Assessment of drought stress indices in cumin (Cuminum cyminum L.) under foliar application of nanosilica

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Abstract

Drought stress significantly reduces the productivity of cumin (Cuminum cyminum L.), particularly during flowering. Therefore, successful measures to reduce the impact of this stress are crucial. This study was designed to analyze the application of foliar nanosilica (0, 2, 4, and 6 mM) as an aid in drought tolerance in three ecotypes (Isfahan, Semnan, and Kashan) under stress levels (80, 60, 40, and 20% field capacity, FC) in Aveh and Bafq regions in Iran. The main results indicated that Kashan could maintain considerably greater yield stability but a lower susceptibility. Application of nanosilica (2 and 4 mM) improved the yield under stress, geometric mean productivity (GMP), and stress tolerance index (STI), especially when moderate stress (40 and 60% FC) was applied. Under severe stress (20% FC) little yield benefit was observed, indicating that the nanosilica could reach a threshold. The moderate to strong correlations between yield under stress (Ys) and the integrated indices demonstrated that these indices should be used when measured together (Mean Productivity: 0.83, Geometric Mean Productivity: 0.98, Harmonic Mean: 0.96). PCA separated the ecotypes on the basis of drought tolerance, and Kashan ecotype outperformed all the other ecotypes. The presence of nanosilica promotes physiological resilience by providing water retention, which is consistent with previous observations of the role of nanosilica in enhancing drought stress resistance. Our findings highlight the benefits of using moderate doses of nanosilica (2 and 4 mM), which helps promote the productivity of cumin in drought-prone Aveh and Bafq.

Keywords: cumin, drought stress, principal component analysis, nanosilica

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Introduction

Cumin (Cuminum cyminum L.) is an economically and medicinally important crop that is extensively cultivated in arid regions. It is widely used because of its antioxidant and anti-inflammatory qualities, as elucidated by Kafi (2006). However, these conditions severely impair the duration of cumin accumulation during the essential stage. Drought can reduce seed yield and essential oil content while deteriorating overall health (Bazrafshan et al., 2023). It negatively impacts photosynthesis, nutrient absorption, and reproduction in various ways. Multiple studies have provided robust evidence for the devastating agricultural impact of drought (Zhang et al., 2018, Gama et al., 2020, Rashmi Poudel, 2023). Crop-specific research has demonstrated dramatic reductions: maize yields can decline up to 70%, soybean yields can decline by 60.3%, and wheat/rice yields can decrease by

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approximately 25-27% (Rashmi Poudel et al., 2023, Zhang et al., 2018). Plant height typically decreased by 15%, whereas seed weight and reproductive components were substantially compromised (Gama et al., 2020). The effect varies by crop type and drought intensity, but the consistent pattern across studies validates the original research claim with strong, multi-crop scientific evidence. Furthermore, drought induces stomatal closure and depletes leaf moisture content, ultimately hindering growth and blooming (Yahaya and Shimelis, 2022). These findings underscore the necessity of investigating improved drought tolerance through agricultural methods. Multi-trait complex character crop improvement, such as for drought tolerance, entails precise selection criteria based on derived biometric models with accuracy (Resende et al., 2016). Various methods to identify stress-tolerant genotypes and various selection indices derived through mathematical functions for associating yield performance under stress and nonstress conditions have been proposed. The stress susceptibility index (SSI) (Fischer and Maurer, 1978) and tolerance index (TOL) (Rosielle and Hamblin, 1981) are very common in measuring the susceptibility of genotypes to abiotic stressors. Furthermore, more integrative measures, such as the stress tolerance index (STI) (Fernandez, 1992), geometric mean productivity (GMP), and harmonic mean (HM) (Bidinger et al., 1987) can be used to analyze the stability of productivity across varying environmental conditions. These developments led to the creation of new indices, such as the drought resistance index (DI) (Gavuzzi et al., 1997), the STI adjusted for normal irrigation (K1STI) and the stress irrigation equivalent (K2STI) (Nouri-Ganbalani et al., 2009), and the stress nonstress production index (SNPI) (Nazari et al., 2024). Furthermore, integrative methods such as the abiotic tolerance index (ATI) (Sabaghnia et al., 2008) and the stress tolerance score (STS) (Khayatnezhad and Gholamin, 2012) provide overall evaluations of genotype tolerance. These indicators facilitate systematic screening and selection of genotypes with optimal stress adaptation and minimum yield loss potential. A promising approach is applying nanosilica to mitigate abiotic stress in crops. Recent studies have highlighted the role of nanosilica in increasing resistance to drought by increasing leaf retention, increasing photosynthetic effectiveness, and furthering root progression (Pishva et al., 2020). These benefits are critical with constrained moisture availability. Owing to its ability to increase development factors and yields in multiple crops, nanosilica application has the potential to strengthen the drought resilience of cumin. It performs by reinforcing cellular walls and stability, decreasing water loss through transpiration (Yadav et al., 2024). It also aids in proline accumulation, thereby maintaining cellular integrity under stressful conditions (Khan and Upadhyaya, 2019). By improving nutrient uptake and antioxidant activity in crops, nanosilica notably alleviates the impacts of drought stress. Key health determinants under drought, such as relative water content, chlorophyll levels, stomatal conductance, and antioxidant activity, provide insight into photosynthesis and development under moisture scarcity. For

Table 1
Meteorological data (obtained from the Iran's Meteorological Organization's official website) during the 2023 cumin planting season at the Aveh and Bafq experimental sites

Location		AT (°C)	AR (mm)	ARH (%)	Eva (mm. day^{-1})	AST (°C)
Aveh	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
Bafq	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.

