

Effects of water stress on *Opuntia ficus-indica* under three different irrigation regimes

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Abstract

Opuntia ficus-indica (OFI) is a vital species in arid and semi-arid regions due to its economic, nutritional, and ecological benefits. As droughts become more severe, food production is increasingly threatened. This study aimed to assess the impact of water stress on the growth and productivity of OFI under various irrigation treatments in the semi-arid region of Coahuila, Mexico. The experimental design included four irrigation treatments with different soil moisture levels (T1: 31.67%, T2: 27.05%, T3: 19.37%, and a control irrigated to saturation) using the Atlixco variety. The variables measured—humidity percentage, plant temperature, OFI cladode temperature, soil temperature, and NDVI—showed no significant differences. However, cladode thickness, particularly at the tip and middle sections, increased under higher stress treatments, suggesting an adaptation to water scarcity. Cladode yield was significantly higher in T2 (5.71 kg) compared to the other treatments, indicating that OFI can sustain productivity under water-limited conditions.

Key words: Drought, opuntia, cladode, NDVI

Introduction

Opuntia ficus-indica (OFI) is the most economically important cactus species in the world. It is cultivated for its fruit, fodder, or as a host for the cochineal insect, but only in Mexico are its young cladodes consumed as a vegetable (Reyes-Agüero *et al.*, 2005). Additionally, prickly pear cladodes and fruits are extremely important for fermentation processes (Hamdi, 1997). *Opuntia* spp. is native to Mexico and well adapted to arid and semi-arid zones (Loukili *et al.*, 2024). In arid and semi-arid regions of the world, plants are often subjected to periods of water deficit during their growth and development (Talbi *et al.*, 2020).

All parts of the OFI cactus possess beneficial properties, whether as a vegetable, fruit, or fodder. Although traditionally recognized as a valuable health-supporting nutrient, the vegetative parts of *Opuntia* spp. plants are rarely used in modern nutrition and medicine (Stintzing and Carle, 2005). OFI cladodes and fruits are important sources of nutrients for both humans and livestock (Lahbouki *et al.*, 2022). Belonging to the *Cactaceae* family, OFI is valued for its physicochemical and nutritional composition, which provides several medicinal properties suitable for industries such as pharmaceuticals, food, and cosmetics (Martins *et al.*, 2023).

The true significance of these plants lies in their ability to produce strong, vigorous growth in arid and semi-arid climates, where few other crops can survive. They play a vital role in preventing soil erosion, inhibiting desertification, and providing protection for wildlife (Mohamed-Yasseen *et al.*, 1996). Specific *Opuntia* species have developed phenological, physiological, and structural adaptations that allow them to thrive in arid

environments, where severe water stress limits the survival of other plant species (Nefzaoui *et al.*, 2014). Additionally, some researchers have developed fast and reliable methods for analysing the shape and colour parameters of OFI cladodes using smartphones, colourimeters, and open-access software (Ali *et al.*, 2022).

Amid rising water scarcity and the uncertainties of climate change, enhancing crop water use efficiency and productivity while minimizing environmental impacts has become crucial to meet the growing global demand for food (Bwambale *et al.*, 2023). This issue is becoming more severe, with arid and semi-arid regions being the most vulnerable to drought. (Zarei, 2018). Droughts are natural hazards induced by a lack of rainfall that can alter vegetation density, especially in arid locations (Ahmadi *et al.*, 2019). The OFI cactus is a drought-resistant plant that thrives in dry, low-water conditions, making it a valuable resource for both fodder and vegetable production in arid regions (Najafinezhad *et al.*, 2024). However, further research is necessary to enhance its cultivation practices and produce cladodes of commercial quality.

This research aimed to evaluate the behaviour of cladodes under three stress conditions, measure the performance of each treatment, and determine the NDVI values between treatments. Additionally, the study aims to assess differences in morphological measurements and cladode thickness across treatments, as well as to measure the temperature parameters of the soil, mother plant, and cladodes, in order to observe any significant differences.

