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Effects of Inorganic Absorbents (Ca_2O_4Si) on Physiological Properties, and Grain Yield of Maize in Central Anatolia

Orta Anadolu Koşullarında İnorganik Absorbantların (Ca_2O_4Si) Mısırın Fizyolojik Özellikleri ve Tane Verimine Etkisi

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EFFECTS OF INORGANIC ABSORBENTS (Ca_2O_4Si) ON PHYSIOLOGICAL PROPERTIES, AND GRAIN YIELD OF MAIZE IN CENTRAL ANATOLIA

ABSTRACT

The trial was conducted during 2022 growing season in trial area of “Selcuk University, Agriculture Faculty, Crop Science Department, Konya, Türkiye” according to “Split-Split Plots Design in Randomized Blocks” with three replications. Irrigation (60% and 100% of the evaporation from Class A Evaporation Pan), genotypes (DKC 5741 and dent maize population with red grains) and calcium silicate (Ca_2O_4Si) treatments (control, 25, 50 and 100 mg kg^{-1} Ca_2O_4Si) were the factors of the trial. DKC 5741 was ahead of RM (red maize) in proline, and grain yield properties (n = 24). The highest plant height, leaf number, leaf area, stomatal conductance and the lowest MDA (malondialdehyde) results were observed in 100 mg kg^{-1} Ca_2O_4Si (n = 12). 50 mg kg^{-1} Ca_2O_4Si treatment was more effective than others in chlorophyll content and grain yield properties (n =12). The lowest proline and MDA values were obtained from control in both irrigation conditions. The highest grain yield (999.63 kg da^{-1}) was observed in 50 mg kg^{-1} Ca_2O_4Si and it was 24.93% higher than the control (n =12). The grain yield obtained from full irrigation of DKC 5741 was also the highest value of the group (n = 12). The results of the trial showed that DKC 5741 can be recommend to the farmers both in deficit and full irrigation conditions and Ca_2O_4Si treatments may be alternative approaches to increase grain yield.

Keywords: Drought, Oxidative Stress, Proline, Silicon.

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ORTA ANADOLU KOŞULLARINDA İNORGANİK ABSORBANTLARIN (Ca_2O_4Si) MISIRIN FİZYOLOJİK ÖZELLİKLERİ VE TANE VERİMİNE ETKİSİ

ÖZ

Deneme 2022 yetiştirme sezonunda “Selçuk Üniversitesi, Ziraat Fakültesi, Tarla Bitkileri Bölümü, Konya, Türkiye” koşullarında “Tesadüf Bloklarında Bölünen Bölünmüş Parseller Deneme Deseni” ne göre üç tekerrürlü olarak yürütülmüştür. Denemede faktör olarak sulama (Class A Evaporasyon kabından gerçekleşen buharlaşmanın %60’ ı ve %100’ ü), genotip (DKC 5741 ve kırmızı tane renkli atdişi mısır popülasyonu) ve kalsiyum silikat (Ca_2O_4Si) uygulamaları (kontrol, 25, 50 ve 100 mg kg^{-1} Ca_2O_4Si) yer almıştır. DKC 5741 prolin ve tane verimi özelliklerinde

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kırmızı renkli mısırın önüne geçmiştir (n = 24). En yüksek bitki boyu, yaprak sayısı, yaprak alanı, stomal iletkenlik ve en düşük MDA (malondialdehit) sonuçları 100 mg kg^{-1} Ca_2O_4Si' de gözlenmiştir (n = 12). 50 mg kg^{-1} Ca_2O_4Si uygulaması klorofil içeriği ve tane verimi özelliklerinde diğerlerinden daha etkili olmuştur (n = 12). Her iki sulama koşulunda da en düşük prolin ve MDA değerleri kontrolden elde edilmiştir. En yüksek tane verimi 50 mg kg^{-1} Ca_2O_4Si (999.63 kg da^{-1}) uygulamasında belirlenmiş ve kontrolden %24.93 daha yüksek olmuştur (n = 12). En yüksek tane verimi değeri DKC 5741' in tam sulamasından elde edilmiştir (n = 12). Denemeden elde edilen bulgular DKC 5741' in üreticiye gerek kısıtlı gerekse tam sulama koşullarında önerilebilecek bir çeşit olduğunu, Ca_2O_4Si uygulamalarının ise tane verimini artırıcı alternatif yaklaşımlardan olabileceğini göstermiştir.

Anahtar Kelimeler: Kuraklık, Oksidatif Stress, Prolin, Silikon.

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1. INTRODUCTION

Maize plays a pivotal role in both the food and livestock industries. Due to its high adaptability and extensive variety, it can be cultivated in almost every region of Türkiye. As a warm-climate cereal, maize utilizes solar energy more effectively than other cereals, resulting in superior productivity (Kırtok, 1998). Whether grown as a primary or secondary crop, it produces the highest amount of dry matter per unit area (Vartanlı and Emeklier, 2007). However, global warming and climate change are rapidly depleting water resources, leading to frequent droughts and subsequent yield reductions (Smirnoff, 1993).

