International Journal of Multiphysics
Volume 18, No. 2, 2024
ISSN: 1750-9548

Foliar Potassium Silicate Application Modulates Growth, Water Relations, Antioxidant Responses, and Nutrient Status of Common Bean (*Phaseolus vulgaris* L.) under Water Deficit

Moamen M. Fahiem, Mohamed S. Boghdady, Seham A. Ibrahim and El-Sayed M. Desoky

Botany Department, Faculty of Agriculture, Zagazig University, Zagazig 44519, Egypt

Corresponding author: Moamen M. Fahiem
E-mail: moamenmohammed179@gmail.com

Abstract

Drought stress represents a severe environmental constraint that drastically limits the growth and productivity of the common bean (*Phaseolus vulgaris* L., cv. Bronco). This study was conducted to comprehensively investigate the efficacy of foliar-applied potassium silicate (K2SiO3) in alleviating drought-induced physiological and biochemical disruptions. Common bean plants were subjected to three irrigation regimes: well-watered control (80% of field capacity, FC), moderate water deficit (60% FC), and severe water deficit (40% FC). These regimes were combined with foliar applications of potassium silicate at concentrations of 2, 4, 6, and 8 mM. The results revealed that drought stress significantly suppressed vegetative growth parameters, yield components, photosynthetic pigments (chlorophyll a, b, and carotenoids), relative water content (RWC), and relative water loss (RWL), while drastically increasing the accumulation of reactive oxygen species (ROS), namely H2O2 and O2-. However, the exogenous application of potassium silicate remarkably reversed these detrimental effects, effectively enhancing leaf relative water content (RWC) and relative water loss (RWL), with the highest concentration (8 mM) showing the optimal recovery. Furthermore, potassium silicate treatments significantly upregulated the activities of key antioxidant enzymes, specifically superoxide dismutase (SOD) and catalase (CAT) thereby actively scavenging ROS and preserving membrane stability. The treatments also improved the leaf nutritional status by maintaining higher concentrations of nitrogen (N), phosphorus (P), and potassium (K). In conclusion, the foliar application of potassium silicate serves as a highly effective, multifaceted, and sustainable biostimulant strategy to fortify drought tolerance, maintain water status, and preserve the yield of common beans cultivated under severe water-limited conditions

Keywords: Phaseolus vulgaris L.; Drought stress; Potassium silicate; Osmoregulation; Antioxidant enzymes; Foliar biostimulant.

1. Introduction

Leguminous crops are anticipated to play a key role in global nutrition as population growth and demand for sustainable food sources continuously rise. Among them, the common bean (*Phaseolus vulgaris* L.) is an essential food and feed crop worldwide, playing a pivotal role in supporting both human and livestock nutrition by providing a highly accessible source of dietary protein, essential vitamins, and vital micronutrients **(Broughton et al., 2003)**. However, the sustainable production of common beans is severely threatened by abiotic stresses. In arid and semi-arid regions, this problem is dramatically worsened by the escalating impacts of climate change and the acute scarcity of irrigation water, conditions that can lead to catastrophic yield losses exceeding 80% under severe water deficit **(Seleiman et al., 2021)**. Drought stress disrupts cellular metabolism, reduces root and shoot

growth, and impairs overall plant performance by triggering osmotic imbalance and inhibiting vital metabolic pathways **(Gupta et al., 2020)**.

A critical consequence of drought stress is the disruption of the electron transport chain, which triggers the excessive generation of reactive oxygen species (ROS), such as superoxide radicals (O_2^-), hydroxyl radicals (OH^-), and hydrogen peroxide (H_2O_2). This excessive ROS generation causes severe oxidative damage, directly attacking the D1 protein of photosystem II (PSII) and accelerating lipid peroxidation, which fundamentally destabilizes cellular membranes and impairs overall carbon assimilation **(Hasanuzzaman et al., 2020)**. To mitigate this cellular damage, plants inherently deploy complex osmoregulatory and antioxidant systems. However, under severe and prolonged drought conditions, the plant's endogenous defense mechanisms are often overwhelmed, necessitating the exogenous application of eco-friendly mitigants and biostimulants to bolster plant resilience **(Foyer et al., 2020)**.