Material and methods

Plant material and experimental area: The mature paddles of the Atlixco variety of OFI were collected from the community of General Cepeda, Coahuila, Mexico, specifically in a town called ‘El Pilar.’ Its geographical coordinates are 25°23’0” N latitude and 101°27’20” W longitude, with an altitude of 1,502 meters. The study was conducted at the experimental station of the Antonio Narro Autonomous Agrarian University, located south of Saltillo, Coahuila de Zaragoza. The station’s coordinates are 25°21’00” N and 101°01’59” W, at an elevation of 1,786 meters above sea level (Fig. 1). The average annual temperature is 16.9°C, and the average yearly precipitation is 435 mm. Planting took place in January 2024.

Volumetric Water Content (VWC%): To determine the soil water content for each tension value, simultaneous measurements of the soil water content were made. These measurements were taken using a TDR (Time Domain Reflectometry) probe with 0.20 m long rods (model HydroSense II, Campbell Scientific, Inc., Logan, Utah, USA) and the average of five Irrrometer brand tensiometers, whose porous capsules were buried at a depth of

0.20 m. The measurements were made from saturation to a tension of 62 kPa. Fig. 2 shows the relationship between the soil water content (θ (% by volume) and the corresponding moisture tension.

Experimental design: The experimental design employed was a randomised block design with five replications. The soil was initially prepared by tillage, harrowing, and ploughing. T1, 31.67 VWC%; T2, 27.05 VWC%; T3, 19.37 VWC% and the control with irrigation until saturation every 10 days, with 5 repetitions. The experimental unit consisted of 10 plants. Irrigation was performed using a drip system with a 0.20 m spacing between drippers, a flow rate of 1.00 L h⁻¹, and an operating pressure of 1 atm. 45 plants were planted for each treatment. The cladodes used were manually removed starting at 12:00 hours for each measurement.

Temperature of the plant and the *Opuntia* cladode: The temperature of the plant and the cladode were measured using the infrared thermometer with the following specifications: 1mW maximum output, 670nm Wavelength, D:S = 8:1.

Soil temperature: This parameter was measured using a Spectrum Technologies, Inc. IR thermometer with a temperature range of -40 to 280°C (-40 to 536°F).

Normalised Differential Vegetation Index (NDVI): We used the Green Seeker Handheld Crop Sensor probe, an optical sensor that measures crop canopy reflectance (Yegül *et al.*, 2020). For the measurements, the probe was positioned at a 45° angle over each treatment line. The measurements were taken between 12:00 and 14:00 hours. The NDVI has been widely used in various studies, including those assessing nitrogen in rice cultivation (Ali *et al.*, 2020), as well as for monitoring and evaluating crop development using the GreenSeeker™ (Gaytán Martínez *et al.*, 2021).

The function (a second-order polynomial) and its coefficients are also shown (Fig. 2).

For measuring the percentage of humidity, a TDR 300 probe (Spectrum Technologies, Inc.) with 0.30 m long sensors was used. A reading was taken for each treatment during the measurement.

Cladodes thickness: the dimensions of the cladodes were measured using a Vernier calliper (Mitutoyo Model CD-6” ASX, Absolute AOS, Digimatic). Measurements were taken in millimetres at the base, middle, and tip of each cladode sample to determine its thickness.

Weight scale: A Silver 40 digital scale was used for weighing. Cladodes longer than 0.21 m were cut for each measurement, and the weight was recorded for each treatment. Cladodes were manually harvested, with this activity starting at 12:00 hours for each measurement.

Statistical analysis: The data obtained from the measurements were analyzed using analysis of variance (ANOVA) in Minitab version 2017. For the variables VWC%, nopal temperature (soil and plant), NDVI, and yield, Tukey’s multiple comparison test was performed ($p \leq 0.05$). For cladode thickness, a Least Significant Difference (LSD) mean comparison was conducted ($p \leq 0.05$).

Results and discussion

After maintaining the crop for five months and conducting periodic evaluations, the effects of stress on the cactus, along with other key variables, were analyzed using ANOVA, yielding the following results (Fig. 3).

