

Article

Foliar Application of K-Silicate and L-Cysteine Enhances Production, Quality, and Antioxidant Activities of Cape Gooseberry Fruits Under Drought Conditions

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Abstract: Water deficit is a notable environmental stress, which leads to negative impacts on crop growth, resulting in yield decline. In the current experiment, the exogenous application of potassium silicate (KSi) and L-cysteine (Cys) was investigated on the productivity, qualitative, and biochemicals of Cape gooseberry fruits subjected to drought stress condition in a 2-year field experiment (2022 and 2023). Our findings indicated that deficit irrigation reduced yield, the membrane stability index, titratable acidity, and the ascorbic acid content of fruits in comparison to the untreated plants in both years. Nonetheless, MDA, H₂O₂, and antioxidant enzyme activities were meaningfully enhanced as a consequence of water deficit conditions. The application of KSi and Cys alleviated water deficit stress by reducing MDA accumulation and provided significantly greater content of total soluble solids, soluble carbohydrate, proline, total soluble protein, total phenols, and flavonoids. KSi and Cys have a positive influence on H₂O₂ accumulation by boosting the actions of antioxidant enzymes. Furthermore, higher values of Cys induced the production of proline, APX, PPO, and PAL activities, which contributed to decreasing the damaging effects of plant drought stress and led to an enhanced yield rate. Overall, the foliar application of KSi and Cys by improving antioxidant components, antioxidant enzyme activity, and proline accumulation had a positive impact on the productivity and quality of Cape gooseberries cultivated under standard and shortage irrigation levels.

Keywords: antioxidant enzymes; malondialdehyde; K-silicate; proline; total soluble carbohydrate



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1. Introduction

The cape gooseberry (*Physalis peruviana* L.) is a plant of the *Solanaceae* family, whose ripe fruit has an edible and medicinal value and contains high amounts of vitamins A, B and C; proteins; phosphorus; iron; and antioxidants [1]. It provides bioactive components that can be useful for human health and the medical industry [1] and has been considered economically as a suitable product for domestic consumption as well as export to other countries [2]. However, due to global climate change, Cape gooseberry production regions are widely prone to periods of drought and water scarcity [3].

To address the food requirements of the growing global inhabitants, enhancing agricultural production is essential, particularly in light of climate change and its exacerbating effects on abiotic stresses [4]. Water stress is a noteworthy abiotic issue that restricts global

plant production by diminishing plant growth, lowering tissue water potential, reducing cell turgor, decreasing the photosynthesis rate, and compromising cell membrane stability, especially in arid and semi-arid areas [5]. Moreover, water scarcity alters the hormonal balance as a consequence of variations in plant metabolism, resulting in an enhanced biosynthesis of reactive oxygen species (ROS), which can alter the normal cellular processes via oxidative stress [6]. However, plants have the capability to naturally cope with this stress via enzymatic antioxidant mechanisms, involving superoxide dismutase (SOD), catalase (CAT), and peroxidase (POX), or through the biosynthesis of phenolics and flavonoids, which can enhance fruit quality [7].

Previous studies on *P. peruviana* demonstrated that in response to deficit irrigation stress, there was an upsurge in pH, total soluble solids, vitamin C, and fruit antioxidant activity. Conversely, biomass accumulation, fruit count, and physalis yield decreased due to higher concentrations of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) [3]. While plants subjected to deficit irrigation face water stress that can adversely impact their growth and performance, this method can effectively reduce water usage. Nonetheless, these stress responses may jeopardize plant production in relation to its duration and intensity, posing a significant challenge in maintaining plant performance under such conditions [8]. Terra et al. [9] have aimed to promote the use of drought-tolerant genotypes, along with biofertilizers and osmotic protectants like amino acids, to alleviate the destructive impacts of stress.

Overall, maintaining proper plant nutrition is essential for alleviating the detrimental effects of water limitations on crop yield. Potassium silicate (KSi) serves as an effective source of both K and Si in agricultural systems, primarily acting as a silica modifier while also supplying significant amounts of potassium [10]. Even though Si is not fundamental for plants [11], it has positive outcomes in agriculture to alleviate the plant inherent abiotic stresses, specifically water deficit stress [12]. Silicon improves resistance to drought stress by regulating root water uptake, decreasing transpiration, improving the antioxidative defense system, eliciting the build-up of osmolytes such as proline, regulating polyamine synthesis, and enhancing the activity of photosynthetic enzymes, all while maintaining the growth and yield of the treated plants [13]. Studies demonstrated that the foliar application of K-silicate and other nano-materials in plants subjected to water stress, could enhance the water status, firmness, metabolic and physiological performances [14], and yield [15] of cucumber; restrict the accumulation of ROS induced by drought; and significantly improve the gas exchange parameters in tomatoes [16]. Also, the use of silicon in *Physalis angulata* L. led to an increase in proline and phenol content [17].

Currently, the use of amino acids as biostimulants has appeared as a novel method to increase the nutritional quality of fruits and vegetables. They also enhance crop growth and yield by stimulating the metabolic pathways or activating antioxidants underneath biotic and abiotic stresses [18] to detoxify ROS and maintain membrane integrity, as well as preserve enzymes or proteins [19].

Cysteine (Cys) is a significant sulfur-containing amino acid featuring a thiol side chain, which plays a role in enzymatic reactions. This unique structure allows Cys to function as a powerful antioxidant and an effective scavenger of ROS generated under oxidative stress [20]. Additionally, Cys serves as the precursor for several functional compounds, comprising hydrogen sulfide, methionine, various vitamins, cofactors, iron–sulfur (Fe–S) clusters, and the ethylene hormone [21]. Recently, Wang et al. [22] found that the postharvest treatment with Cys in goji (*Lycium barbarum* L.) fruits significantly enhanced the levels of total phenolics, ascorbic acid, and total glutathione, as well as the ratio of glutathione to oxidized glutathione, enhancing the antioxidant capacity. This treatment notably reduced both decay rates and weight loss while preserving the total fruit soluble

solid content. Similarly, Cys application also boosted the total phenolic in litchi fruits [23], elevated polyphenol levels in fresh-cut beets [24], and enhanced the action of superoxide dismutase (SOD), ascorbate peroxidase (APX), catalase (CAT), and peroxidase (POX) in wheat [25].

In many countries, including Iran, the importance of water conservation has resulted in sustainable agriculture practices that require fewer water resources a priority. Although the beneficial effects of biostimulant application on plants are well recognized, there are currently no definitive data clarifying the roles of KSi and Cys in Cape gooseberry fruits subjected to water deficit stress. Thus, this study wanted to assess the physiological influences of different levels of KSi and Cys in alleviating the detrimental impacts of deficit irrigation on the qualitative and biochemical traits of Cape gooseberry fruits.

2. Materials and Methods

2.1. Experimental Design, Genetic Material, and Treatments

The field experiment was performed at the University of Zanjan, Iran, which is located at 36 degrees 40 min north longitude, 48 degrees 24 min east latitude, and an altitude of 1596 m above sea level, over two years, from May to October in 2022 and 2023. The experiment was conducted using a split-plot design with three irrigation regimes (50, 75, and 100 crop evapotranspiration percentages (%ETc)) as the main plot, three levels of potassium silicate (KSi) (500, 1000, and 1500 mg L⁻¹), two levels of L-cysteine (Cys) (20 and 40 mg L⁻¹) and by spraying distilled water (control) on the sub-plot in three replicates. The seeds of Cape gooseberries (*Physalis peruviana* L.) (“Pakan seed” company, Isfahan, Iran) were placed in the seedling trays loaded with peat moss and perlite (50:50). The seedlings were cultivated in a climate-controlled greenhouse at the University of Zanjan (day: 25 ± 2 °C; night: 20 ± 2 °C; RH: 60–70%) starting from March 15 in both 2022 and 2023. The seedlings were transplanted at the 4- to 5-leaf stage, spaced 50 cm apart in rows and 150 cm between rows. Different concentrations of treatments (KSi and Cys) were sprayed on the experimental plants only at the true 8–10th leaf stage (400 mL plant⁻¹) until run off using a mechanical mist sprayer and continued at 15-day intervals at anthesis (800 mL plant⁻¹), as well as fruit setting (1200 mL plant⁻¹) stages. In this study, 3 irrigation levels were considered: 50% (I₅₀), 75% (I₇₅), and 100% (I₁₀₀) of crop evapotranspiration (ETc). I₁₀₀ was employed as the control for setting the irrigations of I₅₀ and I₇₅ (drought-stressed plots). The water requirements for crops were determined by the actual Cape gooseberry evapotranspiration (ETc); it was calculated as follows: $ET_c = ET_0 \times K_C$

Here, ET₀ is the reference evapotranspiration [26] (mm day⁻¹), and K_C is the plant coefficient. The K_C values were different depending on the plant stage; for initial, mid-season and the end of the season, they were considered 0.6, 1.15, and 0.9, respectively. All climatic data were collected from the meteorological station at the University of Zanjan.

Crops were watered via a drip irrigation system with tape pipes (2 L/h). The soil characteristics of the experimental fields and the climatic data are displayed in Tables 1 and 2, respectively.

Table 1. Soil physical and chemical properties on the site of the experimental field.

Soil Texture	Organic Matter (%)	pH	EC (dS m ⁻¹)	N (%)	Ca (g kg ⁻¹)	Na (g kg ⁻¹)	K (g kg ⁻¹)
Loam clay	0.94	7.4	1.49	0.07	0.12	0.13	0.20

Table 2. Average daily data of meteorological parameters at the synoptic weather station at the University of Zanjan, Iran, during the growing season (2022 and 2023).