Recently, Silicon (Si) has emerged as a quasi-essential, highly beneficial element that plays a fundamental role in plant resistance against multiple abiotic stresses, particularly drought and salinity **(Cooke & Leishman, 2016)**. Although Si is the second most abundant element in the earth's crust, its bioavailable form (monosilicic acid) is often severely limited in agricultural soils. The exogenous foliar application of potassium silicate (K_2SiO_3) provides a highly efficient, dual-benefit strategy: it supplies highly soluble Si alongside Potassium (K), a critical macronutrient required for stomatal regulation, enzyme activation, and osmotic adjustment **(Zargar et al., 2019)**. Silicon mitigates drought stress primarily by depositing silica gel (phytoliths) beneath the leaf cuticle, acting as a structural and mechanical barrier that significantly reduces non-stomatal cuticular transpiration and maintains tissue turgor **(Debona et al., 2017)**.

Beyond its structural role, recent molecular and biochemical evidence indicates that Si actively participates in regulating the plant's physiological machinery. Silicon promotes active ROS scavenging by extensively upregulating the endogenous antioxidant enzymes and enhancing the biosynthesis of osmoprotectants such as proline and soluble sugars **(Etesami & Jeong, 2018)**. Concurrently, the supplemented potassium ensures optimal guard cell functioning, allowing the plant to rapidly close stomata to conserve water while maintaining sufficient CO_2 assimilation rates **(Rizwan et al., 2015)**. Therefore, comprehensively investigating the physiological and biochemical responses of common beans to potassium silicate under drought stress is crucial. With this objective, the current study was designed to investigate the influence of foliar treatments with various concentrations of potassium silicate on the growth, osmoregulation, antioxidant defense systems, and yield of common bean plants subjected to varying levels of drought stress.

2. Materials and Methods

2.1. Experimental Design and Treatments Twenty days after planting, upon achieving full emergence, the pots were divided into three groups corresponding to different irrigation regimes (drought stress treatments): well-watered control (80% of field capacity, FC), moderate water deficit (60% FC), and severe water deficit (40% FC). Each irrigation group was further divided into five foliar spray regimes: distilled water (DW) as a control, 2, 4, 6, and 8mM potassium silicate (K_2SiO_3). These treatments were allocated to pots in a completely randomized design with three replicates each. Soil pH was regularly adjusted to maintain the control range of 6.2–6.5 using diluted sulfuric acid throughout the experiment. The entire experimental period lasted 55 days, at which point the common bean plants were harvested for analysis.

2.2. Preparation and Application of Potassium Silicate

Potassium silicate (K_2SiO_3) solutions were prepared using high-purity laboratory-grade reagents dissolved in distilled water to achieve the precise required concentrations (2, 4, 6, and 8 mM). Foliar treatments using the potassium silicate solutions were applied at 20, 35, and 50 days after sowing. Applications were made by spraying with a pressurized bottle containing 0.1% Tween 20 as a surfactant to ensure maximum leaf surface adherence, with distilled water sprays serving as controls.

2.3. Vegetative Growth and Yield Assessment

Ten plants from each treatment plot were harvested to measure growth parameters such as plant height (cm), leaflet area (cm^2), and shoot dry weight (g). Shoots were dried at 70°C in an electric oven until a constant weight was achieved. At the green pod stage, samples from thirty randomly selected plants were collected to estimate the number of pods/plants, average pod weight/plant (g), and total green pod weight/plant.

2.4. Photosynthetic Pigments and Nutrient Content Analysis

Chlorophyll a & b and carotenoids were extracted from fresh leaf using pure acetone according to **Fadeels (1962)**. The O_2^- content in bean leaves was determined as A580 g-1 FW according to **(Kubis, 2008)**. Hydrogen peroxide (H_2O_2) was determined using the method of **Mukherje and Choudhuri (1983)**. Relative water content (RWC) was estimated according to **Barrs and Weatherley (1962)**. Relative Water Loss (RWL) was then calculated following **(Gavuzzi et al., 1997)**. Digesting 0.2 g of dried leaf with H2SO4 acid in the presence of H_2O_2 **(Wolf, 1982)**. Total nitrogen was determined using a microkjeldahl method according to **Chapman and Pratt (1982)**. Total phosphorus was determined colourmetrically using ascorbic acid method **(Watanabe and Olsen, 1965)**. Total Na and K concentrations were measured directly using Flame photometer **(Lachica et al., 1973)**.

2.5. Determination of antioxidants activities

The enzymes were extracted according to **Vitoria et al. (2001)**. The concentration of catalase (CAT) enzyme was measured by spectro-photochemically according to **Chance and Maehly (1955)**. Ascorbate peroxidase (APX) was determined using spectro-photo-chemically according to **Fielding and Hall (1978)**. Activity of superoxide dimutase (SOD) was determined by recording the drop in absorbance of superoxide-nitro blue tetrazolium complex by the enzyme **(Sairam et al., 2002)**.

