ZEOLITE MODULATES SOIL PROPERTIES AND ENHANCES PLANT GROWTH AND FORAGE YIELD ON THREE NOPAL (*Opuntia* spp.) MORPHOTYPES UNDER LIMITED IRRIGATION

LA ZEOLITA MODULA LAS PROPIEDADES DEL SUELO Y MEJORA EL CRECIMIENTO DE LA PLANTA Y EL RENDIMIENTO FORRAJERO DE TRES MORFOTIPOS DE NOPAL (*Opuntia* spp.) BAJO RIEGO LIMITADO

Claudia González-Nieves, Aurelio Pedroza-Sandoval*, Fabián García-González, Ricardo Trejo-Calzada and Isaac Gramillo-Ávila

Universidad Autónoma Chapingo, Unidad Regional Universitaria de Zonas Áridas, Bermejillo, Durango, México.

**Corresponding author* (apedroza@chapingo.uruza.edu.mx)

SUMMARY

Nopal is a succulent plant with a crassulacean acid metabolism (CAM) pathway that allows it to adapt to dry environments. The study aimed to evaluate plant growth, cladode development and fresh forage yield responses to zeolite application in three nopal (*Opuntia* spp.) morphotypes under water deficit conditions. A randomized complete block design in a split-plot arrangement with three replicates was used. The main plots consisted of zeolite doses applied to the soil: 10 and 20 t ha^{-1}, and the control without application. The split plots were the nopal morphotypes identified as C-CH, C-NA and C-HE. Soil moisture content (SMC) was maintained at approximately 15.6 % above the permanent wilting point (PWP) (13 %) during the study period. Higher soil moisture contents were recorded in May, August and September 2024, associated with irrigation (May) and rainfall (August and September) with values of 15.4, 14.5 and 36.4%, respectively, compared to the control, where zeolite was not applied. Plant growth responses varied according to the zeolite dose and nopal morphotype. In the C-CH morphotype, plant height, width and thickness of cladode were larger in 15.3, 9.2 and 7.8 %, respectively, when applying 20 t ha^{-1} of zeolite at the first percentage value, and 10 t ha^{-1} in the second and third percentage values, and 15.3 % higher in fresh forage yield (FFY) when applying 20 t ha^{-1}, all this compared to the control, whereas the C-HE morphotype had a 35.1 % increase in cladodes per plant at 20 t ha^{-1} dose of zeolite compared to the control; the FFY in the C-NA morphotype is enhanced by increasing the zeolite dose. In conclusion, *Opuntia* spp. is a viable option for fresh forage production, and productivity can be significantly improved by applying a soil moisture retainer and biostimulant agent, such as zeolite, to mitigate water stress in drought conditions.

Index words: *Opuntia* spp., drought, fresh biomass yield, plant biostimulants, plant water stress.

RESUMEN

El nopal es una planta suculenta con metabolismo ácido crasuláceo (MAC) que le permite adaptarse a entornos áridos. El objetivo del presente estudio fue evaluar las respuestas de crecimiento de la planta, desarrollo de cladodios y rendimiento de forraje fresco a la aplicación de zeolita en tres morfotipos de nopal (*Opuntia* spp.) en condiciones de déficit hídrico. Se utilizó un diseño de bloques completos al azar con arreglo en parcelas divididas con tres repeticiones. Las parcelas principales fueron las dosis de zeolita aplicadas al suelo: 10 y 20 t ha^{-1}, y el control sin aplicación. Las parcelas chicas fueron los morfotipos de nopal identificados como C-CH, C-NA y C-HE. El contenido de humedad del suelo (CHS) se mantuvo aproximadamente en 15.6 % sobre el punto de marchitez permanente (PMP) (13 %). Se registraron mayores contenidos de humedad del suelo en mayo, agosto y septiembre de 2024, asociándolos con el riego (mayo) y las precipitaciones (agosto y septiembre), con valores de 15.4, 14.5 y 36.4 %, respectivamente, en comparación con el control, donde no se aplicó zeolita. Las respuestas de crecimiento de las plantas variaron según la dosis de zeolita y el morfotipo de nopal. En el morfotipo C-CH, la altura de la planta, ancho y grosor del cladodio fueron mayores en 15.3, 9.2 y 7.8 %, respectivamente, al aplicar 20 t ha^{-1} de zeolita en el primer valor porcentual, y 10 t ha^{-1} en el segundo y tercer valor porcentual, y 15.3 % mayor en el rendimiento de forraje fresco (RFF) al aplicar 20 t ha^{-1}, todo ello en comparación con el control, mientras que el morfotipo C-HE tuvo un aumento del 35.1 % en el número de cladodios por planta con dosis de 20 t ha^{-1} de zeolita en comparación con el control; el RFF en el morfotipo C-NA aumentó al incrementar la dosis de zeolita. En conclusión, *Opuntia* spp. es una opción viable para la producción de forraje fresco, y su productividad puede mejorarse significativamente mediante la aplicación de un retenedor de humedad del suelo y acción bioestimulante, como la zeolita, para mitigar el estrés hídrico en condiciones de sequía.

