showed a reduction in the emission of new cladodes and, consequently, in the forage accumulation.

In the last 2 cycles (Figure 5), the cladode emission rate showed different values and behaviour, as well as the AGR and the ideal harvest timing. The clone that stood out in the phenological scope (i.e., the appearance of a new physiological phase) was the MIU that, on average, reached at least the fourth vegetative phase. Most clones had strictly maintained the same development level, except for F8 (Figure 5G), V19 (Figure 5L) and IPA. However, IPA showed a decline in the last cycle, emitting only second-order cladodes (Ph2).

In the MIU clone, the maximum forage accumulation occurred in phase 2 and subsequently declined in the middle of phase 3. This reduction made it possible to determine the moment to cut the cactus, which already had a low AGR during the emission of 4th-order cladodes. AGR of OEM and IPA clones remained higher than the others; OEM reached 0.0327 Mg ha^{-1} ADD in the third cycle, and IPA, 0.030 Mg ha^{-1} ADD in the fourth. The OEM, OEA and V19 clones did not show a decline in AGR. Therefore, the ideal harvest moment surpassed the experimental period. For clone F8, the harvest timing was early at the beginning of the cycle due to the low forage accumulation.

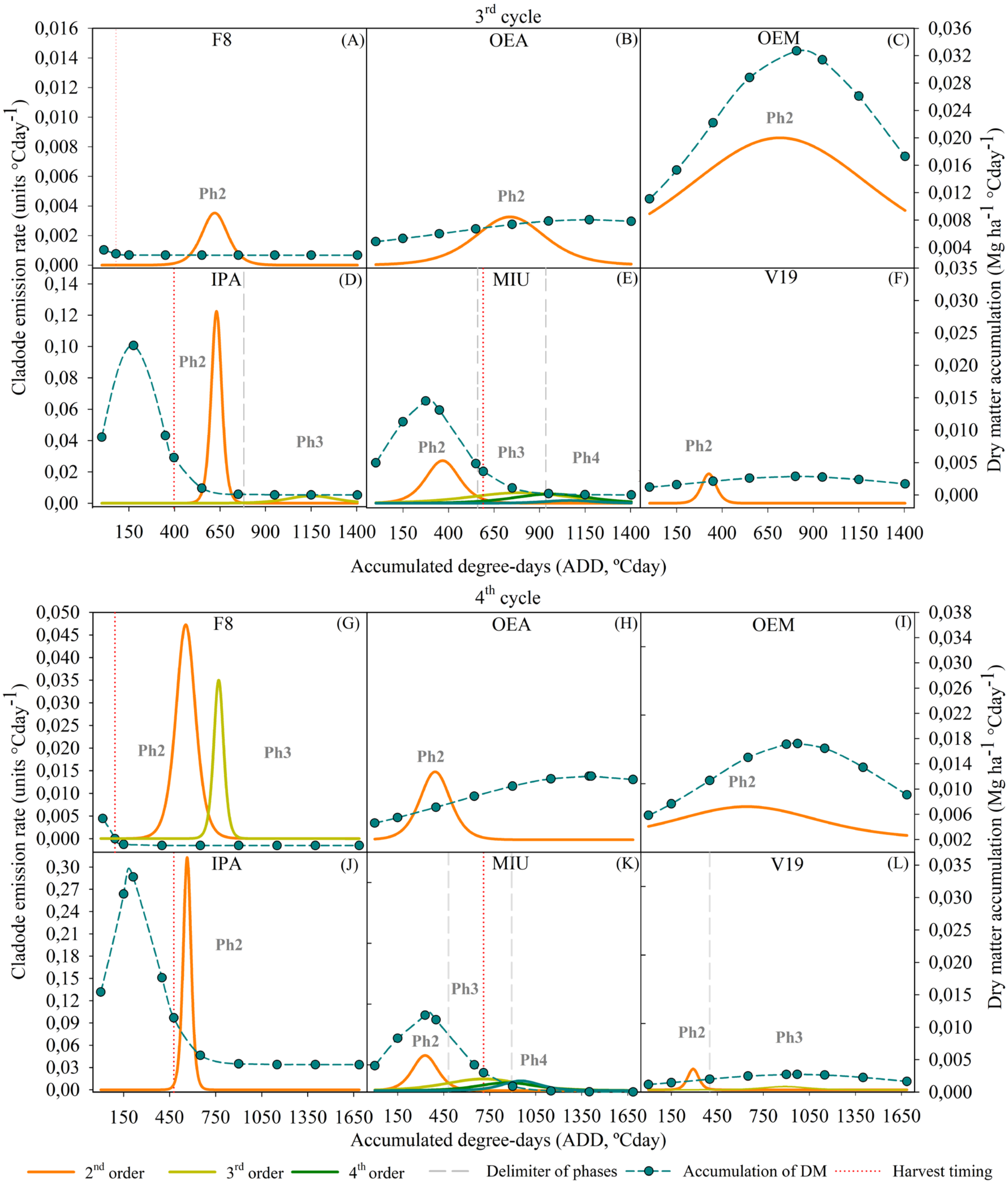

FIGURE 5 | Cladode emission rate, AGR, and ideal harvest timing of forage cactus clones in the third and fourth cropping cycle.