2.6. Data analysis

Significant differences among mean values were determined using Duncan's Multiple Range Test at $p \leq 0.05$, with statistical analyses performed using COSTAT software (version 6.303).

3. Results and Discussion

3.1. Vegetative Growth and Yield Components

The results of the present study revealed that drought stress significantly suppressed the morphological traits and yield of common bean (*Phaseolus vulgaris* L., cv. Bronco) plants. As water deficit intensified from 80% to 40% field capacity (FC), there were drastic reductions in plant height, leaflet area, and shoot dry weight, which subsequently led to a severe decline in the total number of pods and pod weight per plant. However, the foliar application of potassium silicate (K_2SiO_3) at concentrations of 2, 4, 6, and 8 mM remarkably reversed these drought-induced damages. The treatments progressively enhanced vegetative growth and yield components, with the highest concentration (8 mM) showing the most optimal recovery, significantly outperforming the untreated stressed plants across all irrigation regimes (Table 1).

Physiologically, plants subjected to drought stress experience significant growth inhibition because water-induced metabolic disorders severely reduce meristematic cell division and elongation, processes that are further hampered by reduced nutrient mobility and loss of cellular turgor under water-deficit conditions (**Seleiman et al., 2021**). The remarkable growth recovery observed in the treated plants can be directly attributed to the dual functionality of silicon and potassium. Silicon actively polymerizes and deposits as amorphous silica gel (phytoliths) within the epidermal cell walls and beneath the cuticle. This structural fortification creates a robust double-layer mechanism that provides mechanical strength to the leaves, maintains a rigid upright posture for optimal light interception, and drastically minimizes non-stomatal transpirational water loss (**Coskun et al., 2019**). Concurrently, the highly mobile potassium (K^+) supplied by the treatment acts as the primary inorganic osmoticum in plant cells. Potassium dynamically drives the influx of water into the guard cells, allowing for rapid and precise stomatal regulation, which prevents catastrophic dehydration while sustaining adequate CO_2 diffusion for photosynthesis and subsequent biomass accumulation (**Luyckx et al., 2017**)

Table (1). Impact of foliar application of Silicon (Si) concentrations on growth and yield characteristics of common bean (*Phaseolus vulgaris* L.) plants subjected to different drought stress levels (field capacity)

Parameter / Treatments		Plant height (cm)	Shot dry weight (g)	Leaflet area $(cm)^2$	Number of pods/plants	Pods weight/plant (g)
drought	**Foliar spray**	**1st season**				
80%FC	**DW**	40.6e	2.37e	24.9d	16.1d	31.8de
	Si 2Mm	41.7d	2.41d	25.9d	17.2c	33.5cd
	Si 4Mm	42.4c	2.48c	32.4c	17.6c	34.5c
	Si 6Mm	43.4b	2.52b	33.7b	19.5b	38.1b
	Si 8Mm	44.0a	2.57a	42.1a	21.5a	42.0a
60%FC	**DW**	34.9j	2.04j	14.7g	11.8g	23.0i
	Si 2Mm	35.6i	2.08i	15.3g	12.8f	25.1h
	Si 4Mm	36.3h	2.11h	18.5f	14.2e	27.7g
	Si 6Mm	37.2g	2.16g	19.2ef	14.6e	28.7fg
	Si 8Mm	37.5f	2.19f	19.9e	15.6d	30.4ef
40%FC	**DW**	24.4n	1.42o	6.50j	6.50l	12.6n
	Si 2Mm	24.9m	1.45n	8.45i	7.12k	13.8m
	Si 4Mm	25.6l	1.48m	10.9h	7.78j	15.3l
	Si 6Mm	25.9l	1.51l	11.8h	8.64i	16.7k
	Si 8Mm	26.6k	1.55k	14.2g	9.51h	19.3j
P-value	**drought**	0.0000	0.0000	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0050	0.0000	0.0001	0.0000
	drought × Foliar	0.0052	0.0004	0.0070	0.0004	0.0000
		2nd season				
80%FC	**DW**	45.0e	2.54e	28.4e	18.9e	37.7d
	Si 2Mm	45.9d	2.60d	29.5d	20.0d	39.8c
	Si 4Mm	46.8c	2.63c	36.9c	20.7c	41.0c
	Si 6Mm	47.5b	2.69b	38.4b	22.9b	45.2b
	Si 8Mm	48.6a	2.76a	48.0a	24.9a	49.6a
60%FC	**DW**	38.7j	2.19j	16.8ij	13.6i	27.2h
	Si 2Mm	39.4i	2.23i	17.5i	15.0h	29.8g
	Si 4Mm	40.2h	2.28h	21.1h	16.6g	33.0f
	Si 6Mm	40.6g	2.33g	21.8g	17.0g	33.9f
	Si 8Mm	41.8f	2.37f	22.7f	18.2f	36.0e
40%FC	**DW**	26.9n	1.53n	7.41n	7.56n	14.9m
	Si 2Mm	27.6m	1.56m	9.63m	8.29m	16.4l
	Si 4Mm	28.3l	1.60l	12.5l	9.14l	18.1k
	Si 6Mm	28.6l	1.63k	13.4k	10.0k	19.9j
	Si 8Mm	29.2k	1.65k	16.2j	10.9j	22.6i
80%FC	**drought**	0.0000	0.0000	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0001	0.0001	0.0000	0.0000
	drought × Foliar	0.0005	0.0005	0.0028	0.0000	0.0005