Meteorological Parameter	May		June		July		August		September		October	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Maximum temperature (°C)	30.2	29.2	33.7	33.1	34.9	34.8	32.2	31.8	27.7	23.8	15.6	19.0
Minimum temperature (°C)	12.2	12.0	15.6	14.9	16.5	15.1	12.2	12.3	9.0	8.6	2.9	5.2
Average temperature (°C)	21.2	20.6	24.7	24.0	25.7	25.0	22.2	22.1	18.4	16.2	9.3	12.1
Average relative humidity (%)	31.4	44.1	30.2	34	34.7	28.8	28.9	36.3	36.2	42.6	65.2	49.1
Total rainfall (mm)	0.1	40.2	0.0	8.2	0.0	2.2	0.0	0.9	0.5	4.2	21.1	2.3
Sum sunshine (hr)	10.5	9.7	11.9	12.3	11.3	10.8	10.3	8.3	9.4	6.6	6.1	6.7

2.2. Plant Productivity and Fruit Nutritional Traits

Fruits were harvested (two times during the growing cycle) once the calyx and fruits changed color from green to orange. The fruit weight per plant (from five plants per replicate) was recorded to calculate the fruit yield, expressed in kg per hectare (kg ha^{-1}).

Six fruits, belonging to 3 plants per replicate, were casually chosen to evaluated TSS and TA contents. The fruit total soluble solids (TSSs) were assessed with a portable digital refractometer (ATago-ATC-20(E), Saitama, Japan) and expressed as °Brix. The percentage acidity (TA), as citric acid, was determined using 3 to 4 drops of phenolphthalein and titrated against 0.1N NaOH.

The ascorbic acid content in fruits ($\text{mg } 100 \text{ g}^{-1}$ fresh weight) was measured by analyzing six fruits from three plants per replicate for each treatment. This assessment followed the titration method outlined by Terada et al. [27].

Total soluble carbohydrates (TSCs) and total soluble proteins (TSPs) were measured from six fruits harvested from 3 plants per replicate. TSCs were assessed using the anthrone colorimetric assay [28]. For extraction, 0.5 g of fresh fruit samples was homogenized in 10 mL of 95% ethanol and centrifuged at 5000 rpm for 10 min. The resulting supernatant was then mixed with 1 mL of supernatant and 3 mL of anthrone, heated at 100 °C for 10 min, and cooled. A standard glucose curve was used at a detection wavelength of 625 nm to quantify TSCs, with results expressed as mg per 100 g of fresh weight. TSP content was determined using the Bradford method [29], employing a potassium phosphate-buffered solution (50 mM, pH 7.8) with EDTA (0.2 mM) and PVP (2%), using bovine serum albumin as the standard at a wavelength of 595 nm.

2.3. POX, CAT, SOD, APX, PPO, and PAL Activities

To measure the activities of antioxidant enzymes (U mg^{-1} protein), 2 g of frozen fruit samples was homogenized with potassium phosphate buffer (50 mM, pH 7.8) containing EDTA (0.2 mM) and PVP (2%). Following centrifugation at 12,000 g for 15 min at 4 °C, the supernatants (50 mL) were used for enzymatic assays. POX activity was measured using the guaiacol (632 μL in 12 mL distilled water) assay method, where a change of 0.01 units per minute in absorbance at 470 nm represented one unit of activity. CAT activity was appraised by monitoring the decomposition of H_2O_2 (541 μL in 4 mL distilled water) at 240 nm using a UV spectrophotometer [30]. SOD activity was assessed as per Giannopolitis and Ries [31], defined as the enzyme amount required to achieve 50% inhibition of nitroblue tetrazolium (NBT) (61.3 mg in 50 mL) reduction at 560 nm. APX activity was measured in the presence of 2.0 mmol L^{-1} ascorbic acid and 2.0 mmol L^{-1} EDTA by recording the decrease in absorbance at 290 nm [32]. Additionally, polyphenol oxidase (PPO) and phenylalanine ammonia-lyase (PAL) activities were evaluated according to Nguyen et al. [33] with minor modifications by using 50 mM phosphate buffer (pH 7.8) and 50 mM borate buffer (pH 8), respectively.

2.4. Fruit Functional Components, Antioxidant Capacity, and the Membrane Stability Index

To assess the total phenolic (mg GAE 100 g⁻¹ FW) and flavonoid (mg QE 100 g⁻¹ FW) contents, six fruits belonging to 3 plants per treatment were randomly collected in triplicate. The total phenol content was assessed via the Folin–Ciocalteu method, employing an extraction solvent of methanol/water (80:20, *v/v*) based on Singleton and Rossi's procedure [34], whereas flavonoids were measured via a colorimetric method [35].

The antioxidant capacity of the fruit tissue was assessed through the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay [36].

The membrane stability index (MSI) of fruits was measured in four fruits belonging to three plants per replicate. The fruit samples were incubated at 40 °C for 30 min in a vial; subsequently, the electrical conductivity (EC₁) of the samples was measured. The samples were then autoclaved at 120 °C for 20 min and allowed to cool to room temperature, after which a second reading (EC₂) was acquired. The MSI was calculated using the following formula [37]:

$$\text{MSI} = (1 - \text{EC}_1/\text{EC}_2) \times 100 \quad (1)$$

2.5. Malondialdehyde, H₂O₂, and Proline

The malondialdehyde (MDA) content in fruits was assessed using the thiobarbituric acid (TBA) method [38] at 532 and 600 nm, and the results are expressed using the formula below as µmol per gram of fresh weight (FW).

$$\text{MDA} = [(A_{532} - A_{600}) \times W \times V/155] \times 1000 \quad (2)$$

The hydrogen peroxide (H₂O₂) content was measured using the potassium iodide method at 390 nm, following the procedure outlined by Alexieva et al. [39], and reported in µmol per gram of FW using a standard curve obtained from various concentrations of H₂O₂. Additionally, the proline content of the fruits was determined following the method established by Bates et al. [40] at 520 nm, with proline levels expressed in mg per gram of FW using a constructed standard curve.

2.6. Statistics

Statistical analysis was accomplished using a split-plot model based on a completely randomized block design, incorporating 3 irrigation levels and 6 spray treatment levels (including 3 concentrations of KSi, 2 concentrations of Cys, and control treatments), with 3 replications for each combination. Data were processed through the SAS 9.4 statistical software (SAS Institute Inc., Cary, NC, USA), and means were compared using Duncan's multiple range test at a significance level of $p = 0.05$. Before analysis, ANOVA assumptions (the Shapiro–Wilk and Levene tests) were accomplished. Results were presented as means with standard errors ($n = 3$). Additionally, Pearson's correlation analysis was conducted using the SPSS software version 25.0 for Windows to explore the relationship between yield and quality measurements collected over two years.

3. Results

Plant Productivity and Fruit Nutritional Traits

Data from 2022 and 2023 indicated that irrigation regimes and treatments with KSi and Cys significantly ($p \leq 0.01$) affected the fruit yield of Cape gooseberries (Figure 1A,B). Based on the results, reducing irrigation from 100 to 50% ETc caused a 39% reduction in yield over both years. The yield of crops obtained from the first year was significantly ($p \leq 0.01$) higher than the second year. The fruit yield per plant was lower under deficit irrigation in both treated and control plants. In both years, the foliar spray of KSi and

Cys significantly increased fruit yield under well and deficit irrigation conditions. In 2022 as well as 2023, the foliar spray of Cys 40 mg L⁻¹ under 100% and 75% ETc, respectively, showed the highest fruit yield. So, the application of Cys 40 mg L⁻¹ resulted in a 64.6% increase and a 58.85% increase in fruit yield under 100% ETc and 75% ETc, respectively, in 2022 and 2023.

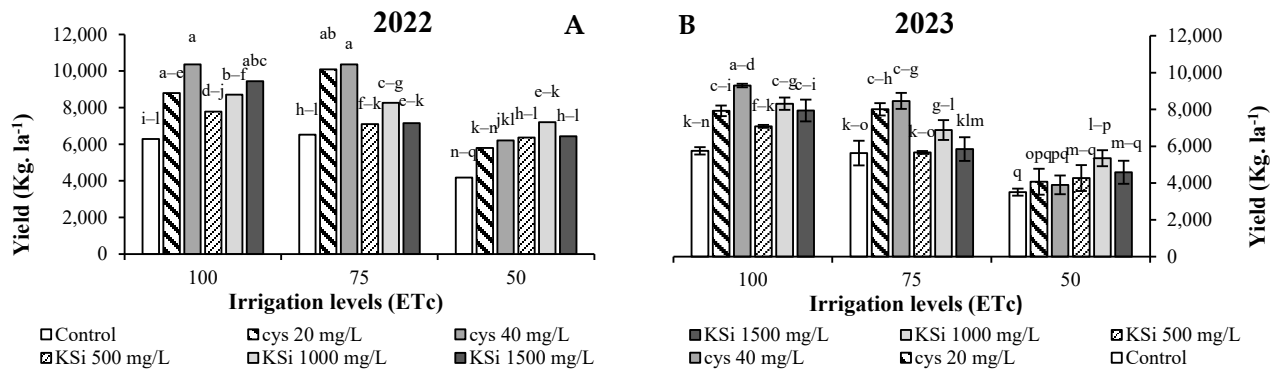


Figure 1. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on fruit yield of Cape gooseberries (*Physalis peruviana* L.) under deficit irrigation in 2022 (A) and 2023 (B). Values shown are means $\pm$ standard errors ($n = 3$). Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

Cape gooseberry fruits exhibited significantly higher TSS content in the first year compared to the second one ($p \leq 0.01$) (Figure 2A,B). The application of KSi and Cys increased TSS levels above those of the control in both years, with a more notable effect in the first year, as Cys increased TSS content by 21.62%, and KSi contributed to a 13.51% increase. In the first year, TSS content decreased under 50% ETc deficit irrigation, while no significant variations in TSS were noticed between irrigation regimes in the second year (Figure 2B). The highest TSS values (15.75 and 15.7 °Brix) were recorded in plants supplied with Cys 20 and 40 mg L⁻¹ under 50% ETc in 2022, which was an increase of 21.6% compared to the control treatment (Figure 2A). As reported in Figure 2C,D, the TA content of fruits exhibited no significant difference between the two years ($p \leq 0.05$). Irrigation significantly affect the TA content, which increased with deficit irrigation in treated and control plants. Due to the foliar application of KSi and Cys, increases of 46.6 and 8.5% in 2022 and 19.6 and 21.3% in 2023 were observed in the TA content under 100% ETc, respectively. According to the results, it can be reported that KSi in 2022 and Cys in 2023 were more effective than other treatments. The highest values of TA (3.09 and 3.08%) were obtained with KSi 1000 mg L⁻¹ under 75% ETc and KSi 500 mg L⁻¹ under full irrigation (I₁₀₀) in 2022.