3.3 | Final Biometrics

The clones showed differences among themselves ($p < 0.05$) for all analysed variables (Tables S2–S7). The OEM and OEA obtained a positive highlight in the dry and fresh forage mass and, together with the MIU, in the growth variables. The TNC produced by the plants' overall experimental periods showed that MIU was statistically different from the other clones ($p < 0.05$), standing out in the second cycle when it produced an average of 51.30 cladode units per plant. In some cases, it was similar to F8 in the first cycle, OEM in the third cycle, and IPA in the fourth cycle. The height and width of the plant only showed a significant difference ($p < 0.05$) in the last 2 cycles. However, it is notorious that, when significant, the F8 clone plants showed lower growth numbers in relation to the other clones. Regarding CL, CW, CT and CP, the highlight is the OEA clone, which presented the highest values during the four cultivation cycles.

3.4 | Dry and Fresh Forage Mass, Water Indices, Coefficient of Biological Utilisation and Nutrient Use Efficiency

Regarding fresh matter, the OEA clone proved to be statistically equal to the OEM in all cycles, except for the third growing season, where the clones differed (OEM = 534.9 Mg ha^{-1}; OEA = 228.3 Mg ha^{-1}) (Table 2). Lesser results were observed

TABLE 2 | Fresh and dry forage mass, dry matter content, irrigation water productivity (WPi), concentrations of N, P, K^+, Ca^{2+}, and Mg^{2+}, coefficient of biological utilization of nutrients (CUB) and nutrient use efficiency (NUE, g mm^{-1}) based on actual evapotranspiration (ETa) of different forage cactus clones, in four crop cycles in the Brazilian semi-arid region.

						Content					CUB					NUE				
Cycle	**Clones**	**YFM**	**YDM**	**DMC**	**WPi**	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**
1	OEM	258.90 a	23.30 a	9.00 a	2.02a	6.44 e	4.29 a	15.78 f	52.61 b	33.57 a	155.28 a	233.24 f	63.36 a	19.01 e	29.79 f	73.55 a	48.96 a	180.24 b	600.81 a	383.43 a
	OEA	252.57 a	12.62 b	5.00 b	1.17b	7.00 d	2.55 e	21.25 e	40.12 d	22.53 e	142.86 b	391.90 b	47.06 b	24.92 c	44.39 b	46.51 c	16.95 c	141.19 c	266.58 b	149.69 c
	V19	287.27 a	14.36 b	5.00 b	1.17b	9.52 b	2.61 d	28.09 d	37.75 e	30.05 b	105.04 d	383.13 c	35.60 c	26.49 b	33.28 e	62.96 b	17.26 b	185.77 a	249.65 c	198.75 b
	MIU	102.81 b	7.20 bc	7.00 ab	0.75c	7.00 d	3.11 c	28.88 c	41.35 c	23.63 d	142.86 b	321.14 d	34.62 d	24.19 d	42.33 c	29.41 d	13.08 d	121.36 d	173.73 d	99.27 d
	IPA	43.43 bc	3.04 c	7.00 ab	0.29d	7.14 c	2.54 f	29.98 b	35.31 f	19.80 f	140.06 c	393.59 a	33.35 e	28.32 a	50.51 a	11.71 e	4.16 e	49.20 e	57.95 e	32.49 e
	F8	21.34 c	1.28 c	6.00 ab	0.11e	9.94 a	3.40 b	32.84 a	53.40 a	28.88 c	100.6 e	293.93 e	30.45 f	18.73 f	34.62 d	5.82 f	1.99 f	19.24 f	31.29 f	16.92 f
	p	< 0.001	< 0.001	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
2	OEM	630.68 a	44.15 a	7.00	6.79a	9.52 d	2.27 b	22.22 d	35.02 d	26.09 c	105.04 c	439.72 e	45.00 c	28.55 c	38.33 d	222.68 a	53.20 a	519.75 a	819.17 a	610.27 a
	OEA	448.13 ab	26.88 ab	6.00	3.71b	9.66 c	1.76 f	12.43 f	41.34 b	23.07 e	103.52 d	569.69 a	80.48 a	24.19 e	43.34 b	122.51 b	22.26 b	157.59 b	524.28 b	292.64 b
	V19	181.95 ab	10.91 ab	6.00	1.54d	10.08 b	1.77 e	28.90 b	29.11 f	34.93 a	99.21 e	565.84 b	34.60 e	34.36 a	28.63 f	54.36 d	9.53 e	155.84 c	156.96 e	188.36 c
	MIU	162.62 ab	9.75 ab	6.00	1.49e	10.64 a	2.22 c	29.21 a	35.75 c	23.61 d	93.98 f	451.23 d	34.23 f	27.97 d	42.35 c	55.48 c	11.56 d	152.32 d	186.40 d	123.13 d
	IPA	157.53 ab	11.05 ab	7.00	1.73c	6.02 f	2.98 a	14.60 e	34.84 e	20.27 f	166.11 a	335.37 f	68.51 b	28.70 b	49.32 a	35.87 e	17.77 c	86.97 e	207.59 c	120.79 e
	F8	14.87 b	0.89 b	6.00	0.29f	8.82 e	1.94 d	28.72 c	46.40 a	27.13 b	113.38 b	516.59 c	34.82 d	21.55 f	36.86 e	8.92 f	1.96 f	29.03f	46.91 f	27.42 f
	p	0.04	0.02	0.1	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01

(Continues)

TABLE 2 | (Continued)

