Asian Journal of Agriculture and Biology
https://doi.org/10.35495/ajab.2025.313

Original Article

Effect of natural zeolite on water use efficiency, growth, and yield of tomato under drought conditions

Mysoon Alamro*
National Agricultural Research Centre (NARC), Al Mashqar Agricultural Research Center, Madaba West Street, Amman, Jordan

**Corresponding author's email:* mysoon.alamro@gmail.com
Received: 30 November 2025 / Revised: 03 February 2026 / Accepted: 09 February 2026 / Published Online: 17 February 2026

Abstract

Climate change and induced droughts are limiting crop production, especially in arid regions like Jordan, requiring urgent need for strategies that improve water use efficiency in agriculture. This study, therefore, investigated the use of natural Jordanian zeolite as a soil amendment to improve soil moisture retention, plant growth, and yield of tomato plants (*Lycopersicon esculentum*) under limited water conditions in pot experiments. A two-season trial was conducted with four irrigation intervals, watering every 2, 4, 6, or 8 days, and five zeolite application doses; zeolite: soil ratios of 0:1, 1:0, 1:1, 1:2, and 1:3 by volume. Average results from both seasons showed that changing irrigation intervals from 2 to 8 days significantly reduced soil moisture, from 18% to 13% in the first season, and increased soil temperature from 21°C to 23.5°C, adversely affecting plant growth and yield. Zeolite amendments improved soil water retention by up to 3-4%, reduced soil temperature by 1-3°C under drought, and increased plant height, leaf area, and chlorophyll fluorescence indices compared to non-zeolite soil. The results also indicate that a 1:3 zeolite to soil ratio produced higher plant height, larger leaf area, and 20-40% higher fruit yield under deficit irrigation than the control which received no zeolite. Water use efficiency was improved with reduced watering frequency and was further enhanced by zeolite; the 1:3 treatment achieved the highest WUE, producing more yield per unit water. On the other hand, excessive zeolite (1:1 mix) did not improve yields on clayey soil. Therefore, incorporating a suitable proportion of natural zeolite into soil can mitigate drought stress and sustain tomato production while conserving irrigation water.

Keywords: Arid region agriculture, Drought, Irrigation frequency, Soil amendment, Water use efficiency, Zeolitic tuff

How to cite this article:

Alamro M. Effect of natural zeolite on water use efficiency, growth, and yield of tomato under drought conditions. Asian J. Agric. Biol. 2026: e2025313. DOI: https://doi.org/10.35495/ajab.2025.313

Introduction

Drought is one of the rising issues for agriculture, particularly in arid and semi-arid regions. Climate change has intensified this issue by increasing temperatures, changing rainfall patterns, and increasing evapotranspiration, all of which reduce soil incident moisture and crop productivity (Cataldo et al., 2021b; Malhi et al., 2021; Porter, 2005; Cataldo et al., 2021a). Many regions of the world face drought conditions, but Jordan ranks among the most water-scarce countries globally, with limited renewable water resources and rising demand from both population growth and agriculture. Agriculture alone consumes over two-thirds of Jordanian freshwater (Alfarra et al., 2011; Ibrahim and Alghamdi, 2021). Improving water use efficiency per unit crop and area, in agriculture is therefore critical to sustaining crop production and conserving scarce water supplies (Xiubin and Zhanbin, 2001; Roghani et al., 2016).

Irrigation and water reuse and recycle have long been used to address these challenges (Madi and Elshazly, 2021), however, improving soil moisture retention within the soil is equally important and implementable. There are different approaches used to conserve soil moisture, among which one approach involves utilization of naturally occuring soil amendments that reduce water loss through evaporation and ensure moisture availability to plants. Natural zeolites, which are characterized as microporous aluminosilicate minerals, are promising in this context due to their ability to hold water and nutrients within their structure and release them gradually to plant roots (Javaid et al., 2024; Polat et al., 2004). Their high surface area and cation exchange capacity (CEC) allow zeolites to act as both water reservoirs and nutrient holders (Belviso, 2025).

Literature has shown that adding zeolite to soil can increase soil water-holding capacity significantly, natural zeolites can retain up to 40–60% of their weight in water due to their porous crystalline structure, effectively increasing available moisture in amended soils compared with non-treated soils (Cataldo et al., 2021b). Using zeolite as soil additive has also showed reduced nutrient leaching, where the cation exchange capacity of zeolites helps capture the nutrients (Wang et al., 2025). For example, a recent study found that fertilizers when coated with zeolite showed retention of up to 85% of sulphate ions when compared with traditional sources of sulphur (Mondal et al., 2021). Such characteristics of zeolite ultimately help nutrient holding within the soil alongside enhancing water holding capacity, so that plants are capable of growing under drought or water limiting conditions (Ferretti et al., 2024).

Different researchers have documented similar benefits, where zeolite application in loess soils showed better water holding by soil, even under different drying periods in comparison with non-zeolite treatments Xiubin and Zhanbin (2001). Soil water conservation helps store water and nutrients within the rootzone (Zougmoré et al., 2004). Another study in aloe vera showed that water use efficiency was higher where zeolite was applied; showing 22.1 g of biomass per litre of water through application of 10 tonnes of zeolite per hectare (Hazrati et al., 2017). Similar results have also been observed in barley (Al-Busaidi et al., 2011), beans (Ozbahce et al., 2015) and tomatoes (Zhang et al., 2023) where, applications of different quantities of zeolite have showed better soil moisture and enhanced crop yields (V et al., 2025) . The response was found linked with soil texture, type and crop plants (Javaid et al., 2024).

Keeping in view the available information, Jordan's agriculture and soils struggling with lower soil moistures and nutrient retentions are very relevant to zeolite application (Dwairi, 1998). There are different zeolite types found in the country which include chabazite, phillipsite, to name a few. Available information asks for utilization of zeolite as a soil amendment to enhance soil moisture and crop yields, especially for tomatoes which face water shortage issues. Hence, this study was planned with the objectives of assessing the effects of zeolite on soil moisture and temperature under different irrigation intervals, and quantifying the impact on tomato growth, yield, and water use efficiency (WUE) under semi-arid Mediterranean conditions.

Material and Methods

Experimental site and soil characteristics

The experiment was conducted at the Al-Mushagar Research Station of the National Agricultural Research Center (NARC) in central Jordan (Latitude: 32°4'45" Longitude: 35°50'36"), for two consecutive growing seasons (spring-summer of 2024 and 2025), keeping the same soil and pot conditions for both the seasons. The climate of the experimental site is semi-arid Mediterranean, characterized by hot, dry summers. The trial was set up outdoors in large plastic

pots; the pot diameter was 41.5 cm, and pot height was 34 cm.
The soil used in the pots was a local agricultural clay loam, which is dominant soil type in the target region. A composite sample of the topsoil (0-15 cm depth) was analysed prior to the experiment. The soil's initial properties were: pH 7.9, electrical conductivity 0.81 dS m^{-1}, organic matter 1.4%, total nitrogen 0.11%, available phosphorus 11.5 mg kg^{-1}, and exchangeable potassium 604.9 mg kg^{-1}.

Experimental design and treatments

A split-plot experimental design was employed, with four irrigation interval treatments as main plots and five soil zeolite levels as sub-plots within each irrigation treatment. Each treatment combination had four replicates (in a randomized complete block arrangement of pots).

Irrigation frequency (main plot)

Tomato plants were irrigated at intervals of 2, 4, 6, or 8 days between watering. Each irrigation event applied a consistent volume of water sufficient to fully wet the pot's soil (until slight drainage, to ensure field capacity was reached). It is noteworthy here that gravimetric replenishment based on pot weight could estimate evapotranspiration, however, due to large pot size; weighing individual pot was not possible. Likewise, the practice of applying fixed volume is the practice in the field, so that was preferred. Over an 8-week period, this meant that the total number of irrigations (and thus total water applied per plant) varied substantially: from very frequent watering (every 2 days, 28-30 irrigations per season) to very infrequent (every 8 days, 7-8 irrigations per season). These irrigations and watering regimes imposed increasing levels of drought on the plants, especially the 6- and 8-day intervals.

Zeolite characterization

The zeolite used in this study was sourced from Jordan via a local supplier. Table 1 represents the physiochemical properties of zeolite.

Table-1. X-ray fluorescence analysis of Jordanian zeolite used in the experiment.

Fe2O3 %	MnO %	TiO2 %	CaO %	K2O %	SO3 %	P2O5 %	SiO2 %	Al2O3 %	MgO %	Na2O %	L.O.I %
10.20	0.135	1.69	9.07	0.776	0.07	0.66	41.50	12.90	7.11	1.11	14.35

Zeolite amendment (sub-plot)

Natural zeolite (clinoptilolite-rich tuff, composition shown in Table 1), sourced from Jordan, was ground to sand-sized particles (approximately 1-6 mm) for soil mixing. Five soil treatments were prepared:

- Control (0:1), 100% soil (no zeolite).
- Z1:0, 100% zeolite (no soil, purely zeolite as the growing medium).
- Z1:1, 1:1 volume ratio of zeolite: soil (50% zeolite by volume).
- Z1:2, 1:2 ratio (33% zeolite, 67% soil by volume).
- Z1:3, 1:3 ratio (25% zeolite, 75% soil by volume).

These soil + zeolite mixtures were thoroughly mixed and used to fill the pots. The rationale for including a pure zeolite treatment (Z1:0) was to observe the effects of zeolite alone on plant growth and water dynamics.

