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Exogenous Application of SA and K_2SiO_3 Enhances Physiological Resilience of *Capsicum annuum* L. Under Drought Stress

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ABSTRACT

This study was performed during the 2023 and 2024 seasons on the Omega F1 hybrid of hot pepper (*Capsicum annuum* L.) under elevated temperature and conditions of drought was assessed at the greenhouse of the University of Cairo's Faculty of Agriculture. The primary goals of this study were to ascertain how different foliar spray stimulants used affect pepper plants' tolerance to drought and heat. Twelve treatments were included in this experiment, which included combinations of four foliar application treatments and three irrigation water levels. The foliar treatments were dispersed randomly in the sub-plots (potassium Silicate (PS) 200 mgL-1, Salicylic Acid (SA) 270 mgL-1, Mix (potassium silicate (PS) 200 mgL-1, Salicylic Acid (SA) 270 mgL-1) and tap water as control).

Based on the findings, the greatest values for the evaluated growth characteristics (plant height, number of branches) were noted when potassium silicate was sprayed on plants at a concentration of 200 mgL-1, followed by the Mix treatment at an irrigation level of 100% of the field capacity, and then at 75 % of the field capacity. However, when plants were treated with a potassium silicate and salicylic acid mixture at 100% field capacity, the greatest values for leaf number and chlorophyll SPAD were observed. Show clearly that the highest increases in proline concentration and ABA in leaves were found when plants were irrigated with 50 % of field capacity combined using tap water (control) during both seasons. Throughout both of the study seasons, the plants were irrigated at 50 % of the field capacity with all spray treatments, PS, SA, and Mix, resulting in the greatest increase in antioxidant content in the leaves comparing to the control (spraying with tap water). Additionally, it was demonstrated that foliar treatment can produce excellent yields with high physical and chemical quality.

KEYWORDS: Hot pepper, foliar application, water requirement, growth, Chemical constituents.

1. INTRODUCTION

The world's agricultural sector is facing formidable obstacles to productivity due to climate change. Abiotic stressors, including water shortage, salt stress, excessive heat, water damage, nutritional inadequacy, toxic heavy metals, and contamination, have a significant impact on crop output around the world. These stressors endanger the world's food security by lowering the average yields of main crops by more than 50%. Abiotic factors like this drastically cut down on chilli production and revenue (Boyer, 1982; Singhal et al., 2016).

Despite the previous increase in global temperatures, it is expected that there will be a further rise in the next century. It is predicted that the highest daily temperatures in a year would rise by 3°C by the middle of the twenty-first century, and by the late 21st century, they are forecasted to rise by approximately 5°C. (IPCC, 2012; Sherwood et al., 2013).

Pepper fruit is rich in natural colors, healthy nutrients, and antioxidants including vitamin C, carotenoids, phenolic compounds, and pro-vitamins (Bosland and Votava, 1999). The second most harmful abiotic stressor to the world's agricultural crop production is water scarcity (Ghahremani et al., 2021b; Namaki et al., 2022b; Ranjbar et al., 2019;). Drought is a major environmental factor that significantly lowers growth rates and yields of essential field and agricultural crops (Ullah et al., 2018a, 2019; Sirisuntornlak et al., 2019). Reduced plant development and photosynthetic rate, as well as decreased root absorption rate and leaf chlorophyll content, are all negative effects of drought stress (Namaki et al., 2022a; Ghahremnai et al., 2021a). Because of the smaller cell size, the bigger stomatal opening area, the thinner leaves, and the loose arrangement of mesophyll cells, high temperatures throughout the development of flowers can drastically impair fruit set. According to Tran and Murakami (2015), reduced pollen viability is the main reason for this decline in fruit set. High temperatures can also adversely affect respiration, photosynthesis, water relations, hormone levels, and the equilibrium between primary and secondary metabolites (Wahid et al., 2007).

One useful strategy to lessen the detrimental effects of environmental stresses on the cultivation of horticultural crops in semi-arid and arid environments may be the use of plant growth regulators at different phases of plant growth and development (Ennab et al., 2020; Nezamdoost et al., 2023). The detrimental effects of heat, salt, and drought on crops have been greatly mitigated through the broad use of exogenous growth-promoting substances like salicylic acid and ascorbic acid. Zahid et al. (2021) and El-Hawary et al. (2023) found that growth hormones had a positive impact on wheat, tomatoes, and roses.

SA is a phenolic substance that dissolves in water and is one of the plant's secondary metabolic products. (Souri and Tohidloo, 2019). Plant growth, development, and stress tolerance of plant rely on this widespread phytohormone (Ge et al., 2020). Plants use SA as a signaling molecule to regulate a variety of physiological and metabolic functions, such as ion transport, proline metabolism, photosynthesis, transpiration, and biotic and abiotic stress tolerance (Sheteiwy et al.,2019; Jayakannan et al., 2015; Sahu, 2013; Abdelaal et al., 2020).

According to Horv'ath et al. (2007) and Maghsoudi et al. (2019), winter wheat can improve its drought resistance when exposed to SA externally. This is because SA increases catalase activity, which in turn improves osmotic adjustment, antioxidant activity, and water status. When examined in a water-scarce scenario, SA was observed to boost photosynthetic indices such as chlorophyll content, water content of leaves potential, nitrate reduction, carbonic anhydrase, CAT, POX, and SOD enzymatic activities, and membrane stability index (Hayat et al., 2008).

Potassium is essential for many plant physiological functions, including enzyme activation, smoregulation, nutrient transport, and primary metabolite distribution (Amtmann et al., 2008). Shen et al. (2010) state that, Silicon (Si) has the ability to decrease the quantity of abiotic stimuli, such as heavy metal-induced toxicity and drought-induced stress, high temperatures, salinity, chilling, and freezing. Si is incorporated into the plant cell walls as silica, enhancing the structural stiffness and strength of the cell walls, as well as increasing plant architecture and the upright position of leaves. Reports indicate that silicon applied by hydroponic supplement or external foliar spraying improves plant development and is crucial for plants to withstand environmental challenges. This information is supported by studies conducted by Balakhnina and Borkowska in 2013, as well as Rizwan et al. in 2015. The main ways in which Potassium silicate (K2SiO3) helps plants deal with abiotic stresses include reducing Rice plants' reactions to heat shock and improving lipid peroxidation, proline accumulation, and uptake processes in stressed tomatoes and spinach (Shen et al., 2010).

Foliar usage is a widely recognized technique that aids plants in alleviating heat stress. It serves as a means to reflect excessive sunlight, regulate metabolism, and act as a physical light film (Mphande et al., 2020).

The primary goals of this study were to ascertain how different foliar spray stimulants used affect pepper plants' tolerance to drought and heat.

2. MATERIALS AND METHODS

2.1. Experimental details

The effects of applying various potassium silicate (PS) and salicylic acid (SA) treatments topically on the biochemical and physiological characteristics of hot peppers (*Capsicum annuum* L.) in the presence of drought and high temperatures was assessed during the two consecutive seasons 2023-2024 at the used plastic greenhouse is 20*40 m at Cairo University's Faculty of Agriculture. Seedlings of Omega cultivar of hot pepper were obtained from a commercial nursery. Pepper seedlings were treated with a fungal disinfectant for 3 minutes before being planted in the permanent ground on the 15th of May for each season. For this research, a drip irrigation network was created. The study was designed as a factorial trial with two completely randomized components. Drought severity and foliar spray treatment were the most important factors. Twelve treatments total—three irrigated rates and four foliage applications—were used in this experiment while foliar application methods were dispersed randomly in the sub-plots (potassium Silicate (PS) 200 mgL^{-1}, Salicylic Acid (SA) 270 mgL^{-1}, Mix (potassium silicate (PS) 200 mgL^{-1}, Salicylic Acid (SA) 270 mgL^{-1}) and water from the tap as a control), deficit water treatments were distributed in the main plots. Six replicates of each treatment were used. From seedling cultivation to sample collection, the process took four months. During the growth of the plants, the average temperature was recorded (Fig. 1).