Palabras clave: *Opuntia* spp., bioestimulantes vegetales, estrés hídrico vegetal, rendimiento de biomasa fresca, sequía.

INTRODUCTION

In several agricultural regions with water scarcity, various technologies have proven effective for improving water management and crop productivity, including efficient irrigation systems (Ray and Majumder, 2024), rainwater harvesting, and the use of soil moisture retainers (Alharbi *et al.*, 2024). In addition, the cultivation of plant species tolerant to water deficit (Haghpanah *et al.*, 2024) and the application of organic and inorganic biostimulants to mitigate environmental stress on plants (Ramzan and Younis, 2022) represent important strategies for enhancing crop performance under limited water availability.

Among these alternatives, the use of aluminosilicates, contained in zeolite, has emerged as a promising technological option due to their beneficial effects on both soil properties and plant growth. It has been demonstrated

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that such compounds represent an innovative and viable technological alternative due to their beneficial effects on the soil and plant, promoting greater resilience in the agroecosystem by retaining water in the soil, improving nutritional status, and facilitating the acquisition of chemical elements by the plant. The chemical nature of zeolite consists of networks of silicon (Si) and aluminum (Al) tetrahedra that share oxygen at their vertices, thus forming cavities called channels. The chemical composition of a zeolite is represented by the following empirical formula: SiO_2 and AlO_2 (Villalba *et al.*, 2019). Due to its physical and chemical characteristics, it is considered a highly porous mineral, with properties that greatly enhance water retention in the soil and nutrient uptake in plants (Lira-Saldívar *et al.*, 2017). Tsintskaladze *et al.* (2017) pointed out that incorporating zeolite into the soil reduces the amount of fertilizer used by promoting efficient water use, as it retains and gradually releases water and nutrients. Zeolite creates a more stable soil moisture content, improving crop growth and development and increasing yield under adverse climatic conditions (Soca y Daza, 2015); furthermore, silicon is an element of nutritional importance for plants (Bhat *et al.*, 2019) and is associated with plant responses to biotic and abiotic stresses. Although aluminum is not an essential element for plants, there is evidence of effects such as increased plant growth and mitigation of biotic and abiotic stresses when applied at low concentrations (Sun *et al.*, 2020). Zeolite applications have been found to alleviate water stress and improve plant growth and yield of *Aloe vera*, as well as increase water use efficiency (Hazrati *et al.*, 2017).

North-central Mexico includes regions with varying degrees of aridity due to low rainfall and the influence of extreme temperatures, where the potential annual evaporation rate is up to 10 times higher than annual precipitation (Medina *et al.*, 2005). This region is one of the main agricultural and livestock areas of the country; however, water scarcity and water quality represent mayor constraints and are the main challenges faced by the production of forage crops required for dairy and meat cattle (Pedroza-Parga *et al.*, 2022). One option is the use of crops adapted to dry environments; some cactus species, including nopal, offer an alternative for animal consumption as fresh fodder (Pérez-Sánchez *et al.*, 2015).

Nopal is a succulent plant with CAM photosynthetic pathway that allows to adaptat to the environmental stress conditions typical of arid zones (Bacarrillo-López *et al.*, 2021). Also, the use of biostimulant products such as zeolite allows the plant to maintain its growth and productivity under water deficit and high temperatures (Melero-Meraz *et al.*, 2022). Nopal is widely distributed in Latin America, South Africa, Mexico, and Mediterranean countries. Mexico is the world's leading producer of nopal, accounting for approximately 36 % of total production (Ponce-Luna *et al.*, 2024). The genus *Opuntia* shows a high biodiversity, with about 150 native species reported to the country, of which almost 60 % are concentrated in the states of Chihuahua and Sonora, as well as in the valleys of Querétaro and Hidalgo (González *et al.*, 2024). Currently, the area of nopal harvested in Mexico covers 12,365 hectares with a production of 872,000 Mg (SIAP, 2023). The main challenge for nopal cultivation in arid zones is the limited availability of water throughout the year due to increased droughts by climate change (Hultine *et al.*, 2023). The objective of this study was to evaluate the effect of zeolite on plant growth, cladode development and fresh forage production in three nopal (*Opuntia* spp) morphotypes under water deficit conditions.

