doi:10.14720/aas.2025.121.4.23310 Original research article / izvirni znanstveni članek

Modulation of yield and physiological attributes of cumin (*Cuminum cyminum* L.) by silicon dioxide nanoparticles under varying drought stresses

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Received August 17, 2025, accepted November 19, 2025
Delo je prispelo 17. avgust 2025, sprejeto 19. november 2025

Modulation of yield and physiological attributes of cumin (*Cuminum cyminum* L.) by silicon dioxide nanoparticles under varying drought stresses

Abstract: Water scarcity, exacerbated by climate change and population growth, threatens sustainable agriculture, particularly in arid regions. This study investigated the potential of silicon dioxide nanoparticles (nSi) to mitigate drought stress in cumin (*Cuminum cyminum* L.). A split-plot experiment, arranged in a randomized complete block design with three replications, was conducted over two cropping seasons in Bafgh, Iran. Drought stress was applied as the main factor at four levels (80 %, 60 %, 40 %, and 20 % of field capacity, FC), while subplots contained four nSi concentrations (0, 2, 4, and 6 mM). Results showed that severe drought stress (20 % FC) significantly decreased seed yield, essential oil yield, and total chlorophyll, while increasing peroxidase activity and malondialdehyde levels. Application of 4 mM nSi significantly improved seed yield and essential oil yield and preserved total chlorophyll, and sustained peroxidase activity, leading to lower malondialdehyde levels. In contrast, 6 mM nSi did not improve seed yield and essential oil yield and, in fact, worsened its effects. Overall, 4 mM nSi can enhance cumin's resilience and productivity under drought, while higher concentrations should be avoided.

Key words: seed yield, essential oil yield, malondialdehyde, eroxidase activity

Modulacija pridelka in fizioloških lastnosti rimske kumine (*Cuminum cyminum* L.) z nanodelci silicijevega dioksida pri različnih sušnih stresih

Izvleček: Pomanjkanje vode, ki ga poslabšujejo podnebne spremembe in rast prebivalstva, ogroža trajnostno kmetijstvo, zlasti v sušnih regijah. Ta raziskava je preučevala potencial nanodelcev silicijevega dioksida (nSi) za ublažitev sušnega stresa pri rimski kumini (*Cuminum cyminum* L.). Poskus z deljenkami, zasnovan kot popolni naključni poskus s tremi ponovitvami, je bil izveden v dveh rastnih sezonah v Bafghu v Iranu. Sušni stres je bil uporabljen kot glavni dejavnik na štirih ravneh (80 %, 60 %, 40 % in 20 % poljske kapacitete, FC), medtem ko so podploskve vsebovale štiri koncentracije obravnavanja z nSi (0, 2, 4 in 6 mM). Rezultati so pokazali, da je huda suša (20 % FC) občutno zmanjšala pridelek semen, pridelek eteričnega olja in vsebnost celokupnega klorofila, hkrati pa povečala aktivnost peroksidaze in ravni malondialdehida. Uporaba 4 mM nSi je znatno izboljšala pridelek semen in eteričnega olja ter ohranila skupni klorofil in trajno aktivnost peroksidaze, kar je vodilo do nižjih ravni malondialdehida. Nasprotno pa uporaba 6 mM nSi ni izboljšala pridelka semen in eteričnega olja in je dejansko poslabšala njegove učinke. Na splošno lahko 4 mM nSi poveča odpornost in produktivnost rimske kumine v suši, medtem ko se je treba večjim koncentracijam izogibati.

Ključne besede: pridelek semena, pridelek eteričnega olja, malondialdehid, aktivnost peroksidaze

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1 INTRODUCTION

Cumin (*Cuminum cyminum* L.), an aromatic herb from the Apiaceae family, has been used globally in medicine and cooking for centuries (Sowbhagya, 2013). Beyond its culinary uses, cumin traditionally alleviates ailments like toothache, diarrhea, epilepsy (Johri, 2011), jaundice, and indigestion (Rudra Pratap, Gangadharappa, & Mruthunjaya, 2017), attributed to antioxidants such as anthocyanins, flavonoids, and phenolic compounds (Alinian & Razmjoo, 2014). Cumin is mainly cultivated in Asia, the Middle East, and North Africa, with India and Iran as leading producers and exporters (Noori, Moosavi, Seghatoleslami, & Fazeli Rostampour, 2022).

Abdollah (2009) research in Torbat-jam, Iran, demonstrated that cumin production under irrigated conditions (513.40 kg ha^{-1}) significantly exceeded that of rain-fed conditions (480.34 kg ha^{-1}), underscoring the critical role of water availability in cumin yield and sustainable agriculture. However, increasing water scarcity, exacerbated by climate change and population growth, necessitates improved water management in arid and semi-arid regions.

Silicon, the second most abundant element in soil (Sharma et al., 2023), enhances plant growth, development, and stress tolerance despite not being essential. It improves disease and pest resistance, reduces pesticide use (Samal, Bhoi, Mahanta, & Komal, 2024), alleviates nutrient imbalance, and boosts physiological functions (Frew, Weston, Reynolds, & Gurr, 2018; Kovács, Kutasy, & Csajbók, 2022). Si also protects against metal toxicity, oxidative stress, and phenolic browning (Leroy, de Tombeur, Walgraffe, Cornélis, & Verheggen, 2019). Foliar Si application benefits plants facing salinity (Mohammadi, Abdollahi-Bastam, Aghaee, & Ghorbanpour, 2024; Teimoori, Ghobadi, & Kahrizi, 2023), drought (Sutulienė et al., 2022), floods (Chu et al., 2018), heat (Xiao, Li, & Jeong, 2022), cold (Alhasnawi & Al-Bayati, 2023), and biological stresses, activating stress-responsive genes and enhancing tolerance pathways (Mir et al., 2022).

While bulk silicon can be phytotoxic, nano-silicon (nSi) is eco-friendly and enhances crop tolerance to both abiotic and biotic stresses (Helaly, El-Hoseiny, El-Sheery, Rastogi, & Kalaji, 2017). Applying nSi is recommended for improving drought tolerance by reducing reactive oxygen species (ROS) in barley (Ghorbanpour, Mohammadi, & Kariman, 2020), wheat (Ahmadi Nouraldinvand, Seyed Sharifi, Siadat, & Khalilzadeh, 2023), faba beans (Desoky et al., 2021), and cherry tomatoes (Haghighi & Pessarakli, 2013). Silicon alleviates abiotic stress by activating plant antioxidants, immobilizing toxic metal ions, and sequestering metals within the plant (Verma et al., 2022).

Foliar and soil applications of fertilizers elicit distinct plant responses. Foliar application, which rapidly delivers nutrients to leaves, boosts plant protection and yield, especially under stress like drought or salinity (Deng et al., 2022). Foliar spraying provides quicker gains in plant height and growth compared to soil methods and is also more economical due to reduced resource use (Alim et al., 2023).