Table 2
Soil characteristics of the farm in the studied regions

Region	Soil Texture	Sand	Clay	Silt	Total Nitrogen	Organic Carbon	Potassium	Phosphorus	Magnesium	Calcium	Sodium
					%		p.p.m			Me/l	
Aveh	Loamy Clay	48	34	18	0.211	3.62	526.2	16.4	12	14	23
Bafq	Loamy	28	29	43	0.1	2.8	415	17.15	39	35	66

Table 3
Drought stress tolerance and susceptibility indices used in this study

No.	Index	Formula	Reference
1	Tolerance Index	$TOL = Yp - Ys$	Rosielle and Hamblin (1981)
2	Mean Productivity	$MP = \frac{Yp + Ys}{2}$	Rosielle and Hamblin (1981)
3	Geometric Mean Productivity	$GMP = \sqrt{Ys \times Yp}$	Fernandez (1992)
4	Harmonic Mean	$HM = \frac{2(Yp \times Ys)}{(Yp \times Ys)}$	Bidinger et al. (1987)
5	Stress Susceptibility Index	$SSI = \frac{1 - (\frac{Ys}{Yp})}{1 - (\frac{Ys}{Yp})}$	Fischer and Maurer (1978)
6	Stress Tolerance Index	$STI = \frac{(Yp \times Ys)}{(Yp)^2}$	Fernandez (1992)
7	Yield Index	$YI = \frac{Ys}{Ys}$	Gavuzzi et al. (1997)
8	Yield Stability Index	$YSI = \frac{Ys}{Yp}$	Bouslama and Schapaugh (1984)
9	Relative Drought Index	$RSI = \frac{(\frac{Ys}{Yp})}{(\frac{Ys}{Yp})}$	Fischer and Wood (1979)

example, a decreasing moisture content typically signifies intensified stress, whereas a relatively high chlorophyll content usually correlates with increased photosynthesis (Soorni et al., 2020). Research has demonstrated that the application of nanosilica enhances drought tolerance in plants by increasing water use efficiency and antioxidant enzyme activity (Ashkvand et al., 2015). Furthermore, according to another investigation, nanosilica modulates indices such as stomatal conductance and proline accumulation, that are important for maintaining cell homeostasis (Verma et al., 2022). These findings suggest that the application of nanosilica improves the physiological performance of cumin, providing a sustainable solution to increase its drought resilience. Understanding plant drought stress responses is critical for cultivating cumin in the context of increasing variability. Common drought indices, such as the standardized precipitation index and soil moisture index, aid assessments by evaluating accessibility on the basis of climatic factors. Understanding drought implications for yields is necessary to reinforce resilience and food security against climate change. Despite the promising effects of nanosilica on other crops, research on cumin remains limited, with most studies neglecting its unique responses. This research gap highlights the need to explore the potential of nanosilica for optimizing cumin cultivation practices. The primary objectives of this study were to address the aforementioned research gap by investigating the impact of nanosilica application on drought stress tolerance indices in cumin (Cuminum cyminum), and to evaluate the potential for cultivating this crop in the drought-prone regions of Aveh and Bafgh.

Materials and Methods

A field experiment was designed as a split plot with three replications at two locations in Iran, Aveh (Central Province, 34° 79' N, 50° 42' E) and Bafq (Yazd Province, 31° 58' N, 55° 04' E). Drought stress was applied at four levels (80, 60, 40, and

Table 4
Values of drought stress tolerance indices without nanosilica application

	Stress level	Ecotype	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Aveh	60% FC	Isfahan	395.13	374.80	20.32	384.96	384.83	384.70	0.10	0.41	1.27	0.95	1.92
		Semnan	604.69	561.82	42.87	583.25	582.86	582.47	0.14	0.95	1.90	0.93	1.88
		Kashan	658.41	604.35	54.07	631.38	630.80	630.22	0.16	1.11	2.04	0.92	1.86
	40% FC	Isfahan	395.13	166.41	228.72	280.77	256.42	234.19	1.14	0.18	0.56	0.42	0.85
		Semnan	604.69	175.39	429.30	390.04	325.66	271.91	1.40	0.30	0.59	0.29	0.59
		Kashan	658.41	201.88	456.53	430.15	364.58	309.01	1.37	0.37	0.68	0.31	0.62
	20% FC	Isfahan	395.13	125.85	269.27	260.49	223.00	190.90	1.34	0.14	0.43	0.32	0.65
		Semnan	604.69	64.27	540.42	334.48	197.14	116.19	1.76	0.11	0.22	0.11	0.22
		Kashan	658.41	122.52	535.89	390.47	284.03	206.60	1.61	0.22	0.41	0.19	0.38
Bafq	60% FC	Isfahan	577.29	444.19	133.10	510.74	506.39	502.07	0.37	0.47	1.56	0.77	2.00
		Semnan	636.25	483.60	152.66	559.93	554.70	549.52	0.39	0.56	1.70	0.76	1.98
		Kashan	826.59	509.66	316.93	668.13	649.06	630.54	0.62	0.76	1.79	0.62	1.61
	40% FC	Isfahan	577.29	145.51	431.78	361.40	289.83	232.43	1.21	0.15	0.51	0.25	0.66
		Semnan	636.25	173.25	463.01	404.75	332.01	272.34	1.18	0.20	0.61	0.27	0.71
		Kashan	826.59	213.92	612.67	520.26	420.50	339.88	1.20	0.32	0.75	0.26	0.67
	20% FC	Isfahan	577.29	81.19	496.10	329.24	216.49	142.36	1.40	0.08	0.28	0.14	0.37
		Semnan	636.25	121.09	515.17	378.67	277.56	203.45	1.31	0.14	0.42	0.19	0.50
		Kashan	826.59	182.86	643.73	504.73	388.78	299.47	1.26	0.27	0.64	0.22	0.58

