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The Role of Zeolite in Mitigating Physiological and Biochemical Stress Responses and Enhancing Seed Yield of Coriander (*Coriandrum sativum* L.) under Drought Conditions

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ABSTRACT

Zeolites, with their dual capacity for water retention and nutrient provision, offer a promising solution to enhance crop resilience under moisture-deficient conditions. To evaluate the effects of zeolite on biochemical traits, chlorophyll fluorescence, and coriander seed yield under water-limited conditions, a two-year (2018–2020) factorial experiment was conducted at the Zendeh Rooh research station in Jopar, Kerman Province, Iran. The study followed a randomized complete block design (RCBD) with three replications. The first factor comprised three irrigation levels: 100% (non-stress), 75% (moderate stress), and 50% (severe stress) of the crop’s water requirement, applied via drip (tape) irrigation. The second factor included five zeolite application rates: 0, 2, 4, 6, and 8 tonnes per hectare (t/ha). The results indicated that all traits studied were significantly affected by the main effects of moisture regimes and zeolite, as well as their interaction effects. Water deficit significantly reduced photosynthetic efficiency (Fv/Fm, ΦPSII), chlorophyll content (Chl C), photochemical quenching (qP), relative water content (RWC), and seed yield (SY), while increasing non-photochemical quenching (NPQ), proline content (PC), and relative membrane permeability (RMP). Zeolite application mitigated these adverse effects by enhancing Chl C, RWC, Fv/Fm, qP, and ΦPSII, while suppressing NPQ, PC, and RMP. Maximum yields occurred at 100% irrigation with 8 t/ha (1,109 kg/ha) and 6 t/ha (1,095 kg/ha). Under 75% and 50% irrigation, 8 t/ha zeolite yielded 893 kg/ha and 608 kg/ha respectively—outperforming 6 t/ha by 6.6% and 4.9%. For optimal coriander productivity in semi-arid regions such as Kerman, Iran, we recommend 6 t/ha zeolite under non-stress or moderate water stress (75–100% irrigation). Under severe drought (50% irrigation), 8 t/ha zeolite is advised to maximize seed yield. These findings highlight zeolite’s potential as a sustainable strategy for water-scarce agroecosystems in Iran and climatically similar regions globally.

Keywords: Water deficit, Fv/Fm, NPQ, Proline, Relative Water Content

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INTRODUCTION

Global warming has made water deficit stress a significant barrier to agricultural expansion and output, particularly in arid and semi-arid areas [1]. Drought stress, as a non-living limiting factor, has a highly adverse effect on the growth and productivity of crops [2]. Water scarcity is a principal limitation for production in arid and semi-arid regions [3].

Coriander (*Coriandrum sativum* L.) is one of the most useful essential oil-bearing spices and medicinal plants belonging to the family Umbelliferae/Apiaceae [4]. It is herbaceous and, when exposed to abiotic stress, exhibits poor growth development, decreased leaf area, and is very susceptible to rootzone dryness [5].

Photosynthetic limitations under drought stress primarily consist of intercellular CO_2 content reduction through stomatal restriction, inactivation of the reaction centers PSI and PSII [6], diminishing the quantum efficiency of Photosystem II, photochemical and Non-photochemical quenching [7], and decline of PSII Maximum quantum efficiency [8]. These conditions also reduce relative water content [9], chlorophyll content [10], relative membrane permeability [11], and ultimately decrease grain yield [12].

Several ways have been assessed to mitigate drought impacts, and one of these approaches involves zeolite application in the soil [13]. This mineral features a porous structure capable of absorbing moisture up to 60% of its weight. Under drought conditions, it gradually releases stored moisture, mitigating water stress. Owing to its high cation exchange capacity (CEC), clinoptilolite reduces nitrogen (N) and potassium (K) fertilizer requirements by up to 30% [14]. Zeolite can positively impact plant growth in various species [15]. Zeolite facilitates the horizontal diffusion of water in the soil [16]; with its high water absorption properties, it increases the water holding capacity in the soil (absorbing more than 41% of its weight) [17]. Finally, it ensures that the water reservoir is in the soil of the root zone [16]. Zeolites can help improve soil nutrients by increasing the soil's cation exchange capacity [18]. Green gram (Vigna radiata) studies where total chlorophyll content significantly decreased under water stress and positively correlated with seed yield [19].