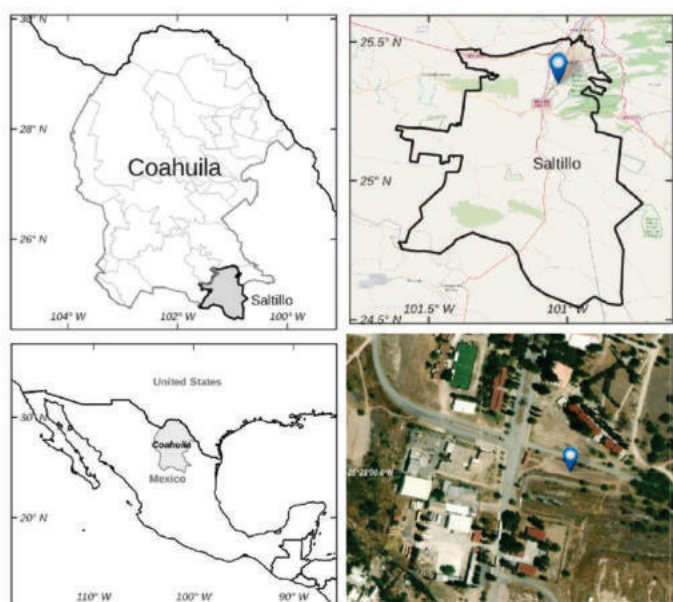


Fig. 1. Location map of the study area

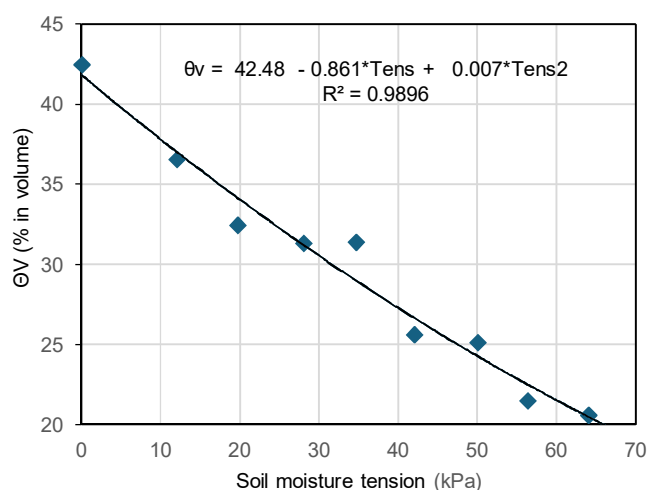


Fig. 2. Relationship between soil water content and the corresponding soil moisture tension at the study site.