Yp: yield productivity, Ys: yield stress, TOL: Tolerance Index, MP: Mean Productivity, GMP: Geometric Mean Productivity, HM: Harmonic Mean, SSI: Stress Susceptibility Index, STI: Stress Tolerance Index, YI: yield Index, YSI: Yield Stability Index, RSI: Relative Drought Index

20% of field capacity, FC), representing varying degrees of water availability) in the main plots, whereas the subplots consisted of four levels of foliar nSi application (0, 2, 4, and 6 mM) (Narimanzadeh et al., 2024, Ismail et al., 2022).

Land preparation began in the fall with deep plowing (up to 30 cm) to prevent soil compaction and improve drainage, followed by initial levelling. The soil texture and nutrient analyses were conducted as shown in Table 2, and the land was left undisturbed until spring. In spring, additional preparations, including disc harrowing and final levelling, were performed to create a uniform planting bed according to the experimental design.

Foliar application of silicon dioxide nanoparticles (nSi, 20–30 nm, supplied by Iranian Pioneers of Nanomaterials Co., Vakilabad, Mashhad, Iran) was carried out twice during the growing season: after the six-leaf stage (late March) and before flowering (mid-April). The nSi solution was supplemented with Jonobgan ionic foliar spray soap (Kerman Zamin Co., Kerman, Iran) as a surfactant. The control plants were sprayed with distilled water supplemented with the same surfactant to ensure that any observed effects were not due to the surfactant. The size of the silica nanoparticles (approximately 30 nm) was confirmed via transmission electron microscopy.

Drought stress was applied after plant establishment and following the six-leaf stage. Soil moisture levels were monitored using the pressure plate method (Dane and Topp, 2002). Soil samples were saturated and subsequently dried under specified pressure levels and analyzed to determine moisture at field capacity (FC) and permanent wilting point (PWP). The volumetric moisture content at FC and PWP was calculated for each drought stress level. To obtain the soil moisture characteristic curve, a volume of dry soil was compacted and passed through a 2-mm sieve. A pre-saturated porous plate (saturated by soaking in water for 24 hours) was placed in the pressure plate chamber. A filter paper was placed on the porous plate, and rings (three rings to account for three replications) were positioned on the filter paper. The rings were filled with soil, and after placing the samples on the plate, distilled water was gently added from beneath the rings using a spray bottle to allow upward saturation of the samples until the soil surface became moist.

Table 5
Values of drought stress tolerance indices under 2 mM nanosilica application

	Stress level	Ecotype	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Aveh	60% FC	Isfahan	504.55	519.98	15.42	512.26	512.21	512.15	0.06	0.73	1.76	1.03	2.09
		Semnan	748.56	623.94	124.61	686.25	683.41	680.59	0.33	1.30	2.11	0.83	1.69
		Kashan	743.55	595.23	148.32	669.39	665.27	661.18	0.39	1.23	2.01	0.80	1.62
	40% FC	Isfahan	504.55	207.90	296.65	356.23	323.88	294.47	1.16	0.29	0.70	0.41	0.84
		Semnan	748.56	231.06	517.50	489.81	415.89	353.12	1.36	0.48	0.78	0.31	0.63
		Kashan	743.55	336.93	406.62	540.24	500.53	463.73	1.08	0.70	1.14	0.45	0.92
	20% FC	Isfahan	504.55	113.91	390.64	309.23	239.74	185.86	1.53	0.16	0.39	0.23	0.46
		Semnan	748.56	166.58	581.97	457.57	353.13	272.52	1.53	0.35	0.56	0.22	0.45
		Kashan	743.55	186.26	557.29	464.90	372.15	297.89	1.48	0.39	0.63	0.25	0.51
Bafq	60% FC	Isfahan	631.58	436.32	195.25	533.95	524.95	516.10	0.50	0.50	1.53	0.69	1.80
		Semnan	853.76	498.85	354.91	676.30	652.61	629.74	0.67	0.77	1.75	0.58	1.52
		Kashan	976.85	559.34	417.51	768.10	739.19	711.36	0.69	0.99	1.96	0.57	1.49
	40% FC	Isfahan	631.58	376.05	255.53	503.81	487.34	471.41	0.66	0.43	1.32	0.60	1.55
		Semnan	853.76	300.34	553.42	577.05	506.38	444.36	1.05	0.47	1.05	0.35	0.92
		Kashan	976.85	277.25	699.60	627.05	520.42	431.92	1.16	0.49	0.97	0.28	0.74
	20% FC	Isfahan	631.58	115.66	515.91	373.62	270.28	195.52	1.33	0.13	0.41	0.18	0.48
		Semnan	853.76	152.95	700.81	503.35	361.36	259.42	1.33	0.24	0.54	0.18	0.47
		Kashan	976.85	123.78	853.08	550.32	347.72	219.71	1.42	0.22	0.43	0.13	0.33

Yp: yield productivity, Ys: yield stress, TOL: Tolerance Index, MP: Mean Productivity, GMP: Geometric Mean Productivity, HM: Harmonic Mean, SSI: Stress Susceptibility Index, STI: Stress Tolerance Index, YI: yield Index, YSI: Yield Stability Index, RSI: Relative Drought Index