As reported in Figure 3A,B, in both years, the ascorbic acid content of Cape gooseberry fruits significantly decreased by reducing the irrigation levels in the treated and control plants ($p \leq 0.01$). The results indicate that by reducing irrigation from 100% ETc to 50% ETc, the ascorbic acid content decreased by 36.12% in 2022 and by 25.24% in 2023.

Throughout both years, the application of KSi and Cys improved the ascorbic acid content under full and deficit irrigation circumstances. In both years, the maximum amount of ascorbic acid was significantly ($p \leq 0.01$) observed in plant supplied with KSi 1000 mg L⁻¹ under full irrigation (I₁₀₀) (Figure 3A,B).

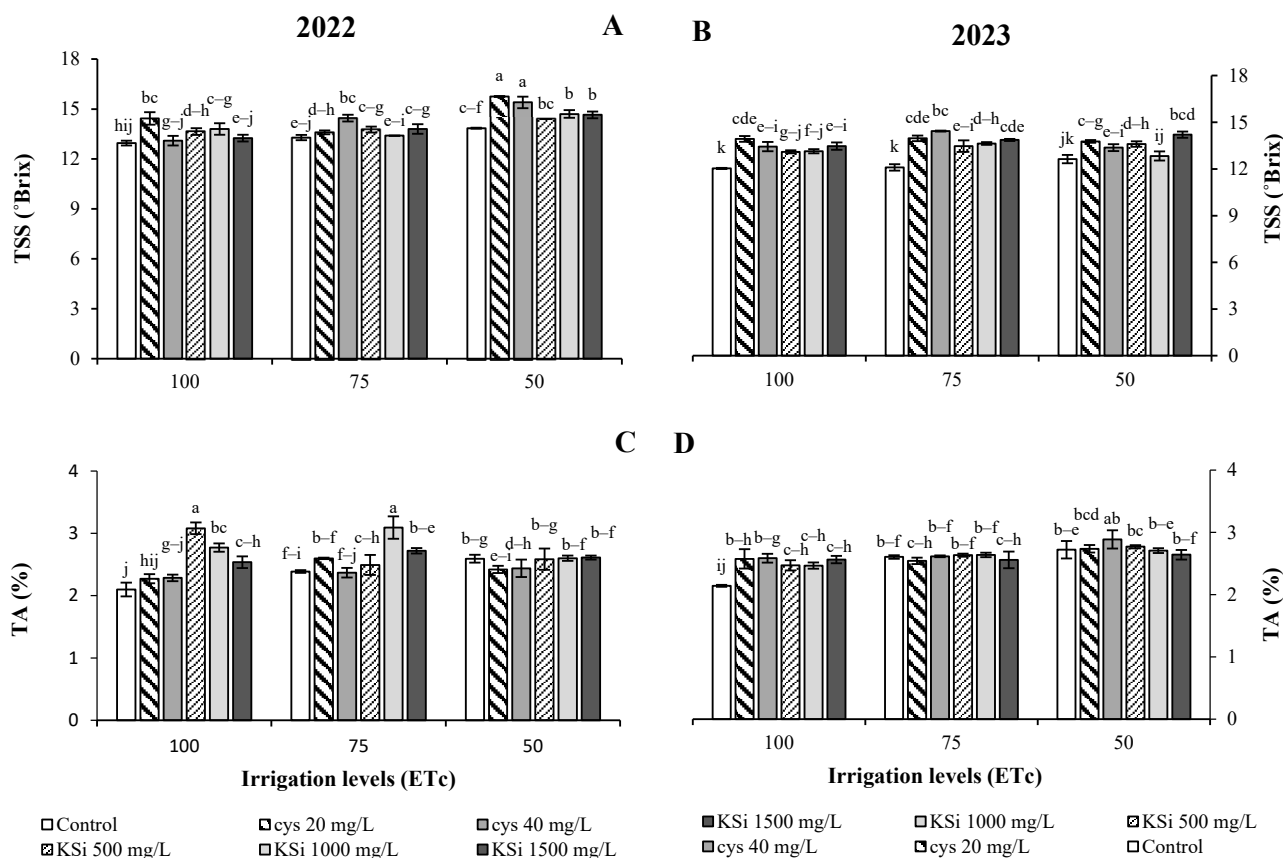


Figure 2. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on TSS (A,B) and TA (C,D) contents of Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

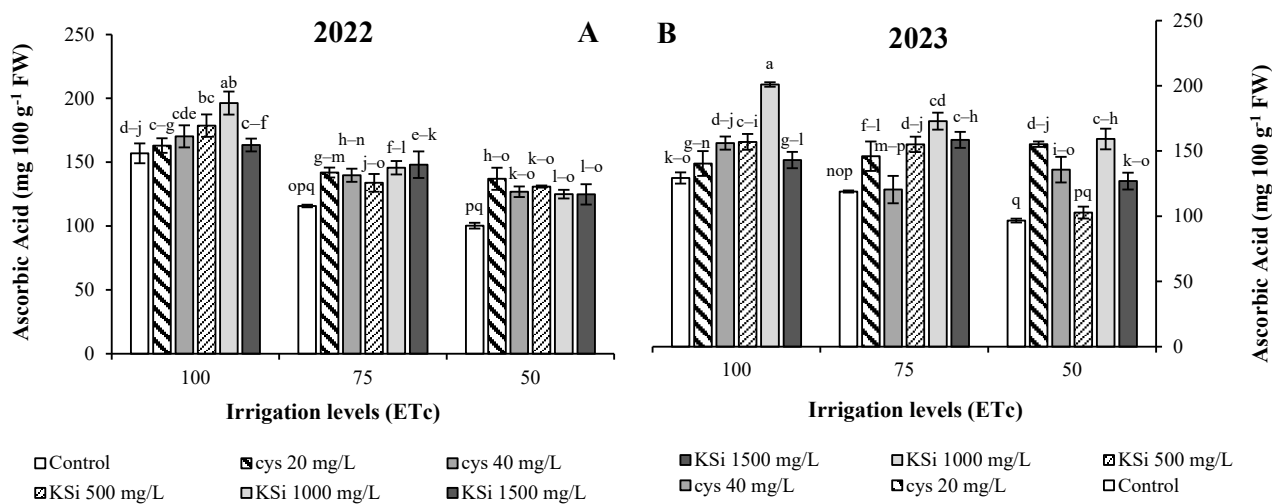


Figure 3. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on ascorbic acid content (A,B) of Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

According to the results (Figure 4A,B), water deficit irrigation meaningfully ($p \leq 0.01$) boosted the fruits' total soluble carbohydrate content (TSC) in both years. In both years,

KSi and Cys treatments significantly increased the TCS value under full irrigation (I_{100}) and deficit irrigation (I_{75} and I_{50}). By reducing irrigation from 100% ET_c to 50% ET_c , the TSP and TSC increased by 38.3 and 80%, respectively. Additionally, applying KSi on the leaves further enhanced these increases to 83.06% for TSP and 116.54% for TSC in 2023. Generally, the TSC content in first year (2022) was considerably higher than that of second year (2023), so the highest TSC content ($33.76 \text{ mg g}^{-1} \text{ FW}$) was obtained in plant fruits treated with KSi 1500 mg L^{-1} under 50% ET_c in the second year.

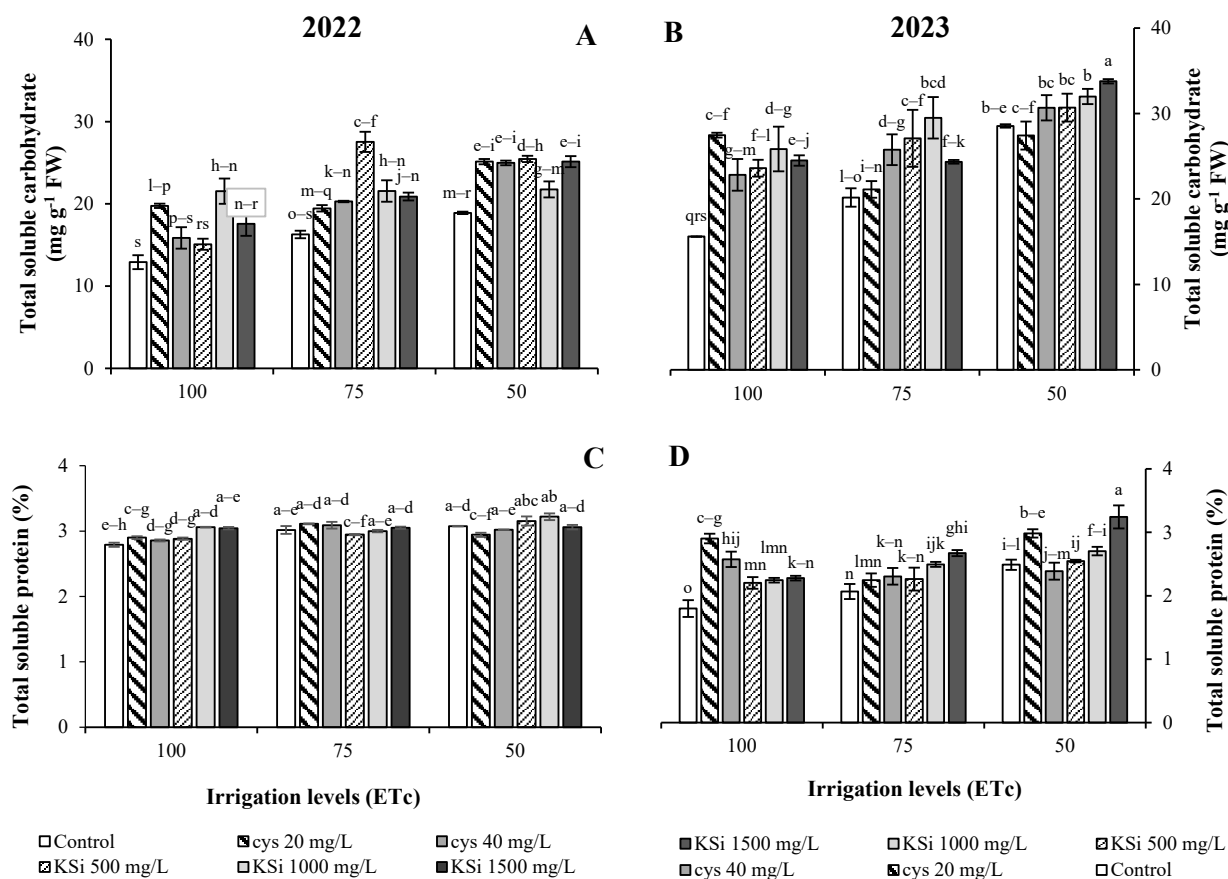


Figure 4. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on total soluble carbohydrate (A,B) and total soluble protein (C,D) contents in Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023, respectively. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