The effect of foliar nSi application on cumin (*Cuminum cyminum* L.) remains understudied. Existing research has either focused on black cumin (*Nigella sativa* L.) or has been conducted in controlled environments. This study investigated foliar nSi application to alleviate water stress in cumin grown under the semi-arid and arid conditions of central Iran, thus addressing a significant research gap.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL DESIGN, LAND PREPARATION, AND CROP MANAGEMENT

A field study was carried out in Bafq city, Yazd province, Iran (31° 58' N 55° 04' E) during two cropping seasons (2022-23) to assess the impacts of foliar application of nSi and drought stress on the growth, yield, and physiological responses of cumin (*Cuminum cyminum* L.). Meteorological data during the 2022 and 2023 planting seasons at experimental site, are presented in Table 1 (https://www.irimo.ir).

The experiment was laid out as a split-plot design with three replications. Drought stress was applied at four levels (80, 60, 40, and 20 % of field capacity) in the main plots to represent varying water availability, while four levels of nSi foliar application (0, 2, 4, and 6 mM) were randomly assigned to the sub-plots (Fig. 1). In each cropping season, the process of land preparation began in the autumn with deep plowing, reaching depths of up to 30 cm, for breaking up soil compaction and enhancing drainage. Subsequently, initial leveling was performed. Following this, assessments of soil texture and nutrient content were conducted. The land remained undisturbed until the spring, when favorable conditions permitted further land preparation activities, including the use of a disc harrow and final leveling, to establish a uniform planting bed following the design plan.

Table 1: Meteorological data (obtained from Iran's Meteorological Organization's official website, https://www.irimo.ir) during the 2022 and 2023 cumin (*Cuminum cyminum* L.) planting seasons at the Bafq experimental site, Yazd provinces, Iran.

Cropping season		AT (°C)	AR (mm)	ARH (%)	Eva (mm. day^{-1})	AST (°C)
2022	February	12.83	0.00	36.16	0.00	3.22
	March	16.64	0.60	41.62	1.80	7.84
	April	21.33	0.10	23.37	8.57	11.07
	May	26.39	0.12	20.19	12.50	14.77
	June	31.85	0.07	19.72	14.98	20.48
2023	February	17.63	0.00	27.42	5.36	7.22
	March	21.47	0.09	24.13	7.58	10.90
	April	25.06	0.10	18.94	10.21	14.13
	May	31.36	0.00	13.52	12.10	18.29
	June	37.62	0.00	12.93	15.72	24.63

AT: Average temperature, AR: Average rainfall, ARH: Average relative humidity, Eva: Evaporation, AST: Average soil temperature.

2.2 FOLIAR NSI AND DROUGHT TREATMENT

Foliar spray with nanoparticles of silicon dioxide (nSi = 20–30 nm, Iranian Pioneers of Nanomaterials Co., Vakilabad, Mashhad, Iran) supplemented with Jonobgan ionic foliar spray soap as a surfactant (Kerman Zamin Co., Kerman, Iran), was applied two times at two growth stages: 1) after the six-leaf stage, and 2) before flowering. Control plants were also sprayed at the same times with distilled water, supplemented with surfactant soap to eliminate any treatment-related effects from the surfactant. Validation of nanoparticle size specifications provided by the manufacturer was performed using transmission electron microscopy, which confirmed a precise particle diameter of approximately 30 nm.

Drought stress was induced post the six-leaf stage, and after plant establishment. Soil moisture levels were monitored using the pressure plate method, which involves preparing soil samples, saturating them under specific pressures, and drying them to measure soil moisture percentage. After calculating the moisture content of soil samples at field capacity and permanent wilting point (PWP) and determining the apparent specific mass of the soil, the volumetric moisture at FC and PWP points was calculated for each drought level.

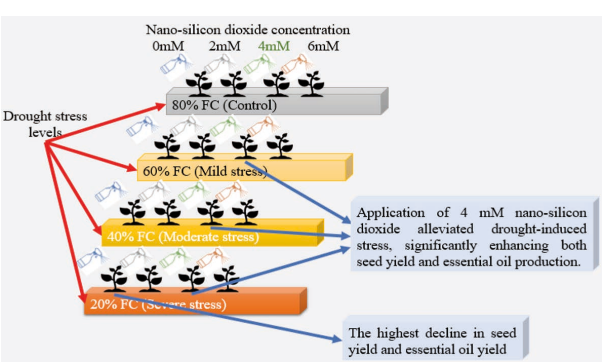

Figure 1: The experimental schematic depicting the foliar application of varying concentrations of silicon dioxide nanoparticles on cumin (*Cuminum cyminum* L.) plants exposed to different drought levels.

2.3 SAMPLING AND TRAIT MEASUREMENT

2.3.1 Physiological and biochemical traits

In each cropping season, one week after the second foliar spray, samples were collected from the plots and frozen for later analysis.

2.3.2 Plant measurements at harvest

After harvest, ten plants were randomly selected from each plot to measure the following traits: seed yield (SY, kg. ha^{-1}), plant height (PH, cm), and number of umbels per plant (NU), number of seeds per umbel (NS), and thousand-seed mass (TSM, g).

2.3.3 Seed and essential oil yield

Seeds were sown in five-row plots (2 m long, 30 cm row spacing) with a 1 m buffer zone. At harvest, samples were taken from each plot to measure seed yield. Samples were air-dried, weighed, and adjusted to standard units (kg ha^{-1}).

Seeds were crushed into a powder, and essential oils were extracted from each sample via hydro distillation using a Clevenger apparatus for 2 hours. Extracts were dried with sodium sulfate, and essential oil yield was calculated as the product of seed yield and essential oil content and reported as kg ha^{-1}.

2.3.4 Leaf analyses

The content of chlorophyll (TChl) was determined following the method of Lichtenthaler and Wellburn (1985).

Malondialdehyde (MDA) content in leaf tissue was quantified by the thiobarbituric acid (TBA) assay according to Senthilkumar, Amaresan, and Sankaranarayanan (2021). Briefly, ~0.1 g of leaf tissue was homogenized in 1 ml ice-cold 0.1% trichloroacetic acid (TCA) and centrifuged at 12,000 g for 10 min at 4 °C. The supernatant (0.5 ml) was mixed with 0.5 ml of 0.5 % TBA in 20 % TCA and incubated at 95 °C for 30 min, then cooled on ice. Absorbance was read at 532 nm and corrected for non-specific absorbance at 600 nm. Malondialdehyde content was calculated using the extinction coefficient and expressed as nmol malondialdehyde per mg protein (protein quantified in the same extract by the Bradford assay).

Peroxidase (POD) enzyme activity was measured following the method outlined by Maehly (1954). This method involved the combination of 50 µl of leaf sample extract with 3 ml of 1.0 M potassium phosphate buffer solution and 50 µl of guaiacol solution. Following this, 50 µl of 3 % hydrogen peroxide was added, and absorbance changes were recorded at 436 nm using a spectrophotometer at intervals ranging from 0 to 3 minutes, with measurements taken every 15 seconds.