						Content					CUB					NUE				
Cycle	Clones	YFM	YDM	DMC	WPi	N	P	K	Ca	Mg	N	P	K	Ca	Mg	N	P	K	Ca	Mg
3	OEM	534.93 a	48.15 a	9.00 a	29.92a	5.74 d	2.70 c	23.44 e	26.23 e	18.81 d	174.22 b	370.94 d	42.67 b	38.12 b	53.15 c	350.32 a	164.53 a	1430.41 a	1601.09 a	1148.20 a
	OEA	228.31 b	11.42 b	5.00 ab	7.76b	6.58 c	2.02 f	27.03 d	31.38 b	25.45 b	151.98 c	494.01 a	37.00 b	31.87 e	39.29 e	112.05 b	34.47 c	460.28 d	534.33 b	433.41 b
	V19	66.81 bc	4.68 b	7.00 ab	2.98e	8.26 a	2.49 d	36.05 a	30.90 c	27.38 a	121.07 e	401.86 c	27.74 f	32.36 d	36.53 f	51.13 e	15.40 e	223.14 e	191.30 e	169.45 e
	MIU	96.28 bc	6.74 b	7.00 ab	4.51d	7.42 b	3.29 b	31.92 b	26.44 d	18.45 e	134.77 d	304.18 e	31.33 e	37.82 c	54.19 b	69.17 c	30.65 d	297.52 c	246.47 d	172.01 d
	IPA	116.23 bc	8.14 b	7.00 ab	4.97c	5.74 d	4.22 a	27.98 c	33.32 a	22.03 c	174.22 b	237.00 f	35.75 d	30.01 f	45.4 d	58.96 d	43.34 b	287.35 d	342.28 c	226.27 c
	F8	1.44 c	0.03 b	2.00 b	0.75f	4.62 e	2.10 e	19.57 f	17.85 f	12.35 f	216.45 a	476.64 b	51.09 a	56.03 a	80.96 a	7.23 f	3.28 f	30.61 f	27.91 f	19.32 f
	p	0.00	< 0.001	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
4	OEM	322.35 a	25.80 a	8.00	29.01b	8.4 c	3.57 a	21.53 c	21.51 e	26.33 a	119.05 c	279.99 f	46.45 d	46.49 b	37.98 f	231.85 a	98.58 a	594.20 b	593.67 b	726.75 a
	OEA	337.15a	30.34 a	9.00	29.04a	8.12 e	1.95 e	29.69 a	27.76 a	22.24 c	123.15 a	511.66 b	33.69 f	36.02 f	44.96 d	225.18 b	54.20 b	823.25 a	769.94 a	616.87 b
	V19	64.20 bc	5.14 b	8.00	5.23e	9.10 b	1.83 f	16.48 f	26.60 c	18.33 d	109.89 d	544.98 a	60.67 a	37.6 d	54.55 c	45.30 e	9.13 e	82.25 e	132.39 d	91.26 e
	MIU	71.96 bc	7.20 b	10.00	6.43d	9.52 a	2.78 c	24.57 b	19.07 f	17.08 f	105.04 e	359.45 d	40.7 e	52.45 a	58.55 a	58.61 d	17.13 d	151.25 d	117.37 e	105.14 d
	IPA	164.14 b	13.13 ab	8.00	12.29c	8.26 d	3.56 b	20.28 d	24.76 d	25.25 b	121.07 b	280.74 e	49.31 c	40.39 c	39.61 e	97.60 c	42.09 c	239.63 c	292.50 c	298.32 c
	F8	5.52 c	0.50 b	9.00	0.48f	9.52 a	2.33 d	19.38 e	27.37 b	18.03 e	105.04 e	429.21 c	51.59 b	36.54 e	55.48 b	4.33 f	1.06 f	8.81 f	12.44 f	8.20 f
	p	< 0.001	0.00058	0.7	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01

Note: OEM: Orelha de Elefante Mexicana. OEA: Orelha de Elefante Africana. MIU: Miúda. IPA: IPA-Sertânia. YFM: fresh matter forage mass ($Mg\,ha^{-1}$). YDM: dry matter forage mass ($Mg\,ha^{-1}$). DMC: dry matter content (%). WPi ($kg\,ha^{-1}\,m^3\,ha^{-1}$). Concentration of nutrients ($g\,kg^{-1}$). CBU: Coefficient of biological utilisation of nutrients ($kg\,kg^{-1}$). N: nitrogen. P: phosphorus. K^+: potassium. Ca^{2+}: calcium. Mg^{2+}: magnesium. NUE-N: nitrogen. NUE-P: phosphorus. NUE-K: potassium. NUE-Ca: calcium. NUE-Mg: magnesium. Lowercase letters that are the same in the row do not differ from each other by the Tukey test at the 1% ($p < 0.01$) and 5% ($p < 0.05$) probability level.

in clone F8 plants, with an average of 10.8 Mg ha^{-1} of fresh forage mass during the entire experimental period. This value is approximately 41 times lower than the average OEM fresh forage mass. The dry matter yield behaved similarly to the fresh matter yield (Table 2). On average, OEM had the best performance in the first 3 cycles, equal to OEA only in the last one. The lowest yields in the first cycle were for clones MIU (8.4 Mg ha^{-1}), IPA (3.0 Mg ha^{-1}) and F8 (1.3 Mg ha^{-1}). However, the MIU dry matter yield results were considered satisfactory since they did not differ statistically from the production of V19 and OEA plants.

In general, OEA and OEM differed significantly from the other clones in terms of fresh and dry matter forage mass. The cumulative production across cycles for OEM was 1746.9 Mg FM ha^{-1} and 140.8 Mg DM ha^{-1}, values higher than those of OEA (1266.2 Mg FM ha^{-1} and 80.1 Mg DM ha^{-1}). DMC showed a significant difference ($p<0.05$) in the first and third cycles. Note that when there was a significant difference, the highest levels were seen in the OEM, reaching 9% of dry matter produced per kg of fresh matter.