Data are means (n=3) ± SE. Means followed by the same letter in each column are not significantly different according to the LSD test ($P \leq 0.05$). DW: distilled water

3.2. Photosynthetic Pigments and Tissue Water Relations

Drought stress caused a sharp deterioration in the photosynthetic apparatus, marked by a significant decline in the concentrations of chlorophyll a, chlorophyll b, and carotenoids. This was accompanied by a severe disruption in tissue water relations, characterized by diminished Relative Water Content (RWC) and decreased Relative Water Loss (RWL). Conversely, the exogenous application of potassium silicate effectively mitigated these deleterious effects. Plants treated with K_2SiO_3 maintained significantly higher concentrations of photosynthetic pigments and exhibited superior leaf water relations, recording the highest RWC and RWL values, particularly under severe stress (40% FC) (Table 2).

Drought typically impairs photosynthetic efficiency by accelerating chlorophyll degradation via enhanced chlorophyllase enzyme activity and causing severe dehydration of the mesophyll tissues **(Dalal & Tripathy, 2012)**. The observed preservation of pigments in this study is intrinsically linked to the superior water status maintained by the potassium silicate treatments. The deposited silica layer essentially seals the leaf surface against excessive evaporation, while the optimized intracellular potassium levels lower the cellular osmotic potential, forcing water retention against the soil's strong matric pull. By maintaining high cellular turgor (high RWC), potassium silicate ensures that the chloroplasts remain fully hydrated and structurally intact, thereby sustaining the electron transport chain and maximizing overall photosynthetic efficiency under severe dehydration **(Gong et al., 2005)**.

3.3. Oxidative Stress Markers and Antioxidant Enzyme Activities Biochemically, the stressed common bean plants exhibited a severe oxidative burst under water deficit, marked by the massive accumulation of reactive oxygen species (ROS), namely hydrogen peroxide (H_2O_2) and superoxide radicals (O_2^-). As a natural defense mechanism, untreated stressed plants showed a moderate increase in the activities of superoxide dismutase (SOD), and catalase (CAT). However, foliar feeding with potassium silicate aggressively suppressed ROS accumulation. The K_2SiO_3 treatments significantly hyper-activated these key antioxidant enzymes far beyond the levels observed in the untreated stressed plants, effectively detoxifying the cellular environment (Table 3).

A critical and lethal consequence of prolonged drought is the excessive generation of highly toxic ROS, which rapidly initiate lipid peroxidation, destroy biological membranes, and cause irreversible macromolecular damage **(Hasanuzzaman et al., 2020)**. The targeted ROS detoxification observed in the treated plants is orchestrated through a massive, silicon-mediated upregulation of the plant's endogenous antioxidant enzymatic machinery **(Zargar et al., 2019)**. Plants counter drought-induced oxidative stress through a sequential enzymatic system where SOD acts as the vital first line of defense by rapidly dismutating the highly reactive O_2^- into H_2O_2. Subsequently, CAT and APX vigorously neutralize the H_2O_2 into harmless water and oxygen molecules. By hyper-activating these specific enzymes, potassium silicate maintains ROS at safe, basal levels. This enhanced antioxidative capacity perfectly shields the phospholipid bilayers from lipid peroxidation, preserving membrane integrity and preventing the leakage of vital intracellular electrolytes **(Shen et al., 2010)**.