To boost leaf adherence, Tween-20 surfactant was added in small drops to the treatment. Treatment was used at the concentration Potassium Silicate (PS) 200 mgL^{-1}, Salicylic Acid (SA) 270 mgL^{-1} and their interaction.

Tap water was sprinkled on the control plants. The treatment was sprayed onto the leaves in such a way that both sides were completely saturated. After two weeks following transplanting, foliar sprayings were administered four times at two-week intervals. Three stages of drought stress were administered to all plants 72 hours following foliar spraying: relaxed circumstances (complete irrigation, i.e. the control group 100 %), moderate levels of stress (75 percent of field capacity), and extreme stress (50 percent of field capacity). By refilling evapotranspiration, water stress was kept at the necessary Field Capacity.

Treatments for drought stress were continued until the end of the trial. Under the experimental site conditions, all additional agromanagement as recommended by the Egyptian Ministry of Agriculture for commercial pepper production, practices such as fertilization, water supply, weed management, and pest and disease control were used as needed.

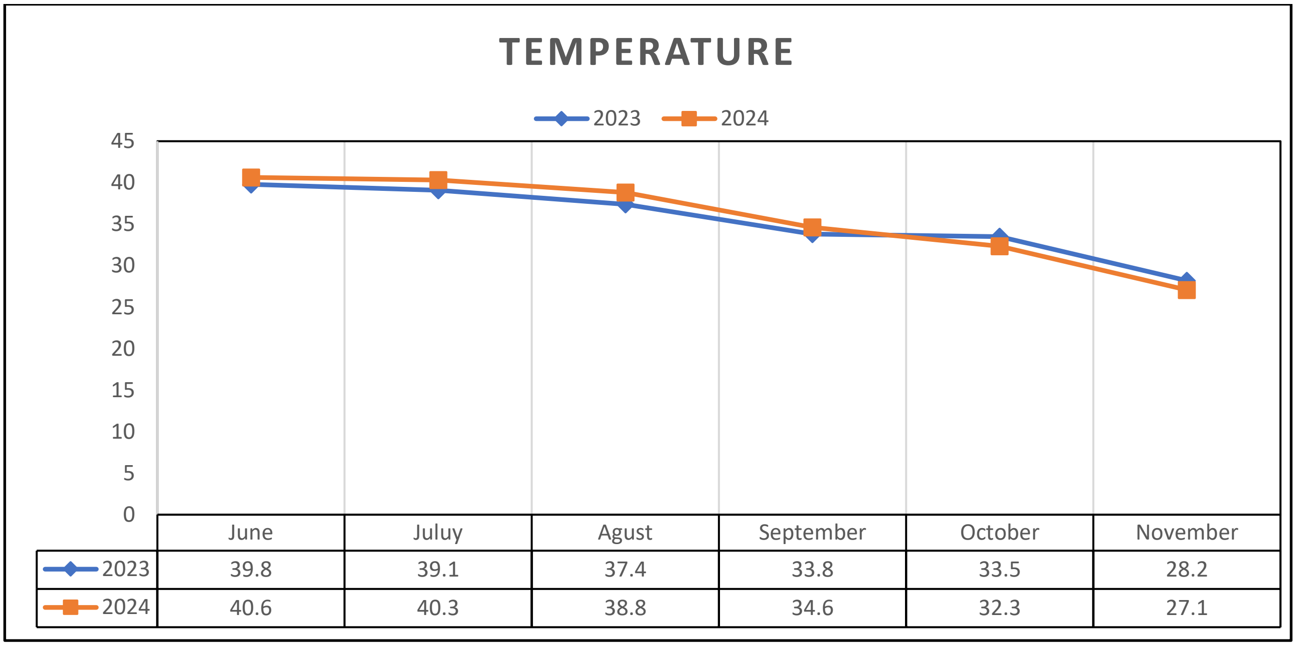


Figure 1. Average temperature during the growth seasons.

2.2.Experimental data collections

Six plants were randomly chosen and tagged from each treatment in each replication to record growth, yield, and Fruit chemical quality data.

2.2.1. Vegetative growth characteristics:

5 plants were randomly chosen after 90 days from hot pepper transplanting, from each plot to determine the following parameters: Plant height (cm), number of branches and leaves per plant as well as chlorophyll SPAD.

2.2.2. Chemical characteristics of leaves:

The amount of proline (mg/100g fresh weight): was determined by applying Jackson's method (2005) and the flame photometer in the digested product

The total amount of phenolic compounds: were established by applying the Folin-Ciocalteu technique (Slinkard and Singleton 1977).

Antioxidant Activity: was measured according to Sanchez-Moreno (2002)

Abscisic acid: as described by Sainiet al. (2022)

2.2.3. Yield parameters:

Fruits of hot pepper were manually harvested, upon maximum size and green in color. The weight of the harvested fruit per each replicate was recorded twice a week to calculate the total productivity and expressed as ton /feddan, in addition to estimating the fruit weight (g).

2.2.4. Fruit chemical quality:

Total soluble solids content (TSS %): A hand refractometer was used to assess it in the fresh fruit juice, per A.O.A.C. (1992).

Vitamin C (mg.100g^{-1}): was established using the indicator of 2,6 dichlorophenol indophenol for titration as the method described in AOAC (2012).

2.3. Anatomical studies

The blade of the simple upper leaf that grew on a third branch from the lowest point of the hot pepper's main stem was one of the tested specimens (*Capsicum annuum* L.) with high temperature and water shortage condition and treated with different treatments of PS, SA and their interaction, were collected during 2023's second season of growth, 75 days after planting. In accordance with Mohammed and Guma (2015). Transverse sections were done with a Leica Microtome RM 2125, and then micrographed and measured using a LeicaLight Image Analysis System DM 750 at the Faculty of Agriculture, Cairo University-Research Park (CURP). The following parameters were recorded: thickness of the midvein (µm), lamina (µm), palisade tissue (µm), spongy tissue (µm), upper and lower epidermis, bundles dimension (µm) and mean vessels diameter (µm).

2.4. Statistical analysis

All of the data collected from six replicates over two growing seasons was analyzed using the computer program "MSTATC," which employs a randomized complete block design with two components (Gomez and Gomez 1984). The LSD test was used to assess changes across treatment modes; a p 0.05 indicates statistical significance (Snedecor and Cochran, 1980).

3. RESULT

3.1.Vegetative growth characteristics:

The combination of irrigation requirement levels and foliar application treatments with (potassium Silicate (PS) 200 mgL^{-1}, Salicylic Acid (SA) 270 mgL^{-1}, mixture of these two treatments significantly affected vegetative growth traits in 2023 and 2024 compared to the control (tap water as a foliar spray).

Fig (2) shows that the highest Plant height was recorded with potassium Silicate (PS) 200 mgL^{-1} combined with 100 % field capacity, followed by Salicylic Acid (SA) 270 mgL-1 at the same field capacity and then 75% field capacity. Conversely, the lowest plant height values were seen with 50% FC irrigation and tap water (control) applied as a foliar spray.

The plants with the greatest number of branches per plant during the first season were those that were irrigated at 100% field capacity and treated with foliar applications of potassium silicate (PS), salicylic acid (SA), or a combination of these substances. Whereas the potassium silicate treatment had the most branches in comparison to the control at 75% and 50% field capacity, the Mix treatment had the most branches per plant in the second season when the field capacity was 100%.

Accordingly, plants irrigated at 100% of field capacity recorded the highest number of leaves per plant, followed by plants irrigated with salicylic acid (SA) and a mixture of SA and potassium silicate (PS) at 75% of field capacity. In contrast, in both seasons, the control treatment and all irrigation levels—especially 50% of field capacity—performed the worst in this regard.

Spraying salicylic acid and the mixture treatment (potassium silicate and salicylic acid) on chili pepper plants significantly increased chlorophyll a (SPAD) at irrigation levels of 100% and 75% of field capacity, respectively.