2.4 STATISTICAL ANALYSIS

Statistical analyses were conducted using SAS software version 9.1 (SAS, 2003), assuming fixed treatment effects of drought stress and foliar nSi, while the cropping season was considered a random effect. Graphs were created in Microsoft Excel 2019 software. The analysis of variance followed the below model Gomez and Gomez (2009). Mean differences between treatments were assessed using Duncan's test.

3 RESULTS

The homogeneity of experimental error variances was assessed before the combined analysis of variance. The combined analysis of variance revealed a significant triple interaction effect of year, drought stress, and foliar application of nSi for all traits studied (Table 2). When the interaction term is significant interpretation of the main effects from the analysis of variance is impossible or at best unreliable (Dunne, 2010). Therefore, this research

Table 2: Combined analysis of variance for drought stress and foliar application of silicon dioxide nanoparticles effects on cumin traits across two cropping seasons.

Source	DF	SY	EOY	PH	NU	NS	TSM	TChl	MDA	POD
Y	1	18477.89	11.8	729.65	41.04	365.66	9.38	562.54	0.08	97.31
Y(R)	4	2476.95	4.56	0.87	9.36	4.83	0.03	0.56	0.2	0.33
D	3	1469608.63 **	559.5 **	743.77 ns	150.05 ns	749.33 **	3.99 ns	212.26 ns	25.44 ns	488.65 ns
Y × D	3	36072.09 **	5.19 ns	87.58 **	31.08 **	9.78 ns	0.84 *	35.26 **	2.82 **	94.83 **
Error 1	12	1540.48	2.13	1.1	4.7	4.49	0.17	0.3	0.18	0.73
nSi	3	103948.19 *	31.2 ns	100.44 ns	23.09 ns	24.02 *	1.54 ns	140.19 ns	9.07 *	52.57 ns
Y × Si	3	5596.78 ns	4.35 *	50.05 **	10.91 **	1.69 ns	0.3 ns	39.62 **	0.52 ns	26.99 **
D × Si	9	24554.88 *	36.01 *	24.35 ns	53.66 ns	16.03 ns	0.52 ns	23.63 *	4.42 ns	17.3 ns
Y × D × Si	9	7084.4 *	10.69 **	41.03 **	24.61 **	7.2 *	0.56 **	5.11 **	3.2 **	6.27 **
Error 2	48	2573.1 ns	1.16	2.42	1.57	2.76	0.12	0.6	0.21	0.78
MPCV %		10.18	22.87	4.42	15.06	10.64	17.28	3.26	9.08	12.15
SPCV %		13.15	16.87	6.54	8.71	8.35	14.46	4.58	9.94	12.61

*, and ** indicate significant at the 0.05 and 0.01 levels of probability, respectively.
Y: Effect of Year; R: Replication; D: Effect of Drought; nSi: Effect of Silicon dioxide nanoparticles; CV: coefficient of variations.
PH: Plant height; NU: Number of umbels per plant; NS: Number of seeds per umbel; TSM: Thousand seed mass; SY: Seed yield; EOY: Essential oil yield; TChl: Total chlorophyll content; MDA: Malondialdehyde content; POD: Peroxidase enzyme activity.

focuses solely on the described triple interaction effect in the presentation and interpretation of the results.

3.1 SEED YIELD

Seed yield response to varying nano-silicon concentrations was non-linear under different drought stress levels. Average seed yield in 2022 was approximately 7 % lower than in 2023. In the absence of foliar nSi, mild, moderate, and severe drought stresses reduced seed yield in 2022 by 7 %, 67 %, and 81 %, respectively, compared to the control. Similar reductions were observed in 2023 (Fig. 2).

Under non-stressed conditions (80 % FC) in 2023, seed yield initially increased significantly with rising nSi concentration, peaking at 4 mM before decreasing at 6 mM. In 2023, 4 mM nSi under mild stress resulted in the optimal yield increase, whereas 6 mM nSi decreased yield. Under moderate stress, nSi mitigated negative impacts on seed yield. In 2023, 2 mM nSi boosted yield by 79 %, and in 2022, 4 mM nSi increased it by 67 %. Under severe stress, 4 mM nSi increased yield by 52 % in 2022 and 29 % in 2023, although these increases were not statistically significant (Fig. 2).

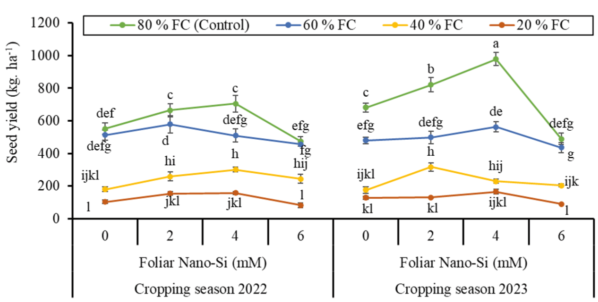

Figure 2: Comparison of average seed yield of cumin (*Cuminum cyminum* L.) under Nano-Silica foliar application and different drought stress levels. Differences between columns with a common letter are not significant according to Duncan's test (α = 0.05).

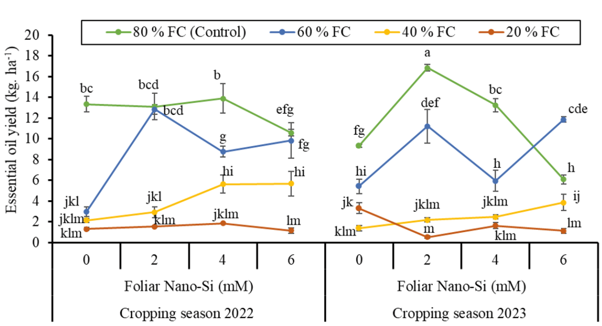

Figure 3: Comparison of average essential oil yield of cumin (*Cuminum cyminum* L.) influenced by Nano-Silica foliar application and different drought stress levels. Differences between columns with a common letter are not significant according to Duncan's test (α = 0.05).

3.2 ESSENTIAL OIL YIELD

Under non-stressed conditions in 2023, 2 mM nano-silicon produced the highest essential oil yield, 81 % greater than the control (Fig. 3).

Foliar nSi application also mitigated drought stress, increasing essential oil yield under mild stress by 3.4-fold (2022) and 2.1-fold (2023) with 2 mM nSi, as compared with the control. Under moderate stress, 4 mM nSi increased essential oil yield by 2.6-fold in 2022, and 6 mM nSi increased it by 2.8-fold in 2023, relative to the control (Fig. 3).

3.3 YIELD COMPONENTS

In 2023 without drought, plant height ranged from 27.74 cm (0 mM nSi) to 46.36 cm (4 mM nSi), but decreased to 33.12 cm at 6 mM nSi. Under mild drought, 4 mM nSi significantly increased plant height compared to the control in both years. Under moderate drought, 6 mM nSi increased plant height in 2022, while 4 mM nSi increased plant height in 2023, both relative to the control. Under severe drought, nSi did not significantly enhance plant height in 2022, but in 2023, 6 mM nSi increased plant height by 40 % compared to the control (Fig. 4).