The water indices (WUEc, *WUEc, WPc, *WPc, GEWPI, NEWPI, EWPc and EWPI) for clones are available in Table S8. Only IPA did not have WUEc statistically similar ($p<0.01$) to the other clones. As for the water use efficiency of the crop based on biomass production (*WUEc), OEM and OEA were more efficient compared to other clones. In general, for this index, OEM had greater efficiencies in all evaluated cycles, with the exception of the fourth, where OEA was superior. For WPc and *WPc, the OEM clone has been more efficient in relation to the other clones in all cycles. WPi (Table 2) indicated an increase for all clones, except F8, over the four evaluation periods, emphasizing OEM, with the highest value recorded (29.92 kg m^3).

For GEWPI and NEWPI, the F8 clone proved to be economically inefficient in terms of irrigation water use. However, the OEA and OEM clones were the most efficient. Economic crop water productivity (EWPc) also showed an upward trend over the evaluated periods. MIU was more economically efficient in terms of water use than the other clones, with an average of 2.35 US$ m^3. The results of the economic irrigation water productivity (EWPI) indicated the same upward trend during the analysed periods, emphasising the MIU, which showed an increase of 535%.

The results of the concentrations of the nutrients found in the cladodes and the CBU differed statistically ($p<0.01$) (Table 2). Clone F8 had high concentrations of N, K^+ and Ca^{2+}. In MIU, high concentrations of N and K^+ stood out. Clone V19 had high concentrations of N and Mg^{2+}. The OEM clone obtained high concentrations of P, Ca^{2+} and Mg^{2+}. The OEA clone had high concentrations of K^+ and Ca^{2+}, and the IPA clone had high concentrations of P and Ca^{2+}. However, the highest CBU values were observed in the clones with the lowest observed concentrations. The OEM, IPA, F8 and OEA clones presented the highest CBU-N values, indicating that these clones produce more dry matter using less nitrogen.

The highest CBU-P values were noted for clones IPA, OEA and V19. OEA was the clone with the highest CBU-P in the second and third cycles, resulting in the second-highest cycle among all cycles (569.69 kg kg^{-1}). Thus, like N, the highest CBU-P was associated with the lowest P concentrations. Four clones (F8, MIU, V19 and OEA) had the highest K^+ concentrations, but in different cycles. On average, V19 was the clone that obtained the highest concentration (36.05 g kg^{-1}). The lowest concentrations were noted for clones OEM, OEA and F8, all of the genus *Opuntia*. However, such concentrations were reflected in the highest CBU-K values. OEA had the lowest K^+ concentration (12.43 g kg^{-1}) but exhibited the highest CBU-K with 80.48 kg kg^{-1}.

Clone F8 had the highest Ca^{2+} concentrations. However, the final cycles showed a significant reduction, where the IPA and OEA clones showed the highest concentrations. This reduction in clone F8 resulted in the lowest Ca^{2+} concentration; on the other hand, it exhibited the highest CBU value for this nutrient, 56.03 kg kg^{-1}. The other cycles indicated that the highest CBU-Ca was obtained for IPA, V19 and MIU with 28.32, 34.36 and 52.45 kg kg^{-1} in the first, second and fourth cycles, respectively.

Magnesium was more present in plants of the genus *Opuntia*, i.e., OEM and V19. In the first and last cycles, the OEM had 33.57 and 26.33 g kg^{-1}; in the second and third, the forage cactus V19 had 34.93 and 27.38 g kg^{-1}, respectively. For CBU-Mg, the highest values were seen in clones of the genus *Nopalea* in three of 4 cycles. In the third cycle, F8 showed the highest value, 80.96 kg kg^{-1}, and IPA and MIU showed the highest values in the other cultivation cycles. The IPA reached 50.51 and 49.32 kg kg^{-1} in the first 2 cycles, while for the MIU, it was higher in the fourth cycle, with 58.55 kg kg^{-1}. The results indicated different nutritional accumulations for clones F8, IPA and MIU, with the following descending order: $Ca^{+2} > K^+ > Mg^{+2} > N > P$. For OEM, OEA and V19, this order was different: $Ca^{+2} > Mg^{+2} > K^+ > N >$ P, indicating that Mg was extracted more than K^+.

NUE results based on ETa for forage cactus clones are shown in Table 2. NUE varied between clones ($p<0.01$). The OEM showed the highest efficiencies in the use of all nutrients in the four cultivation cycles, except for cycle four, where the NUE-K and NUE-Ca were higher for the OEA clone (823.25 g K ha^{-1} mm^{-1}, 769.94 g Ca ha^{-1} mm^{-1}, respectively). Clone F8, on the other hand, proved to be the least efficient during all cycles for the analyzed nutrients.

The other nutrients showed the same trend of increase until the third cycle, but reduced in the last cycle. The third cycle found the highest values, where water application via irrigation and rainfall was the lowest among the cycles. All clones differed from each other ($p<0.01$), with the highest values being those of the *Opuntia* genus, except for F8. The two clones of the genus *Nopalea* (IPA and MIU) exhibited the lowest values, being just above F8 in most results and outperforming clone V19 in some cycles (e.g., NUE-P and NUE-Ca in cycle 2, NUE-N in cycle 3). In the third cycle, IPA was just below OEM for NUE-P and outperformed, in that order, MIU, V19 and F8 clones on NUE-Ca and NUE-Mg. In the fourth cycle, IPA showed the same expression of results seen previously, being more efficient than V19, MIU and F8 in the use of all nutrients.