In recent years, global food security has been severely threatened by the intensifying challenges climate change poses to agricultural production. Crops are increasingly exposed to a spectrum of abiotic and biotic stressors, including drought, extreme temperature fluctuations, soil salinity, heavy metal contamination, and rising pathogen pressures. As the global population continues to grow, ensuring a stable food supply becomes a critical concern, particularly as these environmental shifts significantly undermine potential crop yields (Abdel Latef et al., 2026).

When plants are exposed to drought stress, they close their stomata to minimize transpiration. This defense mechanism, however, leads to a decrease in CO_2 uptake and a slowdown in photosynthesis, ultimately resulting in lower grain yields (Dolferus, 2014; Farooq et al., 2009). Beyond gas exchange, drought triggers various metabolic disorders. It is well-documented that drought stress accelerates the formation of ROS (Reactive Oxygen Species), which damage pigments, membrane lipids, nucleic acids, proteins, and enzymes (Arora et al., 2002; Ecem, 2010; Yordanov et al., 2000).

The most visible symptoms of oxidative stress in drought-affected plants are a reduced photosynthetic rate and a decline in chlorophyll content (Anjum et al., 2011; Marcińska et al., 2013; Yavaş et al., 2016). These physiological disruptions lead to significant yield losses. For instance, Harder et al. (1982) demonstrated that water shortages at different growth stages negatively impact maize grain yield. Furthermore, İncik (2019) reported that a two-week period of water scarcity resulted in a 33% loss in grain yield, linked to a 15% reduction in the number of grains per cob.

Silicon (Si) is the second most prevalent element in the Earth's crust. It exists primarily as silicon dioxide (SiO_2) alongside various Si-rich minerals in crystalline, poorly crystalline, or amorphous states. Despite its abundance, only a small fraction of soil Si is soluble and accessible for plant absorption; the vast majority remains locked within mineral structures (Akca et al., 2026).

Nevertheless, the significance of Si in modern agriculture is well-established. Extensive research highlights its role in boosting plant resilience against both biotic and abiotic stressors. Exogenous application of Si has been shown to effectively enhance drought tolerance and mitigate adverse impacts. Studies indicate that Si promotes suberization, lignification, and silicification, which strengthens cell walls and provides mechanical support, particularly for monocots and pteridophytes (Coskun et al., 2016; He et al., 2013).

Common Si sources used in agriculture include calcium metasilicate ($CaSiO_3$), magnesium metasilicate ($MgSiO_3$), and potassium silicate (K_2SiO_3). Within plant tissues, Si is most commonly found in the form of monosilicic acid (Laane, 2018).

This study was conducted to determine the effects of calcium silicate (Ca_2O_4Si) applications on the morphological, physiological, and photosynthetic properties, as well as the grain yield of maize, under limited irrigation conditions in the field environment of Central Anatolia.

2. MATERIALS AND METHODS

The experiment was conducted during the 2022 growing season at the Prof. Dr. Abdulkadir AKÇIN Experimental Area of Selcuk University, Faculty of Agriculture, Department of Field Crops, in Konya, Türkiye. The trial was established according to a Split-Split Plot Design in Randomized Complete Blocks with three replications. In the experimental layout, irrigation levels constituted the main plots, genotypes were assigned to the sub-plots, and Si applications were allocated to the sub-sub plots. The experimental factors consisted of two irrigation levels as the main plots, where 60% and 100% of the cumulative water loss from a Class A Evaporation Pan was applied as irrigation water. Two distinct genotypes were assigned to the sub-plots, including DKC 5741 (a standard hybrid dent maize variety with yellow grains) and a red-grained dent maize population. Furthermore, Si applications were allocated to the sub-sub plots, featuring four different doses of calcium silicate (Ca_2O_4Si) as control, 25, 50, and 100 mg kg^{-1}.

Soil analyses of the experimental area revealed a clayey texture with varying organic matter levels, measured at a moderate 2.25% in the upper layer (0 – 30 cm) and dropping to a low 1.23% in the subsoil (30 – 60 cm). The site is characterized by an alkaline reaction (pH ranging from 8.00 to 8.05) and high calcareous content (34.4% – 37.6%), though it remains free of salinity issues. Regarding nutrient availability, the soil is significantly deficient in both plant-available phosphorus (1.34 – 1.79 kg/da) and zinc (0.32 – 0.34 ppm). Conversely, concentrations of iron (8.74 – 14.74 ppm), copper (1.70 – 1.74 ppm), and manganese (5.76 – 7.50 ppm) were found to be at adequate levels for crop production (Tamüksek and Ceyhan, 2022).