3.4. Nutrient Content

Under severe drought (40% FC), untreated plants suffered from a severe reduction in leaf nitrogen (N), phosphorus (P), and potassium (K) contents. Remarkably, the application of potassium silicate effectively reversed this drought-induced nutrient starvation, significantly enhancing and restoring the N, P, and K contents in the stressed leaves (Table 4).

Active osmoregulation is paramount for plant survival under severe drought. Beyond its role as a simple osmolyte to lower osmotic potential, proline acts as a crucial molecular chaperone that stabilizes delicate protein structures, protects membrane integrity, and severely buffers cellular redox potential under extreme dehydration **(Meena, Savouré et al., 2019)**. Silicon is known to upregulate the expression of genes involved in proline biosynthesis while simultaneously downregulating its degradation pathways, resulting in robust cellular protection **(Etesami & Jeong, 2018)**. Furthermore, drought stress severely restricts the root uptake and xylem transport of essential macronutrients by decreasing soil hydraulic conductivity and nutrient solubility **(Hu & Schmidhalter, 2005)**. Silicon mitigates this by enhancing root architecture and upregulating nutrient transporter genes, while the direct foliar supply of potassium circumvents the dry soil barrier, ensuring that metabolic and enzymatic functions

remain uninterrupted **(Rizwan et al., 2015)**. Consequently, potassium silicate provides comprehensive, multifaceted protection reinforcing structural barriers, enhancing osmoregulation, and amplifying antioxidative defenses ultimately ensuring higher resilience and yield preservation.

Table (2). Impact of foliar application of Silicon (Si) concentrations on photosynthetic pigment contents, relative water content (RWC) and relative water loss (RWL) of common bean (*Phaseolus vulgaris* L.) plants subjected to different drought stress levels (field capacity)

Parameter / Treatments		Chlorophyll a (mg g^{-1})	Chlorophyll b (mg g^{-1})	Carotenoids (mg g^{-1})	RWC (%)	RWL (%)
drought	**Foliar spray**	**1st season**				
80%FC	**DW**	1.27f	0.428ef	0.591e	64.8d	60.7fg
	Si 2Mm	1.41de	0.459d	0.671d	71.8c	62.9f
	Si 4Mm	1.53c	0.515c	0.745c	72.8c	70.5d
	Si 6Mm	1.65b	0.569b	0.819b	78.3b	78.8b
	Si 8Mm	1.85a	0.625a	0.879a	88.4a	87.6a
60%FC	**DW**	1.01i	0.334h	0.480g	46.0fg	50.1ij
	Si 2Mm	1.11h	0.380g	0.522f	49.2f	54.1h
	Si 4Mm	1.20g	0.405f	0.601e	54.9e	59.1g
	Si 6Mm	1.36e	0.454de	0.669d	55.3e	66.9e
	Si 8Mm	1.45d	0.505c	0.719c	62.7d	74.4c
40%FC	**DW**	0.56l	0.193k	0.256k	25.7j	42.8k
	Si 2Mm	0.60l	0.202k	0.296j	30.9i	47.4j
	Si 4Mm	0.68k	0.228j	0.325i	33.9i	52.2hi
	Si 6Mm	0.73k	0.252i	0.346i	40.5h	57.8g
	Si 8Mm	0.829j	0.274i	0.377h	44.3gh	60.2fg
P-value	**drought**	0.0000	0.0000	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0000	0.0000	0.0000	0.0000
	drought × Foliar	0.0000	0.0000	0.0000	0.0000	0.0000
		2nd season				
80%FC	**DW**	1.37ef	0.469ef	0.739e	69.1d	58.8f
	Si 2Mm	1.54d	0.514d	0.811d	76.2c	66.8d
	Si 4Mm	1.69c	0.553c	0.907c	76.7c	73.6c
	Si 6Mm	1.93b	0.618b	1.01b	84.5b	79.0b
	Si 8Mm	2.05a	0.675a	1.06a	96.3a	87.4a
60%FC	**DW**	1.11h	0.372h	0.598g	51.5hi	50.1hi
	Si 2Mm	1.25g	0.411g	0.649f	54.3gh	54.6g
	Si 4Mm	1.35f	0.442f	0.733e	59.0fg	62.2e
	Si 6Mm	1.45e	0.482e	0.797d	62.3ef	67.5d
	Si 8Mm	1.59d	0.556c	0.886c	66.4de	73.0c
40%FC	**DW**	0.61l	0.207k	0.327k	29.5l	43.1j
	Si 2Mm	0.66l	0.224k	0.366j	32.9l	47.6i
	Si 4Mm	0.74k	0.254j	0.389j	38.2k	51.3h
	Si 6Mm	0.818j	0.272j	0.438i	45.4j	56.6fg
	Si 8Mm	0.930i	0.305i	0.481h	48.8ij	62.9e
80%FC	**drought**	0.0000	0.0000	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0000	0.0000	0.0000	0.0000
	drought × Foliar	0.0000	0.0000	0.0000	0.0000	0.0000

Data are means (n=3) ± SE. Means followed by the same letter in each column are not significantly different according to the LSD test ($P \leq 0.05$). DW: distilled water.