3.5 | Meteorological Conditions and Soil Water Balance

The values of the meteorological variables collected during the four growing cycles are shown in Figure 6. From planting to the end of the fourth cycle, total irrigation was 1127.9 mm in the 1st cycle (Figure 6A), 673.6 mm in the 2nd cycle (Figure 6B), 155.3 mm in the 3rd cycle (Figure 6C), and 101.3 mm in the 4th cycle (Figure 6D). The accumulated precipitation was 2092.0 mm in the 1st cycle, 2193.6 mm in the 2nd cycle, 813.3 mm in the 3rd cycle, and 1163.3 mm in the 4th cycle. The daily average of ET_0, in the 4 cycles, was 4.8, 4.9, 4.7 and 4.7 mm day^{-1}.

The soil water balance components evaluated in four growing seasons of different forage cactus clones are shown in Table S9. The first growing season totaled 2095 mm of water in the cropping system via rainfall and irrigation (R + ID) in 585 evaluation days. In all clones, deep drainage (DD) was greater than capillary rise (CR); the highest values were seen in clone F8 and the lowest in OEM. It is noted that the periods in which there was a greater increase in water (first and fifth) were those that presented high values of surface runoff (SR) but also a greater volume of actual evapotranspiration (ETa). Soil water storage variation (ΔS) showed different values among clones. It is noted that the greatest variations in the volume of water present in the soil occurred between the fifth and seventh periods. At the end of the first season, V19 showed the highest ETa (mean −2001.8 mm) with less water stored in the soil (−10 mm). The smallest ETa was in F8 (−1979.1 mm), with ΔS of 12 mm.

The second evaluation period comprised 483 days, with rainfall of 1520 mm and a total irrigation volume of 673 mm, totaling 2193.00 mm. The MIU and V19 clones stood out in the DD (20.36 and 20.17 mm, respectively). The greater amount of water applied in the system caused greater surface runoff and a lower evapotranspiration rate. However, greater water storage was observed in the control layer (Z = 0.60 m). Clone V19 showed the lowest ETa value (−1922.3 mm), even with the highest variation in soil water storage (118.4 mm). The OEA clone had the highest evapotranspiration value among all cultivated systems (−1966.9 mm).

The third cycle, note that the actual evapotranspiration values were similar for five of the six forage cactus clones, ranging from 746 to 760 mm. OEA was the clone with the lowest ETa (706.5 mm) and, at the end of the period, exhibited 35.6 mm of water stored in the soil control layer (0.6 m).

In the fourth period, the total amount of water inserted was 1163.00 mm (R + ID) during 381 days. In the periods with the highest amount of water inserted in the system (3, 4 and 6), higher ETa values were noted, except for period 3, and less water storage in the soil, indicating that the increase in water supply