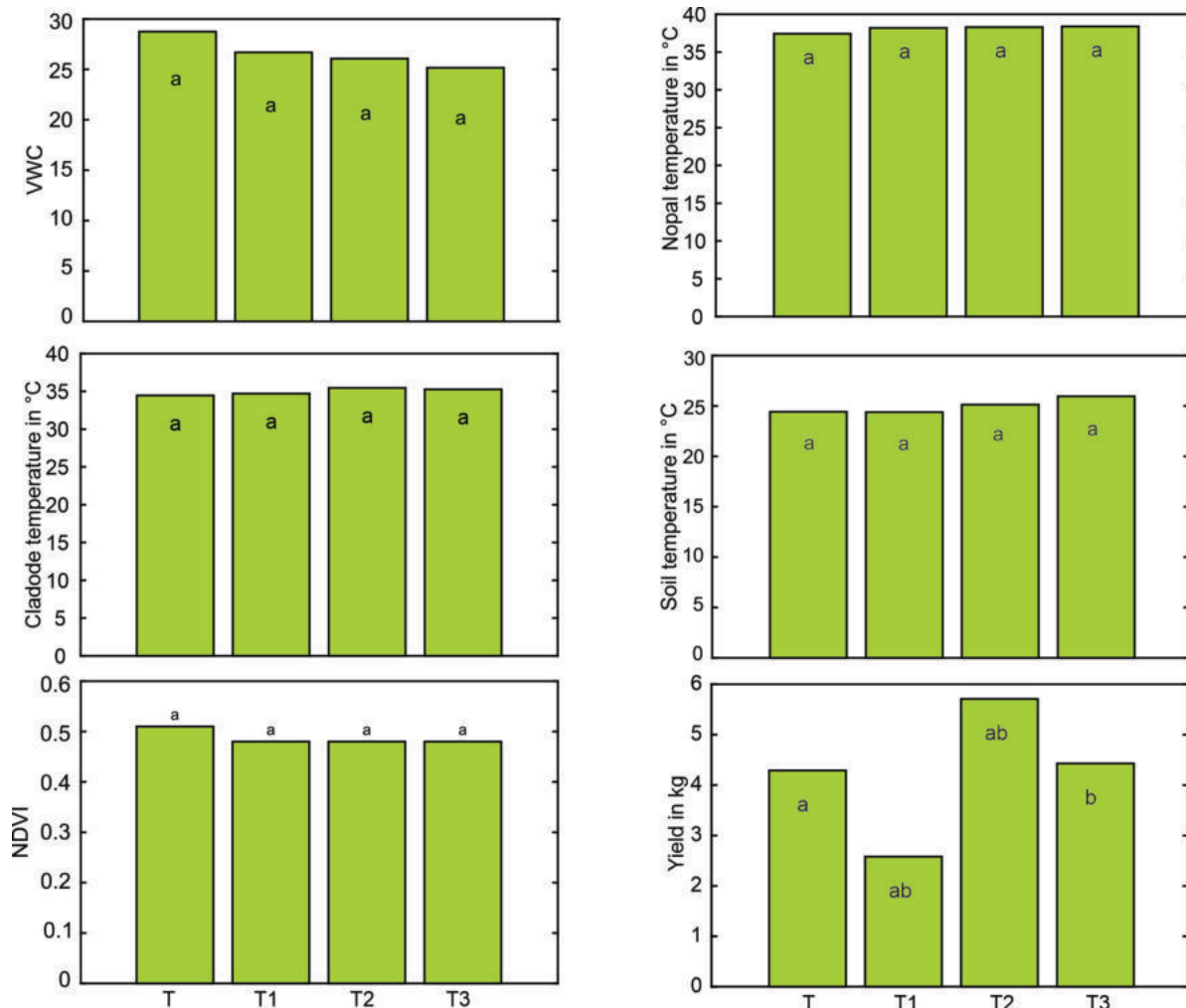


Fig. 3. Relationship between soil water content (a), nopal temperature (b), cladode temperature (c), soil temperature (d), NDVI (e), and crop yield (f) across treatments.

The percentage of water content in the ANOVA analysis showed a p -value of 0.190, indicating no significant difference between the treatments in terms of water percentage. Increasing water use efficiency (WUE) in agricultural systems, defined as the yield obtained per unit of water applied (Howell, 2001), is achievable through the use of appropriate irrigation scheduling (Buttaro *et al.*, 2015). In a study conducted by Lahbouki *et al.* (2022), the results showed that the growth, physiological, and biochemical parameters of cactus cladodes cultivated for 8 months were negatively impacted by drought. Due to their high productive performance, several studies have been conducted on cacti (*Opuntia* spp. and *Nopalea* spp.) in semi-arid environments, focusing on management practices and evaluating the effects of water deficit on crop growth and productivity (Kumar *et al.*, 2023).

Cladode temperature, prickly pear cactus vegetable temperature and soil temperature: The ANOVA for these variables suggests that none of the treatments significantly affected the temperature between treatments, including the temperature of the cactus ($P = 0.839$) and the temperature of the cactus vegetation ($P = 0.840$). The soil temperature also showed no significant effects, with a p -value of 0.473. The temperature did not vary between treatments, which is favourable since it has been found that there is a relationship between thickness and temperature (Schroeder, 1975). It has been evaluated whether

water availability and temperature influence the size of *Opuntia* cladodes, and it has been determined that there is indeed a relationship between cladode thickness and temperature variation (Scalisi *et al.*, 2016). This relationship is not exclusive to this variety; other species within the *Nopalea cochenillifera* group also exhibit similar traits. This species of the *Cactaceae* family is renowned worldwide for its tolerance to abiotic stress and its ability to survive in regions with low annual rainfall (250–450 mm) (Winter and Smith, 2022).