MATERIALS AND METHODS

Geographic location of the study area

The study was conducted at the experimental field of URUZA-UACh in Bermejillo, Mapimi, Durango, Mexico, located between 24° 22' and 26° 23' N latitude, 101° 41' and 104° 61' W longitude, at an altitude of 1,100 m. The region has a dry climate with Summer rainfall and cool Winters, with a mean annual temperature of 21 °C. Average annual precipitation is 258 mm, and potential evaporation averages 2,000 mm (Medina *et al.*, 2005). Rainfall during the experimental period was recorded using a microclimate station (Model 6162, Davis Instruments, Hayward, California, USA) located approximately 600 m from the experimental area.

Plant material

The nopal (*Opuntia* spp.) morphotypes used in this study belong to URUZA-UACh Nopal Germplasm Bank located in Bermejillo, Durango, Mexico. This germoplasm bank contains 55 accessions collected from different ecological regions of the country, including the State of Mexico, San Luis Potosí, Coahuila, Aguascalientes and Zacatecas (Flores, 1994). Currently, the three nopal accessions have been identified using ID keys: C-CH, C-NA, and C-EH (Figures 1A, 1B, and 1C, respectively). These morphotypes are propagated asexually by planting cladodes.

Physicochemical characterization of zeolite

Zeolite is a granular inorganic compound extracted from a mineral mine in the State of Chihuahua, northern Mexico. It contains four macronutrients (N, P, K and Ca), two micronutrients (Fe and Mn), and high concentrations

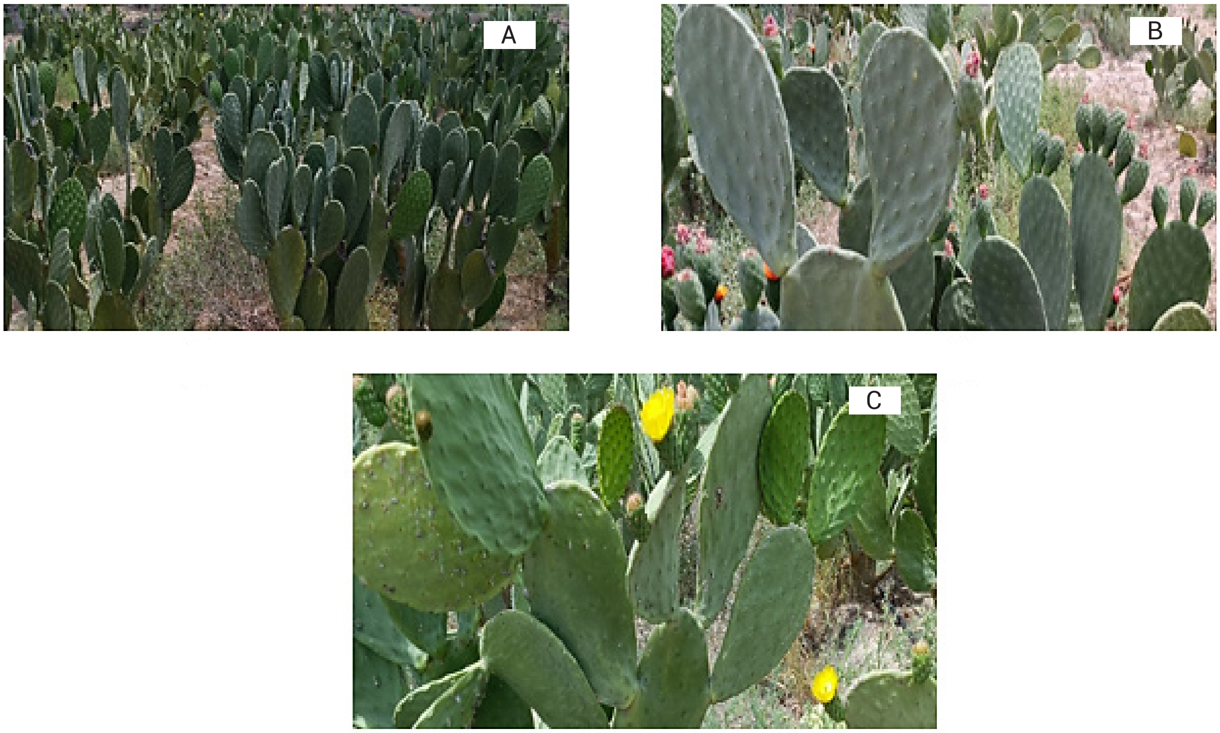

Figure 1. Accessions of nopal named through ID: A) C-CH, B) C-NA, C) C-HE.

of aluminum and silicon, both recognized as favorable nutrients with multiple benefits (Kaur *et al.*, 2023).