Each pot was planted with one tomato seedling. The tomato cultivar 'Revenant', known for its performance in the region was used. Seedlings at the 4-5 true leaf stage were transplanted into the pots in early spring each year. Standard agronomic practices were followed, and pots were kept weed-free. No mulch was used, to allow natural soil evaporation.
Notably, in the second season (2025), tomatoes were replanted into the same pots without replacing the soil or zeolite. This was done to observe any cumulative effects of the zeolite in the substrate from the previous year, e.g., improved soil structure or nutrient build up. However, to avoid nutrient depletion confounding the results, additional fertilizer was applied to replenish soil fertility as needed based on soil tests or standard practice.

Data collection

Soil moisture: Just before each scheduled irrigation, i.e., at the end of each drying cycle, soil volumetric moisture content (%) was measured in each pot using a digital soil moisture meter (ECDAD Electronics Co., Amman, Jordan). The probe was inserted to a 10 cm depth near the center of the pot, avoiding the immediate root zone to get a representative reading of soil moisture available to the roots. This provided a consistent measure of the lowest soil moisture reached under each irrigation regime (since right after irrigation the soil would be at field capacity). Readings were taken throughout the season and averaged, and particular attention was paid to weeks with peak flowering/fruiting when limited water effects would be most pronounced.

Soil temperature was recorded at a 10 cm depth in each pot using a Checktemp digital soil thermometer (Hanna Instruments HI98501, Romania).

Morphological traits: The height of each tomato plant was measured at 8 weeks after transplanting, mid-way through the fruiting stage. Similarly, three fully expanded leaves per plant (from the mid-canopy position) were sampled at mid-season and their leaf area was measured. ImageJ software (NIH, USA) was used to calculate leaf area after photographing the leaves against a scale. Furthermore, chlorophyll fluorescence parameters were measured on intact leaves using a Handy PEA fluorimeter (Hansatech Instruments Ltd., UK). Measurements were taken pre-dawn (for dark-adapted Fv/Fm readings) on one young but fully expanded leaf per plant. The fluorescence induction curve was recorded for each sample, from which the maximum quantum yield of PSII (Fv/Fm), and Performance Index (PI_ABS) were determined.

Tomato fruits were harvested gradually as they ripened (at least 75% of the fruit surface turning red). Harvests occurred twice weekly from around 6 weeks after transplant until the end of the season (12 weeks). At each harvest, fruits from each plant were counted and weighed. Likewise, total fruit number per plant, marketable and non-marketable fruit number, total yield per plant, and average fruit weight were measured. Additionally, Fruit diameter (in mm) was measured for a representative sample of 5 fruits per plant to measure fruit size; the average fruit diameter per treatment is reported.

Water use efficiency (WUE)

Water use efficiency was calculated at the plant level as the ratio of total fresh yield (g per plant) to the total volume of irrigation water applied (L per plant) over the season (Payero et al., 2008). Since each irrigation event delivered the same volume (for example, if each pot received 2 L per irrigation), plants watered every 2 days received substantially more water than those watered every 8 days. WUE (g/L) thus provides a measure of how efficiently each plant converted water into economic yield. Higher WUE indicates more yield output per unit water input, which is desirable under water-limited conditions. WUE was computed for each replicate, and treatment means were compared.

Statistical analysis

All measured variables were subjected to analysis of variance (ANOVA) appropriate for the split-plot design, using Statistix 10 software (Analytical Software, USA). Since seasons were analyzed separately, season was treated as a fixed factor. Irrigation interval (4 levels) was considered a fixed main factor, zeolite level (5 levels) as a fixed sub-factor, and season (2 years) was also analyzed where applicable (though for clarity, seasons are sometimes presented separately when interactions were significant). Replicates (blocks) were considered random effects. For each season, two-way ANOVAs (Irrigation × Zeolite) were performed when data were analyzed season-wise. Where ANOVA indicated significant effects ($p < 0.05$), treatment means were compared using Fisher's Least Significant Difference (LSD) test at the 5% significance level. All statistical comparisons mentioned are at $p < 0.05$ unless otherwise stated. Data are presented as means ± standard deviation (SD) where appropriate.

Results

Soil moisture content: Soil moisture content was significantly affected by irrigation frequency, zeolite amendment, and their interaction in both seasons ($p < 0.001$,
Figure-1).

Irrigation frequency: Soil moisture declined progressively as irrigation intervals increased (Figure 1). In Season 1, mean soil moisture before irrigation decreased from 16.4% (2-day) to 12.9% (8-day). A similar pattern occurred in Season 2, with corresponding values of 17.9% and 14.5%, respectively. Moisture levels in Season 2 were consistently 1-2% higher than Season 1 across treatments.

Zeolite amendment: Across irrigation regimes, zeolite significantly increased soil moisture retention ($p < 0.001$). The Z1:3 treatment consistently recorded the highest moisture (16.3% in Season 1; 17.9% in Season 2), while the control had the lowest (13.5% and 15.0%, respectively). Pure zeolite and intermediate mixtures showed intermediate values.

Interaction: The irrigation × zeolite interaction was highly significant ($p < 0.001$). Differences among zeolite treatments were small under frequent irrigation but pronounced under long intervals. At the 8-day interval in Season 1, soil moisture dropped to 8.5% in the control but remained 12% in Z1:3; in Season 2, corresponding values were 10.1% and 14%. Thus, Z1:3 under an 8-day interval maintained moisture comparable to the control at a 6-day interval, indicating a buffering effect of zeolite (Figure 1).

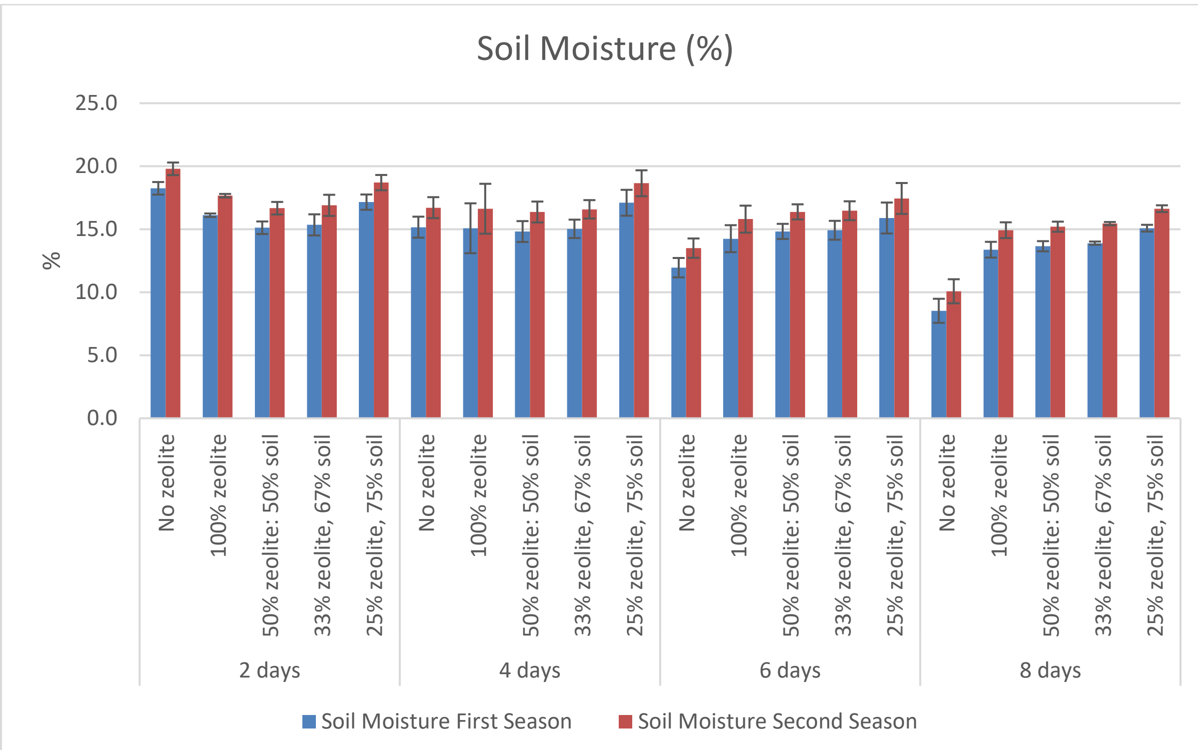

Figure-1. Soil moisture content (%) in tomato plots under different irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

Soil temperature: Soil temperature at 10 cm depth was significantly influenced by irrigation frequency and its interaction with zeolite in both seasons (
Figure-2).

Irrigation frequency: Increasing irrigation intervals led to higher soil temperatures. In Season 1, temperature increased from 21.1°C (2-day) to 23.5°C (8-day) ($F = 58.27$, $p < 0.0001$). Season 2 showed a similar but weaker trend (22.8-23.8°C; $p < 0.0001$).