A decrease in chlorophyll content [10] is a significant cause of reduced grain yield in crops [12]. Zeolite application improves soil properties like water retention capacity and cation exchange, enhancing plant growth conditions. This leads to increased leaf area index (LAI) and improved chlorophyll fluorescence (an indicator of photosynthetic efficiency), ultimately boosting crop yield [20].

The Chlorophyll fluorescence characteristics collected from measurements may give useful information about the plant's photosynthetic efficiency, resistance to stress (abiotic and biotic), or the plant's normal physiological state [21]. These methods have evolved into a widely used, rapid, non-invasive approach to studying photosynthetic operation under stress conditions [22]. Chlorophyll fluorescence imaging frequently monitors stress levels in various crops [23].

The most influential chlorophyll fluorescence parameters include non-photochemical quenching (NPQ), Maximum quantum efficiency of PSII (F_v/F_m), photochemical quenching (qP), and Photosystem II quantum yield (ΦPSII), which are applied in plant stress physiology studies [24]. Hence, assessing alterations in fluorescence parameters, including F_v/F_m, ΦPSII, and NPQ, yields valuable information regarding the operation and control of PSII while also being an indicator for early stress detection [25]. The F_v/F_m parameter is evaluated as an effective tool for detecting damage to the photosynthetic apparatus before it becomes apparent in plant morphology [26].

Considering the adverse effects of dehydration and the growing significance of medicinal plants, this study aimed to evaluate whether zeolite can serve as a natural and effective solution to reduce chlorophyll fluorescence while enhancing biochemical traits and coriander seed yield under water-deficient conditions.

MATERIALS AND METHODS

Description of the Study Area, Weather, and Soil Analysis

This study was conducted over a two-year period (2018–2020) at the Research Farm of the Shahid Zinda Rooh Agricultural Institute, located 18 kilometers along the Kerman-Jopar Road in Kerman, Iran (30°7'32" N, 57°3'34" E, elevation: 1805 meters above sea level).

Prior to planting, soil samples were collected from the top 0–30 cm layer to analyze the physicochemical properties of the site (Table 1). Soil-available phosphorus was measured using the Olsen method [29]. Available potassium (K) in the soil was extracted using flame photometry [30].

The physicochemical properties of the soil samples, as determined by the method of Hesse [27], are summarized in Table 1. Average monthly precipitation and temperature data for the 2018–2020 growing seasons are presented in Figure 1.

Experimental Setup

This experiment employed a factorial design with two factors: irrigation regime and zeolite application rate. Three irrigation regimes were tested: I_1 (100% of water requirement, no stress), I_2 (75% of water requirement, mild stress), and I_3 (50% of water requirement, severe stress). These were combined factorially with five zeolite application rates (0, 2, 4, 6, and 8 tonnes per hectare). The treatments were arranged in a randomized complete block design with three replicates and conducted over two consecutive crop years (2018-2019 and 2019-2020). This combination yielded $3 \times 5 = 15$ distinct treatments, applied to 45 individual plots. Each plot measured 4 meters in length and 3 meters in width, featuring five ridges spaced 60 cm apart.

Zeolite (Clinoptilolite) was applied via surface broadcasting and mixed into the topsoil layer (15–30 cm depth) prior to planting. This method enhances water-holding capacity in the root zone and minimizes moisture evaporation from the soil surface [14].

Seeds were hand-sown in double-row arrangements on each ridge at 2-3 cm depth on February 15 during both experimental years (2019-2020). Final plant density reached 40 per m² [28]. The experimental plots measured 4 × 3 m (12 m²), with 1 m spacing between plots and 3 m spacing between replications (blocks). Irrigation regimes were initiated once the plants were fully established, typically with 6 to 8 leaves (the vegetative stage). Data from the Shahid Zinda Rooh Agricultural Research Institute's meteorological station was used to compute water requirements. Reference evapotranspiration (ETo) was estimated using the Version 3.1 ETo Calculator [31]. This software employs the FAO Penman-Monteith equation [32] to compute ETo. Crop evapotranspiration (ETc) for coriander was calculated by multiplying the crop coefficient (Kc) by the reference evapotranspiration (ETo) (Equation 1) [33].