In 2023, the number of umbels per plant ranged from 15.3 to 25.5 with 0-2 mM nSi, but decreased to 15.9-22.4 with 4-6 mM. Under mild drought, 2 mM nSi increased this trait compared to the control in both years. Likewise, under moderate drought, 6 mM nSi improved the number of umbels per plant in 2022 (47 %) and 2023 (74 %). During severe drought in 2023, nSi did not enhance this trait, but in 2022, 4 mM nSi increased it by 29 % (Fig. 4).

In 2023 without drought, the number of seeds per umbel ranged from 26.5 to 31.2 under 0–4 mM nSi, decreasing to 27.1 at 6 mM. With mild stress, 6 mM nSi increased seed number in 2023 but not in 2022. Under moderate stress, nSi had no effect in 2023, but 6 mM nSi increased it in 2022. During severe drought, 4 mM nSi resulted in the highest seed number, with no significant difference from 2–6 mM. The maximum seed number was observed in 2023 under normal conditions with 4 mM nSi (Fig. 4).

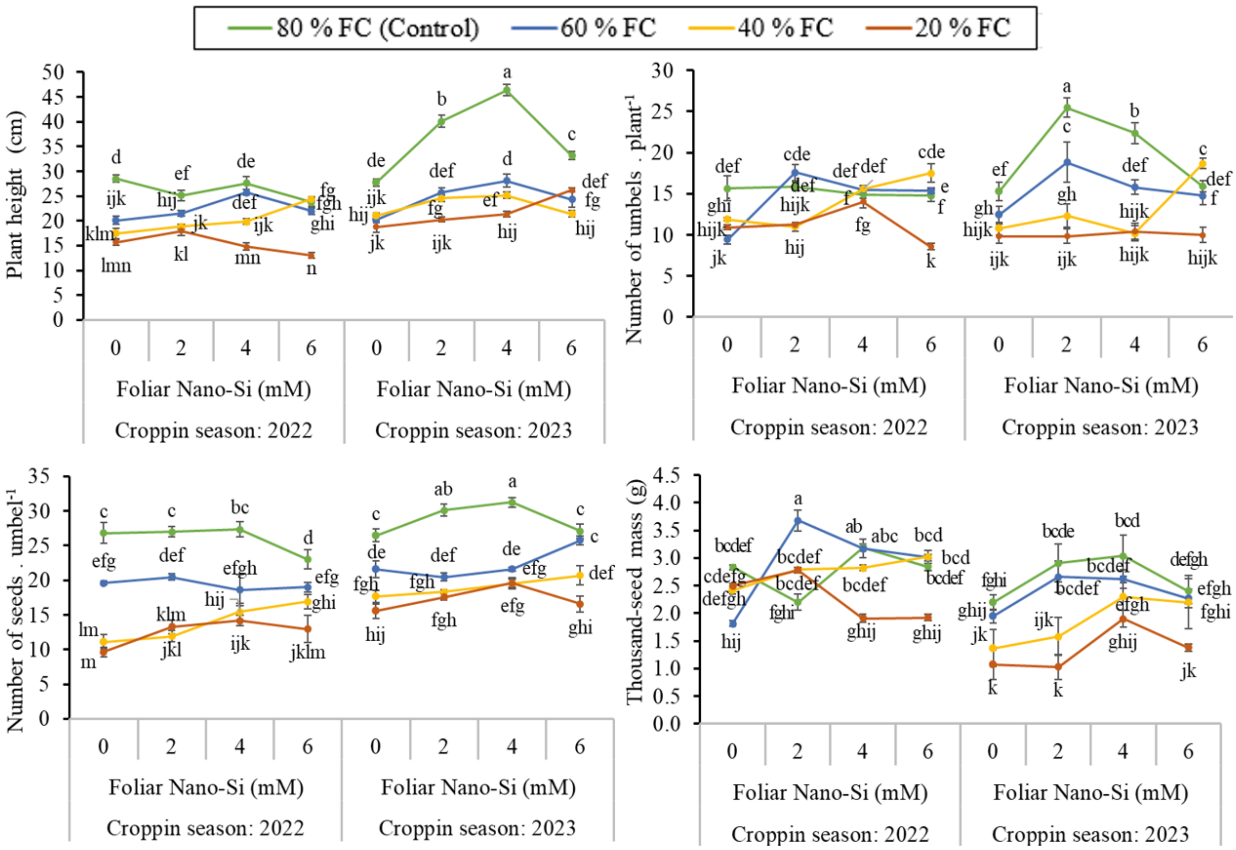

Figure 4: Average seed yield component traits in cumin (*Cuminum cyminum* L.) under nano silica foliar application and different drought stress levels during the 2022-2023 cropping seasons.
Differences between means sharing a common letter are not significant according to Duncan's test (α = 0.05).

In 2023, drought reduced thousand-seed mass regardless of nSi treatment, while no reduction occurred in 2022. Without drought, nSi increased thousand-seed mass in both years. 4 mM nSi significantly increased 1000-grain mass compared to the control, but 6 mM nSi provided no further increase. Under mild stress, 2 mM nSi improved thousand-seed mass. Under moderate stress, nSi had no effect in 2022, but in 2023, 4 mM nSi increased thousand-grain mass by 68 %. During severe drought, nSi had no effect in 2022, but in 2023, 4 mM nSi increased 1000-grain mass by 77 %.

3.4 BIOCHEMICAL CHARACTERISTICS

In 2023, 4 mM nSi significantly increased total chlorophyll content compared to the control, but 6 mM nSi offered no additional benefit. Without drought in 2023, 4 mM nSi significantly increased chlorophyll content, while 6 mM nSi slightly decreased it. Under mild and moderate stress, 4 mM nSi significantly improved chlorophyll content compared to the control. Under severe drought, 2 mM nSi increased the trait by 26 % in 2022, while 4 mM nSi more than doubled it in 2023 (Fig. 5).

Under normal irrigation, 6 mM nSi increased malondialdehyde, suggesting stress. However, under mild stress, both 4 and 6 mM nSi reduced malondialdehyde in 2022. In 2023, 4 mM nSi also resulted in the lowest malondialdehyde, though not significantly lower than the control. Overall, 4 mM nSi significantly decreased malondialdehyde compared to the control under both mild and severe stress (Fig. 5).

In 2022, 6 mM nSi increased peroxidase activity under non-drought and mild stress, but not in 2023. Under moderate stress, 2 and 6 mM nSi resulted in the highest peroxidase activity in 2022; in 2023, only 6 mM nSi significantly increased it compared to the control. Under severe drought, 2 mM nSi enhanced peroxidase activity in 2022, while 2 and 4 mM nSi increased it in 2023 (Fig. 5).