3.2.Chemical constituents of plant foliage:

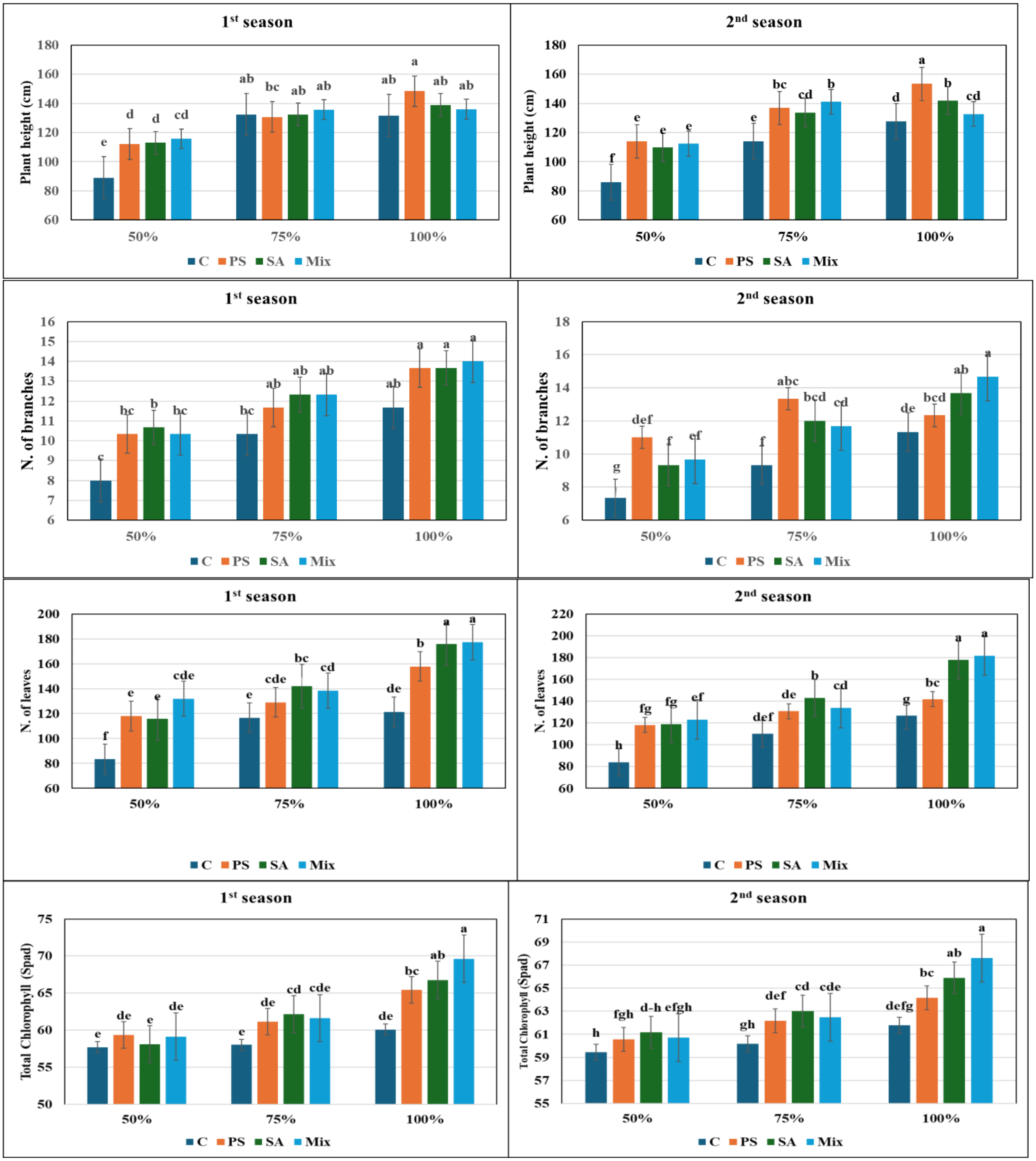
Proline concentration in leaves increased most when plants were irrigated with 50% of field capacity and tap water (control) in both seasons, according to the data obtained and tabulated in fig (3).

In this regard, it was also noted from the results in fig 3 that proline content in leaves gradually increased with water deficiency of less than 100% field capacity and the highest concentration was observed when interacting with tap water foliar spray. There is an inverse relationship between proline concentration and irrigation rate. When the irrigation rate increases, the proline concentration decreases, and the opposite is true.

The highest ABA values were achieved for plants irrigated with 50% of field capacity with tap water (control) during the two seasons of the study. Regardless of all irrigation levels, the control treatment (tap water) exhibited the highest values of ABA.

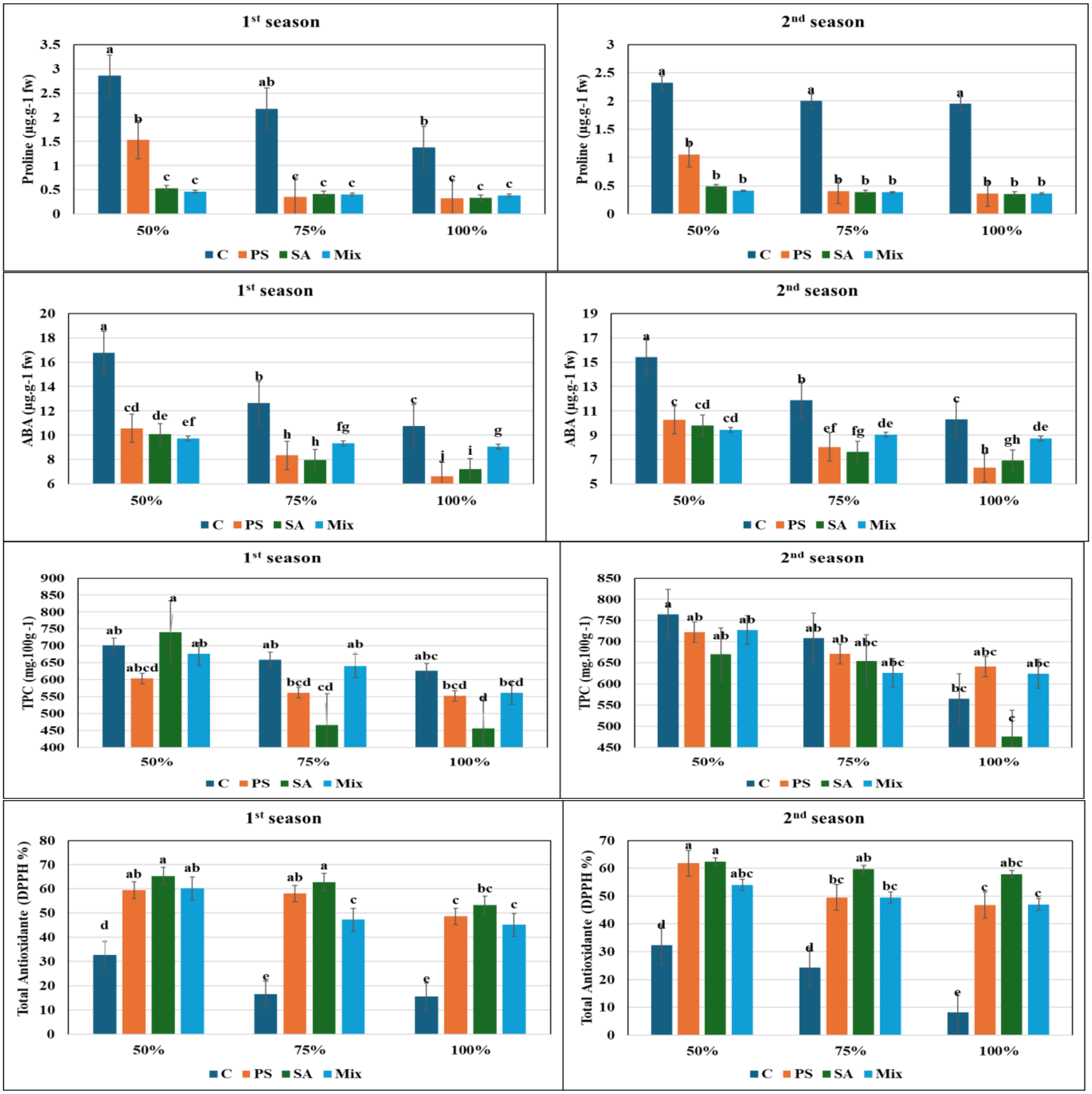
Figure 3 shows that the maximum TPC was achieved by irrigation at 50% field capacity with foliar spraying of salicylic acid (SA). This was followed by a mix of salicylic acid (SA) and potassium silicate (PS) and a control treatment (tap water) for the first season. Meanwhile, control treatment (spraying with tap water) came first by any irrigation level from 75 to 100% field capacity. The second season of the study, however, showed no discernible difference between the spraying treatments and the control treatment at 75 and 50% field capacity.