NDVI: The analysis of NDVI revealed a p -value of 0.300, suggesting that the treatments did not significantly impact the vegetation index. This sensor can measure the nutritional status of plants in real-time (Awad *et al.*, 2019). The NDVI measures light in two spectra: near-infrared (700–1000 nm) and visible red light (620–750 nm) (Karantzalos *et al.*, 2017). Its values range from 0.1 to 0.9, reflecting the energy absorbed (active photosynthetic radiation) by the plant's pigments (chlorophyll) and the light reflected by cellular structures (Wang *et al.*, 2003). The NDVI values, which reflect the greenness of the plants, remained similar across treatments, and the spectral index showed no significant differences. This suggests that the plants had a good photosynthetic rate, which helps estimate biomass, as noted by Jardim *et al.* (2023), who evaluated NDVI in *Nopalea cochenillifera* and obtained an average value of 0.19. In comparison, our crop yielded a value between 0.48 and 0.51.

These values help determine whether the vegetation is healthy or stressed, as values closer to 1 indicate optimal plant nutrition (Gaytán *et al.*, 2021).

Cladodes yield by treatment: In contrast to the previous variables, the performance analysis ($P = 0.011$) revealed significant differences between treatments. The Tukey test comparison of means revealed that treatment T2 (with a mean of 5.717) was significantly superior to the others, followed by T3 and T4 (with means of 4.433 and 4.259, respectively). Meanwhile, T1 (with a mean of 2.588) showed a significantly lower performance.

The results suggest that, overall, the treatments did not significantly alter the environmental conditions measured in this study. However, performance was influenced by the treatments, emphasizing the need to consider other unmeasured factors or characteristics that may affect performance. This is particularly important, as droughts impact the physiological and biochemical processes of plants, leading to alterations in their growth and development (Ait-El-Mokhtar *et al.*, 2020). Although our crop was subjected to water stress,

some treatments yielded results comparable to the control. In the study by Najafinezhad *et al.* (2024), different irrigation periods were evaluated: 9, 14, and 19 days in the first year; 14, 19, and 24 days in the second year; and 16, 21, and 26 days in the third year. The highest yield was observed with the 14-day irrigation period in the first year and the 16-day irrigation period in the third year. They concluded that this crop could be suitable for arid regions with water scarcity, which may explain the adaptation of plants in our experiment to water stress. In some cases, varying irrigation levels can enhance yields.

Thickness of cladodes: There were no significant differences in the thickness of the base of the cladode, with a p -value of 0.214. However, significant differences were observed in the thickness of the tip, where the control showed less thickness compared to the cladodes subjected to stress, with a P -value of 0.03. Additionally, in the middle section of the cladodes, T3 exhibited greater thickness than the other treatments, with a p -value of 0.01 (Fig. 4). In terms of performance, some treatments resulted in thicker OFI cladodes compared to the control. This may be attributed to the OFI ability to store water as a drought resistance strategy. Changes in cladode thickness can indicate dehydration or stress. With optimal irrigation, the plant accumulates water in the parenchymal tissue, forming a layer in the cladode that acts as a buffer against drought. Some treatments resulted in thicker OFI cladodes than the control, likely due to the plant's ability to store water, which helps it resist drought.

Our evaluations showed that the thickness of the cladode at the tip and middle was greater than that of the control, suggesting that, despite limited irrigation, the plant did not experience severe stress. Under optimal conditions, thickness typically ranges between 2 and 4 cm (Martins *et al.*, 2023). Bacarrillo-López *et al.* (2021) evaluated three *Opuntia* varieties under three different humidity levels, measuring the thickness, length, and width of the cladodes. Under unfavourable moisture conditions, the Chapingo, H. Escobar, and Narro varieties exhibited thickness values of 0.66 cm, 0.55 cm, and 0.53 cm, respectively. In contrast, T3 treatment yielded higher values across all measurements, suggesting that the variety used in our experiment has a greater capacity for water retention. Najafinezhad *et al.* (2024) evaluated the effect of drought stress on the yield and some morphological and agronomic traits of OFI in the Shahmaran region of Kerman, where three levels of stress were applied based on accumulated evaporation. The results for cladode thickness were 2.4 cm, 1.42 cm, and 0.9 cm for normal irrigation, moderate stress, and severe stress, respectively—values higher than those obtained in our experiment.