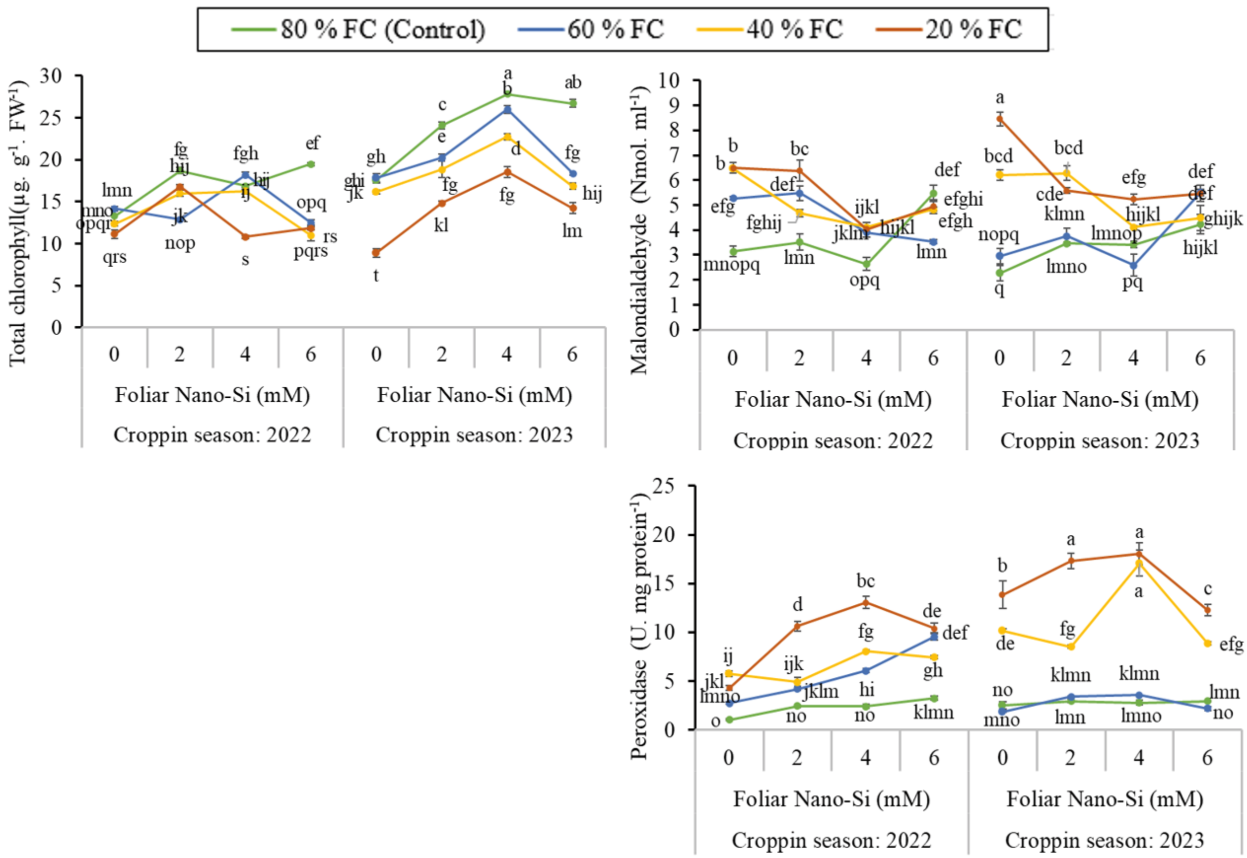

Figure 5: Average biochemical traits of cumin (*Cuminum cyminum* L.) under nano-silica foliar application and varying drought stress levels during the 2022-2023 cropping seasons.
Differences between means sharing a common letter are not significant according to Duncan's test (α=0.05).

4 DISCUSSION

4.1 EFFECTS OF SILICON NANOPARTICLES AND DROUGHT ON YIELD AND YIELD-RELATED TRAITS

Cumin seed yield was lower in 2022 than in 2023. Lower soil and air temperatures in 2022 likely impacted cumin reproductive mechanisms by affecting key physiological processes like photosynthesis and respiration, crucial for flowering and reproductive development, especially the transition from vegetative to reproductive stages (Valdés & Ehrlén, 2022). Conversely, higher rainfall in 2022 compared to 2023 may have reduced the effectiveness of nano-silica application due to foliar washout (Fageria, Filho, Moreira, & Guimarães, 2009). Regression analysis indicated that cumin seed yield was primarily influenced by traits thousand-seed mass and the number of seeds per umbel, while the number of umbels per plant had no significant effect, suggesting drought stress reduces cumin yield mainly through degradation of thousand-seed mass and the number of seeds per umbel.

These results confirm that drought stress negatively affects cumin yield and related traits, consistent with previous studies. Safari, Mahdi Mortazavian, Sadat-Noori, and Foghi (2015) reported a 34 % seed yield reduction under drought. This study aligns with Timachi, Armin, Jamimoeini, and Abhari (2023) and Salajegheh, Yavarzadeh , Payandeh, and Akbarian (2021), who showed that water deficit reduces the number of umbels per plant, number of seeds per umbel, thousand seed mass, seed yield, and essential oil yield.

Under non-stress conditions, foliar application of silicon nanoparticles up to 4 mM significantly increased cumin yield by 44 % and improved yield-related traits compared to controls. This increase is likely due to nSi's role in enhancing photosynthetic pigments, as shown by Thind et al. (2020) and Rastogi et al. (2021). Under moderate drought, nSi effectively mitigated drought-induced impacts on seed yield and yield-related traits. Bijanzadeh, Barati, and Egan (2022) found that 1 mM sodium silicate mitigated drought stress in corn. Supporting this, Rastogi et al. (2021) suggested that silicon enhances photosynthesis under stress by preserving chloroplast structure. Consistent with these findings, nSi foliar application significantly increased chlorophyll levels under drought. However, nSi application did not significantly alleviate severe drought stress, and increasing nSi concentration under these conditions showed diminishing returns.

Malondialdehyde analysis revealed that nSi concentrations above 4 mM acted as a stressor, negatively affecting cumin seed yield and related traits. Alzahrani, Kuşvuran, Alharby, Kuşvuran, and Rady (2018) concluded that 4 mM Si was optimal for mitigating drought stress in wheat. Verma et al. (2022) similarly found that nSi application enhanced shoot length in barley under drought, while reducing superoxide radical formation and minimizing membrane damage.

Drought stress reduces turgor, light absorption, and metabolites needed for cell division. This impairs mitosis, cell elongation, and expansion, leading to reduced growth, seed yield, and related traits (Sintayehu Musie & Radácsi, 2022). In addition, essential oil yield may vary with seed yield, and observed differences could reflect initial seed proportions or seed-function indices (Bayati, Karimmojeni, & Razmjoo, 2020). As mentioned by Bayati et al. (2020) essential oil content reduced in black cumin with intensified drought; however, the decrease was depend on both drought level and genotype, while drought stress may increase essential oil content.