Experimental design and treatments

The experiment was established using a randomized complete block design with a split-plot arrangement and three replicates. The main plots corresponded to zeolite doses applied to the soil: 10 and 20 t ha^{-1}, plus the control without zeolite application. The split plots were the nopal morphotypes, identified as C-CH, C-NA and C-HE. The experiment had a total of nine treatments, arranged as a 3 × 3 factorial. The experimental unit consisted of two beds with two rows of nopal plants per bed, measuring 8 m long and 3.4 m wide in both beds. The experiment was conducted in an established plantation with an age of five years. The crop was planted in double row, spaced 0.85 m within beds and 1.7 m between beds, and a spacing of 50 cm between plants in a 3-plant cluster arrangement, corresponding to a planting density of 6,667 plants per hectare.

Irrigation system set up

The experiment was conducted with supplemental irrigation to maintain a maximum moisture content of 15.6 %, equivalent to 2.6 % above the PWP. This study aimed to evaluate the effect of zeolite on soil moisture retention capacity under water deficit conditions and its nutritional impact, as well as the differential response of nopal morphotypes to this treatment. Soil moisture constants were previously determined using the membrane pot method according to the methodology provided by Richards (1948), where FC corresponded to a moisture of 27 % moisture, and PWP 13 % in clay-loam soil. A main sprinkler system was installed with a 2.54 cm PVC pipe, with a stopcock to control irrigation times. Each main plot was controlled by a stopcock, this allowed irrigation to be timed through lines in each row of nopal independently at a flow rate of 3 L h^{-1} per dripper. Soil moisture content was measured monthly using a digital meter (Model MO750, Extech Instruments Co., Laredo, Texas, USA) with real-time readings. After the initial irrigation that standardized soil moisture to field capacity (FC), soil moisture was allowed to decrease from 27 to 11.5 %; subsequently, supplemental irrigation was applied to restore soil moisture to 15.5 ± 1.5 %.

Measured variables

Plant height was measured using a measuring tape. Cladode length and width were determined by measuring the vertical and horizontal midsections of the cladode, respectively, also with a measuring tape. Cladode thickness was measured with a Vernier caliper. In addition, the number of cladodes per plant and fresh biomass production (g) were recorded at the time of harvesting the cladodes using a digital scale (CHIMADZU AW320, Kyoto, Japan). All variables were evaluated at the end of the experiment, in November 2024, corresponding to 260 days after the experiment establishment.

Data analysis

The effects of treatments were evaluated by analysis of variance (ANOVA) and Tukey tests ($P \leq 0.05$). Statistical analyses were performed using SAS version 9.0, and graphics were generated with Microsoft Excel version 7.0.

RESULTS

The annual rainfall recorded from January to December 2024 was 216.4 mm, lower than the regional annual average (258 mm). The months with the highest rainfall were July, August and September, with 93.2, 39.2 and 44.2 mm, respectively. The temperature ranged from -2.9 °C in December to 39.48 °C in June (Figure 2).

Soil moisture content (SMC)

Zeolite had significant effects ($P \leq 0.05$) on the soil moisture retention capacity. This effect was associated with water availability from irrigation or rain. In May, the application of 20 t ha^{-1} allowed the soil to retain 14 % more moisture as compared to the control (15.4 vs. 13.5 %). Also, in August and September, the treatment of 10 t ha^{-1} of zeolite increased soil moisture content up to 24.6 and 39.9 %, respectively, compared to the control. During the months of June, July, October and November, when only supplementary irrigation was applied, there was no significant difference in SMC between the zeolite treatment and the control. They only exception was July, the rainiest month; however, because the rainfall occurred at the end of the month, its effect was reflected until August (Table 1).

Plant and cladode growth

Plant height was statistically greater ($P \leq 0.05$) in the C-CH morphotype, reaching 152 cm at a 20 t ha^{-1} dose, which represented a 25.6 % increase compared to the C-NA morphotype under the control treatment (no zeolite application), where the lowest plant growth was recorded. An intermediate effect was observed in the three nopal morphotypes when 10 t ha^{-1} were applied (Figure 3A).

Cladode thickness showed significant differences ($P \leq 0.05$) between treatments. The highest value was recorded in morphotype C-CH (0.96 cm) when 10 t ha^{-1} of zeolite were applied. The C-NA and C-HE morphotypes, without zeolite application, exhibited lower thickness with values of 0.70 and 0.71 cm, respectively, which represents a 37.1 % increase in the C-CH morphotype, compared to the other two morphotypes. Treatments receiving 20 t ha^{-1} of zeolite showed an intermediate value (Figure 3B).

The length and width of cladodes varied in response to the treatments. A slight increase in cladode length was observed in the C-HE control and C-CH when 10 t ha^{-1} were applied, with values of 32.4 and 31.8 cm, respectively. The remaining treatments had intermediate values, ranging from 28.7 to 30.9 cm. A similar trend was observed in cladode width, with a slightly higher response in the C-CH morphotype when 10 t ha^{-1} of zeolite were applied, while the most negatively affected morphotype was C-NA when 20 t ha^{-1} were applied (Figure 3C).