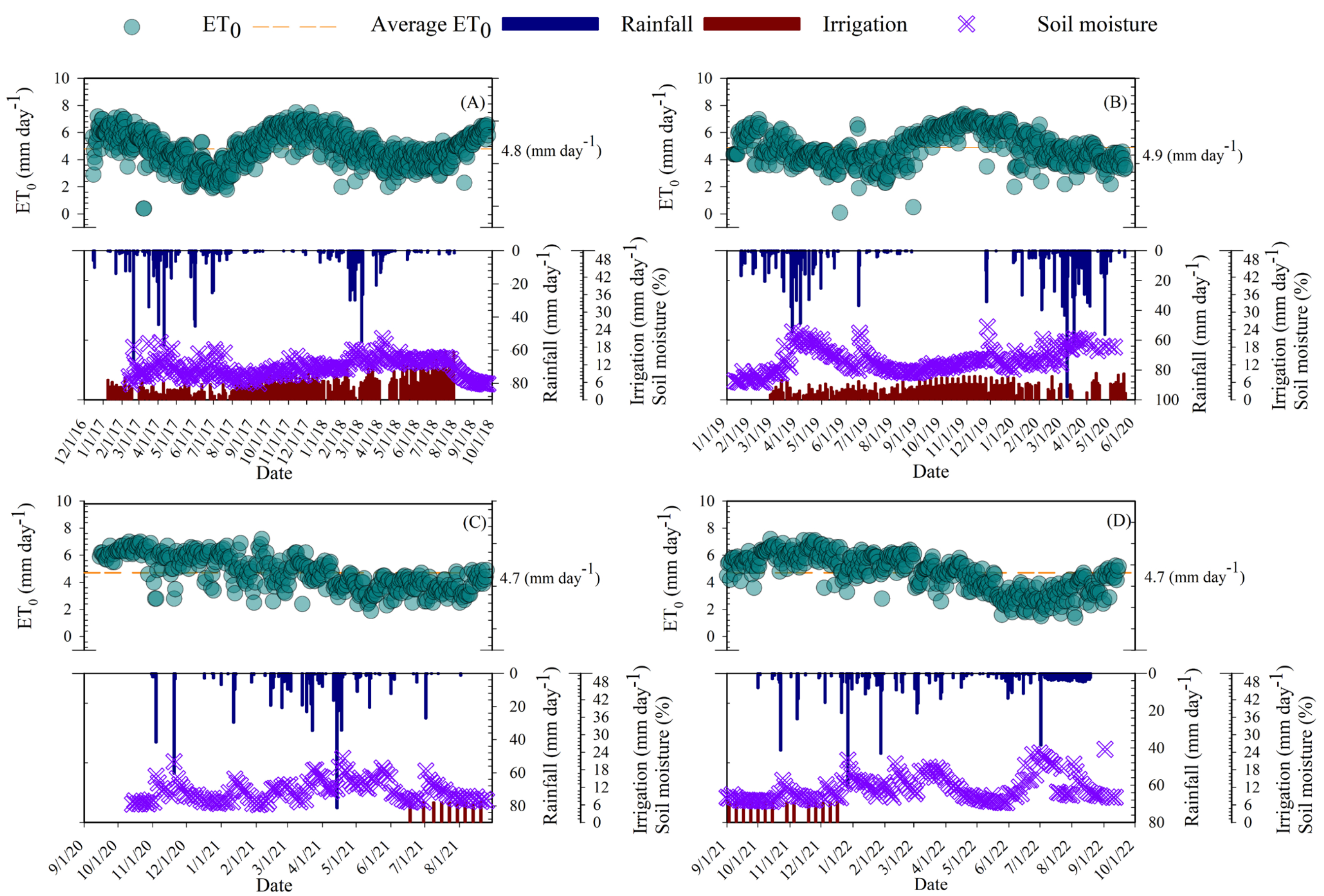

FIGURE 6 | Reference evapotranspiration (ET_0), soil moisture, rainfall, and irrigation depth applied in the cultivation of different forage cactus clones in the period of (A) first cycle, (B) second cycle, (C) third cycle, and (D) fourth cycle.

for the clones added water absorption by the roots of forage cactus clones. Furthermore, it is noted that the CR values were much higher than the DD values, where clone V19 exhibited the highest value among the clones (9.22 mm).

4 | Discussion

4.1 | Phenological Phases, Morphophysiology and Harvest Timing

The differences in heat energy accumulation are a result of the early removal of the crop from the field (Figure 3). This can occur due to several factors, such as the age of the forage cactus, environmental conditions and the accumulation of dry matter (Silva et al. 2015b). After the first cut, the maintenance of the basal cladode influences the stabilisation of the crop in the field, providing assimilates already maintained in the cladodes that remained in the plant for the development of new cladodes (Pinheiro et al. 2014). The environment will influence the plant's physiological processes and can promote conditions of low radiation and high humidity, which influence the crop's evapotranspiration and, consequently, development. From the interaction of these factors, the plant will accumulate more or less dry matter. If the accumulation continues with an upward behaviour (e.g., emission of new cladodes), it is recommended to keep the plant in the field. Otherwise, the correct option is to harvest, avoiding waste of time, space and economics (Amorim et al. 2017; Jian et al. 2024).

In general, SCA showed the highest values in clone F8. In this case, the clone presented the lowest values for fresh and AGR in all cycles, in addition to low values for the biometric variables. Queiroz et al. (2015) indicated that SCA is inversely proportional to cladode thickness. As SCA is the ratio between dry matter forage production and cladode area, the high values of F8 indicate that the cladodes produced by this clone had low thickness due to the low production of parenchyma and, therefore, essential photosynthetic structures for dry forage accumulation by plants (e.g., chloroplasts) (Jardim et al. 2021a). Therefore, clone F8 was the most efficient in converting photoassimilates into dry forage, even under adverse conditions, such as water restriction.

On a larger scale for F8, and smaller for the other clones. NAR exhibited high values at the beginning of the cycle in response to the investment made in leaf area production. This is done by the plant to promote greater light interception and increase photoassimilates concentration (Câmara et al. 2017). Such findings may correlate with the observed results, where the highest initial values were in the clone of the genus *Opuntia*, which, characteristically, has a large leaf area. The subsequent reduction in NAR can be explained by the self-shading of the plants promoted by the emergence of new cladodes, which results in a higher cladode area index (Queiroz et al. 2015).

The OEM clone was responsible for exhibiting the highest AGR values, which can be explained by the striking characteristics of clones of the genus *Opuntia*, such as the larger cladode area that promotes greater light interception and increases efficiency in the use of natural resources, increasing dry forage accumulation (Rocha et al. 2017; Silva et al. 2015b). Unlike AGR, RGR showed decreasing growth from the beginning to the end of each cycle. At the beginning of each cycle, the high RGR values recorded are related to the cellular development of the plants in order to produce new tissues to promote leaf area increase. Over time, the RGR decreases as a result of the reduction in the photosynthetic area and the need for the plant to maintain other organs (Araújo Júnior et al. 2021b; Pommerening and Muszta 2016). Similar results were described by Araújo Júnior et al. (2021c), with the MIU clone reaching the highest number of phenophases. This is explained by the ability of *Nopalea* clones to emit a greater number of cladodes, especially of a higher order; this causes a new phase to be confirmed every time the emission rate of upper-order cladodes exceeds the emission rate of lower-order cladodes (Amorim et al. 2017).

The time of each phenophase depends on the characteristics of each clone and the management adopted. In OEM, OEA and IPA clones, the duration of the phenophase is a structural characteristic explained by the superior distribution of first and second-order cladodes in these clones. This does not occur in MIU plants with this greater distribution from the third-order cladodes (Nunes et al. 2020b). The harvest timing is linked to the AGR of each clone; the ideal harvest timing is influenced by the productive characteristics of each one of them. The highest accumulations of dry forage were seen in the OEM, an expected result due to the high yield values presented by it. However, the difference from the other clones is associated with high rates of water use efficiency and cladode area, which favour greater water accumulation and increased mass accumulation by this clone (Araújo Júnior et al. 2021b; Jardim et al. 2020; Silva et al. 2014b).