When the plants were irrigated at 50% of the field capacity using all spray treatments (potassium silicate, salicylic acid, and mix treatment, the concentration of antioxidants in the leaves increased the most, as demonstrated by the data in Figure (3). This was in contrast to the control (tap water) during the two study seasons. Conversely, foliar spraying with tap water (control) had the lowest antioxidant concentration values.



C: water from the tap as a control PS: potassium Silicate SA: Salicylic Acid Mix: potassium Silicate and Salicylic Acid

Figure 2. Effect of the combination between foliar spraying treatments and water requirements on the vegetative growth of hot pepper plants in the 2023 and 2024 seasons

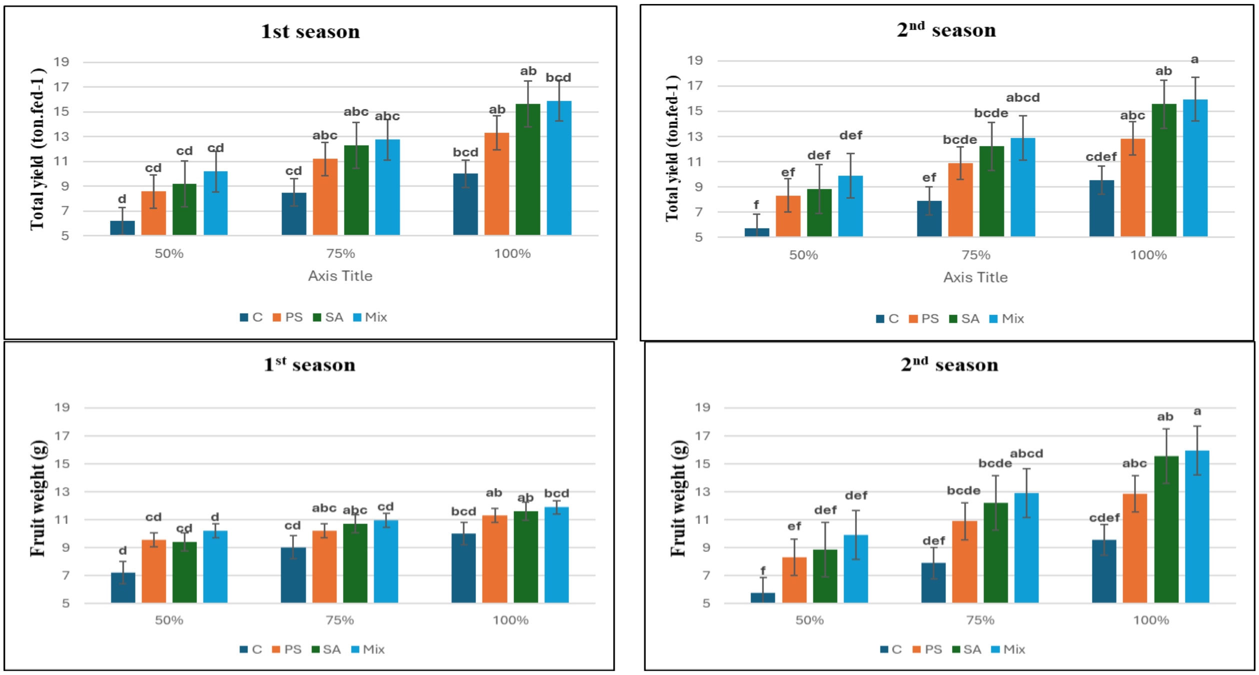


C: water from the tap as a control PS: potassium Silicate SA: Salicylic Acid Mix: potassium Silicate and Salicylic Acid

Figure 3. Effect of the combination between foliar spraying treatments and water requirements on Chemical constituents of plant foliage of hot pepper plants in the 2023 and 2024 seasons

3.3.Yield parameters:

In both seasons, the data collected and displayed in Fig (4) clearly demonstrate that the greatest increases in hot pepper yield were observed at 100% of field capacity, followed by 75% of field capacity with all foliar spray treatments (compared to foliar spray with tap water at an irrigation level of 50% of field capacity). For both seasons, the greatest yield increase was observed with the mixed treatment (potassium silicate and salicylic acid), which was followed by foliar spraying of potassium silicate and salicylic acid. In both experimental seasons, it was discovered that lowering field capacity from 100% to 50% led to a reduction in yield when



C: water from the tap as a control PS: potassium Silicate SA: Salicylic Acid Mix: potassium Silicate and Salicylic Acid

Figure 4. Effect of the combination between foliar spraying treatments and water requirements on Yield parameters of plant foliage of hot pepper plants in the 2023 and 2024 seasons

irrigation water was reduced from 100% to 50%. Regarding foliar spray, it is noted from Fig (4) that spraying plants with any of the three tested materials recorded positive results compared to tap water with regard to fruit yield in both seasons.

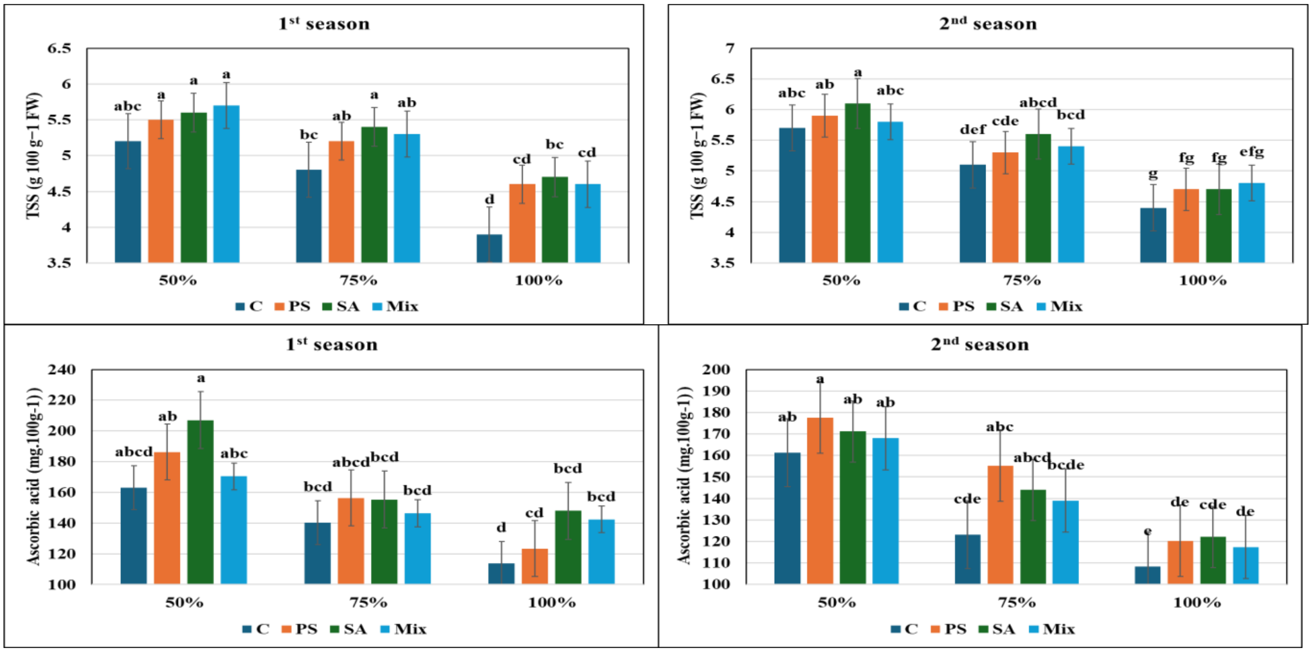
The fruit weight of hot peppers was considerably raised by all preharvest foliar spray treatments (Fig 4). In both seasons, the foliar spray containing tap water had the lowest fruit weight. In contrast to foliar spray with tap water at an irrigation level of 50% of field capacity, fruit weight increased at 100% of field capacity and then at 75% of field capacity with all foliar spray treatments in 2023 and 2024.