Drought stress significantly reduces cumin plant height, contradicting Alinian and Razmjoo (2014) but consistent with Timachi et al. (2023). This reduction likely stems from impaired cellular division and elongation under drought conditions (Salajegheh et al., 2021). Foliar application of silicon nanoparticles (nSi) effectively alleviates drought-induced height limitations, supporting Liu and Lal (2015) hypothesis that nanoparticles can mitigate stress-related morphological constraints. This enhancement may be due to nSi deposition in the leaf apoplast, creating a protective barrier against environmental stressors (Wang, Hu, Duan, Feng, & Gong, 2016). The growth-promoting effects of nSi are potentially linked to enhanced protein content, nutrient absorption, photosynthetic efficiency, and reduced cell membrane damage (Raza et al., 2023), as well as increased water and photosynthetic pigment accumulation during drought.

4.2 EFFECTS OF SILICON NANOPARTICLES AND DROUGHT ON BIOCHEMICAL CHARACTERISTICS

Drought stress in cumin plants generally reduces total chlorophyll content while increasing peroxidase activity and malondialdehyde levels. The decrease in total chlorophyll content likely results from drought-induced damage to chloroplast structure via ROS, disrupting electron transfer in photosystem II (PSII) and impacting chlorophyll content (Hu, Zhang, & Guo, 2023; Qiao, Hong, Jiao, Hou, & Gao, 2024). Plants may also increase stomatal conductance under drought, leading to decreased relative water content in aerial parts (Lv, Li, Chen, Rui, & Wang, 2023). Drought stress elevates peroxidase enzyme activity, a common antioxidant defense mechanism against oxidative damage (Zhang & Kirkham, 1994).

Foliar application of nSi enhances total chlorophyll content in cumin plants while reducing malondialdehyde levels, an indicator of stress-induced lipid peroxidation. This treatment also increases peroxidase activity, bolstering the plant's antioxidant defenses. As reported in previous studies, nSi reduces superoxide radical formation and membrane damage in drought-stressed plants by improving chlorophyll and proline levels, maintaining membrane integrity and water content, thus mitigating drought's negative effects (Yavaş, 2021). Silicon dioxide nanoparticles may also lessen the impact of drought on photosynthetic pigments by promoting cytokinin production, which restores chlorophyll formation and improves chloroplast structure (Khan et al., 2020). Furthermore, nSi enhances nutrient availability, boosting photosynthetic efficiency (Asgari, Majd, Jonoubi, & Najafi, 2018), increases cell wall thickness, and facilitates nutrient transport via xylem opening, significantly improving photosynthesis (Raza et al., 2023). In coriander, foliar nSi application enhanced antioxidant capacity and increased essential oil yield under moderate drought (Afshari, Pazoki, & Sadeghipour, 2021). Overall, foliar nSi application can mitigate the adverse effects of drought stress on plants in arid environments (Dilnawaz, Misra, & Apostolova, 2023; El-Beltagi et al., 2024).

This study aimed to determine the optimal concentration of silicon nanoparticles for alleviating drought stress in cumin plants. Foliar application of 4 mM nSi significantly improved yield and biochemical traits under drought conditions. However, a 6 mM concentration had detrimental effects, further reducing these traits. Excessive nSi can cause nutrient imbalances, reduced photosynthesis, and stunted growth. While moderate concentrations can enhance growth and stress resistance, excessive levels may hinder root development, cause toxicity, or interfere with nutrient uptake (Karimi & Mohsenzadeh, 2016). Consistent with this, Karimi and Mohsenzadeh (2016) found that nSi concentrations exceeding 200 mg l^{-1} negatively impacted wheat seedlings, significantly reducing root and shoot fresh and dry mass, chlorophyll a and b levels, and carotenoid content, while increasing proline, lipid peroxidation, and catalase activity. They also suggested that lower concentrations (50 and 100 mg l^{-1}) could have adverse or beneficial effects on wheat seedlings.

5 CONCLUSION

Foliar application of nSi at 4 mM significantly improves cumin plant growth and physiological resilience under drought. This treatment enhances plant height, grain yield, essential oil yield, and related traits. The benefits of nSi include increased peroxidase activity and chlorophyll content, reduced drought stress, decreased malondialdehyde levels, mitigated reactive oxygen species, and minimized cellular damage. Therefore, foliar application of nSi at 4 mM is recommended for cumin cultivation; however, concentrations above 4 mM may worsen drought stress.

6 DATA AVAILABILITY

The data underlying this study are openly available in Harvard Dataverse at https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/BEO42B (Ameri Bafqi, 2025).

7 REFERENCES

Abdollah, M. (2009). *Effect of planting dates and rows spacing on yield of dryland and irrigated Cumin (Cuminum cyminum L.).* Paper presented at the I International medicinal and aromatic plants conference on culinary herbs, Antalya, Turkey.

Afshari, M., Pazoki, A., & Sadeghipour, O. (2021). Foliarapplied silicon and its nanoparticles stimulate physiochemical changes to improve growth, yield and active constituents of coriander (*Coriandrum sativum* L.) essential oil under different irrigation regimes. *Silicon, 13*(11), 4177-4188. doi:10.1007/s12633-021-01101-8

Ahmadi Nouraldinvand, F., Seyed Sharifi, R., Siadat, S. A., & Khalilzadeh, R. (2023). Effects of bio-fertilizers and nano-silicon on phosphorus uptake, grain yield and some physiological traits of wheat (*Triticum aestivum* L.) under withholding irrigation conditions. *Environmental Stresses in Crop Sciences, 16*(3), 711-726. doi:10.22077/escs.2023.4931.2090

Alhasnawi, N. J. R., & Al-Bayati, A. S. (2023). *Synergistic effects of low tunnel polyethylene covering and silicon spraying on growth and yield of two radish varieties under cold stress.* Paper presented at the 4th International Conference of Modern Technologies in Agricultural Sciences, Najaf, Iraq. doi:10.1088/1755-1315/1262/4/042067

Alim, M. A., Hossain, S. I., Ditta, A., Hasan, M. K., Islam, M. R., Hafeez, A. S. M. G., . . . Islam, M. S. (2023). Comparative efficacy of foliar plus soil application of urea versus conventional application methods for enhanced growth, yield, agronomic efficiency, and economic benefits in rice. *ACS Omega, 8*(39), 35845-35855. doi:10.1021/acsomega.3c03483

Alinian, S., & Razmjoo, J. (2014). Phenological, yield, essential oil yield and oil content of cumin accessions as affected by irrigation regimes. *Industrial Crops and Products, 54*, 167-174. doi:10.1016/j.indcrop.2014.01.028

Alzahrani, Y., Kuşvuran, A., Alharby, H. F., Kuşvuran, S., & Rady, M. M. (2018). The defensive role of silicon in wheat against stress conditions induced by drought, salinity or cadmium. *Ecotoxicology and Environmental Safety, 154*, 187-196. doi:10.1016/j.ecoenv.2018.02.057

Ameri Bafqi, M. E. (2025). *Replication Data for: Modulation of physiological and yield attributes of cumin (Cuminum cyminum L.) by silicon dioxide nanoparticles under varying drought stresses*. Retrieved from: doi:10.7910/DVN/BEO42B