Using the equation provided, the ET_o was determined by multiplying the crop coefficient (Kc) in the coriander potential evapotranspiration (ETc) values (Equation 1[33].

$ETc = Kc \times ET_o$ (Equation 1)

Where ETo is reference crop evapotranspiration (mm/day), Kc is the crop coefficient (dimensionless), and ETc is potential crop evapotranspiration (mm/day) [33]. Prior to irrigation, a soil sample was taken from the root zone of each plot to calculate the irrigation volume. Based on empirically determined crop coefficients (Kc) for coriander across all phenological stages: germination (Kc=0.4), vegetative development (Kc=0.95), flowering (Kc=1.25), and maturity (Kc=0.6), with 85% water application efficiency for drip irrigation (T-tape) and a 10% leaching fraction to address potential salinity in sandy loam soil, the calculated gross irrigation requirements per hectare are: full irrigation (100% crop water requirement, no stress): 4939 m³/ha, deficit irrigation (75% crop water requirement, mild stress): 3704.25 m³/ha and deficit irrigation (50% crop water requirement, severe stress): 2469.5 m³/ha. With irrigation applied every 5 days using drip irrigation, coriander received a total of 17 irrigation events. For each event, the water application rates for the 100% full irrigation treatment, 75% deficit irrigation treatment, and 50% deficit irrigation treatment were 290.5 m³/ha, 218.5 m³/ha, and 145.3 m³/ha, respectively.

Depending on the treatment, specified amounts of zeolite were hand-broadcast across the field prior to planting. The soil was then plowed to a depth of 25 cm [34]. Afrazand Mineral Co., [35] based in Semnan, Iran, supplied zeolite.

Fertilizers were applied simultaneously before plowing and two rounds of harrowing. We did not apply potassium or phosphorus fertilizers, as soil analysis showed that available potassium levels exceeded the critical threshold (Table 1). Table 2 presents the specifications and properties of the zeolite utilized. A coriander cultivar (*Coriandrum sativum*), sourced from Pakanbazr Co. in Isfahan, Iran, was selected as the experimental plant (Table 3). Before planting, we tested the seeds for germination to make sure they were viable.

The seeds were hand-planted in the grooves on both sides of the ridges, at a depth of 2-3 cm [36].

Three weeks after planting (at the four-leaf stage), thinning, replanting, and the first weeding were carried out simultaneously. The second weeding took place three weeks after the first. Weed control was performed manually throughout the experiment, with no application of pesticides or herbicides. Harvesting was conducted on August 23rd every other crop year.

Plant Sampling and Analysis

Relative Water Content (RWC)

The fresh weight (FW) and turgid weight (TW) of the leaf samples were measured after six hours in water and subsequent oven drying. The Relative Water Content (RWC) was then calculated using the following formula:

$RWC = [(FW - DW) / (TW - DW)] \times 100$

In this equation:

- FW (fresh weight). The weight of the plant tissue (leaf) immediately after harvest
- TW (turgid weight): Float the sample in distilled water for 6 hours (in darkness to prevent photosynthesis), then blot dry and weigh
- DW (dry weight) Dry the sample in an oven (80°C) for 24 hours until constant weight is achieved [37].

Relative Membrane Permeability (RMP)

Relative Membrane Permeability (RMP) was determined according to the method described by Yang *et al.,* [38]. Leaf samples were cut into 1 cm^2 pieces and incubated in test tubes containing 20 mL of deionized distilled water. Each sample consisted of 0.5-0.8 g of fresh leaf tissue.