3.4.Fruit chemical characteristics

Salicylic Acid (SA) applied as a foliar spray at an irrigation level of 50% field capacity yielded the greatest vitamin C values in the first season, followed by potassium silicate (PS), as shown in fig (5). However, in the second season, there was no discernible difference between the foliar spray treatments at 50% field capacity of vitamin C.

Ata in fig (5) show that no significant difference between the foliar application treatments at 50% field capacity of TSS in both season. In contrast, plants sprayed with salicylic acid (SA) recorded the highest TSS value at 75% field capacity.

On the other hand, irrigation with 100% FC and tap water (control) as a foliar spray showed the lowest values in Fruit chemical characteristics.



C: water from the tap as a control PS: potassium Silicate SA: Salicylic Acid Mix: potassium Silicate and Salicylic Acid

Figure 5. Effect of the combination between foliar spraying treatments and water requirements on Fruit chemical characteristics of hot pepper plants in the 2023 and 2024 seasons

3.5.Leaf anatomy

Anatomically speaking, the pepper leaf possesses stomata on both sides of its adaxial and abaxial epidermis. A thin coating of cuticle covers the surface of the epidermal cells' outer walls. A single layer of palisade parenchyma cells and three to five layers of spongy parenchyma cells with a lot of intercellular space make up the mesophyll. Phloem faces both sides of the leaf, and the midrib's vascular bundle is bicollateral, encircled by collenchyma cells (Figures 6 and 7).

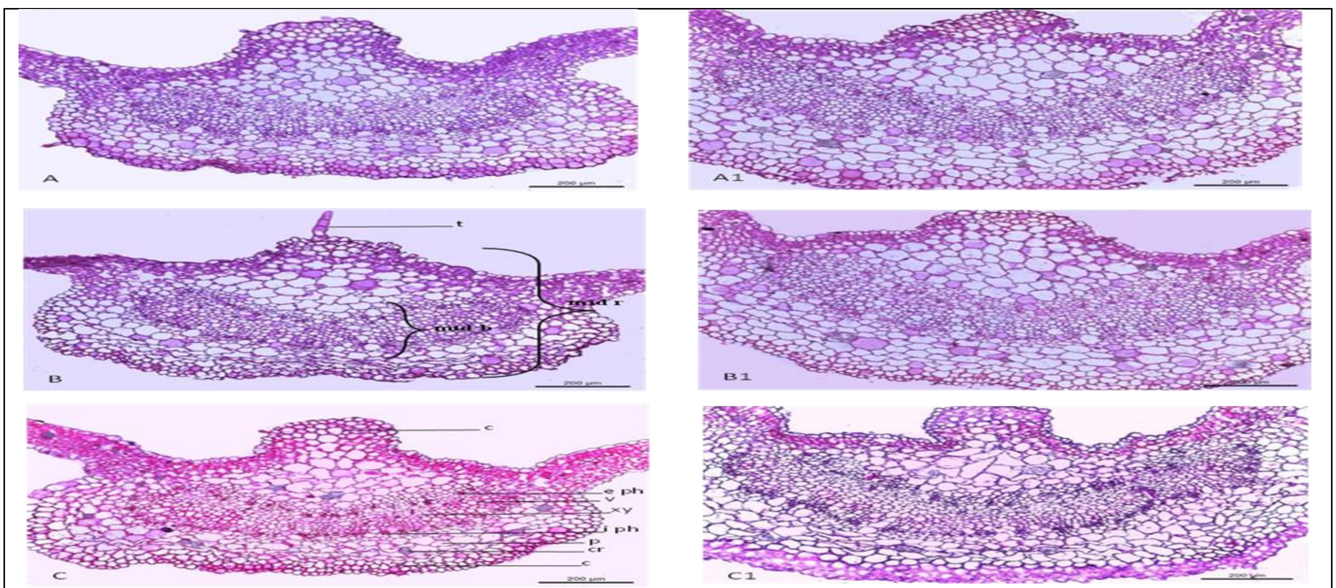
According to data in Table (1) and Figures 6, 7, and 8 A, B, and C, plants exposed to drought moderate stress (75 % of field capacity) and severe stress (50 % of field capacity) showed decreases in the most anatomical characteristics under investigation, including the thickness of the midvien, lamina, upper and lower epidermis, palisade tissue, spongy tissue, bundles dimension, and mean vessel diameter by 1.27%, 17.75%, 1.32%, 3.22%, 22.22%, 15.56%, 3.76%, and 3.56%, respectively, for the plants were exposed to the drought moderate stress (75 % of field capacity) and by 8.32%, 36.74%, 0.68%, 0.37%, 39.72, 33.93%, 12.64 and 4.83% , respectively, for the plants were exposed to the drought severe stress (50 % of field capacity) when compared with the control (full irrigation) (Fig. 6, 7 A, B and C).

When compared to the control (full irrigation), the plants treated with a mix of PS and SA showed the highest numbers in the thickness of the midvein, lamina, upper and lower epidermis, palisade tissue, spongy tissue, bundles dimension, and mean vessel diameter by 29.98%, 16.22%, 3.11%, 0.56%, 10.32%, 20.51%, 28.95%, and 5.38%, respectively (Fig. 6, 7 A and A1).

In comparison to plants exposed to drought moderate stress (75 percent of field capacity), it is noteworthy that the application of a mixture of PS and SA to pepper plants under this stress improved the anatomical features of the leaves, including the thickness of the midvein, lamina, upper and lower epidermis, palisade tissue, spongy tissue, bundles dimension, and mean vessels diameter by 22.68%, 14.77%, 1.27%, 0.92%, 11.79%, 18.11%, 25.91%, and 3.9%, respectively (Fig. 6, 7 B and B1).

Table 1. Measurements (µm) and counts of some histological aspects in the blade of the simple upper leaf that grew on a third branch from the lowest point of the hot pepper's main stem was one of the tested specimens (*Capsicum annuum* L.)

Histological aspects	Treatments					
	control (full irrigation).	75 % of field capacity	50 % of field capacity	full irrigation + mix between PS and SA	75 % of field capacity + mix between PS and SA	50 % of field capacity + mix between PS and SA
Thickness of midvein	1069.766	1056.173	980.700	1390.583	1295.781	1152.086
Thickness of upper epiderm	16.327	16.111	16.215	16.836	16.317	16.640
Thickness of lower epiderm	16.750	16.210	16.688	16.845	16.360	17.182
Thickness of lamina	143.527	118.043	90.787	166.807	135.482	110.096
Thickness of palisade tissue	64.400	50.090	38.817	71.052	55.998	45.930
Thickness of spongy tissue	78.670	66.425	51.970	94.807	78.457	65.600
Dimentions of main midvein bundle	547.766	527.141	478.494	706.365	663.755	520.041
Mean diameter of vessel	20.876	20.132	19.867	22.000	20.920	20.231