The samples were left for some time to reach full saturation. Subsequently, the saturated samples were subjected to pressures of 0.3 and 15 bar for FC and PWP determination, respectively. Upon pressure application, excess water was expelled from the samples via the device's outflow tube. After water discharge ceased, the filter paper was carefully removed from the sample, and the soil was weighed. The sample was then placed in an oven at 105-110 °C; after 24 hours, it was removed and weighed to determine the soil moisture percentage. Assuming atmospheric suction for field capacity and permanent wilting point, the resulting moisture content represented the soil moisture at FC and PWP, respectively. Subsequently, through consecutive sampling, the gravimetric soil moisture in the field was measured using the aforementioned methods. Following the calibration of the gravimetric moisture with the moisture characteristic curve at the target points, the timing and amount of irrigation were calculated, and irrigation according to drought levels was applied. To compare the stress tolerance and susceptibility indices, Table 3 was utilized:

Statistical analyses were performed via SAS software (version 9.4). Principal component analysis was conducted on performance under stress and nonstress conditions, as well as on

Table 6
Values of drought stress tolerance indices under 4 mM nanosilica application

	Stress level	Ecotype	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Aveh	60% FC	Isfahan	531.74	455.81	75.93	493.78	492.32	490.86	0.28	0.67	1.54	0.86	1.74
		Semnan	697.07	550.59	146.48	623.83	619.51	615.23	0.41	1.07	1.86	0.79	1.60
		Kashan	887.08	524.34	362.74	705.71	682.01	659.10	0.81	1.29	1.77	0.59	1.20
	40% FC	Isfahan	531.74	196.06	335.68	363.90	322.88	286.49	1.24	0.29	0.66	0.37	0.75
		Semnan	697.07	328.13	368.94	512.60	478.25	446.21	1.04	0.64	1.11	0.47	0.95
		Kashan	887.08	382.51	504.58	634.79	582.51	534.53	1.12	0.94	1.29	0.43	0.87
	20% FC	Isfahan	531.74	127.32	404.43	329.53	260.19	205.44	1.50	0.19	0.43	0.24	0.49
		Semnan	697.07	196.96	500.10	447.02	370.54	307.14	1.41	0.38	0.67	0.28	0.57
		Kashan	887.08	151.86	735.22	519.47	367.04	259.33	1.63	0.37	0.51	0.17	0.35
Bafq	60% FC	Isfahan	818.35	525.81	292.54	672.08	655.97	640.25	0.58	0.78	1.84	0.64	1.67
		Semnan	1000.31	590.98	409.34	795.65	768.87	743.00	0.66	1.07	2.07	0.59	1.54
		Kashan	1118.87	571.15	547.72	845.01	799.40	756.25	0.79	1.16	2.00	0.51	1.33
	40% FC	Isfahan	818.35	215.98	602.37	517.16	420.41	341.76	1.19	0.32	0.76	0.26	0.69
		Semnan	1000.31	201.95	798.37	601.13	449.46	336.05	1.30	0.37	0.71	0.20	0.53
		Kashan	1118.87	272.93	845.94	695.90	552.60	438.82	1.23	0.55	0.96	0.24	0.64
	20% FC	Isfahan	818.35	134.72	683.63	476.54	332.04	231.35	1.36	0.20	0.47	0.16	0.43
		Semnan	1000.31	171.20	829.11	585.76	413.83	292.37	1.35	0.31	0.60	0.17	0.45
		Kashan	1118.87	189.87	929.00	654.37	460.92	324.65	1.35	0.39	0.67	0.17	0.44

Yp: yield productivity, Ys: yield stress, TOL: Tolerance Index, MP: Mean Productivity, GMP: Geometric Mean Productivity, HM: Harmonic Mean, SSI: Stress Susceptibility Index, STI: Stress Tolerance Index, YI: yield Index, YSI: Yield Stability Index, RSI: Relative Drought Index

drought tolerance indices, via JMP Pro software, and the results were displayed in biplot graphs.

Results

Table 4 presents drought stress tolerance indices, e.g., Yp, Ys, TOL, MP, and SSI, for three ecotypes (Isfahan, Semnan, and Kashan) under varying stress levels (60%, 40%, and 20% FC) without nanosilica application.

Under 60% FC, nanosilica application increased Ys in most ecotypes, with Isfahan (Aveh) showing a notable increase from 504.55 to 519.98, suggesting enhanced stress mitigation (Table 5). The stress susceptibility index (SSI) decreased in several cases, whereas the yield stability index (YSI) improved, indicating better stress adaptation with nanosilica. The STI and GMP values increased under nanosilica, particularly at Kashan (Bafq, 60% FC: STI from 0.76 to 0.99), reflecting improved productivity under stress. The TOL values increased under severe stress (e.g., Kashan at 20% FC: 557.29-853.08), but nanosilica helped maintain higher MP (mean productivity) values in some cases (e.g., Aveh at 40% FC, with values ranging from 356.23 to 540.24). RSI improved under nanosilica application, for example, Isfahan at 60% FC, with values ranging from 1.92 to 2.09, suggesting better cellular stress resistance. On the other hand, the Kashan ecotype consistently outperformed the other ecotypes in Yp and Ys under nanosilica, whereas Semnan presented moderate gains, highlighting genetic variability in silica uptake efficiency. At Aveh Kashan's ecotype,

Table 7
Values of drought stress tolerance indices under 6 mM nanosilica application