The experimental area was prepared for sowing using appropriate agricultural machinery. Fertilization was performed based on a pure nutrient calculation per decare, applying 25 kg of nitrogen (N), 12 kg of phosphorus (P), and 6 kg of potassium (K). The entire phosphorus requirement was applied at the time of sowing. Sowing was carried out manually on May 13, 2022, with a 70 cm × 20 cm spacing in each sub-sub plot, which consisted of four 5-meter-long rows. Following sowing, a total of 70 mm da^{-1} of water was applied to each sub-sub plot until May 30, 2022, by which time 80% emergence had been achieved. Controlled irrigation based on cumulative evaporation from a "Class A Pan" was initiated on May 31, 2022. The experimental field was irrigated using a drip irrigation system, with 16 mm diameter lateral pipes and drippers spaced every 20 cm, positioned between each row.

The amount of irrigation water applied to the plots was determined according to the methodology described by Öktem et al. (2003). Throughout the growing season, a total of 402 mm da^{-1} of irrigation water was applied to the water-stressed plots (60%), while 681 mm da^{-1} was applied to the full irrigation plots (100%).

Deficit irrigation treatments were initiated on June 6, 2022, with a total of 13 irrigation events occurring during the growing season; the final irrigation was conducted on September 15, 2022. Relevant climate data for the 2022 growing season are presented in Table 1.

Table 1. Climate data of long years and during 2022 growing season

		May	June	July	August	September	October
Mean Temperature (C⁰)	**2022**	14.9	20.6	21.9	25.2	19.9	12.9
	1929-2022	15.9	20.1	23.5	23.3	18.8	12.8
Mean Relative Moisture (%)	**2022**	55.1	51.0	40.6	38.9	40.1	61.0
	1929-2022	55.9	48.4	42.1	42.9	48.0	50.8
Total Precipitation (mm)	**2022**	39.9	10.4	7.9	2.0	11.5	24.2
	1929-2022	43.0	25.9	7.5	6.3	13.5	29.6

Calcium silicate (Ca_2O_4Si) treatments were prepared based on concentrations of 25, 50, and 100 mg kg^{-1} (Amin et al., 2018), while the control plots received no Si application. All Ca_2O_4Si doses were applied during the flowering period, specifically when 50% of the plants in the plots exhibited tasseling. Following the procedure by Amin et al. (2018), the Ca_2O_4Si was dissolved in distilled water containing KOH (potassium hydroxide) and heated to 71°C. Once the solution reached room temperature, it was applied uniformly beneath the irrigation laterals between the crop rows just prior to irrigation. All subsequent observations, measurements, and analyses were performed 20 days post-flowering.

2.1. Observations, Measurements and Analysis

2.1.1. Morphological traits

Plant height (Amanullah et al., 2009), leaf number and leaf area (Guendouz et al., 2016) properties were determined in the 10 plants of 2nd and 3rd rows of each plot.

2.1.2. Photosynthetic properties

Chlorophyll content (Pietrini et al., 2002), stomatal conductance and photosynthetic efficiency features were determined in the flag leaf of 10 plants of 2nd and 3rd rows in each plot. Chlorophyll content was detected with SPAD meter "SPAD 502" and recorded as SPAD according to Cagnola et al. (2021). Stomatal conductance was determined with the porometer "Model SC – 1 Decagon Devices" and recorded as mmol m^{-2} s^{-1} and the photosynthetic efficiency was determined with "Plant Efficiency Analyser, PEA; Hansatech Instruments LTD" and recorded as Fv Fm^{-1}.

2.1.3. Stress indicators

Proline contents of maize leaves were determined according to Bates et al. (1973). Absorbances of the extracts were measured at 520 nm with a spectrophotometer, the values obtained were modified with the help of a calibration curve and recorded as µmol proline g^{-1} FW. Lipid peroxidation analysis was performed according to Madhava and Sresty (2000). Absorbances of the extracts were measured at 532 – 600 nm with a Mecasy α-Optizen spectrophotometer.

2.1.4. Grain yield

Grain yield values of each genotype were determined at 15% moisture according to Özdemir and Sade (2019) and recorded in kg da^{-1}.

2.2. Statistical Analysis

The findings obtained from the experiment were analysed in the MSTAT – C (ANOVA) statistical analysis program according to the "Split-Split Plots Design in Randomized Blocks", and the means were grouped according to "LSD Test" ($p<0.05$).

3. RESULTS

The analysis of variance (ANOVA) revealed statistically significant differences across various parameters (Table 2). Specifically, irrigation levels significantly affected the number of leaves ($p < 0.05$), chlorophyll content ($p < 0.05$), proline levels ($p < 0.01$), MDA content ($p < 0.01$), and grain yield ($p < 0.01$). At the genotype level, significant variations were observed in plant height ($p < 0.05$), proline ($p < 0.05$), MDA ($p < 0.01$), and grain yield ($p < 0.05$).