Zeolite amendment and interaction: In Season 1, zeolite effects were modest ($p < 0.0005$), with pure zeolite showing slightly higher temperatures than the control. In Season 2, the effect was stronger ($p < 0.0001$), with all zeolite-amended soils cooler than the control; Z1:3 was the coolest (22.5°C). The irrigation × zeolite interaction was significant in both seasons (Season 1 $p < 0.05$; Season 2 $p < 0.0001$), particularly under long irrigation intervals. At the 8-day interval in Season 2, soil temperature reached 26.1°C in the control but remained 23.0°C in Z1:3 (Figure 2).

https://doi.org/10.35495/ajab.2025.313

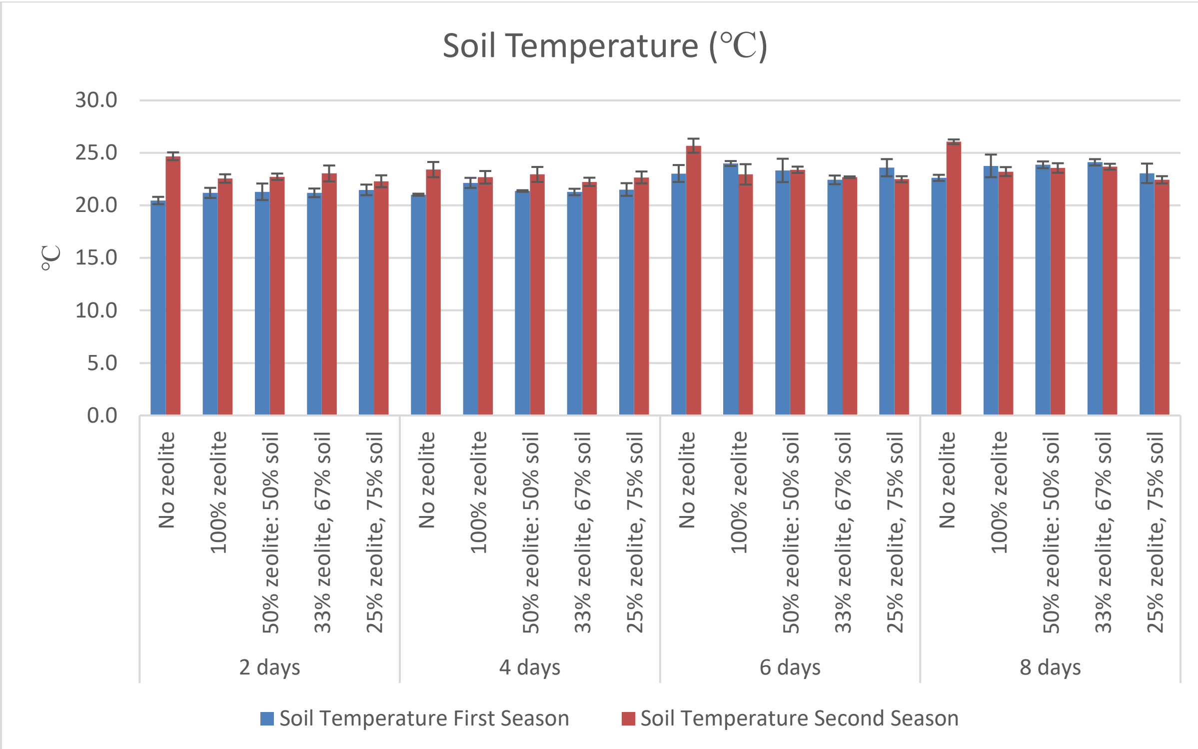

Figure-2. Soil temperature (°C) at 10 cm depth under varying irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

Vegetative growth characteristics

Plant height: Plant height was significantly affected by irrigation, zeolite, and their interaction in both seasons (Figure-3).

Irrigation frequency: In Season 1, plant height declined from 38.2 cm (2-day) to 32.4 cm (8-day) ($p < 0.0001$). In Season 2, the reduction was from 40.9 cm to 33.1 cm ($p < 0.0001$).

Zeolite amendment: Zeolite effects were significant in both seasons (Season 1 $p < 0.01$; Season 2 $p < 0.0001$). In Season 1, Z1:1 produced the tallest plants (36.1 cm), while pure zeolite resulted in the shortest (32.9 cm). In Season 2, Z1:3 gave the greatest height (41.3 cm), outperforming the control and higher zeolite proportions.

Interaction: Under frequent irrigation, treatment differences were small, whereas under 8-day irrigation zeolite-amended plants maintained greater height than the control (Season 1 $p < 0.05$; Season 2 $p < 0.05$).

https://doi.org/10.35495/ajab.2025.313

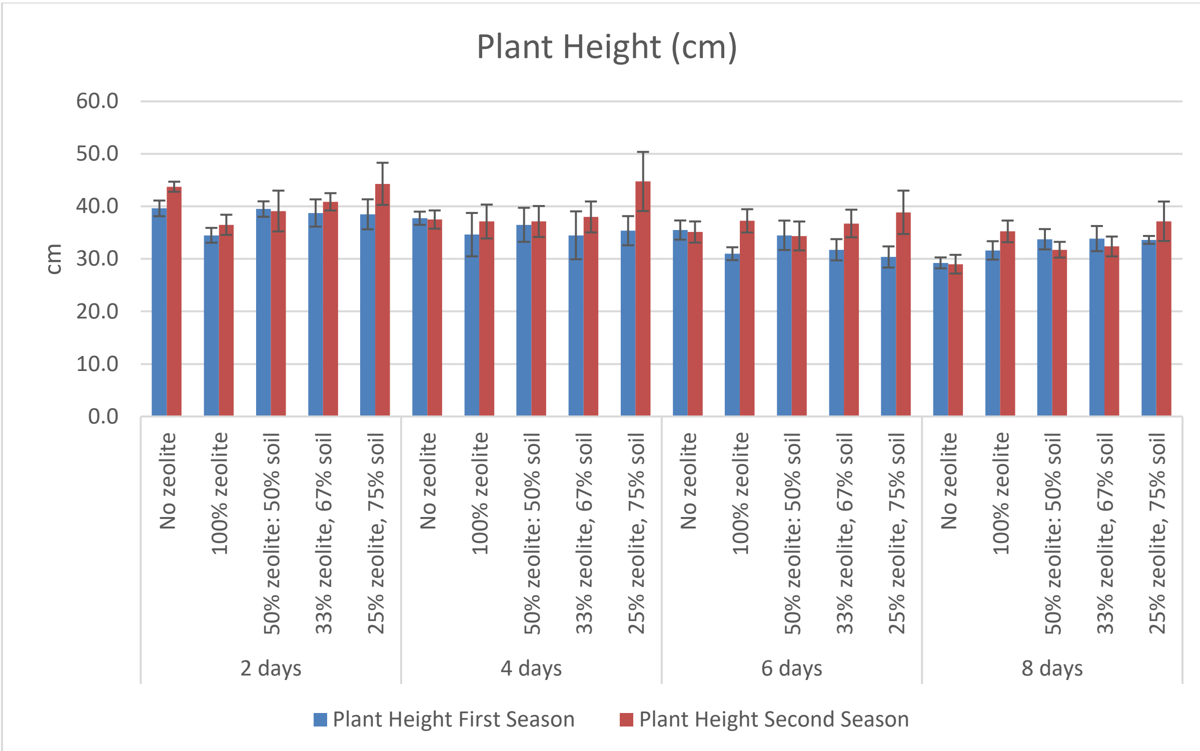

Figure-3. Plant height (cm) of tomato plants as affected by irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

Leaf area: Leaf area showed strong responses to irrigation, zeolite, and their interaction in both seasons (Figure-4).

Irrigation frequency: Severely limited water sharply reduced leaf area. In Season 1, leaf area declined from 72.9-77.5 cm^2 (2-4 day) to 42.7 cm^2 (8-day) ($p < 0.0001$). In Season 2, leaf area declined from 152.7 cm^2 (2-day) to 101.2 cm^2 (8-day).

Zeolite amendment: Zeolite significantly increased leaf area ($p < 0.0001$). In both seasons, Z1:3 consistently produced the largest leaves (68.9 cm^2 in Season 1; 151.1 cm^2 in Season 2), while the control had the smallest.

Interaction: Zeolite effects were amplified under limited water (Season 1 $p < 0.0001$; Season 2 $p < 0.001$). Under 8-day irrigation in Season 2, leaf area was 46.8 cm^2 in the control but 120 cm^2 in Z1:3 (Figure 4).

Chlorophyll fluorescence measurement

Maximum quantum yield (Fv/Fm): Fv/Fm was primarily influenced by irrigation in Season 1 ($p < 0.05$, Figure-5) but not by zeolite or interaction (Figure 5). Values declined from 0.76-0.77 (2-4 day) to 0.72 at the 8-day irrigation interval. In Season 2, Fv/Fm values were uniformly lower (0.69-0.71), with no significant treatment effects.

Performance index (PI_ABS): PI was more responsive to stress than Fv/Fm (Figure-6). In Season 1, irrigation significantly affected PI ($p < 0.001$), which declined from 2.65 (2-day) to 1.32-1.37 (6-8 day). Zeolite had no significant main effect. In Season 2, irrigation alone was not significant, but the irrigation × zeolite interaction was significant ($p < 0.01$). Across intervals, zeolite-amended treatments had higher PI (1.3-1.4) than the control (0.92), indicating improved photochemical performance under stress.