Asgari, F., Majd, A., Jonoubi, P., & Najafi, F. (2018). Effects of silicon nanoparticles on molecular, chemical, structural and ultrastructural characteristics of oat (*Avena sativa* L.). *Plant Physiology and Biochemistry, 127*, 152-160. doi:10.1016/j.plaphy.2018.03.021

Bayati, P., Karimmojeni, H., & Razmjoo, J. (2020). Changes in essential oil yield and fatty acid contents in black cumin (*Nigella sativa* L.) genotypes in response to drought stress. *Industrial Crops and Products, 155*, 112764. doi:10.1016/j.indcrop.2020.112764

Bijanzadeh, E., Barati, V., & Egan, T. P. (2022). Foliar application of sodium silicate mitigates drought stressed leaf structure in corn (*Zea mays* L.). *South African Journal of Botany, 147*, 8-17. doi:10.1016/j.sajb.2021.12.032

Chu, M., Liu, M., Ding, Y., Wang, S., Liu, Z., Tang, S., . . . Li, G. (2018). Effect of nitrogen and silicon on rice submerged at tillering stage. *Agronomy Journal, 110*(1), 183-192. doi:10.2134/agronj2017.03.0156

Deng, C., Wang, Y., Cantu, J. M., Valdes, C., Navarro, G., Cota-Ruiz, K., . . . Gardea-Torresdey, J. L. (2022). Soil and foliar exposure of soybean (*Glycine max*) to Cu: nanoparticle coating-dependent plant responses. *NanoImpact, 26*, 100406. doi:10.1016/j.impact.2022.100406

Desoky, E.-S. M., Mansour, E., El-Sobky, E.-S. E. A., Abdul-Hamid, M. I., Taha, T. F., Elakkad, H. A., . . . Yasin, M. A. T. (2021). Physio-biochemical and agronomic responses of faba beans to exogenously applied nano-silicon under drought stress conditions. *Frontiers in Plant Science, 12*, 637783. doi:10.3389/fpls.2021.637783

Dilnawaz, F., Misra, A. N., & Apostolova, E. (2023). Involvement of nanoparticles in mitigating plant's abiotic stress. *Plant Stress, 10*, 100280. doi:10.1016/j.stress.2023.100280

Dunne, R. P. (2010). Synergy or antagonism—interactions between stressors on coral reefs. *Coral Reefs, 29*(1), 145-152. doi:10.1007/s00338-009-0569-6

El-Beltagi, S. H., Mubarak Alwutayd, K., Rasheed, U., Sattar, A., Ali, Q., Alharbi, M. B., . . . Hamada, M. A. M. (2024). Sole and combined foliar application of silicon and putrescine alleviates the negative effects of drought stress in maize by modulating the morpho-physiological and antioxidant defence mechanisms. *Plant, Soil and Environment, 70*(1), 26-39.

Fageria, N. K., Filho, M. P. B., Moreira, A., & Guimarães, C. M. (2009). Foliar fertilization of crop plants. *Journal of Plant Nutrition, 32*(6), 1044-1064. doi:10.1080/01904160902872826

Frew, A., Weston, L. A., Reynolds, O. L., & Gurr, G. M. (2018). The role of silicon in plant biology: a paradigm shift in research approach. *Annals of Botany, 121*(7), 1265-1273. doi:10.1093/aob/mcy009

Ghorbanpour, M., Mohammadi, H., & Kariman, K. (2020). Nanosilicon-based recovery of barley (*Hordeum vulgare*) plants subjected to drought stress. *Environmental Science: Nano, 7*(2), 443-461. doi:10.1039/C9EN00973F

Gomez, K. A., & Gomez, A. A. (2009). *Statistical procedures in agricultural research* (January 1, 2009 ed.): John Wiley & Sons.

Haghighi, M., & Pessarakli, M. (2013). Influence of silicon and nano-silicon on salinity tolerance of cherry tomatoes (*Solanum lycopersicum* L.) at early growth stage. *Scientia Horticulturae, 161*, 111-117. doi:10.1016/j.scienta.2013.06.034

Helaly, M. N., El-Hoseiny, H., El-Sheery, N. I., Rastogi, A., & Kalaji, H. M. (2017). Regulation and physiological role of silicon in alleviating drought stress of mango. *Plant Physiology and Biochemistry, 118*, 31-44. doi:10.1016/j.plaphy.2017.05.021

Hu, F., Zhang, Y., & Guo, J. (2023). Effects of drought stress on photosynthetic physiological characteristics, leaf microstructure, and related gene expression of yellow horn. *Plant Signaling & Behavior, 18*(1), 2215025. doi:10.1080/15592324.2023.2215025

Johri, R. K. (2011). *Cuminum cyminum* and *Carum carvi*: An update. *Pharmacognosy Reviews, 5*(9), 63-72. doi:10.4103/0973-7847.79101

Karimi, J., & Mohsenzadeh, S. (2016). Effects of silicon oxide nanoparticles on growth and physiology of wheat seedlings. *Russian Journal of Plant Physiology, 63*(1), 119-123. doi:10.1134/S1021443716010106

Khan, Z. S., Rizwan, M., Hafeez, M., Ali, S., Adrees, M., Qayyum, M. F., . . . Sarwar, M. A. (2020). Effects of silicon nanoparticles on growth and physiology of wheat in cadmium contaminated soil under different soil moisture levels. *Environmental Science and Pollution Research, 27*(5), 4958-4968. doi:10.1007/s11356-019-06673-y

Kovács, S., Kutasy, E., & Csajbók, J. (2022). The multiple role of silicon nutrition in alleviating environmental stresses in sustainable crop production. *Plants, 11*(9), 1223. doi:10.3390/plants11091223

Leroy, N., de Tombeur, F., Walgraffe, Y., Cornélis, J.-T., & Verheggen, F. J. (2019). Silicon and plant natural defenses against insect pests: impact on plant volatile organic compounds and cascade effects on multitrophic interactions. *Plants, 8*(11), 444. doi:10.3390/plants8110444

Lichtenthaler, H., & Wellburn, A. R. (1985). Determination of total carotenoids and chlorophylls a and b of leaf in different solvents. *Biochemical Society Transactions, 11*, 591-592.

Liu, R., & Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of The Total Environment, 514*, 131-139. doi:10.1016/j.scitotenv.2015.01.104

Lv, X., Li, Y., Chen, R., Rui, M., & Wang, Y. (2023). Stomatal responses of two drought-tolerant barley varieties with different ROS regulation strategies under drought conditions. *Antioxidants, 12*(4), 790. doi:10.3390/antiox12040790

Maehly, A. C. (1954). The assay of catalases and peroxidases. In *Methods of Biochemical Analysis* (pp. 357-424).