The results showed that despite water stress, the OFI successfully maintained consistent environmental parameters across all treatments. Significant differences in cladode thickness were observed, with certain treatments exhibiting greater thickness than the control. This is likely a result of the OFI ability to store water as part of its drought resistance strategy. Significant differences in yield were observed among the treatments, with T2 yielding the highest results. This can be attributed to the OFI high capacity for water retention and its adaptation to limited irrigation conditions. OFI is a drought-resistant species that can thrive in arid conditions. No significant differences were found in the NDVI between treatments, suggesting stable photosynthetic activity across all conditions. The NDVI values indicate that the plants maintained a healthy nutritional status, which is consistent with their ability to survive and grow under water stress. The temperature parameters of the

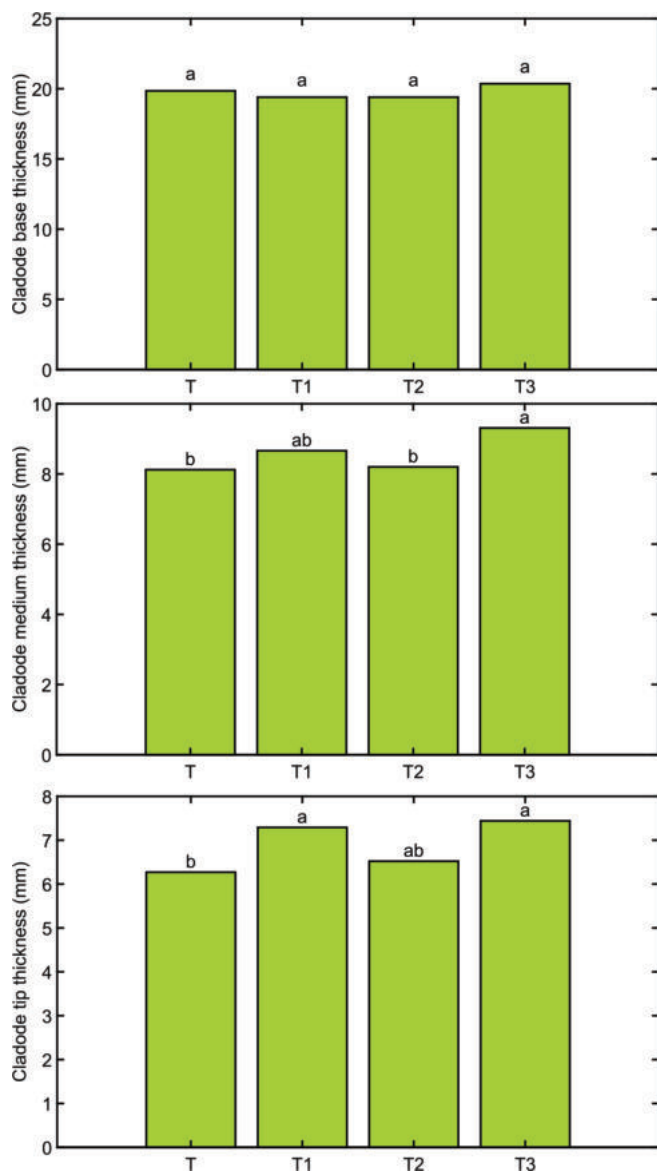


Fig. 4. Effect of water stress on cladode thickness at the base (a), tip (b), and middle (c) section.

soil, the mother plant, and the cladode did not show significant differences, indicating that these factors remained stable even under varying water stress conditions.

Conflict of interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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