Early harvest reduces nutrient use efficiency (NUE) because it decreases productivity before the maximum biomass accumulation. Although young cladodes may present higher nutrient concentrations (Naorem et al. 2022), this effect does not compensate for the lower yield. Thus, early cuts, as observed in clone F8, result in lower efficiency compared to cuts performed near the peak of accumulation, as in clone OEA.

Overall, the OEM and OEA clones showed the most balanced phenological performance, combining adequate dry matter accumulation with favourable harvest timing. Their productive stability ensures greater forage availability throughout the year, which is crucial for maintaining feed supply in semi-arid regions. From a practical perspective, these clones represent the best option for producers, as they guarantee both efficiency and consistent biomass accumulation for forage use.

4.2 | Growth and Yield Performance of Dry and Fresh Mass

MIU is known to exhibit high emission of higher-order cladodes due to its morphological characteristics, having a high concentration of tertiary and quaternary cladodes. This high production of cladodes (third- and fourth-order cladodes) increases the total dry matter of the plant (Pinheiro et al. 2014). The OEA clone, which had the largest cladode dimensions (CL, CW, CP and CT), is based on the fact that it has the morphological characteristics present in plants of the genus *Opuntia*, which have a larger photosynthetic area precisely because they have larger cladodes in relation to plants of the genus *Nopalea* (Silva et al. 2015a). The relation between the number of shoots and the size of the cladode area can be explained by the source-sink relationship since the concentration and distribution of photoassimilates to a smaller number of organs intensifies the growth and development of other parts of the plant. In this way, a plant with a large photosynthetic area (source) and with less drain (e.g., young higher-order cladodes) provides an increase in the already existing areas (Santos et al. 2021).

Yields obtained during the four forage cactus cuts showed the productive potential of clones of the genus *Opuntia*; however, clone F8 (*Opuntia atropes* Rose) had low yields of fresh and dry matter due to the high mortality rate. However, it does not portray the potential of dry matter production since the matter content remained stable. This finding corroborates the results found by Pessoa et al. (2020), who evaluated the dry matter content of three clones in three phenological stages: F8, IPA-20 (*Opuntia ficus-indica* (L.) Mill.) and Gigante (*O. ficus-indica* (L.) Mill.). According to the authors, on average, F8 had the highest dry matter content among the three clones (106 g kg of fresh matter), indicating a high potential for dry matter production under normal conditions.

The OEM and OEA clones exhibited higher values of fresh matter and dry matter productivity, which may be due to the high adaptability and aggressiveness of these plants (Rocha et al. 2017; Rule and Hoffmann 2018). In addition, morphophysiological characteristics favor a higher dry forage accumulation due to the greater photosynthetic area (i.e., greater cladode area) found in cacti of this genus, which enables greater metabolic activity (Araújo Júnior et al. 2021a; Morais et al. 2017; García-Nava et al. 2015). The MIU clone stood out in the numerical production of cladodes, a striking morphological characteristic of the clone, which invests in the production of new cladodes, instead of developing inferior cladodes (1st and 2nd order) (Silva et al. 2017).

Such productive differences were described by Araújo Júnior et al. (2021a), when comparing the productivity of three clones of irrigated forage cactus, one of the genus *Opuntia* (OEM) and two of the genus *Nopalea* (MIU and IPA), where the OEM presented a fresh matter yield of 312 Mg ha^{-1} and 31 Mg ha^{-1} of fresh matter higher than MIU (191 Mg ha^{-1} FM and 19 Mg ha^{-1} DM) and IPA (83 Mg ha^{-1} FM and 7 Mg ha^{-1} DM). Under rainfed conditions, Campos et al. (2021) confirmed the productive difference between clones of the genera *Opuntia* and *Nopalea*, with higher fresh matter yields for clones of OEM (*Opuntia stricta* (Haw.) Haw.), Gigante and Orelha de Onça (both *Opuntia ficus-indica* (L.) Mill.) in relation to MIU and IPA plants (both of the species *Nopalea cochenillifera* (L.) Salm-Dyck).

4.3 | Water Balance and Water Indices

All clones, with the IPA clone in a lower condition, were efficient in using the water inserted into the system. Since WUEc informs, through the dimensionless ratio, that all water applied via irrigation and rainfall was lost by evapotranspiration by the clones (Fernandez et al. 2020). As in the water balance, it was possible to notice that there were no major differences between the clones, and the accumulated actual evapotranspiration (ΣETa) was higher in periods with greater water increases. This direct relationship is described by Machado et al. (2015), who, as well as the data described in Table S7, found that the highest ETa were a consequence of high water increase events in the same period. The variations in evapotranspiration among clones, when analysed together with productivity data (Table 2), contribute to the interpretation of water use efficiency. Thus, the clones with higher dry matter productivity proved to be more efficient in using the water depth, as there was little difference in ETa between the clones. However, it is worth noting that the intrinsic morphological characteristics of each clone must be considered when determining which is the most efficient (Barbosa et al. 2017).

For *WUEc, WPc and *WPc, the OEM and OEA clones outperformed others due to their naturally high productivity. When these clones are well-managed hydrologically, the results are particularly significant (Santos et al. 2024). Consequently, these clones are well-suited to livestock activities that aim to minimize water consumption. Therefore, in regions with water deficits, irrigation management should be the primary consideration to prevent waste and economic losses (Fernandez et al. 2020).

As clone F8 obtained low productivity values, it was expected that economically, the results of this clone would be conditioned by financial losses. The use of irrigation water should always be considered as a factor driving forage production, providing the farmer with a significant net income (Shammout et al. 2018). Thus, the water economic indicators used in this study indicated which clones were more economically efficient. The OEM and MIU clones were those that would provide the greatest gross and net profit, as, receiving the same amount of water, both produced high fresh and dry forage mass and a high number of cladodes.