Mir, R. A., Bhat, B. A., Yousuf, H., Islam, S. T., Raza, A., Rizvi, M. A., . . . Zargar, S. M. (2022). Multidimensional role of silicon to activate resilient plant growth and to mitigate abiotic stress. *Frontiers in Plant Science, 13*, 819658. doi:10.3389/fpls.2022.819658

Mohammadi, H., Abdollahi-Bastam, S., Aghaee, A., & Ghorbanpour, M. (2024). Foliar-applied silicate potassium modulates growth, phytochemical, and physiological traits in *Cichorium intybus* L. under salinity stress. *BMC Plant Biology, 24*(1), 288. doi:10.1186/s12870-024-05015-6

Noori, H., Moosavi, S. G., Seghatoleslami, M. J., & Fazeli Rostampour, M. (2022). Morpho-physiological and yield responses of cumin (*Cuminum cyminum* L.) to the application of growth regulators under drought stress. *Iranian Journal of Plant Physiology, 1*(12), 4013-4025. doi:10.30495/ijpp.2022.689076

Qiao, M., Hong, C., Jiao, Y., Hou, S., & Gao, H. (2024). Impacts of drought on photosynthesis in major food crops and the related mechanisms of plant responses to drought. *Plants, 13*(13), 1808. doi:10.3390/plants13131808

Rastogi, A., Yadav, S., Hussain, S., Kataria, S., Hajihashemi, S., Kumari, P., . . . Brestic, M. (2021). Does silicon really matter for the photosynthetic machinery in plants…? *Plant Physiology and Biochemistry, 169*, 40-48. doi:10.1016/j.plaphy.2021.11.004

Raza, M. A. S., Zulfiqar, B., Iqbal, R., Muzamil, M. N., Aslam, M. U., Muhammad, F., . . . Habib-ur-Rahman, M. (2023). Morpho-physiological and biochemical response of wheat to various treatments of silicon nano-particles under drought stress conditions. *Scientific Reports, 13*(1), 2700. doi:10.1038/s41598-023-29784-6

Rudra Pratap, S., Gangadharappa, H. V., & Mruthunjaya, K. (2017). *Cuminum cyminum* – A popular spice: An updated review. *Pharmacognosy Journal, 9*(3), 292-301. doi:10.5530/pj.2017.3.51

Safari, B., Mahdi Mortazavian, S. M., Sadat-Noori, S. A., & Foghi, B. (2015). Effect of water stress on yield and yield components of cumin (*Cuminum cyminum* L.) ecotypes. *Journal of Plant Physiology and Breeding, 5*(2), 51-61.

Salajegheh, M., Yavarzadeh , M., Payandeh, A., & Akbarian, M. M. (2021). Effects of titanium and silicon nanoparticles and super absorbent polymer on morphological and functional traits of cumin plant under drought stress. *International Journal of Modern Agriculture, 10*(3), 189 - 200.

Samal, I., Bhoi, T. K., Mahanta, D. K., & Komal, J. (2024). Establishing the role of silicon (Si) in plant resistance to insects: A bibliometric approach. *Silicon, 16*(5), 2119-2128. doi:10.1007/s12633-023-02821-9

SAS. (2003) (Version Release 9.1 for windows). Cary, NC, USA.: SAS Institute Inc.

Senthilkumar, M., Amaresan, N., & Sankaranarayanan, A. (2021). Estimation of malondialdehyde (MDA) by thiobarbituric acid (TBA) assay. In *Plant-Microbe Interactions: Laboratory Techniques* (pp. 103-105). New York, NY: Springer US.

Sharma, B., Kumawat, K. C., Tiwari, S., Kumar, A., Dar, R. A., Singh, U., & Cardinale, M. (2023). Silicon and plant nutrition—dynamics, mechanisms of transport and role of silicon solubilizer microbiomes in sustainable agriculture: A review. *Pedosphere, 33*(4), 534-555. doi:10.1016/j.pedsph.2022.11.004

Sintayehu Musie, M., & Radácsi, P. (2022). Influence of drought stress on growth and essential oil yield of ocimum species. *Horticulturae, 8*(2), 175. doi:10.3390/horticulturae8020175

Sowbhagya, H. B. (2013). Chemistry, technology, and nutraceutical functions of cumin (*Cuminum cyminum* L): An overview. *Critical Reviews in Food Science and Nutrition, 53*(1), 1-10. doi:10.1080/10408398.2010.500223

Sutulienė, R., Ragelienė, L., Samuolienė, G., Brazaitytė, A., Urbutis, M., & Miliauskienė, J. (2022). The response of antioxidant system of drought-stressed green pea (*Pisum sativum* l.) affected by watering and foliar spray with silica nanoparticles. *Horticulturae, 8*(1), 35. doi:10.3390/horticulturae8010035

Teimoori, N., Ghobadi, M., & Kahrizi, D. (2023). Improving the growth characteristics and grain production of camelina (*Camelina sativa* L.) under salinity stress by silicon foliar application. *Agrotechniques in Industrial Crops, 3*(1), 1-13. doi:10.22126/atic.2023.8681.1081

Thind, S., Hussain, I., Ali, S., Hussain, S., Rasheed, R., Ali, B., & Hussain, H. A. (2020). Physiological and biochemical bases of foliar silicon-induced alleviation of cadmium toxicity in wheat. *Journal of Soil Science and Plant Nutrition, 20*(4), 2714-2730. doi:10.1007/s42729-020-00337-4

Timachi, F., Armin, M., Jamimoeini, M., & Abhari, A. (2023). The effect of times and type of stress modulator on quantitative and qualitative yield of cumin under rainfed and irrigated conditions. *Journal of Medicinal plants and By-Products, 12*(2), 145-157. doi:10.22092/jmpb.2021.341798.1182

Valdés, A., & Ehrlén, J. (2022). Microclimate influences plant reproductive performance via an antagonistic interaction. *Basic and Applied Ecology, 64*, 13-29. doi:10.1016/j.baae.2022.07.007

Verma, K. K., Song, X.-P., Singh, M., Huang, H.-R., Bhatt, R., Xu, L., . . . Li, Y.-R. (2022). Influence of nanosilicon on drought tolerance in plants: An overview. *Frontiers in Plant Science, 13*. doi:10.3389/fpls.2022.1014816

Wang, Y., Hu, Y., Duan, Y., Feng, R., & Gong, H. (2016). Silicon reduces long-term cadmium toxicities in potted garlic plants. *Acta Physiologiae Plantarum, 38*(8), 211. doi:10.1007/s11738-016-2231-6

Xiao, J., Li, Y., & Jeong, B. R. (2022). Foliar silicon spray to strawberry plants during summer cutting propagation enhances resistance of transplants to high temperature stresses. *Frontiers in Sustainable Food Systems, 6*, 938128. doi:10.3389/fsufs.2022.938128

Yavaş, İ. (2021). The effect of nanoparticle applications on plants under some stress conditions. *Turkish Journal of Range and Forage Science, 2*. doi:10.51801/turkjrfs.954843

Zhang, J., & Kirkham, M. B. (1994). Drought-stress-induced changes in activities of superoxide dismutase, catalase, and peroxidase in wheat species. *Plant and Cell Physiology, 35*(5), 785-791. doi:10.1093/oxfordjournals.pcp.a078658