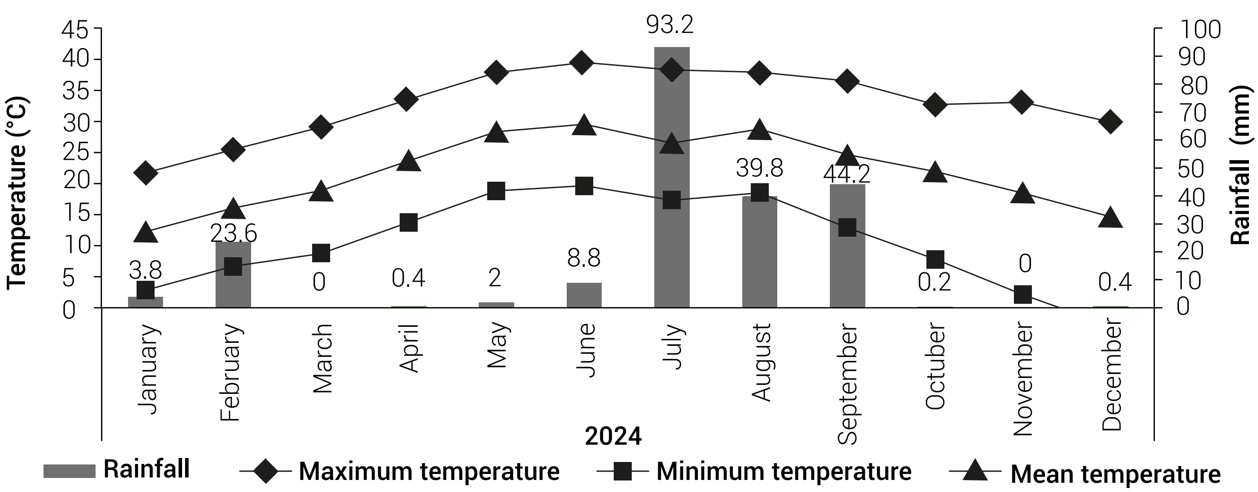

Figure 2. Average Rainfall and mean, maximum and minimum temperature recorded at a weather station located 600 m from the open field experimental area from January to December 2024. Bermejillo, Durango, Mexico.

Table 1. **Eeffect of zeolite application on soil moisture retention during the 2024 growing season. Bermejillo, Durango, Mexico.**

Treatment	Soil moisture content (%)						
	May	June	July	August	September	October	November
Control (No zeolite)	13.5 ab	22.1 a	19.0 a	11.6 b	26.0 b	10.8 a	7.1 a
	± 1.54	± 1.56	± 3.62	± 2.71	± 4.04	± 2.58	± 1.7
Zeolite (10 t ha^{-1})	13.0 b	23.0 a	19.6 a	14.5 a	36.4 a	11.1 a	8.0 a
	± 1.36	± 2.08	± 2.45	± 1.26	± 10.35	± 1.9	± 1.44
Zeolite (20 t ha^{-1})	15.4 a	23.3 a	17.0 a	12.7 ab	30.8 ab	9.5 a	7.9 a
	± 2.22	± 1.47	± 4.44	± 2.49	± 10.52	±0.65	± 0.47

Tukey's test (P ≤ 0.05). Means with the same letters within the same column are statistically equal. Values after ± are standard deviations.