The initial electrical conductivity (EC_0) of each sample was measured after 3 seconds of vortex mixing. Following 24 hours of storage at 4°C, the conductivity (EC_1) was measured again. The samples were then autoclaved for 15 minutes, cooled to ambient temperature, and the conductivity (EC_2) was measured a third time. Finally, the relative membrane permeability was determined using the equation below:

$RMP = (EC_1 - EC_0 / EC_2 - EC_0) \times 100$

Proline Content (PC)

Proline was extracted from 0.5 g leaf samples using 3% (w/v) aqueous sulfosalicylic acid and estimated with ninhydrin reagent according to the method of Bates *et al.,* [39]. The absorbance of the toluene-containing fraction from the liquid phase was measured at 520 nm. Proline concentration was determined using a calibration curve and expressed as µmol proline/g FW.

Chlorophyll Content (Chl C)

We employed the method of Lichtenthaler *et al.,* [40] to determine chlorophyll a and chlorophyll b content. Total chlorophyll (Chl a + b) was calculated as the sum of chlorophyll a and chlorophyll b.

Chlorophyll Fluorescence Measurements

Chlorophyll fluorescence parameters were measured using a PAM-2500 chlorophyll fluorometer (Walz Heinz GmbH, Effeltrich, Germany). Prior to measurement, the plants were dark-adapted for 30 minutes. The minimum fluorescence from open PSII centers was recorded under measuring light. The maximum fluorescence was then determined by applying a 0.8-second saturating light pulse (6000 $\mu mol \cdot m^{-2} \cdot s^{-1}$) to close the PSII centers, with the measurement taken after 30 minutes in the dark. Steady-state chlorophyll fluorescence was measured under red actinic light. Using saturating pulses on light-adapted samples (Table 4) [41], we calculated the following parameters:

NPQ (Non-photochemical quenching): $(F_m - F'_m)/F'_m$
ΦPSII (Photosystem II quantum yield): $(F_m - F_t)/ F_m$
qP (photochemical quenching): $(F'_m - F_t)/(F'_{m'} - F_0)$
Where:
F_0 (F-zero): Minimum Fluorescence
Fm (F-m): Maximum Fluorescence
F'm (F-prime-m): Light-Adapted Maximum Fluorescence
Ft (F-t): Fluorescence at time t (Steady-State Fluorescence)

Seed Yield Measurements

To determine seed yield, center rows totaling one square meter were manually harvested from each plot. The seed heads were separated from the plants. The seeds were then threshed from the heads, weighed using a scale accurate to 0.01 g, and the yield was calculated and recorded in kilograms per hectare [28].

Statistical Analyses

All test data were statistically analyzed using SAS 9.2 software. Bartlett's test was first performed to assess the homogeneity of variances. After verifying ANOVA assumptions—including data normalization, testing residual error distributions, and checking error uniformity ($\alpha=0.05$)—a combined analysis of variance (ANOVA) was conducted. Means were compared using Duncan's Multiple Range Test (D'MRT) at a 0.05 significance level.

RESULTS AND DISCUSSION

The two-year combined analysis of variance revealed that the interaction between irrigation regimes and zeolite application significantly affected Chl C, Fv/Fm, qP, ΦPSII, NPQ, RWC, PC, RMP, and seed yield ($p < 0.01$) (Table 5). Except for RWC, Fv/Fm, ΦPSII, and NPQ ($p = 0.05$), the year had no significant effect on the other studied traits. Furthermore, the interaction effects between year and the other treatments, as well as the three-way interaction of year, irrigation, and zeolite on the studied traits, were not significant (Table 5).