https://doi.org/10.35495/ajab.2025.313

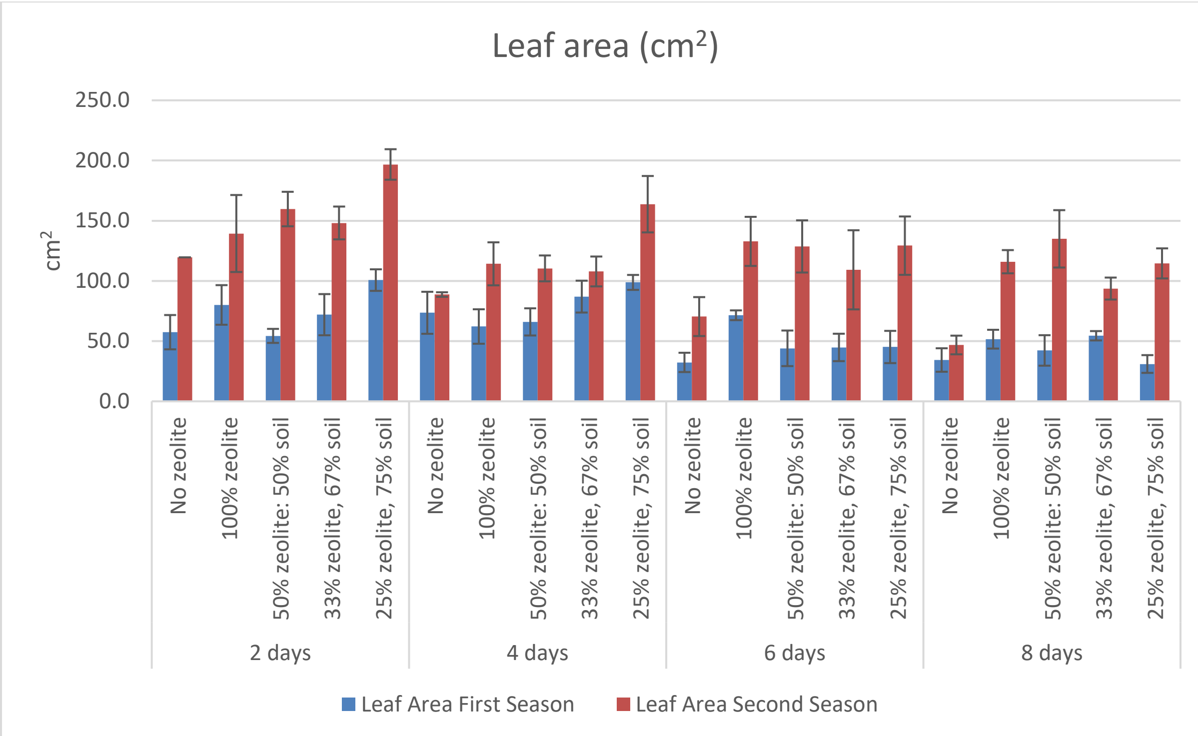

Figure-4. Leaf area (cm²) per plant under different irrigation intervals and zeolite levels.
Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

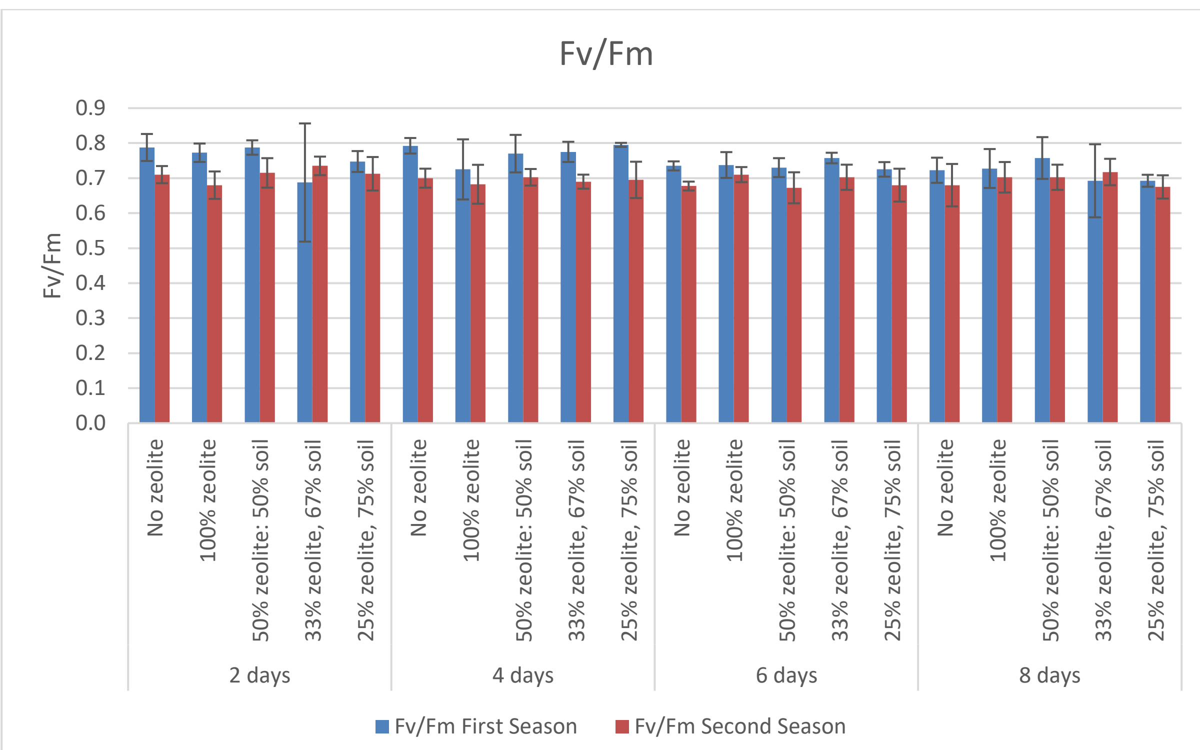

Figure-5. Maximum quantum yield (Fv/Fm) of tomato leaves under different irrigation and zeolite treatments.
Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

https://doi.org/10.35495/ajab.2025.313

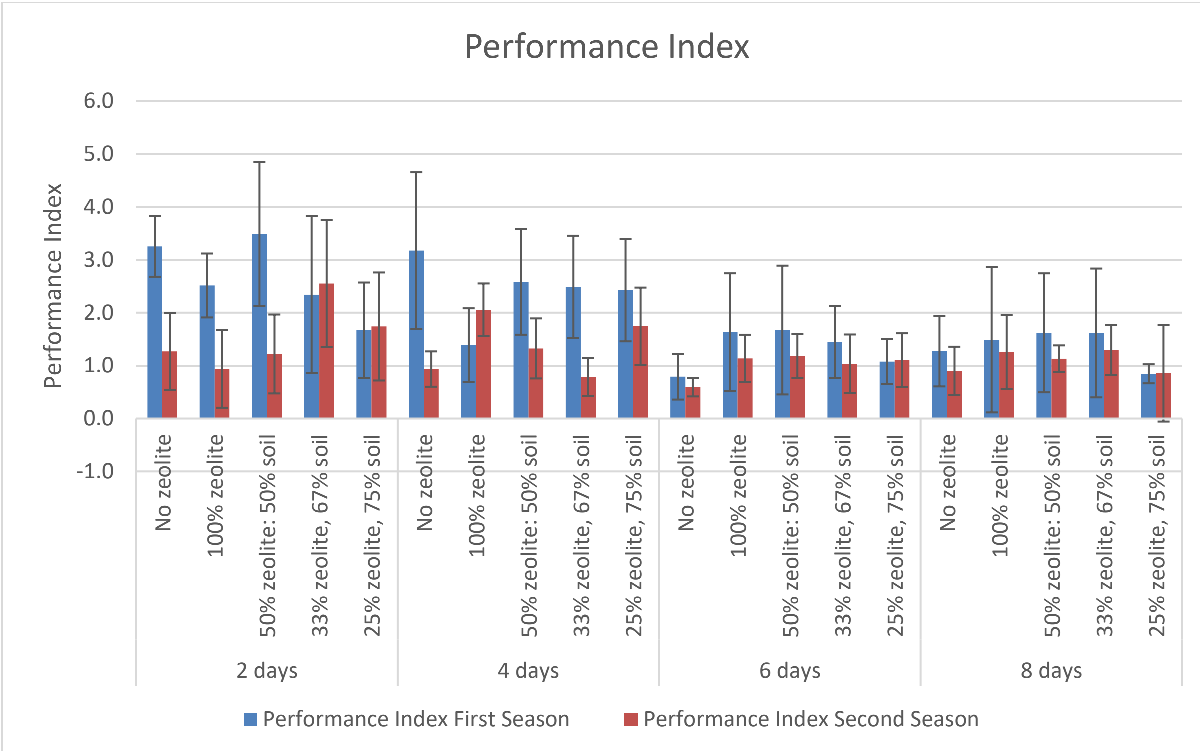

Figure-6. Performance Index (PI) of tomato plants under different irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

Yield, fruit quality and water use efficiency

Fruit yield and number

Effect of irrigation frequency**:** Tomato fruit yield and fruit number were strongly reduced as irrigation intervals increased (Figure-7 and Figure-8). In Season 1, yield declined from 613.4 g plant^{-1} (2-day) to 265.5 g plant^{-1} (8-day), a 57% reduction ($p < 0.001$). Fruit number followed the same pattern, decreasing from 29.8 fruits plant^{-1} (2-day) to 15.3 fruits plant^{-1} (8-day) ($p < 0.001$). In Season 2, yield remained higher overall but still declined significantly from 924 g plant^{-1} (2-day) to 580 g plant^{-1} (8-day) ($p = 0.0008$), and fruit number decreased from 39 to 25 fruits plant^{-1} across the same intervals.

Effect of zeolite amendment: Zeolite significantly affected yield and fruit number in both seasons ($p < 0.01$), but responses were not strictly proportional to amendment rate. Across irrigation levels, Z1:3 and the control produced the highest yields, whereas Z1:2 consistently recorded the lowest yield and fruit number. Pure zeolite (Z1:0) and higher proportions (e.g., Z1:1) generally produced intermediate values.