Table 2. Variance analysis results for the studied features of maize (means square)

	DF	PH	LN	LA	CC	SC	PE	Proline	MDA	GY
R	2	2380.04	2.05	31403.57	22.50	42.11	0.000	1.34	0.04	17883.48
I	1	4892.23	6.38*	23109.40	244.39*	617.05	0.022	18.27**	6.61**	845328.23**
Error	2	1113.57	0.20	5629.58	3.63	64.58	0.005	0.02	0.00	6322.28
G	1	3838.65*	0.25	2385.57	55.27	39.06	0.003	3.96*	1.11**	420651.53*
I × G	1	675.52	0.20	652.76	17.63	1.02	0.000	10.90**	0.43*	309962.98*
Error	4	274.28	0.44	1389.03	12.65	45.04	0.001	0.31	0.03	25179.93
T	3	3810.18**	3.43**	17021.31*	34.88*	96.79*	0.062**	8.61**	0.31*	93652.80*
I × T	3	181.29	0.84	453.72	4.53	20.85	0.003	14.97**	0.19**	14217.42
G × T	3	396.22	0.16	2646.56	2.23	26.29	0.001	2.39*	0.00	9239.92
I × G × T	3	485.93	0.18	1292.07	4.93	17.00	0.000	6.27**	0.04	4783.55
Error	24	586.72	0.52	4423.91	11.44	29.25	0.002	0.63	0.01	23727.81
Total	47									
CV (%)		10.85	5.95	10.42	6.51	17.02	5.65	15.16	6.25	16.60

*p<0.05, **p<0.01, DF (degree of freedom), CV (coefficient of variation)
I (Irrigation) – G (Genotype) – T (Treatment) – R (Replication)
PH (cm): Plant height – LN: Leaf number – LA (cm^2): Leaf area – CC (Spad): Chlorophyll content
SC (mmol $m^{-2}s^{-1}$): Stomal conductance – PE (Fv Fm^{-1}): Photosynthetic efficiency – Proline (µmoles proline g^{-1} of FW) – MDA (nmol g^{-1}): Malondialdehyde – GY (kg da^{-1})

All examined traits showed significant responses to Si treatments. Furthermore, the Irrigation × Treatment (I × T) interaction significantly influenced proline ($p < 0.01$) and MDA ($p < 0.01$) levels, while the proline content was also significantly affected by Genotype × Treatment (G × T, $p < 0.05$) and Irrigation × Genotype × Treatment (I × G × T, $p < 0.01$) interactions. Regarding plant height (Table 3), the red-grained (RM) genotype was 8.34% taller than DKC 5741. When examining the effects of Si doses, the highest plant height was recorded at the 100 mg kg^{-1} Ca_2O_4Si application, followed by the 50 mg kg^{-1}, 25 mg kg^{-1}, and control groups, respectively.

Table 3. Means of plant height (cm)

	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	151.94	211.22	181.58	206.03	217.33	211.88
25 mgkg^{-1} Ca_2O_4Si	207.94	229.67	218.80	240.72	241.22	240.97
50 mgkg^{-1} Ca_2O_4Si	220.17	229.39	224.77	231.97	247.94	239.95
100 mgkg^{-1} Ca_2O_4Si	222.08	233.41	227.74	233.78	247.94	240.86
Means (I × G)	200.53	225.92		228.22	238.61	
Means of Irrigation	**%60;** 213.22			**%100;** 233.41		
Means of Genotypes	**DKC 5741;** 214.38 b			**Red Maize;** 232.26 a		
Means of Treatments	**Control** 196.73 b	**25 mgkg^{-1} Ca_2O_4Si** 229.88 a	**50 mgkg^{-1} Ca_2O_4Si** 232.36 a		**100 mgkg^{-1} Ca_2O_4Si** 234.30 a	

LSD (Treatments; 0.05) = 20.41

The average leaf number (Table 4) was significantly impacted by the irrigation regime; full irrigation resulted in a 6.17% higher leaf count compared to the restricted irrigation plots. Similarly, Ca_2O_4Si applications positively influenced leaf number, with the highest values obtained from the 100 mg kg^{-1} dose, followed by 25 mg kg^{-1}, 50 mg kg^{-1}, and the control. Silicon application also had a significant effect on mean leaf area (Table 4). The highest leaf area was achieved with the 100 mg kg^{-1} Ca_2O_4Si dose, followed by the 50 mg kg^{-1} and 25 mg kg^{-1} doses, respectively, compared to the untreated control. Notably, the 100 mg kg^{-1} Ca_2O_4Si treatment enhanced the average leaf area by 13.75% relative to the control group.