	Stress level	Ecotype	Yp	Ys	TOL	MP	GMP	HM	SSI	STI	YI	YSI	RSI
Aveh	60% FC	Isfahan	363.84	404.94	41.11	384.39	383.84	383.29	0.22	0.41	1.37	1.11	2.26
		Semnan	586.36	522.47	63.90	554.41	553.49	552.57	0.21	0.85	1.77	0.89	1.81
		Kashan	473.28	442.59	30.69	457.94	457.68	457.42	0.13	0.58	1.50	0.94	1.90
	40% FC	Isfahan	363.84	177.42	186.42	270.63	254.07	238.52	1.01	0.18	0.60	0.49	0.99
		Semnan	586.36	241.09	345.27	413.72	375.98	341.69	1.16	0.39	0.82	0.41	0.83
		Kashan	473.28	317.56	155.72	395.42	387.68	380.09	0.65	0.42	1.07	0.67	1.36
	20% FC	Isfahan	363.84	111.40	252.44	237.62	201.32	170.57	1.37	0.11	0.38	0.31	0.62
		Semnan	586.36	61.75	524.61	324.05	190.28	111.73	1.76	0.10	0.21	0.11	0.21
		Kashan	473.28	67.01	406.27	270.15	178.09	117.40	1.69	0.09	0.23	0.14	0.29
Bafq	60% FC	Isfahan	458.24	408.52	49.72	433.38	432.67	431.96	0.18	0.34	1.43	0.89	2.32
		Semnan	507.61	454.46	53.15	481.03	480.30	479.56	0.17	0.42	1.59	0.90	2.33
		Kashan	505.18	446.25	58.92	475.72	474.80	473.89	0.19	0.41	1.56	0.88	2.30
	40% FC	Isfahan	458.24	153.80	304.44	306.02	265.48	230.31	1.08	0.13	0.54	0.34	0.87
		Semnan	507.61	162.29	345.32	334.95	287.01	245.94	1.10	0.15	0.57	0.32	0.83
		Kashan	505.18	298.73	206.45	401.95	388.47	375.44	0.66	0.27	1.05	0.59	1.54
	20% FC	Isfahan	458.24	74.33	383.92	266.29	184.55	127.91	1.36	0.06	0.26	0.16	0.42
		Semnan	507.61	97.23	410.38	302.42	222.16	163.20	1.31	0.09	0.34	0.19	0.50
		Kashan	505.18	99.59	405.59	302.38	224.30	166.38	1.30	0.09	0.35	0.20	0.51

Yp: yield productivity, Ys: yield stress, TOL: Tolerance Index, MP: Mean Productivity, GMP: Geometric Mean Productivity, HM: Harmonic Mean, SSI: Stress Susceptibility Index, STI: Stress Tolerance Index, YI: yield Index, YSI: Yield Stability Index, RSI: Relative Drought Index

Ys at 40% FC improved by 67% (336.93 vs. 201.88), outperforming Bafq's smaller gains (e.g., Bafq Kashan: 277.25 vs. 213.92). Kashan's SSI at Aveh decreased from 1.37 to 1.08 at 40% FC, indicating that nanosilica mitigates stress susceptibility. Isfahan's ecotype at Bafq SSI at 20% FC improved from 1.33 to 1.33 (no change), indicating ecotype-specific responses. At Bafq, Kashan's STI increases from 0.27 to 0.49 at 20% FC, which aligns with the improvements in GMP (347.72 vs. 388.78 without nanosilica).

As shown in Table 6, the application of 4 mM nanosilica generally increased drought tolerance across ecotypes, particularly at 60% and 40% FC (field capacity), as indicated by increased Yp (potential yield) and Ys (stressed yield) values. For example, Kashan (Bafq) presented a substantial Yp of 1118.87 under 60% FC, the highest among all the treatments, suggesting the effectiveness of nanosilica in improving productivity under moderate stress. The stress susceptibility index (SSI) decreased in most cases, indicating improved stress adaptation. For example, Isfahan (Aveh) had an SSI of 0.28 at 60% FC compared with higher values without nanosilica. The STI (stress tolerance index) and GMP (geometric mean productivity) improved significantly, particularly at Kashan and Semnan, suggesting the role of nanosilica in sustaining yield stability. For example, Kashan (Bafq, 60% FC) had an STI of 1.16, indicating strong stress resilience. At 20% FC, nanosilica benefits diminished, as reflected by the lower yield stability index (YSI) and relative stress index (RSI) values (e.g., Kashan (Bafq) RSI decreased to 0.44). This aligns with previous findings that nanosilica efficacy decreases under extreme drought. Kashan consistently outperformed Isfahan and Semnan in most indices, suggesting genetic superiority in the use of nanosilica for stress mitigation. Conversely, Isfahan showed fewer improvements, possibly due to differing physiological adaptations. The RSI was highest at 60% FC (e.g., Isfahan (Aveh) RSI: 1.74), indicating that nanosilica is most effective under rare and moderate, not extreme, drought conditions.