Interaction (irrigation × zeolite): The interaction between irrigation and zeolite was significant for yield and fruit number ($p < 0.05$), indicating that zeolite effects were more evident under longer irrigation intervals. Under severe deficit irrigation (8-day), Z1:3 consistently maintained higher yield and fruit number than the control, whereas under frequent irrigation (2-day), the control often achieved the maximum yield potential (Figure 7 and Figure 8).

https://doi.org/10.35495/ajab.2025.313

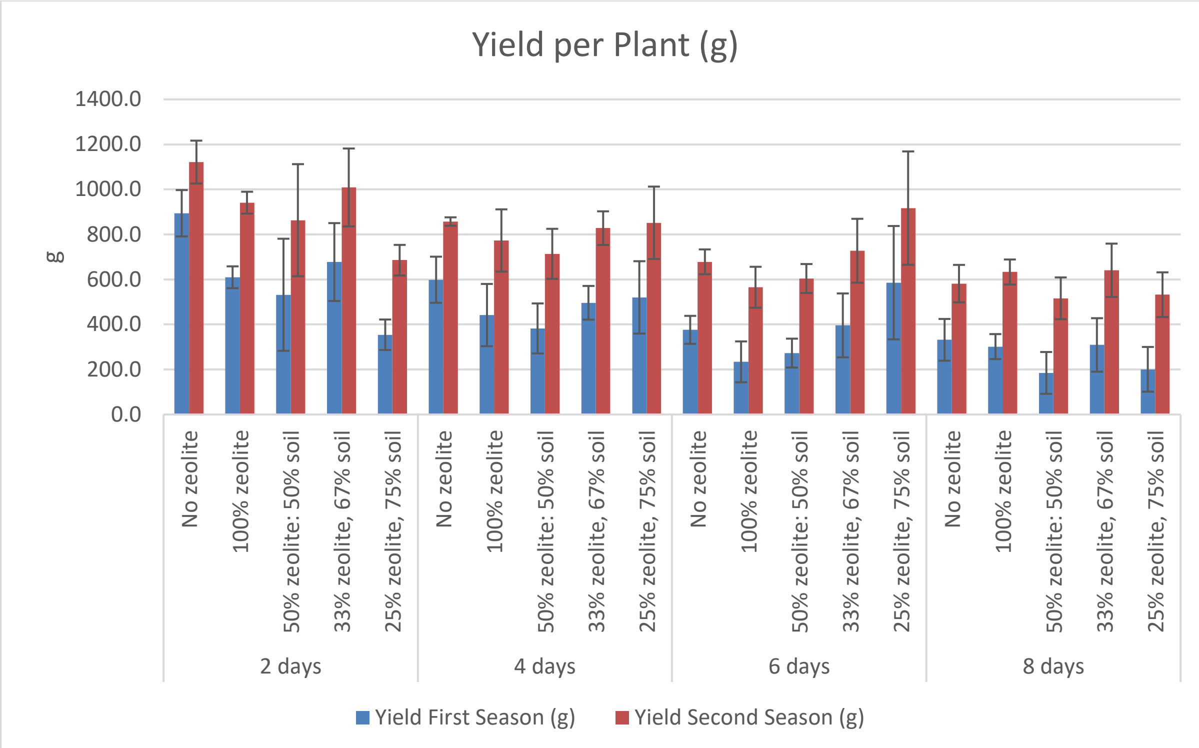

Figure-7. Fruit yield per plant (g) under different irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

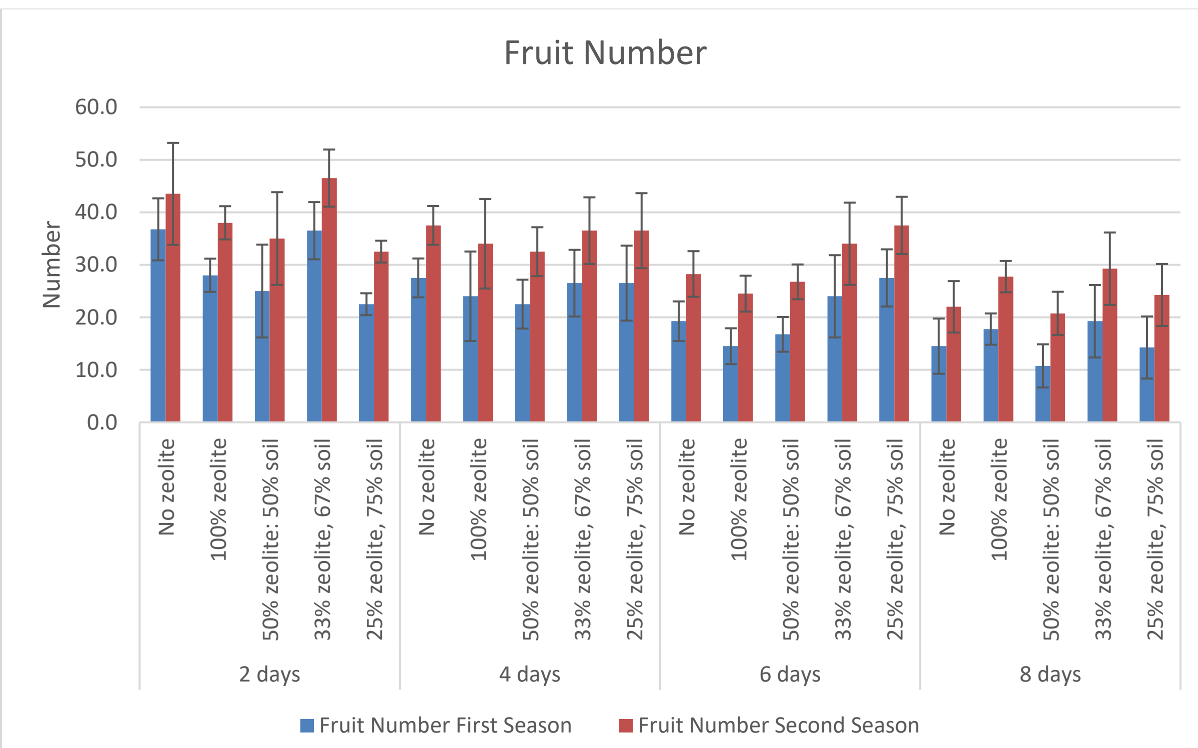

Figure-8. Total fruit number per plant under different irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

https://doi.org/10.35495/ajab.2025.313

Fruit quality (size and marketability)

Marketable vs unmarketable fruit: Limited water significantly reduced marketable fruit number ($p < 0.001$) (Figure-9 and **Figure-10**). In Season 1, marketable fruit declined from 27.3 fruits plant^{-1} (2-day) to 13.8 fruits plant^{-1} (8-day). In Season 2, the same decreasing trend occurred, with the highest marketable fruit numbers observed under frequent irrigation (particularly in combinations involving Z1:3). Zeolite generally increased marketable fruit number, with Z1:3 producing the highest marketable fruit counts among zeolite treatments, while Z1:2 tended to be lowest. The interaction effect on marketability was not significant, indicating that zeolite mainly influenced marketable output by increasing total fruit number rather than changing the proportion of marketable fruits.

Fruit size (diameter): Fruit diameter was moderately affected by irrigation interval, with significant reductions mainly at the longest interval ($p < 0.05$) (Figure-11). In Season 1, fruit diameter was 34-35 mm under well-watered treatments and decreased to 29.4 mm at the 8-day interval. In Season 2, fruit diameter was slightly larger overall (2-day 35.7 mm) and again declined under 8-day irrigation (30-32 mm). Zeolite effects on fruit size were smaller than irrigation effects, but Z1:3 (and in some cases Z1:2) tended to maintain slightly larger diameters than the control under deficit irrigation.

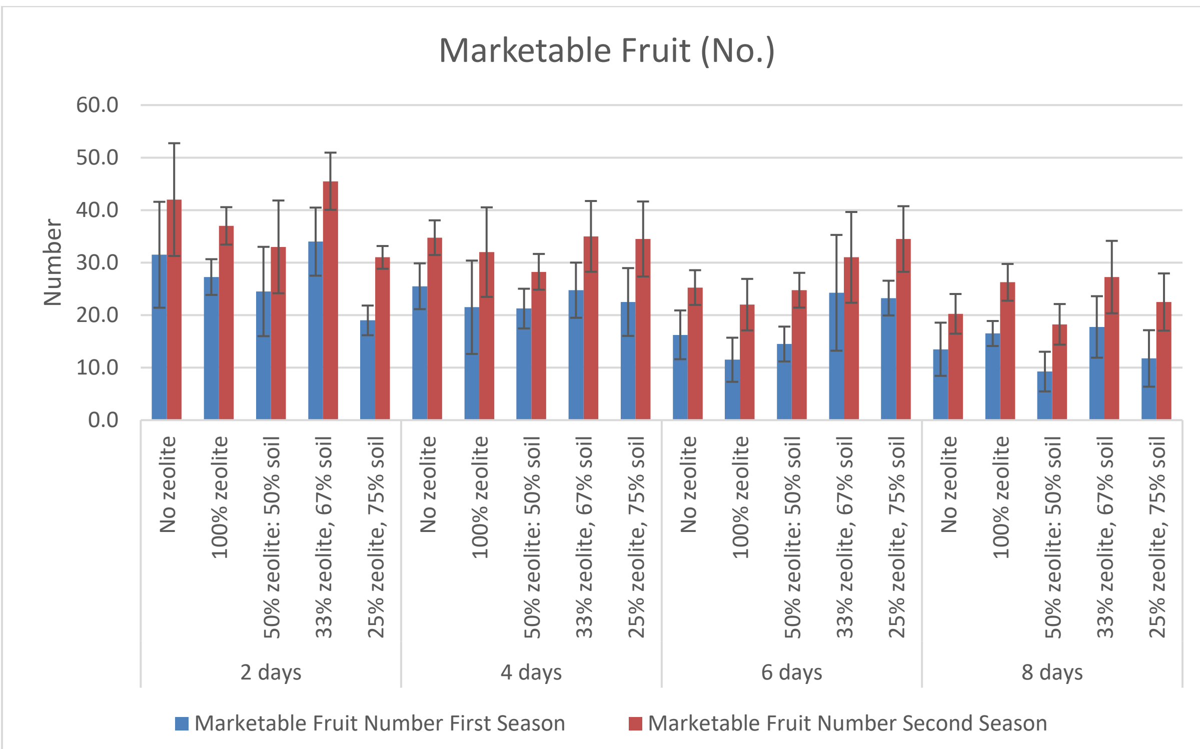

Figure-9. Marketable fruit number per plant of tomatoes grown under various irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