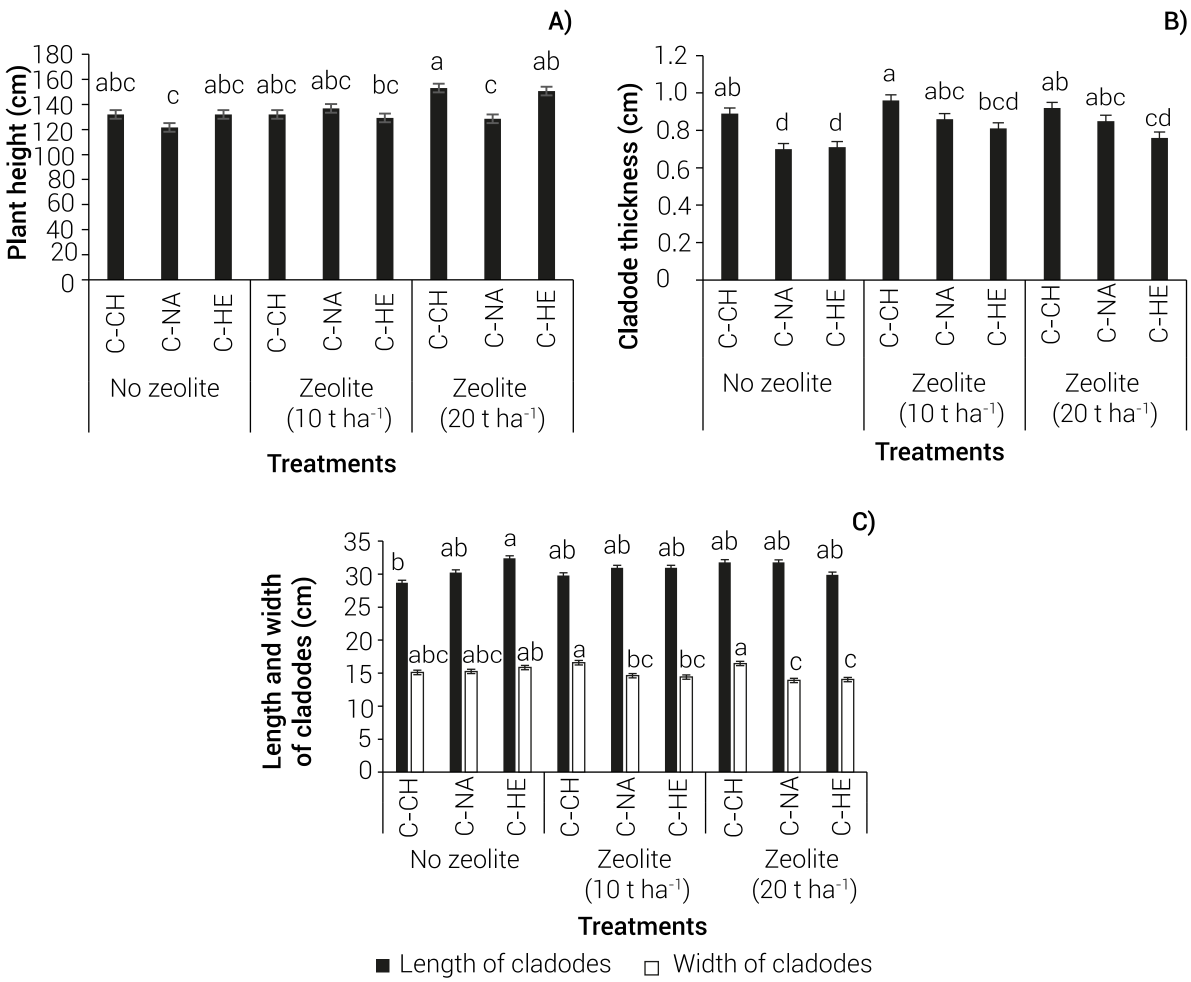

Figure 3. A) Plant height, B) cladode thickness, C) cladode length and width of three morphotypes of nopal (*Opuntia* spp.) at different doses of zeolite under water stress conditions. Tukey test (P ≤ 0.05). Means with the same letters on the bars are not statistically different.

Number of cladodes and fresh biomass production per plant (FBPP)

The number of cladodes per plant is one of the variables most closely associated with fresh biomass production and largely depends on genotype rather than environmental conditions, which in this study were represented by soil moisture content influenced by zeolite application. The number of cladodes tended to increase with increasing zeolite rates applied to the soil. The highest response was observed when 20 t ha^{-1} were applied to the C-HE morphotype, which produced 40.8 cladodes per plant. This value represents an increase of 68.6 % compared to the C-CH morphotype without zeolite application, which produced 24.2 cladodes per plant. Intermediate values were obtained when 10 t ha^{-1} were applied to the three morphotypes (Figure 4A). Morphotype C-CH recorded a significantly higher yield ($P \leq 0.05$) with a value of 292.2 g of FBPP when applying 20 t ha^{-1} of zeolite, compared to the C-NA morphotype, which recorded 224.1 g of FBPP when no zeolite was applied. The difference means 30.4 % more FBPP than C-NA under control conditions (Figure 4B).

DISCUSSION

The prevailing climatic conditions during the 2024 experimental period were suitable for conducting the study under water deficit stress. Total rainfall did not exceed the historical annual average of the region (258 mm) as reported by Medina *et al.* (2005). The highest precipitation (216.4 mm) was recorded between late July and September. These conditions are particularly relevant for studies conducted in arid regions, as they allow a better understanding of plant responses and tolerance to environmental stress, particularly water deficit (Seleiman *et al.*, 2021).

Soil moisture content

Soil moisture content ranged from 11.5 to 16.5 %, with an average of 14 %. The initial irrigation that increased the soil moisture to FC (27 %), and subsequent rainfall events showed that zeolite increased soil moisture when the soil water content was above 16%, but there was no effect when moisture was close to PMP (13 %). This suggests that zeolite can best act as a retainer of soil moisture from medium to high water content in the soil, exceeded 16%, whereas no effect was detected when soil moisture approached permanent wilting point (PMP, 13 %). These results suggest that zeolite acts more effectively as a soil moisture retainer under moderate to high soil, water content. As a result, greater moisture retention occurs when soil water content is closer to FC, whereas this retention effect diminishes as soil moisture approaches PMP, where the mean moisture content becomes similar to that of the control. Inadequate soil moisture content affects nutrient availability and the uptake of macro- and microelements by plants; therefore, their growth and development are affected (Solgi *et al.*, 2018).