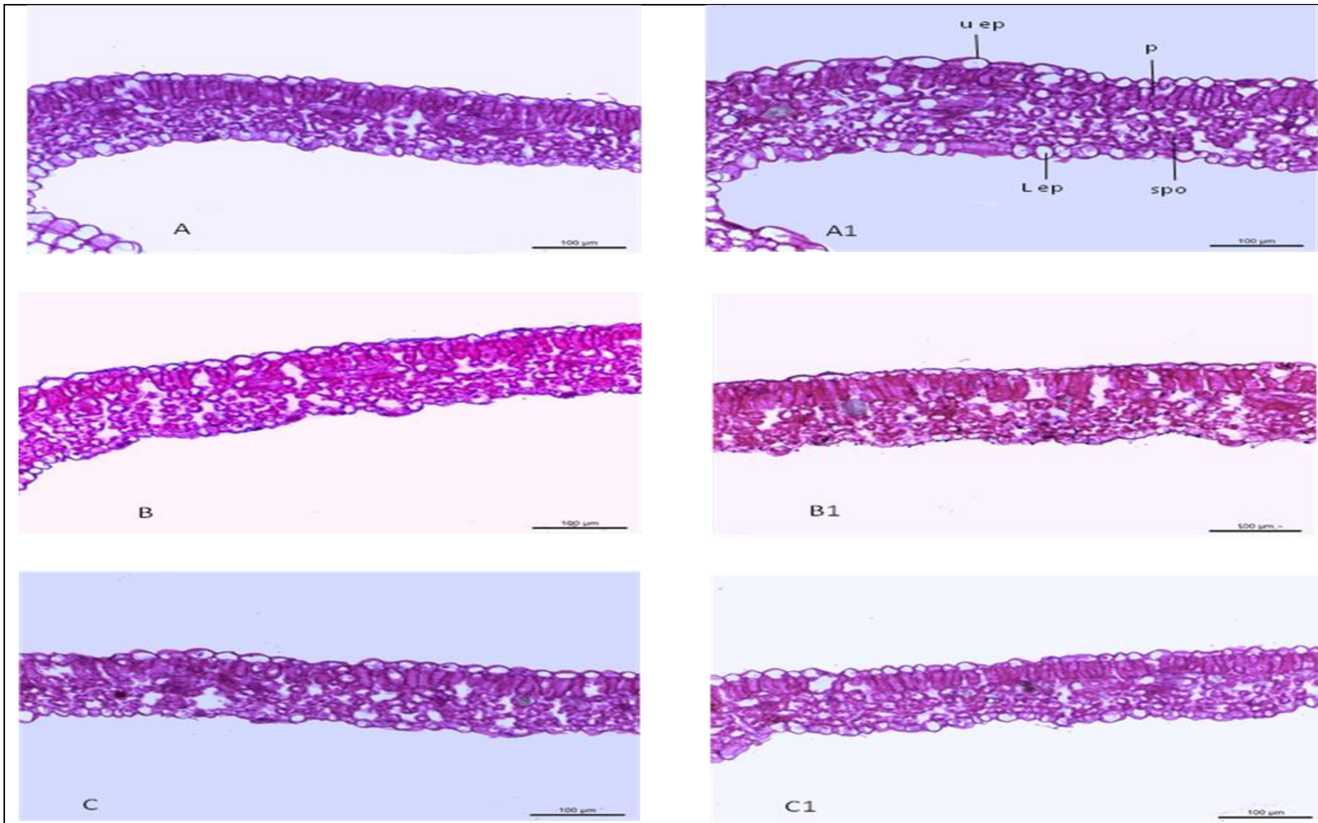
A- control (full irrigation) A1- The plants with full irrigation + mix between PS and SA
B- plants exposed to drought moderate stress (60 percent of field capacity) B1- plants exposed to drought moderate stress + mix between PS and SA
C- plants exposed to drought severe stress (40 percent of field capacity) C1- plants exposed to drought severe stress + mix between PS and SA
Details: mid b, midvein bundle; mid r, midvein region; t, trichome; e ph, external phloem; i ph, internal phloem; v, vessel; xy, xylem; t, trichome; cr, cells with dark content containing calcium oxalate crystals; p, parenchyma and c; collenchyma.

Figure 6. Microphotographs of cross sections through the blade of the simple upper leaf developed on the third branch from the base of the main stem of hot pepper (*Capsicum annuum* L.) plants, aged 75 days. Scale bars = 500 µm.

When compared to plants exposed to severe drought stress (50 % of field capacity), the plants treated with a combination of PS and SA showed the greatest improvement in the anatomical characteristics of the thickness of the midvein, lamina, upper and lower epidermis, palisade tissue, spongy tissue, bundle dimension, and mean vessel diameter. These improvements were 17.47%, 21.26%, 2.62%, 2.96%, 18.32%, 26.22%, 8.68%, and 1.83%, respectively (Fig. 6, 7 C and C1).

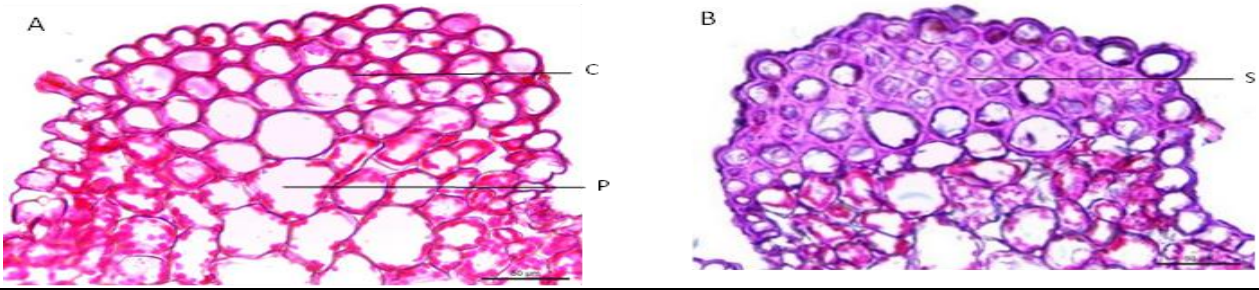
Microscopic observations also reveal that the plants were subjected to extreme drought stress. Moreover, plants given a combination of PS and AS exhibited a greater number of sclerenchyma cell rows (Fig. 8) as well as an increase in the cell wall thickness of subepidermally located collenchyma of the leaf midvein region, which caused these collenchyma cells to change into sclerenchyma cells.

Table 1. Counts and measurements in micro-meters (μm) of certain histological characters in transverse sections through the blade of the simple upper leaf developed on the third branch from the base of the main stem of hot pepper (*Capsicum annuum* L.) under high temperature and drought condition and treated with different treatments of potassium silicate (PS), Salicylic Acid (SA) and their interaction, aged 75 days (Means of three sections from three specimens)



A- control (full irrigation) A1- The plants with full irrigation + mix between PS and SA
B- plants that exposed to drought moderate stress (60 percent of field capacity) B1- plants that exposed to drought moderate stress + mix between PS and SA
C- plants that exposed to drought severe stress (40 percent of field capacity) C1- plants that exposed to drought severe stress + mix between PS and SA
Details: l ep, lower epidermis; u ep, upper epidermis; spo, spongy tissue and pal, palisade tissue

Figure 7. Magnified portions of the leaf blade lamina of hot pepper (*Capsicum annuum* L.) plants, aged 75 days. Scale bars = 100 μm.



A- Plants that were exposed to drought severe stress. Visible three layers of collenchyma cells
B- Plants that exposed to the drought severe stress + mix between PS and SA. Visible foure layers of scleranchyma cells
Details: p, peranchyma; c, collenchyma and s, scleranchyma

Figure 8. Magnified portions of the leaf blade midvein region of hot pepper plants, aged 75 days. Scale bars = 50 µm.

4. DISCUSSION

Food availability and productivity in agriculture are greatly impacted by abiotic stressors. Among the most important abiotic factors that impair crop growth and yield globally is drought (Fahad et al., 2017; Ullah et al., 2019). According to several studies (Ullah et al., 2017a; Sirisuntornlak et al., 2019), it significantly lowers agricultural yields and affects plants in morphological, biochemical, and physiological ways. Stunting of plant growth and yield due to drought stress is believed to be caused by a reduction in photosynthesis and stomatal conductance (Khan et al., 2015). Water shortage disrupts pore opening and shutting, which affects photosynthesis (Li et al. 2020), also lowers greenness levels (Aranjuelo et al., 2007). Drought stress also increases active oxygen radicals, disrupting cellular oxidative equilibrium (Choi et al., 2007).