The ecotypes in Table 7 show severe yield declines, for example (Ys = 196.06 vs. Yp = 531.74), highlighting dose-dependent variability. The SSI values ranged widely (from 0.22 to 1.76), with Semnan-Aveh (20% FC) showing the highest SSI (1.76), indicating poor stress adaptation, whereas Isfahan-Aveh (60% FC) had the lowest SSI (0.22), suggesting stress-beneficial effects. At 20% FC, the YSI and RSI decreased sharply (e.g., Semnan ecotype at Aveh: YSI = 0.11, RSI = 0.21), confirming that 6 mM nanosilica cannot fully mitigate extreme drought, which aligns with Ashraf et al. (2010) on the limitations of silica under severe stress. Kashan consistently outperformed Isfahan and Semnan in STI, GMP, and MP (e.g., Semnan-Bafq at 60% FC: STI = 0.85, GMP = 582.51), reinforcing its genetic resilience, similar to findings by Pour-Aboughadareh et al. (2017) on ecotype-specific drought adaptation. Application of 4 mM nanosilica improved tolerance (Table 5), whereas the use of 6 mM nanosilica led to mixed results, with some ecotypes (e.g., Kashan-Aveh at 40% FC: RSI = 1.36) benefiting, whereas others (e.g., Semnan-Aveh at 20% FC: RSI = 0.21) suffering, indicating that optimal dosing is critical. At 20% FC, YI fell below 0.5 for most ecotypes (e.g., Semnan-Aveh: YI = 0.21), underscoring that nanosilica cannot fully compensate for extreme water deficits, which is consistent with Liu et al. (2020) on the threshold effects of silica. The Kashan ecotype at Bafq, the GMP at 20% FC, decreased to 224.30 (vs. 347.72 with 2 mM), indicating that nanosilica overdose disrupts yield stability. Bafq's TOL remained high (e.g., Kashan: 405.59 at 20% FC), but Yp-Ys gaps widened, reducing practical utility. Application of 6 mM nanosilica enhanced drought tolerance under moderate stress (40–60% FC) in resilient ecotypes (e.g., Kashan) but failed under extreme drought (20% FC).

Ys (yield under stress) highly positively correlated with MP (0.96), GMP (0.99), and HM (0.98), indicating that these indices are reliable predictors

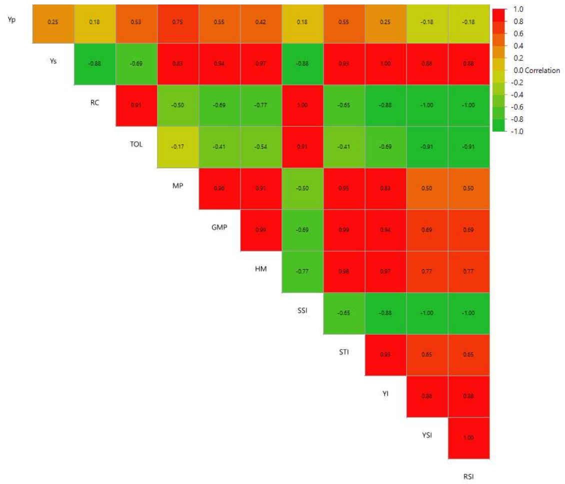

Fig. I. Heatmap of correlation between various drought tolerance indices and other related parameters in Aveh using Pearson method; AR: Abiotic Resistance, RSI: Relative Stress Index, YSI; Yield Stability Index, YI: Yield Index, STI: Stress Tolerance Index, SSI: Stress Susceptibility Index, HM: Harmonic Mean, GMP: Geometric Mean Productivity, MP: Mean Productivity, TOL: Tolerance Index, Ys: Yield under Stress

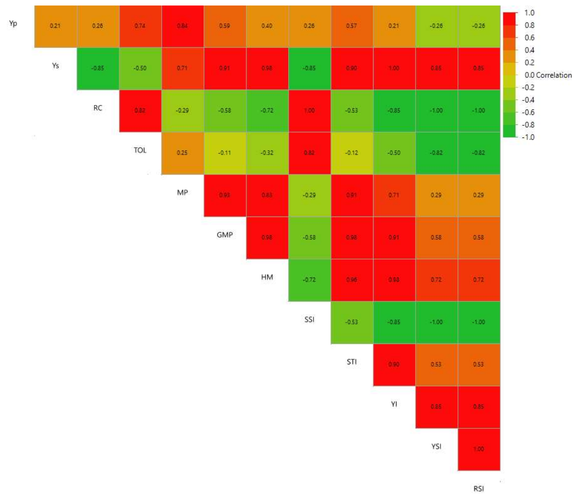

Fig II. Heatmap of correlation between various drought tolerance indices and other related parameters in Bafq using Pearson method; AR: Abiotic Resistance, RSI: Relative Stress Index, YSI; Yield Stability Index, YI: Yield Index, STI: Stress Tolerance Index, SSI: Stress Susceptibility Index, HM: Harmonic Mean, GMP: Geometric Mean Productivity, MP: Mean Productivity, TOL: Tolerance Index, Ys: Yield under Stress

of stress performance (Fig. I). The stress tolerance index (STI) strongly correlated with YI (0.93) and YSI (0.85), reinforcing its utility for selecting drought-tolerant genotypes. The stress susceptibility index (SSI) had strong negative correlations with Ys (-0.83) and the STI (-0.65), confirming that higher SSI values correspond to poorer stress adaptation.

Strong correlations between Ys and MP (0.83), GMP (0.98) and HM (0.96) strongly substantiated the use of indices as reliable indicators of drought tolerance (Fig. I). The strong association between the STI, YI (0.85) and YSI (1.00) confirms the role of the STI in screening for tolerant genotypes that have high yield potential. Pour-Aboughadareh et al. (2017) emphasized that genotypes with low TOL values are better suited for drought conditions because of their ability to maintain yield and recover after stress. The moderate correlation between Yp and MP (0.74) alongside a negative correlation with Ys (-0.85) highlights the trade-off between yield potential and drought resilience.