Chlorophyll Content

Increasing drought stress led to a reduction in chlorophyll content (Table 6). The highest chlorophyll levels occurred under both 100% and 75% irrigation when zeolite was applied at 8 t/ha and 6 t/ha, respectively. At full irrigation (100%), chlorophyll content reached 3.31 mg/g fresh leaf weight with 8 t/ha zeolite and 3.19 mg/g with 6 t/ha zeolite. Under reduced irrigation (75%), the values were 2.31 mg/g (8 t/ha zeolite) and 2.25 mg/g (6 t/ha zeolite). At the 50% irrigation level, the maximum chlorophyll content (1.72 mg/g fresh leaf weight) was achieved with the 8 t/ha zeolite application (Table 6). Research indicates that drought stress damages chloroplasts and reduces chlorophyll a and b content. Furthermore, drought stress inhibits the biosynthesis of new plastids and chlorophyll a and b [42], leading to an overall decrease in total chlorophyll. Under drought conditions, increased activity of the enzymes chlorophyllase and peroxidase is a key contributor to chlorophyll degradation. Due to their high porosity, zeolites enhance plant growth by improving the long-term availability of water and nutrients [13]. Given the positive correlation between chlorophyll content and Non-Photochemical Quenching (NPQ), increasing SPAD readings (an indicator of chlorophyll content) could potentially enhance NPQ capacity (Table 7). Environmental stresses lead to saturation of the electron transport chain, promoting proton accumulation in the thylakoid lumen and thus increasing non-photochemical quenching (NPQ) [24]. Therefore, a higher NPQ value indicates an enhanced ability to mitigate the negative effects of environmental stress at the chloroplast level, as these organelles can dissipate excess excitation energy [43].

Photosystem II Quantum Yield (ΦPSII)

Reducing the water supply to the plant reduced ΦPSII (Table 6). ΦPSII was reduced by 26.9% under severe drought stress (I_3) relative to the control (I_1) (Table 7). Instead, zeolite application mitigated the adverse effects of low irrigation conditions, and ΦPSII efficiency increased (Table 6). The highest ΦPSII value (0.85) was observed in the $I_1 \times Z_8$ treatment, which was comparable to the $I_1 \times Z_6$ and $I_1 \times Z_4$ treatments (Table 6). A reduction in ΦPSII under drought stress has been reported by Bashir *et al.,* [8].

Consistent with the negative correlation between ΦPSII and NPQ, enhancing NPQ can decrease ΦPSII (Table 7). Indeed, the decline in ΦPSII results from the inactivation of PSII reaction centers, serving as a photoprotective mechanism or potentially as a process that adjusts PSII efficiency to the photosynthetic photon flux density [44].

Drought triggers the closure of PSII reaction centers, restricting electron transfer and reducing the light energy available for photochemical reactions within PSII [45]. Moreover, the decline in ΦPSII under drought stress indicates that PSII photoinhibition has occurred [46].

Reduced photosynthetic activity and the subsequent storage of its products limit electron transfer and the production of ATP and NADPH in the light-dependent reactions. This, in turn, lowers the quantum yield of Photosystem II [26].

In photosynthesis, water molecules serve as electrons sources for Photosystem II through photolysis. Water scarcity hinders the replenishment of lost electrons in PSII, reducing ΦPSII. However, applying zeolite to soil maintained plant moisture levels under drought-stress conditions [20].

Photochemical Quenching Coefficient (qP)

Under full irrigation (100% water requirement, no drought stress), application of different zeolite levels resulted in the highest qP value (0.80) (Table 6). The lowest value (0.43) was observed in the $I_3 \times Z_0$ treatment (Table 6). Under both mild and severe drought stress conditions, applying higher amounts of zeolite produced even greater increases in qP compared to the no-zeolite condition (Table 6). qP decreased with increasing drought stress (Table 6). Previous studies have shown that qP decreases under drought stress [47]. The qP value reflects the energy consumed in photosynthesis. Therefore, qP is directly dependent on the rate of NADPH, proton (H^+), and ATP utilization generated by the photosynthetic electron transport chain [48]. Our results confirm this, showing a negative relationship between qP and NPQ (Table 7).

The inconsistent effects of water stress on photochemical quenching (qP) reported by Terzi *et al.,* [49]. The observed decrease in qP value may result from dehydration directly affecting Rubisco, increasing hydrolysis [50].

In all irrigation regimes studied, applying zeolite resulted in higher qP than non-zeolite treatments (Table 6). These results are because zeolites can adsorb more than 41 % of their weight in water [17]. Thus, in arid and semi-arid regions, they improve the soil's ability to hold water and prevent stress-related damage to the photosynthetic apparatus [51].

Non-photochemical Quenching Coefficient (NPQ)

NPQ increased in response to intensifying drought stress (Table 6). Similar findings were reported by Lauterberg *et al.,* [52]. Elevating NPQ is a mechanism plants use to increase resistance to dehydration stress. Consequently, higher NPQ is observed in drought-resistant plants than in drought-sensitive plants under drought conditions [53].