By increasing the amount of chlorophyll, relative water, and stomatal conductance in the leaves, SA foliar application seems to increase the photosynthesis ratio of pepper plants. Enhancing photosynthesis rate is a primary factor in improving the morpho-physiological properties of fruits (Ghahremani et al., 2021a; Nezamdoost et al., 2022).

An important nutrient, potassium is essential for many plant processes, including enhancing the process of photosynthesis triggering enzymes, preserving cell turgor, controlling water balance, and boosting the production of sugars and polysaccharides. Stomatal regulation in plants relies on potassium to control the functioning of stomata. Potassium is crucial for improving the flavor and quality of fruit. Additionally, Tomato fruit's ascorbic acid content is influenced by the availability of potassium (Irfan, 2015). One possible explanation for the increase in potassium uptake is that Silicon activates the ATP ase H+ pump in the root plasma membrane (Pei et al., 2009). Water balance, turgor pressure, stomatal opening and shutting, carbon hydrate accumulation and transport, and increased stress tolerance are all greatly impacted by potassium. The cellulose layer of the epidermal layer contains silicon, which serves to keep plants from transpiring too much water. The buildup of silicon reduces cuticular evaporation by 30% by forming a thick coating of silicate on the leaf surface. In the epidermal cell wall, silica gel is linked to cellulose; however, less gel permits water to escape more quickly. According to Abdel-Aziz and Geeth (2018), silicon is regarded as an antitranspirant because it inhibits stomata without interfering with photosynthesis, preventing normal loss of moisture without influencing plant growth or respiration.

Under conditions of drought and elevated temperatures, potassium silicate, which includes 10.25% K2O, can boost the total dry mass that accumulates in sweet pepper plants. Given that potassium is believed to stimulate meristematic growth of tissues and nitrate levels, this could be the result of higher photosynthesis rates and potassium-regulated stomata.

Potassium also helps roots translocate photo assimilates, expand root surface area, and absorb more water and minerals (Abdel-Aziz and Geeth, 2018). In a study conducted by Kamal (2013), It was demonstrated that adding potassium silicate at a rate of 1.5 kg per feed and kaolin at a concentration of 4% improved vegetative development traits of sweet pepper plants. Silicon reduces stomatal pore diameter, which reduces transpiration and water loss (Efimova and Dokynchan, 1986). Silicon may also increase plant tissue osmotic adjustment (Romero-Aranda and Cuartero, 2006).

Nevertheless, when soil moisture deficiency reached 50% FC, the application of SA proved ineffective due to the interacting effect with the soil moisture regime. Applying SA topically at a dose of 150 mg L-1 produced statistically comparable yields between 75% and 100% FC, which shows that spraying treatment helps preserve production of fruit under moderate soil moisture levels (Chakma et al., 2021).

Numerous scientists have discovered that water stress negatively affects the vegetative development traits of a number of plant species, like Capsicum annuum (Ali et al., 2014). With less water, the plants got shorter, had fewer stems and leaves, and produced less. Exogenous SA treatment made these qualities much better when there was water stress. Support for the study came from Hussain et al. (2008), who discovered that adding SA greatly enhances sunflower's head diameter and oil yield when the plant was under water stress.

Reduced plant height because of a disturbance in processes of cell elongation and division, which is a direct result of drought stress (Farooq et al., 2009a; Ilyas et al., 2017; Ullah et al., 2018a). According to Sirisuntornlak et al. (2019), maize (Zea mays L.) growth metrics, yield of grains, and yield elements decreased when the soil moisture level was decreased from well-watered (100 % FC) to severely water stressed (50 % FC). This resulted from a reduction in the processes of cell elongation and division. In extreme cases of water stress, the xylem's water surge may not reach the surrounding expanding cells as quickly, which can slow down cell elongation (Nonami, 1998). It has been demonstrated that applying SA increases pepper plant development, demonstrating its function in enhancing tolerance to stress and lessening the adverse effects of drought (Senaratna et al., 2000). Additional research has shown that SA contributes to better nutrient absorption (Yildirim et al., 2009), promoting the development of roots (Shen et al., 2014), and increasing division of cells in the upper part of the root meristem, leading to overall plant development (Sakhabutdinova et al., 2003). The observed impact of externally applied SA is likely linked to its ability to decrease transpiration by causing stomatal closure or reducing the size of stomata, as described by Pennazio and Roggero (1984). Numerous writers (Gharib, 2006; Szepsi et al, 2005; and Zamaninejad et al, 2013) have also confirmed SA's positive effects on promoting development. This is attributed to its ability to increase carbon dioxide assimilation, photosynthetic rate, and mineral uptake in plants experiencing stress, among other factors. This may be linked to the physiological function of SA in the stimulation of growth because of producing more internodes. In a similar vein, Fathy et al. (2000) found that plants that received external SA treatment increased in height, the amount of branches, the number of leaves, and dry weight.

Numerous studies examining how drought affects plant growth have consistently discovered that drought-induced stress causes a significant drop in relative growth rates (Maes et al., 2009). Applying SA further increases the content of TSS in fruit irrespective of the techniques of application, and there was a definite pattern of increased amount of TSS with lowering the amount of moisture in the soil in the present study. Similar to what Yildirim and Dursun (2009) found, which shows that foliar SA treatment increases TSS in greenhouse-grown tomatoes. Additionally, Kamal (2013) discovered that foliar spraying sweet pepper fruits with kaolin and potassium silicate increased their total carbohydrates and TSS (%). The irrigation levels at 60% and 80% Etc and 300 ppm silicate potassium improve total soluble solids because potassium silicate helps fruit synthesize more sugar.

The investigation's conclusions showed that when pepper seedlings were exposed to severe drought, their levels of chlorophyll significantly decreased. Razavizadeh et al. (2017) noticed that when Carum copticum plants were stressed by dryness, their levels of chlorophyll decreased. Additionally, they observed a rise in phenolic compounds, flavonoids, and anthocyanin in these plants. Similarly, Sánchez-Blanco et al. (2004) observed that when Rosmarinus officinalis plants were exposed to drought stress, their chlorophyll concentration decreased. On the other hand, the amount of chlorophyll increased when SA was applied. Tang et al. (2017) discovered that when plants were subjected to dry circumstances, the use of salicylic acid spray increased the amount of chlorophyll. The application of exogenous SA just like a foliar spray raised the SPAD persent by as much as 150 mg L–1.

Similarly, Hayat et al. (2008) demonstrated that spraying SA increased SPAD values of tomato plants. Increasing SPAD chlorophyll in plants with SA treatment enhances photosynthetic rate, improving plant development and fruit output (Singh and Usha, 2003; Hayat et al., 2008; Nazar et al., 2015). Possible causes of the chloroplast membrane loss and lipid droplet development occur during drought-induced (El-Saadony et al.,2017). Chlorophyll depletion due to water stress is mostly caused by chloroplast injury (Smirnoff, 1995). A drop in leaf chlorophyll concentration, perhaps caused by several factors, including alterations in the lipid-protein ratio of pigment-protein complexes, a rise in the breakdown of chlorophyll and chlorophyllase activity, suppression of photosynthetic pigment synthesis, or both (Singh and Dubey 1995; Levitt 1980). Additionally, according to Saha et al. (2010), when drought stress increases, so does the activity of the enzyme chlorophyllase, resulting in a gradual decline in chlorophyll levels in Vigna radiata. A frequent indicator of oxidative stress under drought stress is a decrease in chlorophyll levels, which may be brought on by photo-oxidation breaking down pigments and chlorophyll (Demmig-Adams and Adams, 1996). Therefore, the primary cause of the deactivation of photosynthesis is thought to be the drop in chlorophyll levels under water stress, which significantly limits primary productivity (Farooq et al., 2009).