At the Aveh experimental site shown in Fig. III, the first two principal components explained 82.2% (PC1) and 172.5% (PC2) of the variance. The negative loadings on PC2 (ranging from -0.3 to -0.10) imply correlated trends among indices, with ecotypes likely clustering on the basis of stress tolerance traits. At Bafq, the progressive negative loadings (-1.0 to -0.9) on PC2 were as follows: 1) There are strong correlations among the drought indices. 2) Clear separation of ecotypes along a stress-tolerance gradient. 3) PC1's extreme dominance suggests that one primary factor (likely overall drought resilience) governs most of the variation.

The first two principal components (PC1 and PC2) in Fid.IV-A explained 57.6% and 42% of the total variance, respectively, for an approximate 99% variability reduction in the dataset. This means great dimensionality reduction, with PC1 being the primary source of variation in the dataset. At the Bafq experimental site, the first two principal components explained 52% and 47.5% of the variance, totaling 99.5%, indicating excellent dimensionality reduction and representation of the data.

PC1 in Fig. V for the Aveh experimental site explained 59.6% of the variance, indicating that it captured the primary drought tolerance trends. PC2 explained 38% of the variance, revealing secondary but significant variation patterns. Consistent negative loadings (-1.0 to -0.5) on both components suggest that there are strong inverse relationships between certain drought indices.

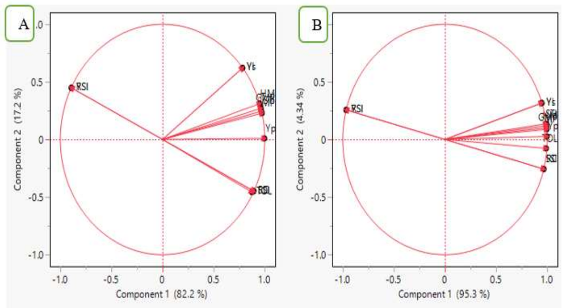

Fig. III. Biplot based on the first two principal components of drought tolerance indices in 60% FC under nanosilica application in cumin ecotypes at A) Aveh and B) Bafq experimental site

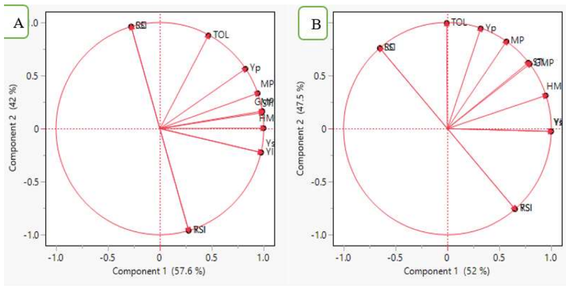

Fig IV. Biplot based on the first two principal components of 40% FC drought tolerance indices under nanosilica application in cumin ecotypes at A) Aveh and B) Bafq experimental site

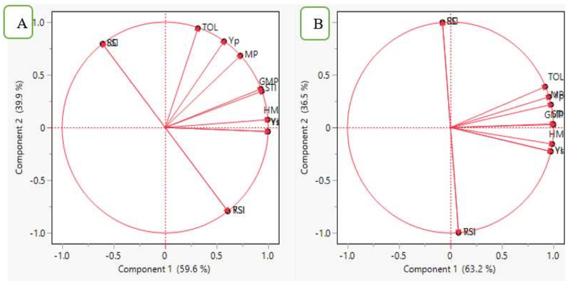

Fig V. Biplot based on the first two principal components of 20% FC drought tolerance indices under nanosilica application in cumin ecotypes at A) Aveh and B) Bafq experimental site

Consistent negative loadings suggest strong inverse relationships between key drought indices (e.g., Ys vs. SSI). It seems that there is clear clustering of ecotypes along a stress-tolerance gradient.

In addition to the findings concerning ecotypes and nanosilica levels, statistical tests, including Bartlett's test, confirmed that the variance of data for indices such as SSI and Ys differed significantly between the two regions ($P<0.05$). This discrepancy may be attributed to different climates in two regions, As shown in the Table 1, the Bafq region, with performance Yp, SSI, and STI indices, may indicate better nanosilica productivity against drought stress in this area. In other words, a pronounced decline in the benefits of nanosilica under severe stress (20% FC) was observed in both regions; however, the rate of this decline was steeper in the region with greater environmental variability (Bafq). This may indicate that in environments with combined and unpredictable stresses, the advantages of stimulatory materials such as nanosilica reach their threshold more rapidly. Furthermore, the differential response of ecotypes suggests that the efficacy of certain genotypes may be more strongly influenced by specific genotype × location interactions.

Discussion

Higher Yp (yield under nonstress) and Ys (yield under stress) values at Kashan suggest greater inherent drought tolerance than those at Isfahan and Semnan. The declining YSI (yield stability index) and RSI (relative stress index) with increasing stress severity indicate reduced resilience under extreme drought (20% FC). Notably, Kashan maintains higher GMP (geometric mean productivity) and STI (stress tolerance index) values, reflecting better yield stability across stress levels. Compared with studies such as Pour-Aboughadareh et al. (2017), these results align with ecotype-specific drought adaptation, but highlight Kashan's superior performance under severe stress, possibly due to genetic or physiological advantages. At 20% FC, nanosilica benefits diminished (e.g., the YSI decreased to 0.13-0.25), indicating threshold limits, which is consistent with Ashraf et al. (2010) on the efficacy of silica under moderate stress. Nanosilica improved indices more effectively than traditional stress mitigators (e.g., biochar in Liu et al., 2020), particularly in terms of GMP and STI, underscoring its potential for drought-prone agriculture. Similar to the findings of Gunes et al. (2007), nanosilica enhanced the RSI and YSI by improving water retention. Bafq ecotypes show dramatic increases in Yp (e.g., Kashan: 976.85 vs. 826.59 without nanosilica), suggesting that nanosilica enhances photosynthetic efficiency.