4.4 | Nutrient Concentrations, CBU and NUE

The results obtained in this study confirmed that nutrient extraction varies significantly depending on the clone (Moreira et al. 2020). The higher concentrations seen in the IPA and MIU clones are due to their higher total soluble carbohydrate content and greater nutritional value compared to clones of the *Opuntia* genus, leading to a greater demand for nutrients (Inácio et al. 2020). The high nutrient concentrations observed in the F8 and V19 clones may be related to environmental conditions or the efficiency of fertiliser incorporation into the soil (Moreira et al. 2020). Except for the third cycle, the concentrations were for all clones in the ideal range of nutrients proposed by Ferraz et al. (2020), which support plant growth. For *Opuntia* clones, the nutrients ranged from 6.7 to 20.6 g N kg^{-1}, 0.8 to 4.7 g P kg^{-1}, 23.0 to 33.4 g K kg^{-1}, 14.9 to 42.0 g Ca kg^{-1} and 5.9 to 14.0 g Mg kg^{-1}. As for *Nopalea* clones, they ranged from 6.7 to 10.5 g N kg^{-1}, 1.0 to 1.6 g P kg^{-1}, 8.3 to 12.1 g K kg^{-1}, 20.6 to 22.5 g Ca kg^{-1} and 10.4 to 17.0 g Mg kg^{-1}. Balanced soil fertility is reflected in the high forage accumulation and morphometric traits of forage cactus (Santana et al. 2021).

The highest coefficient of biological utilisation (CBU) occurred in clones with the lowest nutrient concentrations. It is worth mentioning that the CBU reflects the contribution of the forage cactus clone to forage production as a function of nutrient absorption (Lédo et al. 2020). Silva et al. (2009) reported that CBU is influenced by biological and edaphoclimatic factors. Regarding nutrient use efficiency based on ETa, the OEM and OEA clones, both from the genus *Opuntia* known for high productivity and water use efficiency (Silva, De Miranda, et al. 2014a), stood out. In contrast, clone F8 (*Opuntia atropes* Rose) showed the lowest nutrient efficiency, likely due to its high mortality and reduced forage mass, which are key components in calculating CBU and NUE. In this work, the increase in nutrient use efficiency over the course of the cycles was caused by the variation in ETa values, which, in turn, depended on the water levels applied. In cycles in which there was a reduction in ETa, the efficiency of nutrient use was increased.

These results suggest that the higher nutrient use efficiency observed in certain clones is not only related to absorption but also to the way nutrients are partitioned among productive plant parts. According to Hütsch and Schubert (2021), nutrient use efficiency involves both uptake and utilisation efficiencies, with efficient partitioning being a decisive factor for high forage production. On the other hand, nutrient dilution can occur when productivity increases more rapidly than absorption, reducing concentrations in tissues (Ciampitti and Vyn 2014). In crops such as maize and cotton, recent studies have confirmed that improvements in NUE depended not only on uptake but also on nutrient redistribution and partitioning during critical developmental stages (Sun et al. 2023; Stewart et al. 2024).

5 | Conclusions

The water and nutrient use efficiencies of forage cactus are highly dependent on the morpho-productive characteristics of each clone. Among the studied genotypes, Opuntia clones, particularly OEM, demonstrated superior agronomic and economic performance. OEM stood out as the most efficient clone, achieving the highest forage accumulation per unit area, the best water efficiency and the highest nutrient use efficiency. While the Miúda clone exhibited a distinct growth pattern with more higher-order cladodes, its overall productivity was lower. Based on that, the OEM clone is recommended for forage production in semi-arid regions due to its superior productivity and resource use efficiency. This implies that adopting high-performance clones like OEM can significantly enhance the sustainability and economic viability of forage systems in water-scarce environments, leading to higher forage accumulation with lower water and fertiliser inputs. For future adoption, it is recommended that farmers and agricultural extension services prioritise the propagation of the OEM clone. For further research, studies should focus on refining water and fertilisation management practices specifically tailored to the OEM clone's requirements under varying irrigation regimes to maximise its potential and resilience.

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Ethics Statement

This study did not involve animal or human subjects. Field research was conducted in accordance with relevant institutional, national and international guidelines for ethical agricultural and ecological research. The authors confirm that the collection, processing and analysis of data adhered to principles of research integrity and transparency.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Research data are not shared.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Physical and chemical attributes of a Haplic Cambisol cultivated with forage cactus measured at a depth of 0.0–0.20. **Table S2:** Biometric variables of different forage cactus clones cultivated in four consecutive cycles. **Table S3:**. Analysis of variance table for fresh and dry matter forage mass. **Table S4:**. Analysis of variance table for dry matter content and total number of cladodes. **Table S5:**. Analysis of variance table for plant height and width. **Table S6:**. Analysis of variance table for cladode length, cladode width, cladode thickness and cladode perimeter. **Table S7:**. Analysis of variance table for cladode area index. **Table S8:** Crop water use efficiency (WUEc, *WUEc), crop water productivity (WPc, *WPc), gross economic irrigation water productivity (GEWPi), net economic irrigation water productivity (NEWPi), economic crop water productivity (EWPc) and economic irrigation water productivity (EWPi) of different forage cactus clones cultivated in four consecutive cycles. **Table S9:** Components of soil water balance in four cultivation cycles of forage cactus clones.