Table 4. Means of leaf number and leaf area (cm^2)

Means of Leaf Number						
	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	10.50	10.94	10.72	12.28	12.06	12.16
25 $mgkg^{-1}$ Ca_2O_4Si	12.00	12.28	12.13	12.22	12.89	12.55
50 $mgkg^{-1}$ Ca_2O_4Si	12.06	12.28	12.16	12.61	12.22	12.41
100 $mgkg^{-1}$ Ca_2O_4Si	12.22	12.39	12.30	13.11	13.11	13.11
Mean (I × G)	11.69	11.97		12.55	12.56	
Means of Irrigation	**%60;** 11.83 b			**%100;** 12.56 a		
Means of Genotypes	**DKC 5741;** 12.12			**Red Maize;** 12.27		
Means of Treatments	**Control**	**25 $mgkg^{-1}$ Ca_2O_4Si**		**50 $mgkg^{-1}$ Ca_2O_4Si**	**100 $mgkg^{-1}$ Ca_2O_4Si**	
	11.01 b	12.34 a		12.29 a	12.70 a	

LSD (Treatments; 0.05) = 0.61

Means of Leaf Area						
	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	571.91	545.03	558.47	611.63	600.37	605.99
25 $mgkg^{-1}$ Ca_2O_4Si	592.75	652.80	622.77	657.21	696.68	676.94
50 $mgkg^{-1}$ Ca_2O_4Si	616.35	653.16	634.75	699.79	665.37	682.58
100 $mgkg^{-1}$ Ca_2O_4Si	641.08	656.98	649.02	658.49	691.60	675.04
Mean (I × G)	605.52	626.99		656.78	663.50	
Means of Irrigation	**%60;** 616.25			**%100;** 660.14		
Means of Genotypes	**DKC 5741;** 631.15			**Red Maize;** 645.25		
Means of Treatments	**Control**	**25 $mgkg^{-1}$ Ca_2O_4Si**		**50 $mgkg^{-1}$ Ca_2O_4Si**	**100 $mgkg^{-1}$ Ca_2O_4Si**	
	582.23 b	649.86 a		658.66 a	662.03 a	

LSD (Treatments; 0.05) = 56.04

Chlorophyll content (Table 5) was substantially influenced by water availability; full irrigation resulted in a 9.07% higher mean value compared to deficit irrigation. Independent analysis of the Ca_2O_4Si treatments revealed that the 50 mg kg^{-1} Ca_2O_4Si dose was optimal, enhancing chlorophyll content by 7.42% relative to the untreated control.

Table 5. Means of chlorophyll content (Spad) and stomatal conductance (mmol $m^{-2}s^{-1}$)

Means of Chlorophyll Content						
	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	45.77	49.87	47.81	52.17	50.00	51.08
25 mgkg^{-1} Ca_2O_4Si	48.23	51.00	49.61	54.20	55.77	54.98
50 mgkg^{-1} Ca_2O_4Si	48.50	52.00	50.25	54.73	57.30	56.00
100 mgkg^{-1} Ca_2O_4Si	49.57	52.63	51.10	53.87	55.67	54.76
Mean (I × G)	48.01	51.37		53.74	54.67	
Means of Irrigation	**%60;**49.69 b			**%100;**54.20 a		
Means of Genotypes	**DKC 5741;** 50.87			**Red Maize;** 53.02		
Means of Treatments	**Control**	**25 mgkg^{-1} Ca_2O_4Si**		**50 mgkg^{-1} Ca_2O_4Si**	**100 mgkg^{-1} Ca_2O_4Si**	
	49.45 b	52.30 a		53.12 a	52.93 a	

LSD (Treatments; 0.05) = 2.85

Means of Stomatal Conductance						
	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	22.59	27.24	24.91	34.13	33.06	33.59
25 mgkg^{-1} Ca_2O_4Si	29.52	28.53	29.02	33.87	31.10	32.48
50 mgkg^{-1} Ca_2O_4Si	26.58	28.80	27.68	34.04	35.68	34.86
100 mgkg^{-1} Ca_2O_4Si	29.92	32.41	31.16	36.40	44.65	40.52
Mean (I × G)	27.14	29.24		34.61	36.12	
Means of Irrigation	**%60;** 28.19			**%100;** 35.36		
Means of Genotypes	**DKC 5741;** 30.88			**Red Maize;**32.68		
Means of Treatments	**Control**	**25 mgkg^{-1} Ca_2O_4Si**		**50 mgkg^{-1} Ca_2O_4Si**	**100 mgkg^{-1} Ca_2O_4Si**	
	29.25 **b**	30.75 b		31.27 b	35.84 a	

LSD (Treatments; 0.05) = 4.55

Regarding stomatal conductance and photosynthetic efficiency, statistically significant variations were observed only among the Si treatments. The highest values for both parameters were obtained from the 100 mg kg^{-1} Ca_2O_4Si application (Table 5, Table 6).