Cladode development and nopal growth

Overall, plant growth assessed through indicators such as plant height, length, width and thickness of cladode

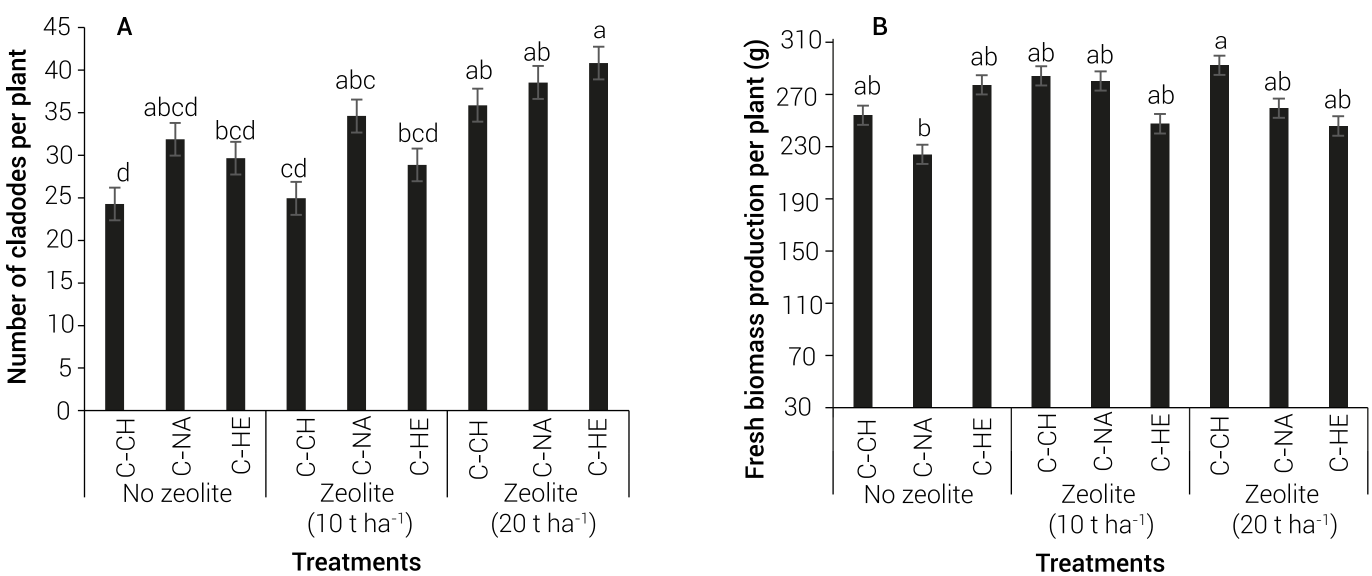

Figure 4. A) Number of cladodes per plant, and B) fresh biomass production per plant of three nopal morphotypes (*Opuntia* spp.) grown under different zeolite doses applied to the soil. Means followed by the same letters on the bars are not significantly different (Tukey, $P \leq 0.05$).

responded favorably to zeolite application under limited irrigation conditions. During the evaluation period, the average soil moisture content was 15.6 %, which was slightly higher (by 2.6 %) than the PWP (13 %). Zeolite application at either of the two doses evaluated in this study (10 and 20 t ha^{-1}) maintained its water retention capacity in the soil, promoting nutrients availability and uptake by plants (Lira-Saldívar *et al.*, 2017; Tsintskaladze *et al.*, 2017); however, the trend was more effective at the dose of 10 t ha^{-1} of zeolite, rather than applying 20 t ha^{-1}, since in some cases the latter dose was not valuable. Obregón-Portocarrero *et al.* (2016) found in maize (*Zea mays*) an increase in leaf area and root volume at dosages of 10 t ha^{-1} of zeolite under water stress. This suggests that dosages higher than 10 t ha^{-1} of this inorganic compound could negatively affect some nopal cultivars as reported by Aslan and Arslan (2024), who showed that high doses interfere with the normal uptake of nitrogen and phosphorus, decreasing the growth of plant tissue.