https://doi.org/10.35495/ajab.2025.313

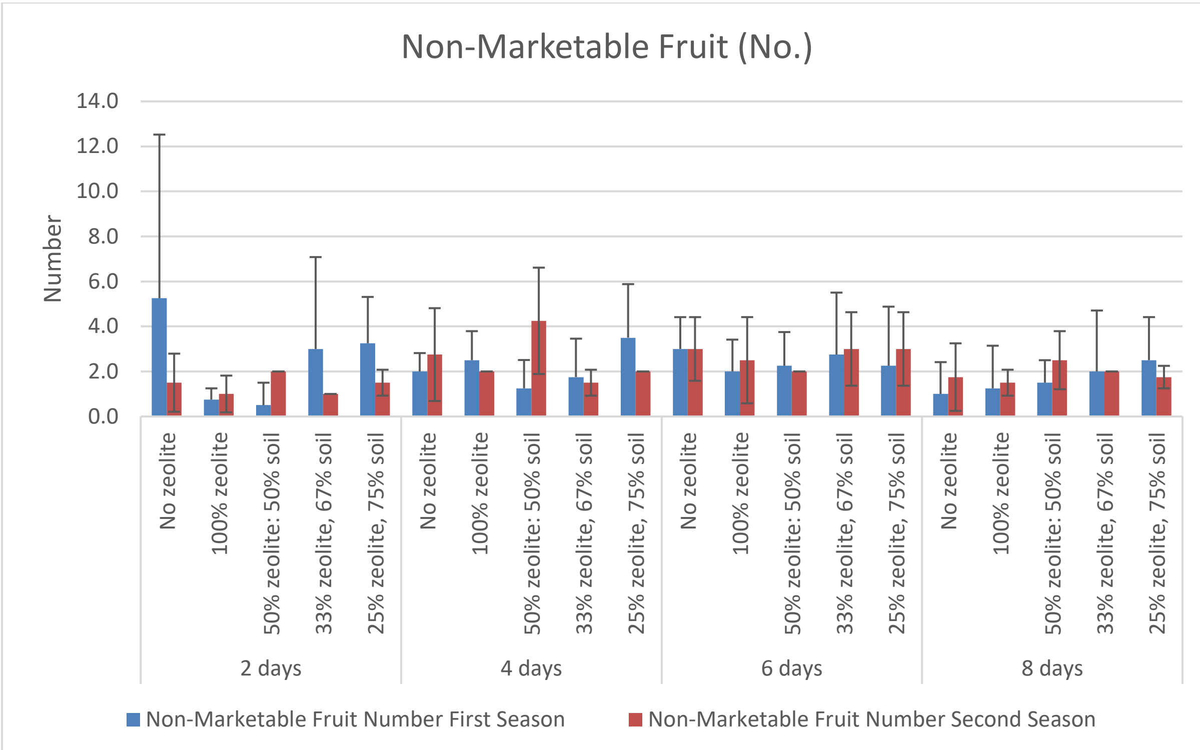

Figure-10. Non-marketable fruit number per plant as affected by irrigation intervals and zeolite levels.
Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

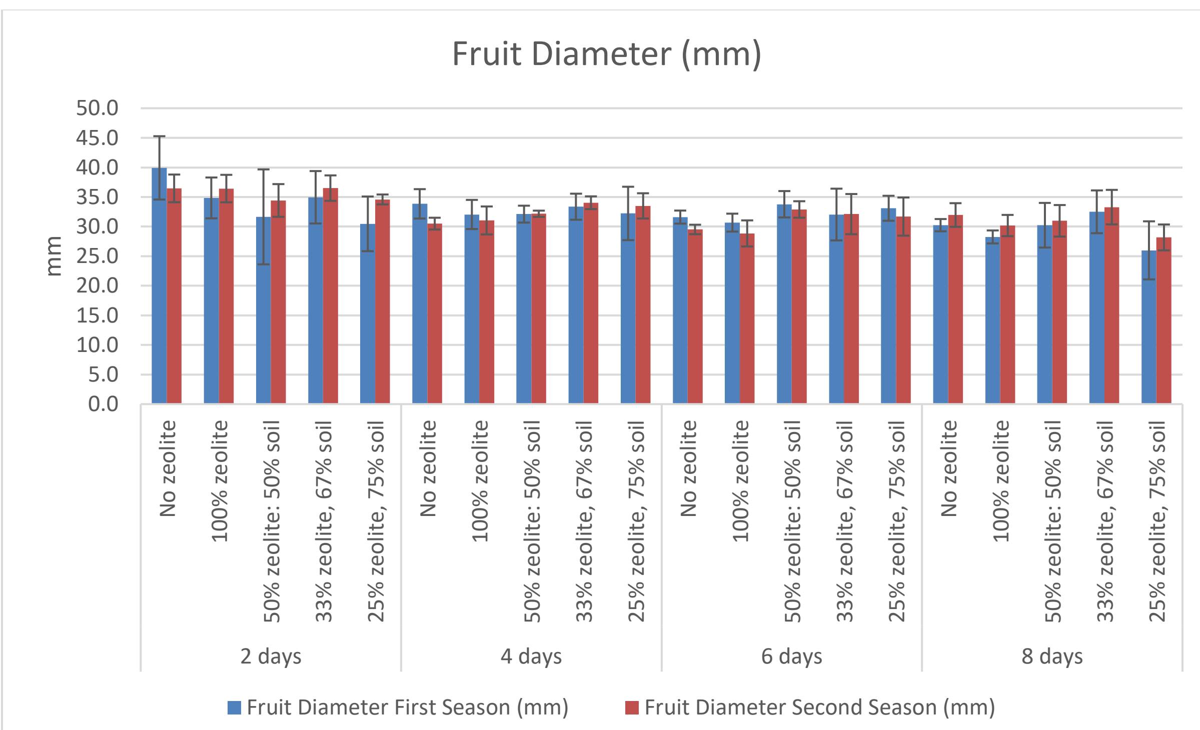

Figure-11. Average fruit diameter (mm) under varying irrigation and zeolite treatments.
Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

https://doi.org/10.35495/ajab.2025.313

Water use efficiency (WUE)

Effect of irrigation frequency: Water use efficiency increased as irrigation interval increased (Figure-12. Water use efficiency (%) of tomato plants under different irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.), indicating higher yield per unit water under deficit irrigation. The highest WUE was generally observed under moderate deficit irrigation (commonly the 6-day interval), where water savings were substantial but yield losses were not as extreme as under the 8-day interval.

Effect of zeolite amendment: Zeolite further improved WUE across irrigation intervals, with the greatest improvements under deficit irrigation (Figure 12). Treatments with Z1:3 frequently produced the highest WUE values, reflecting its ability to sustain higher yields at reduced watering frequency.

Seasonal difference: WUE was generally higher in Season 2 than Season 1, consistent with the higher yields recorded in Season 2 under comparable irrigation regimes.

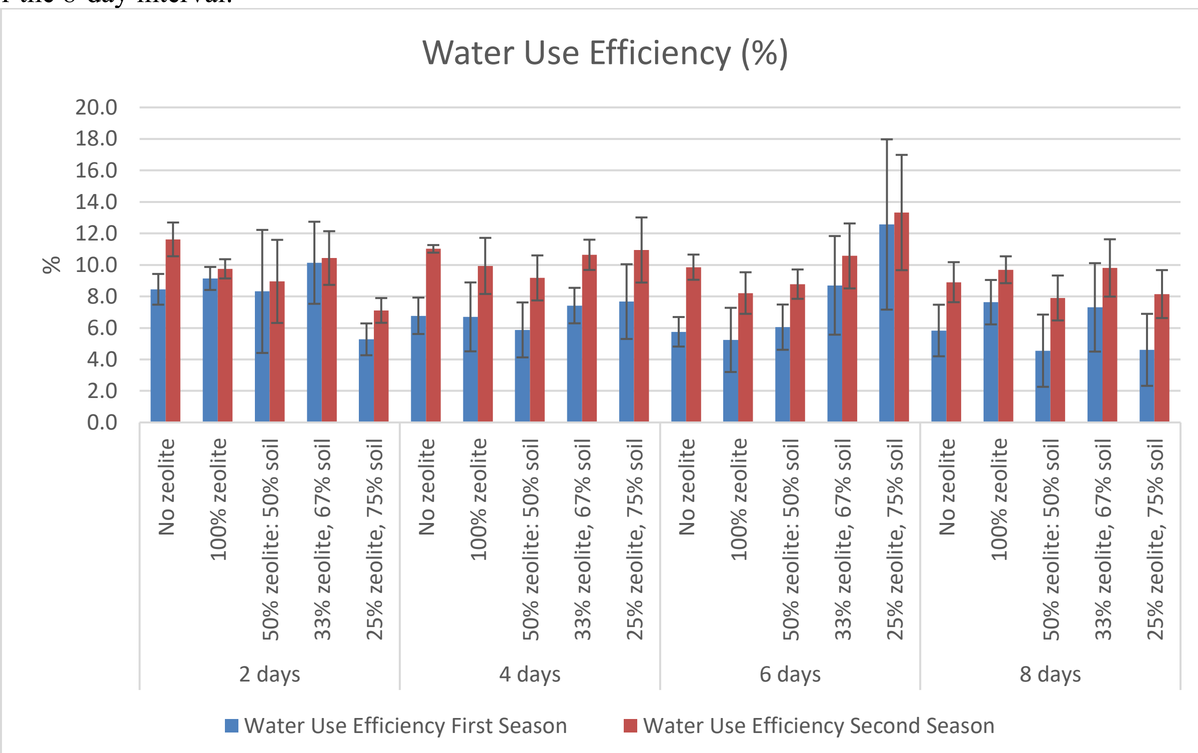

Figure-12. Water use efficiency (%) of tomato plants under different irrigation intervals and zeolite amendment levels. Blue bars represent the first season, red bars represent the second season. Bars show mean ± standard deviation.