Table 6. Mean values of photosynthetic efficiency (Fv Fm^{-1})

	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	0.641	0.634	0.638	0.644	0.624	0.634
25 $mgkg^{-1}$ Ca_2O_4Si	0.709	0.706	0.707	0.770	0.746	0.766
50 $mgkg^{-1}$ Ca_2O_4Si	0.749	0.711	0.730	0.802	0.772	0.787
100 $mgkg^{-1}$ Ca_2O_4Si	0.772	0.779	0.775	0.833	0.840	0.836
Mean (I × G)	0.718	0.707		0.766	0.745	
Means of Irrigation	**%60;** 0.713			**%100;** 0.756		
Means of Genotypes	**DKC 5741;** 0.742			**Red Maize;** 0.726		
Means of Treatments	**Control**	**25 $mgkg^{-1}$ Ca_2O_4Si**		**50 $mgkg^{-1}$ Ca_2O_4Si**	**100 $mgkg^{-1}$ Ca_2O_4Si**	
	0.636 c	0.737 b		0.758 b	0.806 a	
LSD (Treatments; 0.05) = 0.037						

Specifically, the 100 mg kg^{-1} Ca_2O_4Si dose increased stomatal conductance by 12.15% and photosynthetic efficiency by 26.72% compared to the non-treated control. Under deficit irrigation conditions, the highest proline content (Table 7) was recorded in the control group of the RM genotype, followed by the DKC 5741 × control and DKC 5741 × 50 mg kg^{-1} Ca_2O_4Si treatments, respectively.

The lowest proline value within the group was recorded in the RM × 25 mg kg^{-1} Ca_2O_4Si treatment. Under full irrigation conditions, the highest proline content was determined in the RM × 50 mg kg^{-1} Ca_2O_4Si application, followed by the DKC 5741 × 50 mg kg^{-1} Ca_2O_4Si and RM × 100 mg kg^{-1} Ca_2O_4Si treatments, respectively. Conversely, the lowest proline content in this group was obtained from the RM control (Table 7).

Regarding lipid peroxidation, the MDA value of DKC 5741 was found to be 15.87% higher than that of the red maize population (Table 7). Analysis of the average MDA values across Ca_2O_4Si applications showed that the highest levels were in the control group, which was 17.27% higher than the 100 mg kg^{-1} Ca_2O_4Si treatment (the lowest value in the group).

Table 7. Means of proline (µmoles proline g^{-1} of FW) and MDA (nmol g^{-1})

Proline

	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	7.96 ab	9.23 a	8.59 a	4.56 e-h	3.57 hı	4.06 c
25 mgkg^{-1} Ca$_2$O$_4$Si	6.44 cd	2.98 ı	4.70 bc	3.67 h-ı	4.45 e-h	4.06 c
50 mgkg^{-1} Ca$_2$O$_4$Si	6.78 dc	3.74 hı	5.26 b	5.45 c-f	5.77 cde	5.61 b
100 mgkg^{-1} Ca$_2$O$_4$Si	5.30 d-g	4.40 fgh	4.84 bc	4.04 ghı	5.43 def	4.73 bc
Means (I × G)	6.61 a	5.08 b		4.42 c	4.80 bc	
Means of Irrigations	**%60;** 5.85 a			**%100;** 4.61 b		
Means of Genotypes	**DKC 5741;** 5.52 a			**Red Maize;** 4.94 b		

Means of Treatments	**Control**	**25 mgkg^{-1} Ca$_2$O$_4$Si**	**50 mgkg^{-1} Ca$_2$O$_4$Si**	**100 mgkg^{-1} Ca$_2$O$_4$Si**
	6.32 a	4.38 c	5.43 b	4.79 bc

LSD (Treatments; 0.05) = 0.66
LSD (I × G; 0.05) = 0.47
LSD (I × T; 0.05) = 0.94
LSD (I × G × T; 0.05) = 1.33

MDA

	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	2.84	2.70	2.76 a	1.95	1.34	1.64 e
25 mgkg^{-1} Ca$_2$O$_4$Si	2.46	2.28	2.37 b	1.96	1.53	1.74 de
50 mgkg^{-1} Ca$_2$O$_4$Si	2.34	2.41	2.37 b	2.12	1.51	1.81 d
100 mgkg^{-1} Ca$_2$O$_4$Si	2.25	2.05	2.15 c	1.66	1.33	1.49 f
Means (S x G)	2.47 a	2.36 a		1.92 ab	1.42 b	
Means of Irrigation	**%60;** 2.41 a			**%100;** 1.67 b		
Means of Genotypes	**DKC 5741;** 2.19 a			**Red Maize;** 1.89 b		

Means of Treatments	**Control**	**25 mgkg^{-1}Ca$_2$O$_4$Si**	**50 mgkg^{-1}Ca$_2$O$_4$Si**	**100 mgkg^{-1}Ca$_2$O$_4$Si**
	2.20 a	2.05 b	2.09 b	1.82 c