Significant amounts of proline are produced by plants during drought stress, an osmolyte (Porcel and Ruiz-Lozano 2004). Proline's significance in plant stress response is up for debate (Delauney and Verma 1993). Buildup of proline in plant tissues may result from proteolysis or protein synthesis reduction. Proline is an osmolyte that also has the ability to shield enzymes and promote membrane integrity under diverse circumstances (Nasir Khan et al., 2007). Accumulation of proline in plant cells may aid in adapting to various stresses and provide an advantage during water shortages (Delauney and Verma 1993). The plants were able to preserve tissue hydration status and prevent drought-induced damages by accumulating more protein and proline when the drought's duration and intensity increased (Abdel-Nasser and Abdel-Aal, 2002, Jiang and Huang, 2002). There's a rise in pea proline content due to water stress. (Alexieva et al, 2001). Water deficiency led to a notable rise in proline content, while the introduction of higher levels of silicate potassium resulted in a gradual decline in proline content. This decline indicates that silicate potassium interferes with the production of proline, which is responsible for osmotic adjustment (Zhu and Gong, 2014). An alternative viewpoint posits that the transpiration of plants may have decreased as a result of silicon fertilizer treatment, leading to decreased proline levels under this condition (Mauad et al., 2016).

Drought and SA treatments increased phenols. Under salicylic acid and drought stress, Khalil et al. (2018) found that Thymus vulgaris L. plants had higher total polyphenol content than controls. Phenols show metabolic activity and resistance to environmental stressors (Sharma et al. 2019). By protecting plants from oxidative damage, polyphenols can withstand stress (Agati and Tattini 2010). Research conducted by Berthelsen and Korndorfer (2005) and Ahmad et al. (2012) found that when silicon was deposited under the leaf epidermis, it triggered the production of phenols. These phenols served as a physical defense mechanism that reduced lodging, stimulated the production of phytoalexin, reduced transpiration losses, and increased the capacity for photosynthesis in crop plants. Consequently, plants subjected to silicon produced more.

According to Wu et al (2005), Hormonal imbalances may be the cause of the correlation with growth rate of crops and drought stress throughout the vegetative stage. This imbalance is characterized by reduced IAA levels and increased ABA levels in stressed plants. Regulation of biochemical and physiological processes like stomatal opening can help plants tolerate water deficits. Stomatal movement is complex, but abscisic acid (ABA) regulates it in response to water shortages. Secondary messengers like ROS, nitric oxide, calcium, and protein kinases prompt stomatal closure.

Other research demonstrated that the content of ASA increased considerably during drought stress, and exogenous SA significantly contributed to the enhancement of non-enzymatic components, including AsA. Drought stress not only inhibits plant growth however, it also increases the levels of certain metabolites, such as ASA (Shan et al. 2011). Ascorbic acid levels rising in reaction to water shortage serves as a crucial antioxidant that safeguards the crop from the detrimental effects of the lack of moisture (Smirnoff, 2005).

Wang et al. (2010) discovered that antioxidant enzyme activity is increased by SA, shielding the plant from harm to its membranes or may lead to the production of other substances that protect plants that are under stress. The proline content of the crops with seeds that received SA treatment also went up. Misra and Saxena (2009) also found the same thing: adding SA to lentil seedlings that were growing in stressful conditions raised the amount of proline in the plants. In plants, proline does many things, including controlling osmotic pressure, keeping membranes intact, keeping enzymes and proteins stable, and getting rid of free radicals (Hare and Cress, 1997). Plants that can handle more stress have been shown to accumulate proline when they are under stress (Mishra and Gupta, 2005).

According to the anatomical study. The drought stress decreased almost all aspects under study, The midvien's density, lamina, upper epidermis, lower epidermis, palisade tissue, spongy tissue, bundles dimension and mean vessels diameter. The current findings concurred with those published by (Khodos et al., 1976), reveal that all of the leaf blade anatomical characteristics were significantly reduced in P. amboinicus plants under extreme drought stress (25% of WHC). According to El-Afry et al. (2012), wheat varieties treated with irrigation water at deficiency levels of 75, 50, and 25% FC showed a decrease in morphological parameters, including ground, mesophyll, and phloem cell thickness, xylem vessel width, and vascular bundle diameters. According to Yang et al. (2007), winter wheat plants' xylem vessel dimensions shrank when exposed to water stress as opposed to the control. According to Desoky et al. (2013), drought stress caused wheat plants' leaf blades to become thinner. Additionally, the accumulation of water needed for photosynthesis was reduced as a result of the leaf blade's vascular bundle's width decreasing. In their 2019 study, Abd Elbar et al. examined how foliage use of putrescine affected the growth, biochemical, vital oil percentage, and morpho-anatomical features of Thymus vulgaris L. under conditions of water deficit. They discovered that dry conditions stress significantly reduced ($P \leq .05$) the area of the leaf cross section (48.4%), leaf thickness (23.2%), palisade tissue area (18%), and spongy tissue area (50%) of thyme leaves when compared to those that received adequate water. Reduced photosynthesis, which results from a reduction in leaf growth, damaged photosynthetic machinery, early leaf senescence, and a corresponding loss in food production, is one of the main effects of drought (Wahid, 2009).

This study demonstrated that the pepper plants treated with the mix between PS and SA and exposed water shortage revealed a rise in the number of cells walls thickness of subepidermally located collenchyma of the leaf midvein region, which is regarded as a drought-adaptation mechanism for plants in order to protect the plant from water loss, that results in the plant's stomata closing and gas exchange being restricted.

To the best of the authors' knowledge, there is no information in the literature regarding the impact of a mixed PS and SA treatment on the anatomical structure of pepper leaf plants grown under drought stress.

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الملخص العربي

المعاملة بحامض الساليسيليك وسيليكات البوتاسيوم تعزز من المقاومة الفسيولوجية لنبات الفلفل الحلو (*Capsicum annuum* L.) تحت ظروف الإجهاد المائي

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أُجريت هذه الدراسة خلال موسمي ٢٠٢٣ و٢٠٢٤ على هجين أوميجا F1 من الفلفل الحار (*Capsicum annuum* L.) تحت ظروف درجات حرارة مرتفعة وجفاف، وتم تقييمها في الصوبه بكلية الزراعة جامعة القاهرة. تهدف الدراسة بشكل رئيسي إلى تحديد مدى تأثير مُحفزات الرش الورقي المختلفة المُستخدمة على تحمل الفلفل للجفاف والحرارة. تضمنت التجربة ١٢ معاملة، شملت ٤ معاملات رش ورقي وثلاثة مستويات من مياه الري. وُزعت المعاملات الورقية عشوائيًا في قطع فرعية) سيليكات البوتاسيوم 200 (PS) ملغم/لتر، حمض الساليسيليك 270 (SA) ملغم/لتر، مزيج) سيليكات البوتاسيوم 200 (PS) ملغم/لتر، حمض الساليسيليك 270 (SA) ملغم/لتر (وماء الصنبور ككنترول .بناءً على النتائج، لوحظت أعلى القيم لخصائص النمو التي تم تقيمها (ارتفاع النبات، عدد الفروع) عند رش النباتات بسيليكات البوتاسيوم بتركيز ٢٠٠ ملجم/لتر، يليه المعاملة بالخليط بمستوى ري ١٠٠٪ من سعة الحقل، ثم ٧٥٪ من سعة الحقل. ومع ذلك، عند معالجة النباتات بخليط من سيليكات البوتاسيوم وحمض الساليسيليك بنسبة ١٠٠٪ من سعة الحقل، لوحظت أعلى القيم لعدد الأوراق والكلوروفيلSPAD . أظهر بوضوح أن أعلى زياده في تركيز البرولين وحمض الأبسيسيك في الأوراق وُجدت عند ري النباتات بنسبة ٥٠٪ من سعة الحقل مجتمعة باستخدام ماء الصنبور (الكنترول) خلال كلا الموسمين. طوال موسمي الدراسة، تم ري النباتات بنسبة ٥٠٪ من سعة الحقل بجميع معاملات الرش، PSو SA ومزيج، مما أدى إلى أكبر زيادة في محتوى مضادات الأكسدة في الأوراق مقارنة بالكنترول (الرش بماء الصنبور). بالإضافة إلى ذلك، فقد تبين أن المعالجة الورقية يمكن أن تنتج محصول ذات جودة فيزيائية وكيميائية عالية.

الكلمات المفتاحية: الفلفل الحار، الرش الورقي، متطلبات المياه، النمو، المكونات الكيميائية