Different trends for total soluble protein (TSP) (Figure 4C,D) were observed in this study. The fruits obtained from the first year had greater TSP values than those from the second year. In the first year, the irrigation and foliar application of KSi and Cys had no significant difference on fruit TSP content. While in the second year, deficit irrigation significantly increased TSP content. Also, the fruit TPS content increased due to the foliar application of KSi and Cys in 2023. The effects of KSi and Cys were dependent on the treatment concentration and irrigation levels, where the highest content of TSP (3.24%) was detected with the foliar supply of 1500 mg L^{-1} KSi under deficit irrigation 50% ET_c in 2023 (Figure 4).

CAT activity showed higher values in 2023 than in 2022 (Figure 5A,B). In both years, deficit irrigation showed no significant influence on CAT activity compared to the control; however in 2023, deficit irrigation 50% ET_c significantly increased CAT activity compared

to all other irrigation levels. In the first year, the foliar application of KSi and Cys had no significant effect on CAT activity under full and deficit irrigation. But in 2023, the CAT activity was elicited with the foliar application of KSi and Cys. In general, the highest CAT activity (17.32 and 16.61 U mg⁻¹ protein) was found in the fruits of plants sprayed with 40 mg L⁻¹ Cys and 1500 mg L⁻¹ KSi, respectively, under deficit irrigation 50% ETc in 2023 (Figure 5A,B).

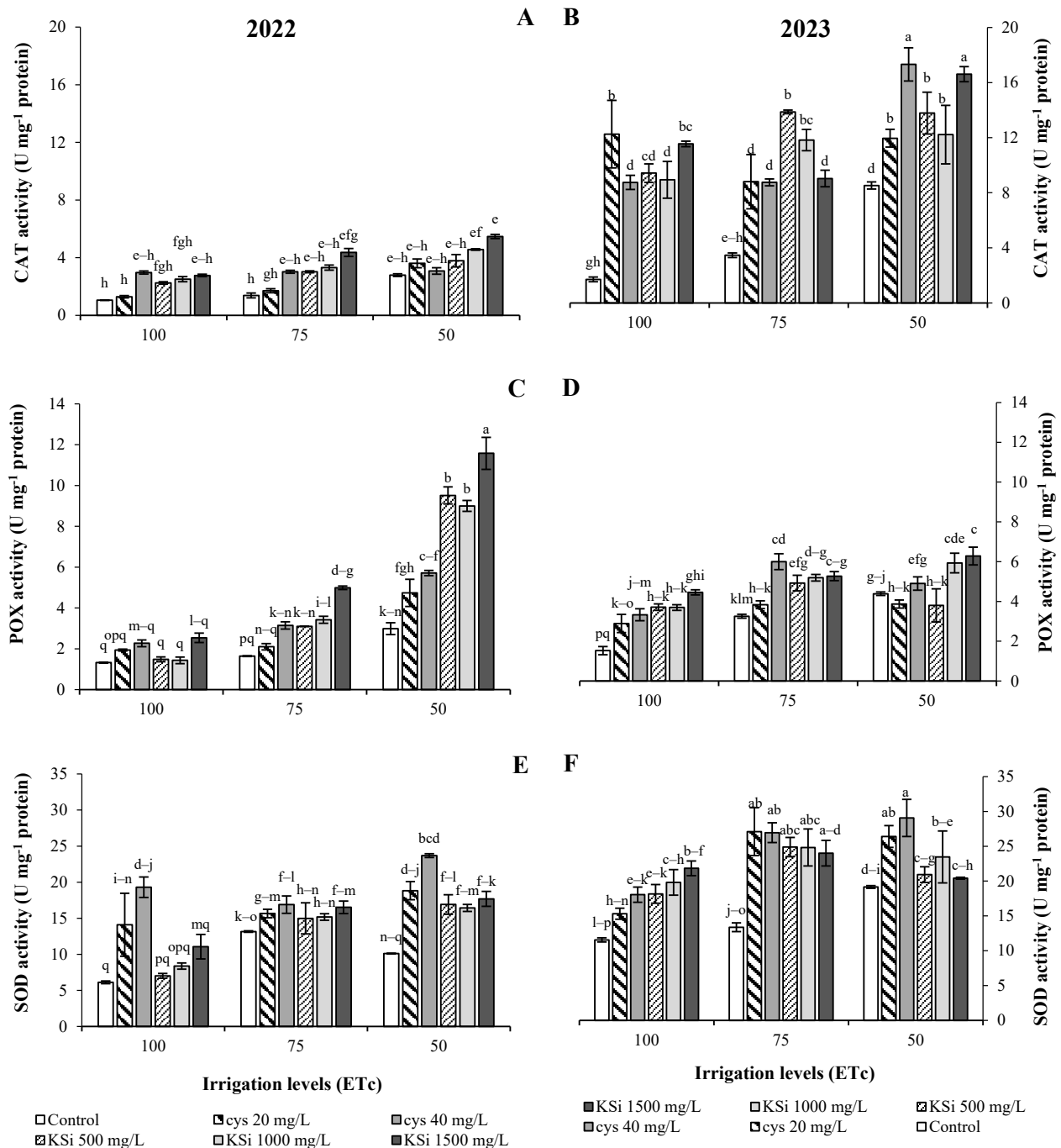


Figure 5. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on CAT (A,B), POX (C,D) and SOD (E,F) activities in Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

Different trends were observed for POX enzyme activity. In both years, deficit irrigation increased POX activity compared to full irrigation. Also, the enhancement in KSi and Cys treatments resulted in a boost in POX activity in both years. So, the highest activity of POX ($11.58 \text{ U mg}^{-1} \text{ protein}$) was obtained in 1500 mg L^{-1} KSi under deficit irrigation 50% ETc during 2022 (Figure 5C,D).

Similar to CAT, SOD activity was significantly higher in 2023 than in 2022 (Figure 5E,F). In 2023, with increasing deficit irrigation, the SOD activity significantly increased. However, in 2022, under deficit irrigation 75% ETc, the SOD activity increased compared to full irrigation and then decreased under deficit irrigation 50% ETc. In general, the application of KSi and Cys significantly enhanced SOD activity compared to the control in both years, and KSi and Cys impact on SOD activity was influenced by the concentration of treatments. The maximum SOD activity was obtained from plants that received treatment with 40 and 20 mg L^{-1} Cys under deficit irrigation 50 and 75% ETc in 2023 (Figure 5E,F).

In both years, the increase in deficit irrigation, as well as KSi and Cys concentrations, promoted an increase in fruit APX enzyme activity, and no noticeable change in APX activity was observed between the two years (Figure 6A,B). While KSi application initially increased APX activity up to 1000 mg L^{-1} , a decrease was noted at higher concentrations. The peak values (86.09 and $83.02 \text{ U mg}^{-1} \text{ protein}$) of APX activity were recorded at 500 and 1000 mg L^{-1} KSi under deficit irrigation 50% ETc in 2022, which was significant similar to 1000 mg L^{-1} KSi and 40 mg L^{-1} Cys under 50% ETc in 2023.