Consistent with these findings, multiple studies indicate that increased NPQ contributes to reduced production of reactive oxygen species (ROS) in plant tissues [54]. Moreover, mutants incapable of performing NPQ are more susceptible to photoinhibition and exhibit reduced tolerance to environmental stressors such as low temperature, salinity, and drought [41].

Environmental stress saturates the electron transport chain, leading to a build-up of protons. This triggers increased non-photochemical quenching (NPQ), enhancing the chloroplast's ability to counteract water deficit stress by dissipating excess excitation energy [24]. Increasing NPQ signals enhanced dissipation of thermal energy through the xanthophyll cycle in PSII [55].

Conversely, increased zeolite consumption led to a decrease in the non-photochemical quenching coefficient (NPQ) (Table 6). Without zeolite application, the highest NPQ value (0.57) occurred under severe water stress (I_3; 50% of the crop’s water requirement). However, when zeolite was applied under both mild (I_2; 75% water requirement) and severe (I_3) stress conditions, NPQ decreased (Table 6).

The generation of Reactive Oxygen Species (ROS) can cause direct damage to Photosystem II (PSII) or block the repair of PSII reaction centers [56]. By reducing electron transfer rate (ETR), high NPQ prevents the formation of ROS [57].

The application of zeolite led to the reduction of the effects of drought stress. These results are in agreement with Bahador and Tadayon [58]. Zeolite mitigates water stress due to its unique microporous structure, which excels at water storage [20].

Maximum Photosystem II Quantum Yield (F_v/F_m)

In many studies, maximum Fv/Fm is used as a measure of the photosynthetic apparatus's photochemical activity [59]. The highest Fv/Fm value (0.85) was achieved with the 8 t/ha zeolite application in the I1×Z8 treatment, showing no significant difference compared to the $I_1 \times Z_6$ and $I_1 \times Z_4$ treatments (Table 6). When plants grow under favorable conditions, the maximum F_v/F_m value is 0.83-0.85 [59].

In the $I_3 \times Z_0$ treatment (without zeolite), the lowest Fv/Fm value (0.47) was obtained (Table 6). A greater decline in Fv/Fm was observed under the I_3 treatment (50% water requirement) relative to the other humidity regimes (I_1 and I_2) (Table 6). The observed decline in Fv/Fm with increasing drought stress can be attributed to chloroplast damage, a conclusion supported by the concurrent decrease in chlorophyll content (Table 6). Our results corroborate the findings of Afshar-Mohammadian *et al.,* [26].

Reduced water availability and increased drought stress led to a significant decrease in the Fv/Fm ratio (Table 6). Sommer *et al.,* [60] observed a decrease in the Fv/Fm ratio under drought stress. This decline indicates reduced PSII efficiency (photoinhibition), resulting from impaired electron transport needed for carbon fixation. Also, this decrease under water deficit stress conditions indicates a decline in PSII efficiency due to diminishing electron transfer from PSI to PSII [61]. Other reasons for reducing the F_v/F_m ratio are less tolerance to drought, down-regulation of photosynthesis or photoinhibition under stress [62]. Plant stomata closure is one of the quick reactions that prevent water loss, which in turn limits CO_2 availability for photosynthesis [63]. This leads to decreased carboxylation efficiency, reducing the Rubisco enzyme regeneration rate, and as a result, it causes a decrease in NADPH and ATP consumption in the Calvin cycle. This issue causes a decrease in electron transfer speed and F_v/F_m ratio [64]. A decrease in the F_v/F_m ratio indicates decreased PSII efficiency due to a reduction in electron transfer from PSI to PSII [61]. The photochemical efficiency of PSII is expressed as the F_v/F_m ratio, and its high ratio indicates higher photosynthetic efficiency [60].

It has also been reported that a reduction in the Fv/Fm ratio under drought stress may result from disturbances in the Calvin cycle, delayed quinone reduction, and damage to the thylakoid membrane electron transport chain [65].