Furthermore, an interesting zeolite-genotype interaction was observed. The C-NA nopal morphotype showed a significantly lower plant height ($P \leq 0.05$) at 20 t ha^{-1} of zeolite, equivalent to the value obtained in the control (no zeolite application), compared to the highest height recorded in the C-CH morphotype at the same zeolite dosage; the C-HE morphotype had an intermediate behavior to the two morphotypes mentioned before. These results are higher than those reported by Ferreira *et al.* (2003), who showed height values ranging from 70 to 122 cm in nopal forage *Opuntia* ficus-indica Mill. This effect can be caused by a strong environment-genotype interaction, referred to a water stress induced by water deficit (Riyaz *et al.*, 2025).

In regard to the development and growth of nopal cladode, the thickness and width in the C-CH morphotype showed a better response to the application of 10 t ha^{-1} of zeolite, contrary to the cladode length, where the C-NA morphotype obtained the highest value with the dose of 20 t ha^{-1} at 32.65 cm. Pérez-Sánchez *et al.* (2015) showed a greater cladode length in *Opuntia* ficus-indica with 42 cm, a thickness and width of 1.6 mm and 14.5 cm, respectively; however, *Opuntia atropes* recorded values of 26.2 cm in length, 12 cm in width and 1.8 mm in thickness under drought conditions. Muñoz-Urias *et al.* (2008) and Hernández-Urbiola *et al.* (2011) found that morphological differences between nopal of the same species, but different ecotypes, may be due to environmental effects, such as soil moisture, temperature, light, type and fertility of the soil. In this study, the direct influence was the availability of water and nutrients produced by zeolite, under water deficit conditions by different mechanisms such as those related to secondary metabolism as well as production of phenolic and polyamine compounds due to the beneficial action of silicon (Si) (Ahanger, *et al.*, 2020; Khan *et al.*, 2019), and aluminum (Al) contained in zeolite (Kaur *et al.*, 2023); in particular, Al at low concentrations increases plant growth by mitigating biotic and abiotic stresses (Sun *et al.*, 2020).

Number of cladodes and fresh biomass production per plant (FBPP)

The number of cladodes per plant is strongly associated to fresh biomass production. The C-HE morphotype showed the highest number of cladodes when 20 t ha^{-1} of zeolite were applied, reaching 40.83 cladodes per plant. Similarly, López *et al.* (2013) reported 43.5 cladodes per plant in an ecotype identified as NDV. These results suggest that this trait is determined by genotype, rather than environmental conditions, although genotype × environment interactions may also influence its expression, as reported by Li *et al.*, (2016).

Fresh biomass weight is the most representative variable in terms of forage importance, it varied depending on the nopal morphotype and the dose of zeolite applied. The interaction of C-CH morphotype - 20 t ha^{-1} recorded the highest FBPP, while C-NA - Control (not applying zeolite) produced the lowest FBPP. In addition, C-NA and C-HE morphotypes recorded a better FBPP response by applying 10 t ha^{-1} compared to 20 t ha^{-1}, this suggests that FBPP is strongly influenced by interaction between genotype and application of moderate doses such as 10 t ha^{-1} of zeolite, while high doses of zeolite, such as 20 t ha^{-1}, negatively affected nopal plants (Hazrati *et al.*, 2017; Tsintskaladze *et al.*, 2017). Bacarrillo-López *et al.* (2021) reported a similar trend with strong genotype-environment interaction in some growth for forage yield under suboptimal soil moisture content and different nopal morphotypes; this means that with moderate doses of zeolite and the use of nopal genetic materials tolerant to water shortages, the biostimulant effect of zeolite is shown by increased moisture retention in the soil, better availability of nutrients and greater uptake of macro- and microelements by the plant, improving its growth, development and productivity (Bhat, *et al.*, 2019).

The main findings indicate that zeolite applied at moderate doses of (10 t ha^{-1}) may be sufficient to mitigate water stress in nopal plants during the dry season; however, in condictions of very low soil moisture, close to or below PWP due to severe drought, the beneficial effects of zeolite diminish, and plant growth, development and productivity are adversely affected. The application of zeolite may have a great effect on water availability and nopal fresh forage production by managing the irrigation system that allows suboptimal soil moisture conditions; nevertheless, the cultivar is an important factor that must be considered to maximize these benefits.

CONCLUSIONS

Nopal plant height, as well as cladode length, width, thickness and fresh forage yield were improved with the application of zeolite, which acts as a soil moisture retainer and modulates the nutrient supply for the plant. The treatment effect varied depending on the interaction between nopal morphotypes and zeolite doses. A moderate rate of 10 t ha^{-1} of zeolite produced the best response for most of these variables in C-NA and C-HE morphotypes. In addition, when 20 t ha^{-1} were applied, the C-CH morphotype increased by 30.4 % compared to morphotype C-NA without zeolite. The findings of this study allow to conclude that the use of zeolite applied at moderate doses in regions with scarce water availability is a viable alternative that mitigates plant stress, increasing the production of fresh nopal forage during periods of drought in arid zones.

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