Discussion

Drought is a critical constraint for agriculture in arid and semi-arid regions, therefore, strategies that enhance soil water retention and crop water use efficiency are essential for better plant production (Zwingmann et al., 2009). This study evaluated the potential of natural zeolite as a soil amendment to mitigate drought stress in tomatoes.

Intervals of water application significantly affected soil moisture (**Figure-1**). Similar findings have been reported by Chartzoulakis and Klapaki (2000) and Król (2020). These periods of dryness within the soils lead to water stress in the plants, where the soils do not hold sufficient water. It was observed that zeolite application enhanced soil moisture retention (**Figure-1**). Similar results have been observed previously by Mumpton (1999) and Polat et al. (2004), who postulated that zeolite and its structure lead to better moisture retention as well as enhanced capillary action which lead to better soil moisture availability

https://doi.org/10.35495/ajab.2025.313

(Eshghi et al., 2024; Zwingmann et al., 2011). These benefits were more evident in 8-day interval irrigation, where moisture unavailability led to water loss stress on plants, coinciding with the findings of Mondal et al. (2021). The soil temperature also followed a similar trend, where drought conditions led to rise in temperatures (
Figure-2). Similar results have been reported previously (He et al., 2024). The results were not evident in the first season as they were in the second, coinciding with the results of Ramesh and Reddy (2011). The results also indicate the capacity of zeolite in regulating soil moisture and temperature, which can have a direct impact on soil as well as plant growth characteristics.

Alongside the soil characteristics, plant growth parameters including plant height and leaf area showed changes due to limiting water circumstances, which is in line with the results observed previously (Bakhsh et al., 2025; Mukherjee et al., 2023; Patanè et al., 2011). However, zeolite-treated plants had more plant height and leaf area, indicating improved water and nutrient availability (Figure-3 and Figure-4). The results are in line with the findings of Paliaga et al. (2025) and Szatanik-Kloc et al. (2021). It was also noteworthy that 25% zeolite was the most effective strategy, which translates it to that optimal levels of zeolite are important. Much higher quantity of zeolite may lead to soil structure degradation, which ultimately may have damaged soil characteristics as put forward by Zhang et al. (2023). The reduced performance at higher zeolite concentrations (Z1:1, Z1:0) may be attributed to over-alteration of soil structure, leading to lower cohesion, faster drainage, and reduced nutrient retention. Moderate doses (~25%) provided optimal pore structure and moisture buffering without compromising nutrient or water-holding balance, as similarly reported by Zhang et al. (2023). Likewise, soil pores may also be changed due to application of zeolite, which can affect the moisture retention. Another notable point was that effect of zeolite was more evident where there were water stress conditions, bringing it to better application strategies. The leaf area as supported by better soil moisture through zeolite (Figure-4), helped plants with better yields. The leaf area linked with photosynthesis; Fv/Fm and Performance Index (Figure-5 and Figure-6), where reduction indicated drought stress (Grieco et al., 2020; Maxwell and Johnson, 2000) in non-zeolite plants, while better values such as 0.7 in zeolite treated plants showed limited to no stress (Stirbet and Govindjee, 2011; Zuo et al., 2025). Zeolite helped maintain PI in Season 2, suggesting better physiological function and stress mitigation (Zhong et al., 2025).

Yield attributes of tomato plant declined significantly with reduced irrigation, as reported in previous studies (Chartzoulakis and Klapaki, 2000; Patanè et al., 2011). However, WUE improved, particularly with moderate deficit irrigation. Zeolite improved yield under stress and raised WUE, confirming its role in conserving water while maintaining productivity. Hazrati et al. (2022) similarly reported WUE improvements with zeolite in drought-stressed crops. Optimal zeolite levels when applied 25% improved performance; higher levels did not provide additional benefits and could reduce yield due to issues like nutrient leaching and changed soil structure. Pure zeolite lacked organic matter and key nutrients, which may have limited performance. This at par with Polat et al. (2004), who recommended moderate zeolite application doses.

Under well-watered and frequent irrigations conditions, zeolite did not boost yield, indicating that the native clay loam retained moisture effectively. But under stress, zeolite-amended soil performed better (Figure-7). These findings replicate the results from biochar and hydrogel research showing that amendments offer the greatest benefits under drought (Tang and Tan, 2026). Practically, a 25% zeolite mix in clayey soils could allow growers to extend irrigation intervals without major yield loss. For example, zeolite-treated plants under 6-day irrigation yielded similarly to untreated plants under 4-day irrigation, saving up to one-third of the water. Jordan's natural zeolite deposits present an accessible and cost-effective resource. If zeolite application is feasible economically, farmers could benefit from its long-term effects, as zeolite is not easily degraded and may improve soil quality across seasons (Antonoglou et al., 2025). Combining zeolite with good practices, drip irrigation, balanced fertilization, and mulching, would enhance benefits further.

Regardless of the zeolite benefits, this study had a few limitations. For example, this research was conducted in pots, and showed potential of zeolite for improving water retention, regulating temperature, and enhancing plant productivity under drought. Field trials are needed to confirm scalability, assess long-term impacts on soil microbiota and fertility, and optimize application methods. Therefore, natural zeolite improves soil water retention, regulates temperature, sustains physiological functions, and enhances WUE in tomatoes under deficit irrigation. Moderate zeolite application (20-30%) is recommended for clay or loam soils. This strategy supports climate-resilient agriculture and water conservation in arid regions like Jordan.

Conclusion

The addition of zeolite significantly improved soil moisture, but the low Z1:3 ratio performed the best and was the most effective. Higher zeolite content did not further improve moisture retention compared to Z1:3. Soil temperature increase was higher as the irrigation interval increased from 2 to a maximum of 8 days in both seasons suggesting a rapid response of the root-soil system. The addition of zeolite reflects the ability to modify the thermal properties of soil under limited water conditions, particularly at long intervals between irrigations. The effectiveness of zeolite is most significant and evident in conditions of drought or infrequent irrigation intervals. It acts as a reservoir or storage of water in the soil, preventing it from drying out rapidly. Adding zeolite is an effective technique for improving soil properties and water requirements, especially in arid or semi-arid regions, or when water is limited as well as being an expensive resource. Using zeolite at a medium to low ratio (Z1:3) yields the best results. High zeolite application is not suitable for clayey soils and may lead to reduced yield due to increased permeability and poor water retention under the conditions of this study.

Acknowledgment
The author sincerely thanks Miqdadi Agricultural Company for the donation of Revenant tomato seedlings.

Disclaimer: None
Conflict of Interest: None
Source of Funding: This research was supported by the Scientific Committee of the National Agricultural Research Center, Jordan (Decision No. 1/8/2023).

References

Al-Busaidi A, Yamamoto T, Tanigawa T and Rahman HA, 2011. Use of zeolite to alleviate water stress on subsurface drip irrigated barley under hot environments. J. ICID. 60**:** 473-480. https://doi.org/10.1002/ird.595

Alfarra A, Kemp-Benedic E, Hötzl H, Sader N and Sonneveld B, 2011. A Framework for Wastewater Reuse in Jordan: Utilizing a Modified Wastewater Reuse Index. J. Water Resour. Manag. 25**:** 1153-1167. https://doi.org/10.1007/s11269-010-9768-8

Antonoglou S , Koutroubas SD, Antoniadis V, Damalas CA, Fotiadis S and Markopoulos T, 2025. Zeolite Enhances the Beneficial Effects of Sewage Sludge on Barley Yield, Increases Nitrogen Use, and Improves Soil Properties. J. Soil Sci. Plant Nutr. 25**:** 5032-5045. https://doi.org/10.1007/s42729-025-02445-5

Bakhsh MS, Sarfraz M, Ilahi N, Rehman MU, Shamshad H, Usman M, Mobin I and Bibi M, 2025. Effects of Deficit Irrigation on Growth, Yield, and Quality of Tomato Under Semi-Arid Regions. J. Biol. Life Sci. Forum. 51: 1. https://doi.org/10.3390/blsf2025051001

Belviso C, 2025. Natural and synthetic zeolites for water management in agriculture: A review. Micropor. Mesopor. Mater. 396: 113731.

Cataldo E, Salvi L and Mattii GB, 2021a. Effects of irrigation on ecophysiology, sugar content and thiol precursors (3-S-cysteinylhexan-1-ol and 3-S-glutathionylhexan-1-ol) on Vitis vinifera cv. Sauvignon Blanc. J. PPB. 164**:** 247-259. DOI: 10.1016/j.plaphy.2021.04.029

Cataldo E, Salvi L, Paoli F, Fucile M, Masciandaro G, Manzi D, Masini CM and Mattii GB, 2021b. Application of Zeolites in Agriculture and Other Potential Uses: A Review. J. Agron. 1, 1547. https://doi.org/10.3390/agronomy11081547

Chartzoulakis K and Klapaki G, 2000. Response of two greenhouse pepper hybrids to NaCl salinity during different growth stages. J. Sci. Hortic. 86**:** 247-260. https://doi.org/10.1016/S0304-4238(00)00151-5.