With zeolite application, most electrons entering the photosynthetic electron transport chain are likely used for ATP and NADPH production, enhancing photochemical quenching. Under drought conditions without zeolite, these electrons are instead diverted into the xanthophyll cycle (reducing damage from excess light energy) or contribute to reactive oxygen species (ROS) generation [66].

Relative Water Content (RWC)

Drought stress reduced the RWC (Fig. 2). Diminished RWC due to drought stress has been reported by Rostami *et al.,* [67] and Moitazedi *et al.,* [68]. Reduced water potential due to stomata's closure reduces the RWC under drought stress conditions [69]. Meanwhile, zeolite application significantly alleviated drought stress effects on RWC (Fig. 2). The highest RWC was observed in the I_1Z_8 treatment, which showed no significant difference compared to the I_1Z_6 and I_1Z_4 treatments (Fig. 2). Applying zeolite at 8 t/ha under 75% and 50% moisture regimes (of the water requirement) increased Relative Water Content (RWC) by 10.83% and 13.72%, respectively, compared to no zeolite application (Fig 2). The percentage increase in RWC under full irrigation (100% water requirement, no drought stress) resulting from raising the zeolite application rate from 0 to 8 t/ha was lower than the increases observed under both the 75% and 50% water requirement conditions, respectively (Fig. 2). Valadabadi *et al*., [70] demonstrated that zeolite amendment significantly enhances RWC in plants under water-deficit conditions. Ouji *et al*., [71] documented that irrigation directly elevates RWC by replenishing soil water, thus enhancing plant water uptake

Zeolite mitigates the harmful effects of dehydration thanks to its ability to absorb and gradually release moisture [72]. Therefore, applying zeolite under water stress improves Relative Water Content (RWC) by stimulating root growth, enhancing water absorption, and increasing soil moisture retention [73].

Relative Membrane Permeability (RMP)

Treatment I_3 (severe stress without zeolite) yielded the highest RMP (68.83%), representing an 8% increase over I_2 (mild stress) and a 32.58% increase over I_1 (normal) (Fig. 3). Reduced water availability and increased drought stress led to higher RMP (Fig. 3). When plant cells dry out, their membranes become permeable to ions. Furthermore, drought conditions increase the production and accumulation of reactive oxygen species like superoxide, hydrogen peroxide, and hydroxyl radicals [74].

RMP decreased with increasing zeolite application (Fig. 3). The strong negative correlation between RWC and RMP (r = -0.88**) indicates that higher RWC was associated with improved maintenance and integrity of the cell membrane and lower RMP (Table 7).

Under reduced humidity conditions (50% of the water requirement), zeolite's role in maintaining and transferring moisture within the plant rhizosphere became significantly more pronounced. With the application of zeolite (8 t/ha), the Relative Moisture Percentage (RMP) was 17.75% lower compared to the control treatment without zeolite (Fig. 3). Due to its unique structure, zeolite has reduced dehydration damage by maintaining moisture conditions [17].

Proline Content (PC)

Proline content increased with the severity of drought stress (Fig. 4). This accumulation is a well-established plant stress response [75]. Specifically, proline accumulation is one of the primary mechanisms by which dehydrating plant tissues mitigate cellular damage during drought [76]. Increased proline levels in coriander under drought stress have also been documented [77]. Proline content was highest in the I_3Z_0 interaction treatment (Fig. 4). Furthermore, PC in I_3Z_0 (1.86 mg/g FW) was 47.31% higher than that in I_1Z_0 (0.98 mg/g FW) (Table 4).

Across all treatments (I_1, I_2, and I_3), zeolite application significantly reduced PC compared to the control (Fig. 4). Applying zeolite at 8 t/ha under moisture regimes of 75% and 50% of the water requirement decreased PC by 26.92% and 30.65%, respectively, relative to treatments without zeolite (Fig. 4). Notably, the percentage reduction in PC when increasing zeolite from 0 to 8 t/ha was 3.73% greater under the 50% water requirement regime (nominally without drought stress) than under the 75% regime, and 13.3% greater than under the 100% water requirement regime (Fig. 4). Zeolite reduces the harmful effects of dehydration due to its ability to absorb and gradually release moisture [72]. Our results are consistent with the findings of Tadayon and Karimzadeh-Soureshjani [72]. Zeolite consumption has increased the water available to the plant due to its high capacity to retain moisture and the stability of the water reservoir in the root area during drought stress [78].