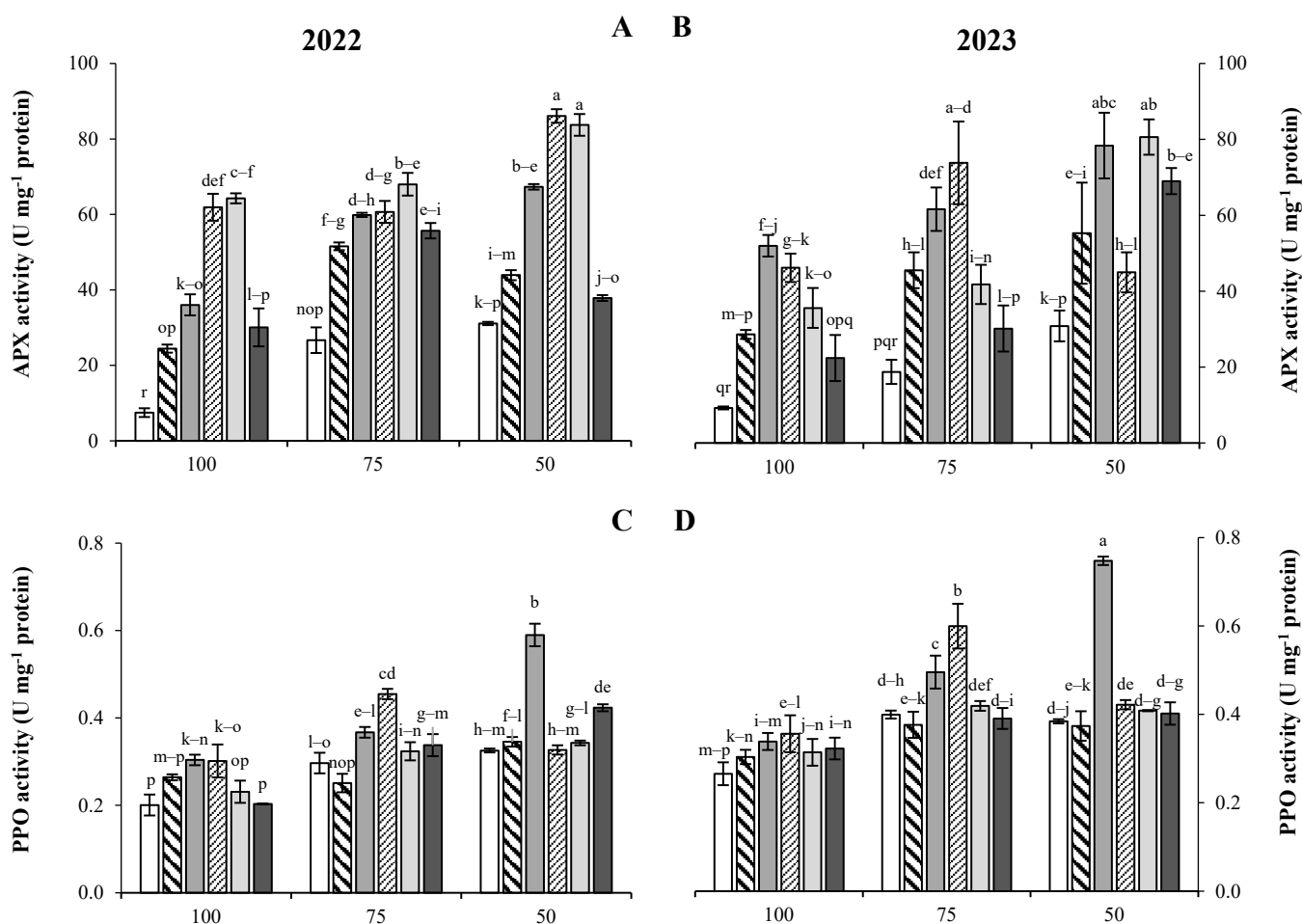


Figure 6. Cont.

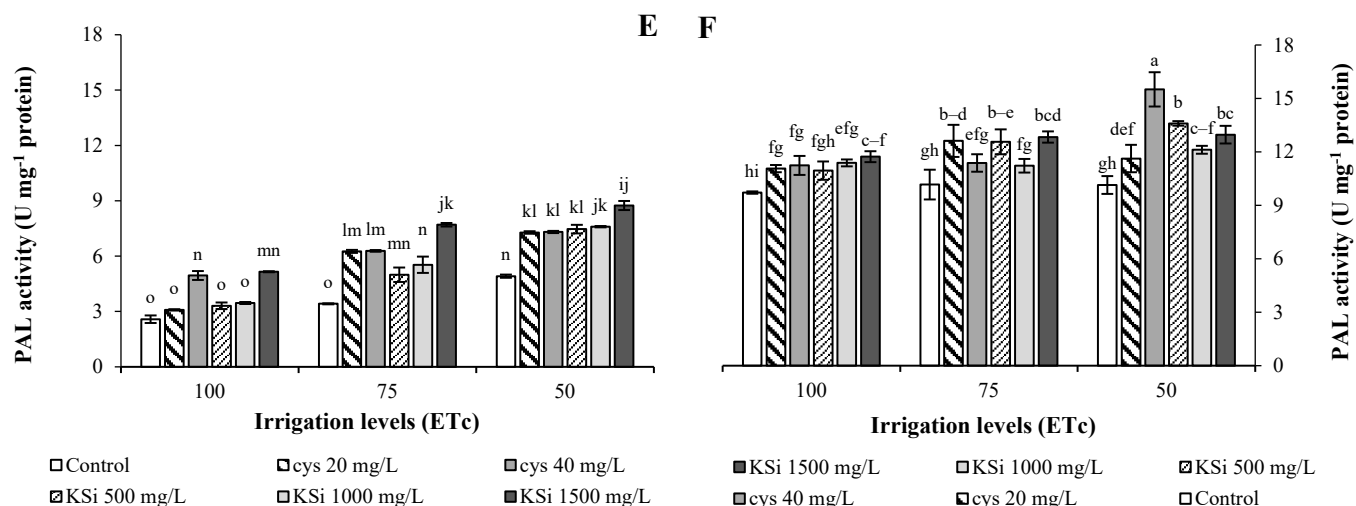


Figure 6. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on APX (A,B), PPO (C,D), and PAL (E,F) activities in Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

In both years, PPO activity increased as the deficit irrigation became more severe, without any significant difference between the two years (Figure 6C,D). The impacts of KSi and Cys effects on PPO activity were related to treatment concentrations and irrigation regimes. Here, the maximum PPO activity ($0.75 \text{ U mg}^{-1} \text{ protein}$) was found in the fruits of plants supplied with 40 mg L^{-1} Cys under deficit irrigation 50% ETc in 2023.

PAL activity was significantly higher in 2023 than 2022. In 2022, 50% ETc significantly boosted PPO activity compared to full irrigation, whereas in 2023, it showed no significant difference on PPO activity among irrigation regimes. In both years, the foliar application of KSi and Cys considerably increased the fruits' PPO activity (Figure 6E,F).

As indicated in Figure 7, the total phenol and flavonoid fruit concentrations in 2023 were significantly higher than those of 2022. Deficit irrigation noticeably increased total phenolic content compared to full irrigation during the two years.

A significant difference ($p \leq 0.01$) in fruits total phenol was noted across various levels of KSi and Cys applications in both years. The effects of these treatments varied based on their concentrations, with the highest phenol values (15.27 and $15.07 \text{ mg GAE } 100 \text{ g FW}^{-1}$) recorded at 500 and 1500 mg L^{-1} KSi under 50% ETc deficit irrigation in 2023 (Figure 7B).

The data highlighted that deficit irrigation had no significant influence on the flavonoid content in the first year (2022). By contrast, in the second year (2023), deficit irrigation significantly boosted the total flavonoid content of fruits. In both 2022 and 2023, the flavonoid content increased with KSi and Cys supply (Figure 7C,D). The highest value of flavonoids ($2.98 \text{ mg QE } 100 \text{ g}^{-1} \text{ FW}$) was acquired in plants supplied with 1500 mg L^{-1} KSi under deficit irrigation 75% ETc in 2023 (Figure 7D).

As shown in Figure 7E,F, the antioxidant activity (AA) of fruits showed no significant difference between the two years. Antioxidant activity did not significantly vary under different irrigation treatments in the first year, whereas it significantly improved under deficit irrigation (I_{50} and I_{75}) compared to full irrigation (I_{100}) in 2023. Furthermore, AA was significantly higher in fruits from plants treated with KSi and Cys compared to control plants, although no significant difference was found in the first year in the AA among KSi and Cys treatment levels under irrigation regimes 100 and 75% ETc.

Based on the results presented in Figure 8A,B, the membrane stability index (MSI) of cape gooseberry fruits was significantly different between the two years ($p \leq 0.01$).

It was observed that irrigation deficit led to a notable reduction in MSI in both years. Nonetheless, the use of KSi and Cys treatments significantly relieved the negative effect of deficit irrigation, resulting in ameliorated MSI. The highest MSI value was achieved in fruits treated with KSi 1500 mg L⁻¹ and Cys 40 and 20 mg L⁻¹ under irrigation 100% ETC, which showed no significant differences compared to lower concentrations of KSi and control treatments (Figure 8A,B).