The results in Table 4 show that nanosilica at Aveh stabilized HM under 40% FC (Kashan: 463.73 vs. 309.01 control), suggesting better yield consistency, and at the Bafq experimental site, nanosilica amplified Yp but exacerbated TOL (e.g., Kashan: 853.08 vs. 643.73 control), indicating trade-offs between yield potential and stress loss. These improvements align with those of Suriyaprabha et al. (2012), who linked nanosilica to increased nutrient uptake and stomatal regulation in drought-stressed plants. The reduced SSI in Aveh matches that reported by Ashkavand et al. (2015), where silica nanoparticles improved osmotic adjustment in wheat. Bafq's STI–GMP correlation under nanosilica mirrors findings by Tale Ahmad and Haddad (2011), who prioritized these indices for high-yield, stress-tolerant genotypes. The findings in Table 5 align with those of Siddiqui et al. (2020), who reported that higher silica doses improve drought resilience but have limited effects under severe stress. The addition of 4 mM nanosilica significantly increased drought tolerance under moderate stress (40–60% FC), particularly for Kashan ecotype, but its benefits decreased under severe drought (20% FC). The results support precision agriculture approaches, where nanosilica application should be tailored to specific crop genotypes and stress levels for maximum efficacy.

The Yp reduction at 6 mM as shown in Table 6 aligns with Siddiqui et al. (2014), who reported nanoparticle toxicity in crops at elevated concentrations due to oxidative stress. The lower STI despite SSI improvements in Bafq (e.g., SSI = 1.30 vs. STI = 0.09) aligns with research by Weisany et al. (2024), which showed that high nanosilica can uncouple stress tolerance from the yield potential. Fernandez (1992) reported that the GMP and HM indices are suitable for revealing stable indicators of yield under stress (drought) and nonstress conditions; thus, these indices are good for screening drought-tolerant genotypes. In addition, Mhike (2013) reported strong positive correlations between Ys and GMP, demonstrating that genotypes with high GMP can produce higher yields under drought. The observations between the SSI and Ys (-0.85) and the STI (-0.53) indicate that genotypes with relatively high susceptibility indices have poor yields under drought, which is corroborated by the literature. Blum et al. (1989) reported that the SSI reflects yield loss under stress, or the greater the SSI value is, the greater the sensitivity direction, which validates the observations. This negative correlation is also supported by Bavandpuri et al. (2022), who reported that drought-tolerant wheat genotypes present relatively low SSI values. According to Fig. III the lack of labeled axes limits precise interpretation but hints at dichotomous groupings (e.g., drought-sensitive vs. tolerant). Like Hosseini et al. (2018), with respect to cumulative drought responses, PCA effectively segregates ecotypes by tolerance, although the anomalous PC2 variance exceeds typical bounds (100%), suggesting data normalization or methodological discrepancies compared with Pour-Aboughadareh et al. (2019). The unusually high PC1 variance differs from typical PCA results in drought studies. For example, Pour-Aboughadareh et al. (2020) reported 55–70% for PC1, but similar loading patterns were observed by Saeidi et al. (2018), although with proper variance summation. The results in Fig. IV are consistent with those reported by Pour-Aboughadareh et al. (2020) and Hosseini et al. (2018) in their studies of drought tolerance in cumin. The first two principal components described a similar proportion of variance, demonstrating that PCA works consistently as a tool to represent most of variations in drought-related traits. Comparatively, similar studies in other species provide more support for these results. For example, Eslami et al. (2021) studied drought tolerance traits in wheat and reported that the first two principal components explained more than 90% of the variability in traits, therefore demonstrating an effective dimensionality reduction. The degree of similarity between species reported from multiple studies highlights the effectiveness of PCA as a useful tool for summarizing complex information on drought tolerance.

The patterns in Fig. V matches the findings of Pour-Aboughadareh et al. (2020), who reported clustered stress-tolerant phenotypes. At bafq, PC1 was 63.2%, and PC2 accounted for 99.7% of the cumulative variance, indicating that these components effectively capture nearly all the variation in drought tolerance traits. This aligns with robust PCA standards for biological data (Jolliffe and Cadima, 2016).

This study demonstrated that Bafq location presented better drought resilience than Aveh, with higher yield potential (Yp) and stress tolerance (STI) across ecotypes. Kashan ecotype outperformed Isfahan and Semnan under moderate drought (40-60% FC), exhibiting superior GMP and STI indices. Under severe drought (20% FC), nanosilica effectiveness diminished, but Kashan still maintained better stability (YSI, RSI) than the other ecotypes. Isfahan performed best under mild stress (60% FC), particularly in Aveh, with improved Ys and SSI reduction under nanosilica. Semnan showed moderate tolerance, benefiting from nanosilica at 40% FC but struggling under extreme drought. Bafq is a location with hot, dry conditions that amplifies ecotype differences, confirming Kashan's adaptability to harsher environments.

Application of nanosilica (2 and 4 mM) significantly enhanced drought tolerance, especially at Kashan, by increasing the MP and HM. Higher nanosilica doses (6 mM) were less effective, suggesting an optimal range for stress mitigation. SSI and TOL correlations confirmed that drought-sensitive genotypes perform poorly, reinforcing the need for tolerant cultivars. PCA validated Kashan's clustering as the most drought-resistant ecotype at both locations. For cultivation in drought-prone regions, Kashan ecotype is recommended with moderate nanosilica application (4 mM).

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