Seed Yield

The highest seed yield (1109.39 kg/ha) was recorded in treatment I_1Z_8, though it showed no significant difference from treatment I_1Z_6 (1095.32 kg/ha) (Table 6). As shown in Table 6, the I_1Z_6 and I_1Z_8 treatments exhibited higher Fv/Fm and qP values compared to the other treatments. Concurrently, these treatments also produced acceptable seed yields (1095.32 and 1109.39 kg/ha, respectively) (Table 6). Under mild and no-stress conditions (75% and 100% water requirement), seed yield peaked at 6 and 8 tonnes per hectare (t/ha) of zeolite application. Under the 50% water requirement regime, the highest seed yield (608.16 kg/ha) was achieved with an application rate of 8 t/ha zeolite (Table 6). These results are consistent with the findings of Shahgholi *et al.,* [79] regarding the reduction in grain yield under drought stress conditions. The positive effect of zeolite on soil moisture and food storage can be considered the most significant factor affecting the increase in yield [80].

Applying zeolite under all irrigation regimes increased seed yield compared to its non-application (Table 6). Furthermore, given the significant interactive effect between Zeolite and Irrigation (Z×I), it can be concluded that zeolite effectively mitigated water stress, likely due to its unique water-retaining properties [20]. Mahmoud *et al.,* [81] have reported decreased seed yield in coriander due to drought stress.

Table 7 shows strong positive correlations between seed yield and several physiological traits: total chlorophyll (ChlC) (r = 0.94**), Fv/Fm (r = 0.90**), ΦPSII (r = 0.88**), relative water content (RWC) (r = 0.88**), and photochemical quenching (qP) (r = 0.79**). These highly significant correlations indicate that higher values for each of these traits are associated with significantly increased seed yield. In contrast, progressive drought stress led to increases in proline content (PC), relative membrane permeability (RMP), and non-photochemical quenching (NPQ) (Table 6). Concurrently, higher levels of PC, RMP, and NPQ were associated with reduced seed yield. This negative relationship is explained by their significant negative correlations with yield: PC (r = -0.74**), RMP (r = -0.88**), and NPQ (r = -0.85**) (Table 7). The identified correlations are mechanistically consistent with established physiological principles: photosynthetic efficiency and water homeostasis promote yield, while oxidative damage and energy dissipation reduce it. These patterns are validated across diverse stress droughts, confirming the robustness of these traits as yield predictors [82].

CONCLUSION

Water deficit reduced Fv/Fm, ΦPSII, Chl C, qP, RWC, and SY but increased NPQ, PC, and RMP. Zeolite application, due to the positive features of these polymers, including strengthening the soil and creating suitable conditions for plant growth, strengthening the soil, preventing soil erosion, and also the ability to absorb water by increasing Chl C, RWC, qP, Fv/Fm, and ΦPSII diminished the detrimental effects of water deficit. Through these mechanisms, zeolite effectively mitigated the adverse impacts of water stress, thereby enabling the achievement of optimal plant performance. The highest seed yield was achieved with two approaches: meeting 100% of the water requirement combined with 8 t/ha zeolite application (1109.39 kg/ha) and 6 t/ha zeolite (1095.32 kg/ha). Both treatments significantly outperformed all others. The next highest yields came from providing 75% of the water requirement with 8 t/ha zeolite (892.96 kg/ha) and 6 t/ha zeolite (1,147.53 kg/ha). Across all three moisture levels studied, zeolite applications of 8 t/ha and 6 t/ha consistently produced the highest seed yields. Consequently, we recommend 6 t/ha as the optimal zeolite application rate to maximize coriander seed yield under all tested moisture conditions in semi-arid regions like Kerman, Iran, and similar climates globally.

Conflicts of Interest

The authors declare no conflict of interest.

Disclosure Statement

The authors report no competing interests to declare.

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