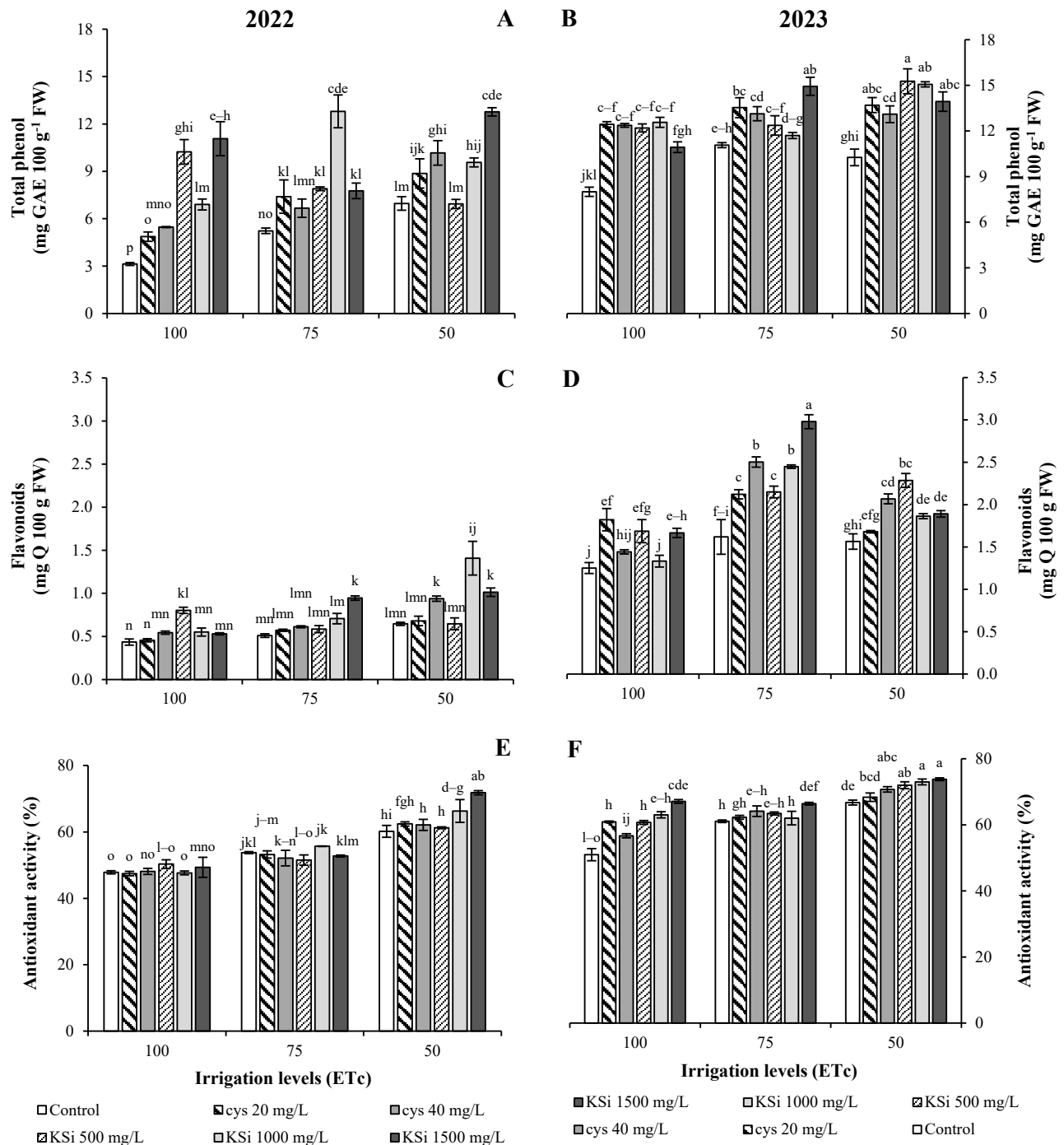


Figure 7. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on the total phenol (A,B) and flavonoid (C,D) contents and antioxidant activity (E,F) of Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

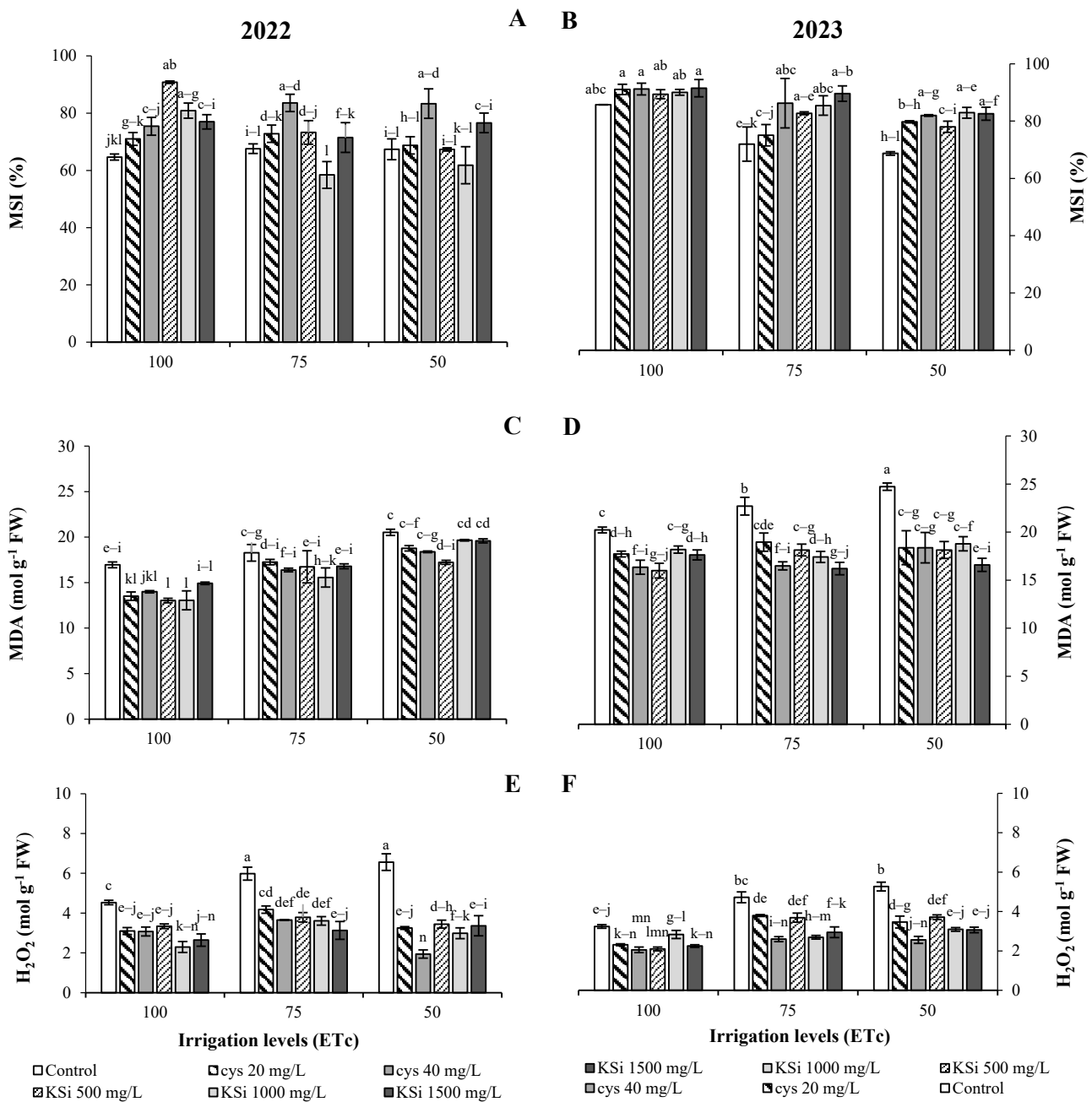


Figure 8. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on MSI (A,B), MDA (C,D), and H₂O₂ (E,F) accumulation in Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

MDA and H₂O₂ accumulation increased linearly in response to the intensification of water deficit stress in both years (Figure 8C–F). The foliar spray of KSi and Cys significantly lowered MDA and H₂O₂ contents in comparison with the control plants under all irrigation conditions. The fruits of plants supplied with Cys 20 mg L⁻¹ and KSi 500 and 1000 mg L⁻¹ under irrigation 100% ETc in 2022 were observed to have the lowest MDA accumulation (Figure 8C,D). A remarkable inhibition outcome on H₂O₂ accumulation was observed in fruits treated with Cys 40 mg L⁻¹ ($p < 0.01$) under 100% ETc in 2022 (Figure 8E,F).

The proline content of fruits increased with increasing deficit irrigation stress (Figure 9). Also, the foliar spray of KSi and Cys significantly increased proline accumulation compared

to the control. Differences between the two years showed no significant impact on the proline content of fruits. The highest (1.99 mg g⁻¹ FW) value of proline was found when KSi 1500 mg L⁻¹ was applied under 50% ETc in first year, which had no significant difference with Cys and lower concentrations of KSi at deficit irrigation 50% ETc in both years (Figure 9A,B).

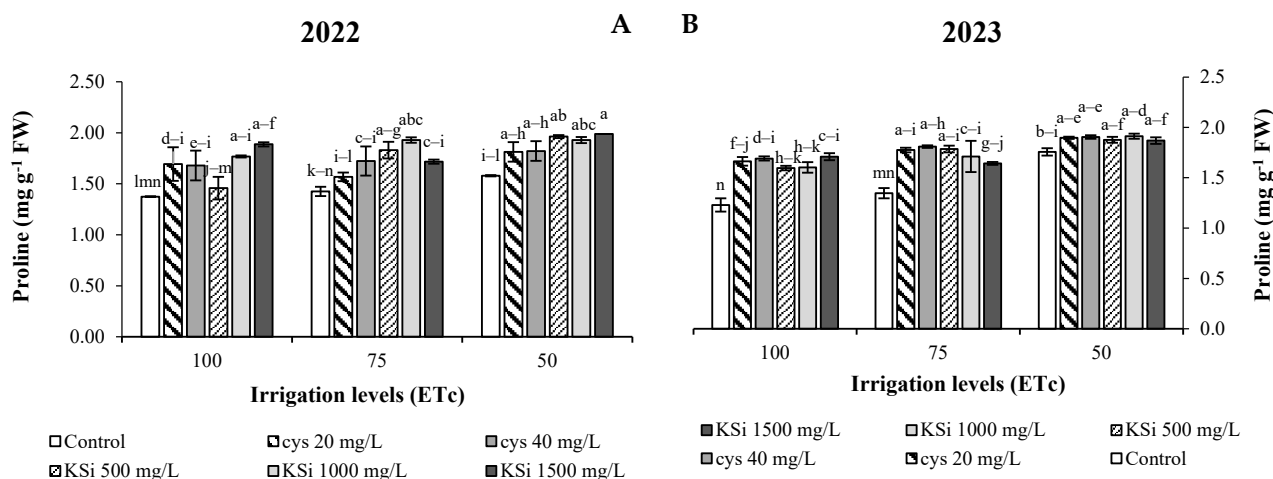


Figure 9. Potassium silicate (KSi) and L-cysteine (Cys) foliar application impact on proline (A,B) content in Cape gooseberry (*Physalis peruviana* L.) fruits under deficit irrigation in 2022 and 2023. Gray bars are means of 3 replications on individual plants ($n = 3$), while vertical lines correspond to $\pm$ values and indicate standard errors. Different letters indicate significant differences between treatments (Duncan's multiple range test at $p < 0.05$).