Dwairi IM, 1998. Evaluation of Jordanian zeolite tuff as a controlled slow-release fertilizer for NH4+. Environ. Geol. 34: 1-4.

Eshghi P, Azadi M and Ahmadi H, 2024. Investigating the geomechanical behavior and mechanism of clay stabilization with natural zeolite and nano-magnetite under accelerated curing conditions (ACC). J. RINENG. 24: 103529. https://doi.org/10.1016/j.rineng.2024.103529.

Ferretti G, Rosinger C, Diaz-Pines E, Faccini B, Coltorti M and Keiblinger KM, 2024. Soil quality increases with long-term chabazite-zeolite tuff amendments in arable and perennial cropping systems. J. Environ. Manage. 354: 120303.

Grieco M, Roustan V, Dermendjiev G, Rantala S, Jain A, Leonardelli M, Neumann K, Berger V, Engelmeier D, Bachmann G, Ebersberger I, Aro EM, Weckwerth W and Teige M, 2020. Adjustment of photosynthetic activity to drought and fluctuating light in wheat. J. Plant Cell Environ. 43: 1484-1500. doi: 10.1111/pce.13756.

Hazrati S, Khurizadeh S and Sadeghi AR, 2022. Application of zeolite improves water and nitrogen use efficiency while increasing essential oil yield and quality of Salvia officinalis under water-deficit stress. Saudi J. Biol. Sci. 29: 1707-1716. https://doi.org/10.1016/j.sjbs.2021.10.059.

Hazrati S, Tahmasebi-Sarvestani Z, Mokhtassi-Bidgoli A, Modarres-Sanavy SM, Mohammadi H and Nicola S, 2017. Effects of zeolite and water stress on growth, yield and chemical compositions of Aloe vera L. J. Agric. Water Manage. 181: 66-72. https://doi.org/10.1016/J.AGWAT.2016.11.026

He H, Zha T and Tan J, 2024. Soil-Moisture-Dependent Temperature Sensitivity of Soil Respiration in a Poplar Plantation in Northern China. J. Forest. 15: 1466. https://doi.org/10.3390/f15081466

Ibrahim HM and Alghamdi AG, 2021. Effect of the Particle Size of Clinoptilolite Zeolite on Water Content and Soil Water Storage in a Loamy Sand Soil. J. Water. 13: 607. https://doi.org/10.3390/w13050607

Javaid A, Munir N, Abideen Z, Siddiqui ZS and Yong JH, 2024. The role of natural and synthetic zeolites as soil amendments for mitigating the negative impacts of abiotic stresses to improve agricultural resilience. J. Plant Stress. 14: 100627. DOI:10.1016/j.stress.2024.100627

Król M, 2020. Natural vs. Synthetic Zeolites. J. Crystals. 10: 622. https://doi.org/10.3390/cryst10070622

Madi AI and Elshazly A, 2021.Mitigating the Impacts of Climate Change on Water Scarcity and Drought: Wastewater Treatment as an Exemplary Solution in the Mediterranean. Lecture Notes in Civil Engineering. 146: 401-409. Springer, Cham. https://doi.org/10.1007/978-3-030-68824-0_43

Malhi GS, Kaur M and Kaushik P, 2021. Impact of climate change on agriculture and its mitigation strategies: A review. J. Sustain. 13: 1318. https://doi.org/10.3390/su13031318

Maxwell K and Johnson GN, 2000. Chlorophyll fluorescence-a practical guide. J. Exp. Bot. 51: 659-668. https://doi.org/10.1093/jexbot/51.345.659

Mondal M, Biswas B, Garai S, Sarkar S, Banerjee H, Brahmachari K, Bandyopadhyay PK, Maitra S, Brestic M, Skalicky M, Ondrisik P and Hossain A, 2021. Zeolites Enhance Soil Health, Crop Productivity and Environmental Safety. J. Agron. 11: 448. https://doi.org/10.3390/agronomy11030448

Mukherjee S, Dash PK, Das D and Das S, 2023. Growth, Yield and Water Productivity of Tomato as Influenced by Deficit Irrigation Water Management. Environ. Process. 10: 10. https://doi.org/10.1007/s40710-023-00624-z

Mumpton FA, 1999. La roca magica: Uses of natural zeolites in agriculture and industry. Proc. Natl. Acad. Sci. U.S.A. 96: 3463-3470. https://doi.org/10.1073/pnas.96.7.3463

Ozbahce A, Tari AF, Gonulal E, Simsekli N and Padem H, 2015. The effect of zeolite applications on yield components and nutrient uptake of common bean under water stress. Arch. Agron. Soil Sci. 61: 615-626.

Paliaga S, Muscarella SM, Alduina R, Badalucco L, Bulacio Fischer PT, Di Leto Y, Gallo G, Mannina G and Laudicina VA, 2025. The effects of enriched biochar and zeolite and treated wastewater irrigation on soil fertility and tomato growth. J. Environ. Manage. 380: 124990. DOI: 10.1016/j.jenvman.2025.124990

Patanè C, Tringali S and Sortino O, 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. J. Scientia Horticul. 129: 590-596. https://doi.org/10.1016/j.scienta.2011.04.030.

Payero JO, Tarkalson DD, Irmak S, Davison D and Petersen JL, 2008. Effect ofirrigation amounts applied with subsurface drip irrigation on corn evapotran-spiration, yield, water use efficiency, and dry matter production in a semiaridclimate. Agric. Water Manage. 95: 895–908.

Polat E, Karaca M, Demir H and Onus AN, 2004. Use of natural zeolite (clinoptilolite) in agriculture. J. Fruit Ornament. Plant Res. 12: 183-189.

Porter JR, 2005. Rising temperatures are likely to reduce crop yields. J. Nature. 436: 174-174. https://doi.org/10.1038/436174b

Ramesh K and Reddy DD, 2011. Chapter Four - Zeolites and Their Potential Uses in Agriculture. Adv. Agron. Acad. Press. 113: 219-241. https://doi.org/10.1016/B978-0-12-386473-4.00004-X.

Roghani M, Nakhli SA, Aghajani M, Rostami MH and Borghei SM, 2016. Adsorption and oxidation study on arsenite removal from aqueous solutions by polyaniline/polyvinyl alcohol composite. J. Water Process Engin.14: 101-107. https://doi.org/10.1016/j.jwpe.2016.10.012.

Stirbet A and Govindjee, 2011. On the relation between the Kautsky effect (chlorophyll a fluorescence induction) and Photosystem II: basics and applications of the OJIP fluorescence transient. J. Photochem. Photobiol. B. 104: 236-57. https://doi.org/10.1016/j.jphotobiol.2010.12.010.

Szatanik-Kloc A, Szerement J, Adamczuk A and Józefaciuk G, 2021. Effect of Low Zeolite Doses on Plants and Soil Physicochemical Properties. J. Mater. 14: 2617. https://doi.org/10.3390/ma14102617

Tang R and Tan J, 2026. Biochar-phytagel hydrogel enhances growth, nutrient uptake, and drought resilience of lettuce microgreens. J. Agric. Food Res. 25: 102573. DOI: 10.1016/j.jafr

Wang H, Krug LJ, LI Z, Sun P, Qlan X and Dittert K, 2025. Zeolite-induced enhancement of soil cation exchange capacity reduces nitrogen gaseous emissions and improves nitrate retention under urea fertilization. Environ. Technol. Innov. 40: 104567.

Xiubin H and Zhanbin H, 2001. Zeolite application for enhancing water infiltration and retention in loess soil. J. Resour. Conserv. Recycl. 34: 45-52. 10.1016/S0921-3449(01)00094-5

Zhang M, Lei T, Guo X, Liu J, Gao X, Lei Z and Ju X, 2023. The Effect of Water–Zeolite Amount–Burial Depth on Greenhouse Tomatoes with Drip Irrigation under Mulch. J. Sustain. 15: 5220. https://doi.org/10.3390/su15065220

Zhong S, Zhang X, Hou P, Ouyang J, Rakotoson T, Zheng C, Tao Q and Sun J, 2025. Biochar amendment enhances water use efficiency in alfalfa (Medicago sativa L.) under partial root-zone drying irrigation by modulating abscisic acid signaling and photosynthetic performance. J. Environ Exp. Bot. 238: 106244.https://doi.org/10.1016/j.envexpbot.2025.106244.

Zougmoré R, Mando A and Stroosnijder L, 2004. Effect of soil and water conservation and nutrient management on the soil–plant water balance in semi-arid Burkina Faso. Agric. Water Manage. 65: 103-120.

Zuo G, Mei W, Feng N and Zheng D, 2025. Photosynthetic performance index and malondialdehyde content determine rice biomass under combined salt stress and prohexadione-calcium treatment. BMC Plant Biol. 25: 823. https://doi.org/10.1186/s12870-025-06826-x

Zwingmann N , Mackinnon IR and Gilkes RJ, 2011. Use of a zeolite synthesised from alkali treated kaolin as a K fertiliser: Glasshouse experiments on leaching and uptake of K by wheat plants in sandy soil. J. Appl. Clay Sci. 53: 684-690. https://doi.org/10.1016/j.clay.2011.06.004

Zwingmann N , Singh B, Mackinnon IR and Gilkes RJ, 2009. Zeolite from alkali modified kaolin increases NH4+ retention by sandy soil: Column experiments. J. Appl. Clay Sci. 46: 7-12. https://doi.org/10.1016/j.clay.2009.06.012