LSD (Treatments; 0.05) = 0.08
LSD (I × T; 0.05) = 0.11
LSD (I × G; 0.05) = 0.55

Calcium silicate applications significantly reduced MDA levels under deficit irrigation conditions. Furthermore, a significant variation in MDA traits was observed between irrigation regimes; specifically, MDA levels under deficit irrigation were 44.31% higher than those under full irrigation. The lowest MDA content was observed in the RM genotype under full irrigation, while the highest was recorded in DKC 5741 under deficit irrigation. Overall, MDA content increased in parallel with water restriction. Water scarcity also significantly impacted grain yield, with full irrigation yielding 33.36% more than deficit irrigation (Table 8). When examining genotypes, the grain yield of DKC 5741 was 22.43% higher than that of the red maize population. Significant differences were also observed among treatments regarding grain yield; the highest value was recorded in the 50 mg kg^{-1} Ca_2O_4Si application, which was 24.93% higher than the control. Genotypes exhibited varying responses to different irrigation levels, with the highest grain yield observed in DKC 5741 under full irrigation, followed by RM under full irrigation, DKC 5741 under deficit irrigation, and RM under deficit irrigation, respectively.

Table 8. Mean values of grain yield (kg da^{-1})

	Deficit Irrigation			**Full Irrigation**		
	DKC 5741	**Red Maize**	**Means (I × T)**	**DKC 5741**	**Red Maize**	**Means (I × T)**
Control	655.84	646.83	651.34	1054.35	843.51	948.93
25 mgkg^{-1} Ca_2O_4Si	805.56	800.07	802.81	1319.02	951.69	1135.35
50 mgkg^{-1} Ca_2O_4Si	942.81	883.97	913.39	1293.06	878.69	1085.87
100 mgkg^{-1} Ca_2O_4Si	830.47	797.78	814.12	1272.78	873.54	1073.16
Means (I × G)	808.67 b	782.16 b		1234.80 a	886.85 b	
Means of Irrigation	**%60;** 795.41 b			**%100;** 1060.83 a		
Means of Genotypes	**DKC 5741;** 1021.73 a			**Red Maize;** 834.51 b		
Means of Treatments	**Control**	**25 mgkg^{-1} Ca_2O_4Si**		**50 mgkg^{-1} Ca_2O_4Si**	**100 mgkg^{-1} Ca_2O_4Si**	
	800.13 b	969.08 a		999.63 a	943.64 a	

LSD (Treatments; 0.05) = 129.80
LSD (I × G; 0.05) = 133.70

4. DISCUSSION

Drought represents a widespread environmental challenge that results in severe water scarcity, acting as a primary restrictive factor for the production of essential crops like maize, wheat, and rice. To alleviate the impact of this issue, various integrated management strategies have been implemented, including the modernization of irrigation infrastructure, the development of stress – resilient cultivars via diverse breeding techniques -ranging from traditional methods to molecular, tissue culture, and genetic engineering- and the strategic use of organic, inorganic, or nano – based fertilizers. (Alwan et al., 2026).

The effects of drought are variable and depend on its intensity, frequency and duration. Some studies have recorded declines in leaf area, leaf number and plant height characteristics of plants exposed to prolonged and severe drought (Dere, 2021; Devi et al., 2022; Katerji et al., 2004; Küçükkömürcü, 2011; Parveen et al., 2019). Silicon accumulates in plant tissues to form silica gel barriers, which promote drought tolerance by reducing water loss, particularly through transpiration (Özdemir, 2022; Özkan and Özdemir, 2022).

The findings of this research align with prior investigations, which similarly demonstrated that Si supplementation boosts both shoot development (including plant height and leaf area) and root system architecture (such as root length, volume, and surface area) during periods of water scarcity. This improved growth performance facilitated by Si under drought conditions can be linked to various underlying physiological and biochemical processes (Ning et al., 2026).