4. Discussion

Similar to our results, water deficit significantly decreased growth, dry matter content, and yield in chickpeas [41] and tomatoes [42]. This decrease in growth and yield is attributed to reduced absorption of essential nutrients, resulting in decreased leaf area, chlorophyll content, and, ultimately, photosynthesis [42]. Plants can reply to stressful conditions via different morphological, physiological, and biochemical mechanisms, including antioxidant activity and osmolyte accumulation to mitigate ROS buildup, which can lead to decreased fruit yield [43]. Additionally, water stress during flowering and pollination can reduce fruit set percentage by causing pollen desiccation and male floral abortion, further impacting yield [44]. In the same way, the data of this study denoted a negative correlation between yield and TSC content, total phenols and flavonoids, DPPH-scavenging activity (AA), antioxidant enzyme (CAT, POX, SOD, PPO, and PAL) activities, and MDA and H₂O₂ accumulation, whereas it has a positive relation with the ascorbic acid content of fruits (Table 3). Silicon application enhances plant resistance to stress by regulating various physiological and biochemical processes, like the regulation of the levels of defense enzymes, antioxidant defense, osmolytes regulation, and phytohormone regulation (decrease ethylene and ABA and increase GA and polyamine (PA)), potentially improving yield attributes [45]. Like our findings, Elkelish et al. [25] demonstrated that Cys treatments ameliorate drought-induced oxidative damage while enhancing photosynthetic pigments, osmolyte accumulation, and antioxidant activity, potentially leading to increased yield. Moreover, Sarojnee et al. [46] found that amino acid application significantly improved various yield-related traits in pepper plants compared to control plants.

Table 3. Correlation between qualitative and biochemical traits of Cape gooseberry (*Physalis peruviana* L.) fruits treated with silicate potassium (KSi) and L-cysteine (Cys) under deficit irrigation in 2022 and 2023.

Attributes	TSS	TA	Vit C	TSC	TSP	CAT	POX	SOD	APX	PPO	PAL	Phenol	Flavonoid	AA	MSI	MDA	H ₂ O ₂	Proline	Yield
TSS	1																		
TA	0.027 ^{ns}	1																	
Vit C	−0.088 ^{ns}	0.007 ^{ns}	1																
TSC	0.181 ^{ns}	0.283 ^{**}	−0.181 ^{ns}	1															
TSP	0.493 ^{**}	0.114 ^{ns}	−0.035 ^{ns}	−0.077 ^{ns}	1														
CAT	−0.070 ^{ns}	0.294 ^{**}	−0.038 ^{ns}	0.734 ^{**}	−0.307 ^{**}	1													
POX	0.420 ^{**}	0.161 ^{ns}	−0.267 ^{**}	0.480 ^{**}	0.160 ^{ns}	0.274 ^{**}	1												
SOD	0.198 [*]	0.108 ^{ns}	−0.069 ^{ns}	0.599 ^{**}	−0.310 ^{**}	0.671 ^{**}	0.398 ^{**}	1											
APX	0.364 ^{**}	0.440 ^{**}	0.036 ^{ns}	0.416 ^{**}	0.298 ^{**}	0.255 ^{**}	0.438 ^{**}	0.354 ^{**}	1										
PPO	0.179 ^{ns}	0.244 [*]	−0.257 ^{**}	0.547 ^{**}	−0.259 ^{**}	0.526 ^{**}	0.395 ^{**}	0.656 ^{**}	0.455 ^{**}	1									
PAL	−0.104 ^{ns}	0.201 [*]	−0.135 ^{ns}	0.678 ^{**}	−0.559 ^{**}	0.850 ^{**}	0.366 ^{**}	0.746 ^{**}	0.163 ^{ns}	0.567 ^{**}	1								
Phenol	−0.030 ^{ns}	0.434 ^{**}	−0.031 ^{ns}	0.614 ^{**}	−0.321 ^{**}	0.724 ^{**}	0.362 ^{**}	0.594 ^{**}	0.251 ^{**}	0.439 ^{**}	0.797 ^{**}	1							
Flavonoid	−0.107 ^{ns}	0.221 [*]	−0.084 ^{ns}	0.573 ^{**}	−0.517 ^{**}	0.773 ^{**}	0.291 ^{**}	0.670 ^{**}	0.092 ^{ns}	0.500 ^{**}	0.870 ^{**}	0.770 ^{**}	1						
AA	0.139 ^{ns}	0.291 ^{**}	−0.335 ^{**}	0.721 ^{**}	−0.157 ^{ns}	0.735 ^{**}	0.653 ^{**}	0.616 ^{**}	0.274 ^{**}	0.533 ^{**}	0.774 ^{**}	0.726 ^{**}	0.682 ^{**}	1					
MSI	−0.064 ^{ns}	−0.001 ^{ns}	0.313 ^{**}	0.241 [*]	−0.373 ^{**}	0.435 ^{**}	−0.088 ^{ns}	0.252 ^{**}	−0.021 ^{ns}	0.183 ^{ns}	0.448 ^{**}	0.422 ^{**}	0.424 ^{**}	0.152 ^{ns}	1				
MDA	−0.219 [*]	−0.033 ^{ns}	−0.514 ^{**}	0.223 [*]	−0.290 ^{**}	0.164 ^{ns}	0.264 ^{**}	0.192 [*]	−0.138 ^{ns}	0.240 [*]	0.361 ^{**}	0.176 ^{ns}	0.245 [*]	0.476 ^{**}	−0.183 ^{ns}	1			
H ₂ O ₂	−0.197 [*]	0.054 ^{ns}	−0.431 ^{**}	−0.254 ^{**}	0.092 ^{ns}	−0.298 ^{**}	−0.187 ^{ns}	−0.276 ^{**}	−0.264 ^{**}	−0.142 ^{ns}	−0.298 ^{**}	−0.341 ^{**}	−0.267 ^{**}	−0.089 ^{ns}	−0.509 ^{**}	0.396 ^{**}	1		
Proline	0.480 ^{**}	0.364 ^{**}	−0.096 ^{ns}	0.528 ^{**}	0.339 ^{**}	0.338 ^{**}	0.551 ^{**}	0.471 ^{**}	0.567 ^{**}	0.360 ^{**}	0.240 [*]	0.366 ^{**}	0.130 ^{ns}	0.398 ^{**}	−0.103 ^{ns}	−0.049 ^{ns}	−0.265 ^{**}	1	
Yield	0.075 ^{ns}	−0.168 ^{ns}	0.392 ^{**}	−0.417 ^{**}	0.157 ^{ns}	−0.395 ^{**}	−0.252 ^{**}	−0.217 [*]	−0.045 ^{ns}	−0.420 ^{**}	−0.395 ^{**}	−0.267 ^{**}	−0.342 ^{**}	−0.566 ^{**}	0.093 ^{ns}	−0.542 ^{**}	−0.324 ^{**}	0.063 ^{ns}	1

ns, *, **: non-significant and significant at $p < 0.05$ or $p < 0.01$, respectively.

Deficit irrigation meaningfully enhanced the fruits' TA and TSS content. This improvement could be related to a reduction in fruit juice content [47], a phenomenon also observed in tomatoes [48], *Physalis angulate* [49], and bell peppers [50]. It is indicated that plants increase TSS levels as a strategy to control osmosis and cope with stress [51]. Severe water stress has also been associated with notable increases in TA, as observed in grapes [52] and strawberries [53]. In our study, the use of KSi and Cys helped maintain the TSS and TA levels in cape gooseberry fruits. Similarly, in tomatoes subjected to drought stress, Si application enhanced both TSS and TA content, which can be attributed to the decrease of respiration and the maintenance of C/N ratios [54]. In addition, maintaining optimal levels of TSS and TA and preventing TA degradation in fruits treated with L-cysteine may suppress the conversion of starch to simple sugars [23], a phenomenon seen in litchi [23] and longan fruits [55]. In this study, there was no significant correlation among fruit TSS and TA contents (Table 3). As illustrated in Table 3, a positive correlation was indicated between TSP content; POX, SOD, and APX activities; and proline accumulation with TSS content. Likewise, the positive correlation between TA, TSC, proline content, antioxidant components, and the activity of antioxidant enzyme activity was evident in this study (Table 3).

In the present trial, deficit irrigation significantly decreased the ascorbic acid content of cape gooseberry fruits compared to well-watered ones, impacting their defense against oxidative stress; this agrees with the data by Abdelhamid et al. [56] in faba beans. As observed in previous research, water stress results in a reduction in ascorbic acid content in tomatoes, attributed to increased respiration and consumption of organic acids. However, the foliar application of Si maintained the ascorbic acid content by reducing respiration [54]. Ascorbic acid content, located in chloroplasts, helps mitigate oxidative stress during photosynthesis and serves as a primary substrate for the enzymatic detoxification of hydrogen peroxide, protecting against oxidative damage [56]. Additionally, Si application enhanced ascorbic acid levels in various plants such as tomatoes [57], coriander [58], and strawberries [59], possibly through adjustments in the phenylpropanoid pathway [60]. Such results pointed out the critical role of inorganic elements like Si in enhancing fruit quality and antioxidative capacity [61]. Results indicated a negative correlation among ascorbic acid content with POX, PPO enzyme activities, DPPH scavenging capacity (AA), and MDA and H₂O₂ accumulation (Table 3). However, a positive relation was found between ascorbic acid content, MSI, and fruit yield (Table 3).