Plant growth and development depend on numerous factors; however, photosynthesis remains one of the most critical physiological processes governing these stages. Photosynthesis is significantly hindered by environmental stress conditions (Ashraf and Harris, 2013; Yavaş and İlker, 2020). Existing literature reports that water stress negatively impacts chlorophyll content (Parveen et al., 2019; Razzaq et al., 2017), stomatal conductance (Makbul et al., 2011), and the overall photosynthetic rate (Ashraf and Harris, 2013; Yavaş and İlker, 2020). Conversely, Si application has been shown to enhance chlorophyll levels (Lee et al., 2010), improve stomatal conductance (Abd El-Mageed et al., 2021), and increase the photosynthesis rate (Ecem, 2010), thereby mitigating the adverse effects of stress. In alignment with existing literature, the administration of Ca_2O_4Si enhanced all evaluated photosynthetic parameters -including chlorophyll levels, stomatal conductance, and photosynthetic efficiency- across the tested genotypes under both water-restricted and optimal irrigation regimes; similarly, Ning et al. (2026) observed that Si treatment effectively sustained robust net photosynthetic rates (Pn), transpiration rates (Tr), and stomatal conductance (Gs) even in the presence of drought-induced stress. It is well established that drought induces significant biochemical changes in plant tissues, one of the most prominent being the alteration of proline levels in response to stress. Kılıcaslan et al. (2020) reported a substantial increase in proline content under water scarcity. However, Sapre and Vakharia (2017) observed that Si application effectively reduced proline levels in maize exposed to drought. Consistently, the current study found that proline content in Ca_2O_4Si treated plots under limited irrigation was lower than in the control group. Oxidative stress is defined as the disruption of the redox balance in favor of oxidants over antioxidants (Özdemir et al., 2023). Reactive Oxygen Species generated by drought stress induce lipid peroxidation, leading to the formation of MDA through the breakdown of polyunsaturated fatty acids (Mittler, 2002). This process severely compromises cell membrane permeability (Esmaili et al., 2022). Silicon has been shown to mitigate the negative impacts of oxidative stress on the selective permeability of the cell membrane (Coskun et al., 2016). In this study, while drought stress increased MDA levels, Ca_2O_4Si applications successfully reduced MDA content in cellular tissues. Furthermore, Song (2000) reported that drought hinders the development of generative organs, such as female flowers in maize, leading to pollination issues that negatively impact yield (Hajibabaee et al., 2012). Previous research has concluded that silicate applications enhance water uptake from roots and increase the photosynthetic rate while reducing leaf water loss and maintaining nutrient balance. Consequently, Si application improves grain yield even under unfavourable soil and climatic conditions (Zhu and Gong, 2014).

In the current work, the fact that the application of 50 mg kg^{-1} Ca_2O_4Si increased grain yield and chlorophyll content can be interpreted as this application ensuring the direct transfer of assimilates to the grain by enhancing the photosynthetic capacity of the plant. The increase in plant height and leaf area with the 100 mg kg^{-1} Ca_2O_4Si application may indicate that high Si concentrations further support the cell wall structure, thereby promoting vegetative growth; indeed, the low MDA contents obtained at the same application dose demonstrate that the increasing dosage protects the plant against oxidative stress. Furthermore, the observation of the highest stomatal conductance at the 100 mg kg^{-1} Ca_2O_4Si dose suggests that the plant can perform more transpiration through a larger leaf area and high stomatal conductance; however, this morphological and physiological advantage did not reflect on grain yield as significantly as the chlorophyll increase observed at the 50 mg kg^{-1} Ca_2O_4Si dose. In conclusion, it can be stated that while the moderate level of Si application plays an optimizing role for physiological efficiency and grain filling, the high dose renders the plant more resilient in terms of metabolic adaptation and physiological defence mechanisms (greater height, wider leaf area, and lower MDA content).

5. CONCLUSIONS

Based on this experiment, as respected grain yield reduced by water restriction. DKC 5741 can be suggested to farmers under water restriction conditions compared to RM. While the Ca_2O_4Si treatments compared to each other, 50 mg kg^{-1} Ca_2O_4Si was ahead of the group. The statistically non-significant interaction between irrigation levels and Ca_2O_4Si applications regarding grain yield indicates that Ca_2O_4Si application had a direct and positive effect on yield, independent of the irrigation level. This situation may be an indication that the physiological support provided by Ca_2O_4Si applications within the plant structure functions similarly under both full and deficit irrigation conditions. In this study, the fact that Ca_2O_4Si enhanced photosynthetic capacity by increasing chlorophyll content and protected the plant against environmental pressures by strengthening the cell wall structure ensured that the grain-filling process continued without interruption, even under water deficit. Consequently, the yield-enhancing effect of Ca_2O_4Si doses did not show a variation depending on the irrigation level; the application itself became one of the primary factors stabilizing plant performance and final grain yield.

For the future perspective;

- The protective effects of Ca_2O_4Si applications against other abiotic stress factors, such as salinity, high temperature, or heavy metal stress, besides drought, should be examined in depth in maize plants.
- Molecular and transcriptomic analyses should be conducted to determine how Si applications activate antioxidant defence mechanisms and stress response genes within the plant structure.
- As an alternative to soil application, the effectiveness and economic profitability of foliar Si applications performed at different growth stages should be compared.
- The plant uptake and impact on yield of nano – silica particles produced by nano – technological methods should be investigated in comparison to traditional Ca_2O_4Si forms.
- The long – term effects of Si applications on soil physical structure, water – holding capacity, and the beneficial microbial population in the rhizosphere should be monitored.
- Breeding studies should be carried out to develop new “silica-friendly” and drought – resistant varieties by screening the Si use efficiency of different maize genotypes.

Conflict of Interest

The author declares that there is no conflict of interest.

Ethics

This study does not require ethics committee approval.

Author Contribution Rates

Design of Study: EÖ (80%), SÖ (20%)

Data Acquisition: EÖ (40%), SÖ (%60)

Data Analysis: EÖ (%90), SÖ (10%)

Writing up: EÖ (%20), SÖ (%80)

Submission and Revision: EÖ (%100)

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