The increased TSC content in the second year could be attributed to water deficit stress, possibly intensified by reduced relative humidity and rainfall in 2023 during harvest time (October) [47]. In the case of pistachios, Pakzad et al. [62] observed a similar increase in TSC and TPS values when exposed to drought stress. Additionally, reduced carbohydrate consumption due to a lower photosynthesis rate may contribute to the accumulation of TSC under abiotic stress [63]. The plant's capacity to sustain growth and avoid cell death under severe stress situations is improved by increasing osmotic regulation through the accumulation of carbohydrates and protecting biomolecules [64]. Cells maintain turgor pressure in water stress conditions by accumulating osmotic regulators like soluble sugars, proline, and soluble proteins to sustain normal physiological activities [65]. Also, an increase in TSP content under water deficit is attributed to the production of new proteins or the upregulation of stress-adaptive proteins, including antioxidant enzymes [66]. Our results showed that foliar treatments, especially KSi, led to a significant increase in TSC and TSP values (Figure 4). In agreement with our results, Si application caused an enhancement of TSP, free amino acids, and, ultimately, the yield of rice [67]. Si enhances photosynthetic pigments, rubisco enzyme activity, and photosynthetic capacity while reducing oxidative stress and protecting macromolecules such as proteins, chloroplast membranes, and cell

membranes, thus promoting photosynthesis and increasing soluble sugars and protein levels in plants [68]. Manivannan and Ahn [69] demonstrated that Si up-regulates osNAC proteins, which play key roles in stress tolerance, proline synthesis, and carbohydrate biosynthesis. As shown in Table 3, a negative correlation was indicated between TSP; total phenols and flavonoids; CAT, SOD, PPO, and PAL enzyme activities; MSI; and MDA content. However, extremely positive significant relations were evident between TSP, TSS ($r = 0.49$), APX activity ($r = 0.29$), and proline ($r = 0.33$) accumulation. Similarly, El-Sayed et al. [70] observed increased TSC content in tomato fruits treated with KSi under water deficit stress, consistent with our findings. Furthermore, studies on fenugreek seedlings showed that silicate and silicon nanoparticle applications enhanced protein synthesis, possibly through the expression of the phosphoenolpyruvate carboxykinase (PEPCK) gene in roots and leaves, which in turn influences nitrogenous complexes like proteins [71]. Contrary to TSP, the results revealed highly significant positive correlations between antioxidant components, antioxidant enzymes, antioxidant activity ($p < 0.01$), MSI, and MDA content ($p < 0.05$). It is worth mentioning that although the correlation between TSP and TSC content was not significant, the existence of a negative correlation between them was clear (Table 3).

Water deficit induces oxidative damage, primarily through the biosynthesis of ROS. However, plants tolerate water stress by inducing defense responses and altering cell metabolism as an innate mechanism [72]. Both enzymatic and non-enzymatic antioxidant defense systems have a role in these mechanisms to safeguard cells from oxidative damage [73]. In agreement with our data, previous experiments in almonds and tomatoes have shown increased antioxidant enzyme activities, including SOD, CAT, POX, glutathione reductase (GR), and APX, in response to water deficit [54,74]. The results of this experiment indicated that KSi and Cys treatments under deficit irrigation led to higher antioxidant enzyme activity. The increase in POX and SOD activities following KSi treatments is consistent with previous research showing increased POX activity in asparagus [75], SOD activity in maize [76], and CAT and SOD activities in tomatoes [77]. Silicon acts as a mediator in reducing water stress in various plant species by activating antioxidant defense systems and stimulating osmolyte accumulation [78]. Research showed that Si supply positively affects fruit yield and reduces the buildup of MDA and H_2O_2 by enhancing antioxidant enzyme activities during water stress in rice [79] and tomatoes [16], compared with the control. They found that decreasing H_2O_2 content may reflect higher antioxidant enzyme activity under deficit irrigation. According to Table 3, a substantial negative correlation was recorded between antioxidant enzyme activity and H_2O_2 accumulation. In this respect, an improvement in antioxidant enzymes via KSi [80,81] and Cys application [82–84] in various plant species was reported.

Furthermore, our findings (Table 3) showed strong positive correlations between antioxidant components, antioxidant enzymes, and antioxidant activity. Thus, it is suggested that Cys and KSi may reduce ROS damage by enhancing antioxidant content and enzyme activity.

Several studies have reported that phenolic compounds, like flavonoids, are the main source of antioxidant activity over the past few years [85]. Based on the results (Figure 7), total phenol, flavonoid content, and antioxidant activity significantly ($p < 0.01$) increased in 2023 compared to 2022. The natural climatic variations that occur over the years may be the cause of these differences [86]. Low temperatures enhance the synthesis of phenolics and flavonoids by increasing the activity of the phenylpropanoid pathway, which relies on higher PAL activity [87]. So, in the current study, a reduction in average temperature and sunshine hours during fruit set and ripening (August and September) (Table 2) can be the reason for this increase. Similar data are reported by Khani et al. [88] in lettuce, where total

phenolic and flavonoid content, along with antioxidant activity, increased because of a high correlation among total phenol and flavonoid content with DPPH-scavenging activity (AA) under deficit irrigation compared to control plants. Their accumulation enhances plant tolerance to water deficit stress by strengthening antioxidant capacity [7] and serving as a carbon sink under stress [89].

Antioxidants, found in both enzymatic and non-enzymatic forms across cellular compartments, stabilize cells by scavenging the excess of ROS [90]. The phenylpropanoid pathway, which synthesizes phenolic compounds and flavonoids derived from phenylalanine, is essential for resisting oxidative damage produced by water deficit stress [91]. These pathways are dependent on photosynthesis, as plants undergo changes in carbon metabolism to balance biomass production by forming defense compounds under stress [92]. In the same way, total phenols and flavonoids were relatively enhanced by the KSi and Cys treatments under deficit irrigation, which was perhaps due to the great incitement of the phenylpropanoid pathway under stress conditions. Si application significantly caused the synthesis of these components in oat plants under stress conditions [93], which is consistent with our results. Additionally, the increase in phenol and flavonoid contents by Cys could be ascribed to the increment of the rate of photosynthesis [25]. In general, photosynthesis mediated with Si under drought stress conditions is related with higher levels of photosynthetic pigments and the activity of specific photosynthetic enzymes [94]. Additionally, Asgari et al. [95] observed SiNPs up-regulating PAL gene expression, leading to increased flavonoids, total phenols, and antioxidant capacity. In this study, it was apparent that there was a correlation between phenols, flavonoid content, antioxidant activity, and PAL activity (Table 3).

Moreover, as shown in Table 3, a negative correlation was indicated between antioxidant components with yield, TSP, and H_2O_2 content. The relations between total phenol, yield, TSP, and H_2O_2 content were -0.26 , -0.32 , and -0.34 ($p < 0.01$) respectively. Furthermore, this study showed a substantial negative correlation between DPPH scavenging capacity (AA), yield, and vitamin C content ($r = -0.56$ and $r = -0.33$, respectively) (Table 3).

Analogous data were also demonstrated in tomatoes [96] and canola [97] under deficit irrigation. Water deficit stress causes oxidative damage by increasing the buildup of ROS such as H_2O_2 and $O_2^{\cdot -}$, lipid peroxidation, and electrolyte leakage. The increase in ROS accumulation and as a result lipid peroxidation is associated with improved lipoxygenase and protease activities, leading to structural and functional changes in proteins and fatty acids [98]. Additionally, MDA accumulation acts as a marker of oxidative stress resulting from membrane lipid peroxidation and reflects the level of acclimatization of water-stressed plants [99]. Excessive H_2O_2 and MDA accumulation reduce membrane stability and cellular functioning, hindering processes such as mineral uptake, assimilation, and photosynthesis in tomato plants [100]. The present study revealed a significant negative correlation between electrolyte leakage and H_2O_2 ($r = 0.509$) (Table 3). An increase in MDA and H_2O_2 was positively correlated with the electrolyte leakage rate.

Our results indicated that KSi and Cys treatments under deficit irrigation exhibited higher MSI levels and lower levels of MDA and H_2O_2 , indicating reduced membrane permeability and the prevention of membrane fatty acid peroxidation, which is in line with the results reported in litchi [23], plums [84], wheat [101], and strawberries [102] following Cys and KSi applications, respectively. Silicon deposition in the cuticle enhances membrane stability, reducing transpiration loss, especially under water deficit [103]. Additionally, Si can help alleviate oxidative damage in plants that grow in stressed environments by enhancing antioxidant activities [104]. The results indicated a negative correlation among H_2O_2 content with TSS, TSC, proline, vitamin C, MSI, yield, and antioxidant activity

(phenols, flavonoids, CAT, SOD, and PAL). Also, a positive relation was found between MDA and H₂O₂ accumulation (Table 3).

Similar to our results, proline content was increased in *Lactuca sativa* [105] and okra [106] under deficit irrigation. Plants improve their antioxidant systems and accumulate osmolytes to scavenge excess ROS, thereby protecting their metabolic processes [43]. Osmolytes like proline, glycine betaine, and soluble sugars play critical functions in preserving water potential, safeguarding enzyme activity, and mitigating stress [107].

Acting as an osmotic regulator, proline efficiently mitigates the detrimental results of stress by stabilizing membranes and macromolecules and scavenging free radicals due to its rich carbon and nitrogen content [108]. In line with the data of present research, the foliar spray of Si increased the accumulation of proline in strawberries [102], sugar beets [109], and basil [110] under water stress conditions. They showed that the positive effects of Si on reducing water deficit stress may be due to the increase in proline content by improving the expression of genes involved in proline synthesis (P5CS) in Si-treated fruits [111]. This effect of silicon on osmolyte accumulation, particularly proline, contributes to improved water stress tolerance in plants [110]. Some studies have illustrated the beneficial impact of Si on physiological activities, nutrient levels, and osmo-regulators, ultimately enhancing plant growth and stress tolerance under water deficit conditions [112]. Results indicated a strong positive correlation between proline content, TSS, TA, TSC, TSP, phenol content, and antioxidant enzymes activities, whereas it had a negative relation with H₂O₂ and the yield of fruits (Table 3).

In summary, the exogenous application of KSi and Cys, particularly at higher concentrations, presents a viable strategy for mitigating the adverse effects of deficit irrigation in Cape gooseberry plants. Future research focused on optimizing application strategies will be critical for unlocking the full potential of these compounds, ultimately enhancing agricultural productivity and economic returns for growers.

5. Conclusions

The findings of this study underscore the significant role of KSi and Cys in mitigating the adverse effects of water deficit stress on Cape gooseberry plants. The application of KSi and Cys not only improved fruit yield but also enhanced qualitative traits by promoting the biosynthesis of total phenols and flavonoids while simultaneously up-regulating antioxidant enzyme activities. This resulted in reduced oxidative stress markers, such as MDA and H₂O₂, and improved membrane stability by maintaining osmotic balance through adjustments in proline, TSC, and TSP. According to these results, we can confirm that the exogenous use of KSi and Cys, especially at higher concentrations, could potentially be beneficial in mitigating deficit irrigation damages and improving quality and yield in Cape gooseberry plants.

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