Table (3). Impact of foliar application of Silicon (Si) on oxidative stress markers and enzymes activities of common bean (*Phaseolus vulgaris* L.) plants subjected to different drought stress levels

Parameter / Treatments		H_2O_2 level (µM g^{-1} FW)	$O_2^{\bullet-}$ level (µM g^{-1} FW)	SOD (A564 min−1 g−1 protein	CAT (A564 min−1 g−1 protein
drought	**Foliar spray**	**1st season**			
80%FC	**DW**	20.2g	0.822gh	2.04n	3.06l
	Si 2Mm	18.9h	0.780hi	2.22m	3.35k
	Si 4Mm	17.9i	0.754ij	2.46l	3.74j
	Si 6Mm	17.1j	0.705j	2.71j	4.06hi
	Si 8Mm	14.6k	0.639k	2.97h	4.49g
60%FC	**DW**	23.6d	0.975d	2.55k	3.85ij
	Si 2Mm	23.5de	0.936de	2.78i	4.22h
	Si 4Mm	22.8ef	0.905ef	3.08g	4.67g
	Si 6Mm	22.7f	0.875fg	3.41f	5.12f
	Si 8Mm	20.7g	0.843g	3.71e	5.647e
40%FC	**DW**	31.5a	1.29a	3.68e	5.584e
	Si 2Mm	28.7b	1.19b	4.05d	6.14d
	Si 4Mm	26.2c	1.09c	4.46c	7.08c
	Si 6Mm	26.0c	1.08c	4.91b	7.72b
	Si 8Mm	23.9d	0.979d	5.40a	8.84a
P-value	**drought**	0.0000	0.0000	0.0000	0.0000
	Foliar	0.0007	0.0000	0.0000	0.0000
	drought × Foliar	0.0017	0.0007	0.0008	0.0000
		2nd season			
80%FC	**DW**	21.2h	0.86hi	2.57m	3.08k
	Si 2Mm	19.9i	0.82ij	2.83l	3.39j
	Si 4Mm	18.9j	0.78jk	3.08k	3.73i
	Si 6Mm	18.0k	0.75k	3.41ij	4.08h
	Si 8Mm	15.4l	0.68l	3.78gh	4.51g
60%FC	**DW**	25.0d	1.03d	3.20jk	3.82i
	Si 2Mm	24.6e	0.99de	3.52hi	4.23h
	Si 4Mm	24.0f	0.94ef	3.89g	4.66g
	Si 6Mm	23.9f	0.93fg	4.29f	5.10f
	Si 8Mm	21.9g	0.88gh	4.70e	5.61e
40%FC	**DW**	33.3a	1.33a	4.64e	5.56e
	Si 2Mm	30.2b	1.23b	5.13d	6.06d
	Si 4Mm	27.7c	1.15c	5.63c	7.20c
	Si 6Mm	27.4c	1.13c	6.18b	7.62b
	Si 8Mm	25.1d	1.03d	6.81a	8.95a
80%FC	**drought**	0.0000	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0004	0.0000	0.0030
	drought × Foliar	0.0042	0.0067	0.0000	0.0045

Data are means (n=3) ± SE. Means followed by the same letter in each column are not significantly different according to the LSD test ($P \leq 0.05$). DW: distilled water, H_2O_2: hydrogen peroxide and $O_2^{\bullet-}$

Table (4). Impact of foliar application of Silicon (Si) on macronutrient contents (N, P, and K) of common bean (*Phaseolus vulgaris* L.) plants subjected to different drought stress levels

Parameter / Treatments		N (%)	p (%)	k (%)
drought	**Foliar spray**	**1st season**		
80%FC	**DW**	2.12d	0.489d	1.79d
	Si 2Mm	2.34c	0.515c	1.94c
	Si 4Mm	2.37c	0.531c	1.96c
	Si 6Mm	2.55b	0.582b	2.10b
	Si 8Mm	2.83a	0.645a	2.44a
60%FC	**DW**	1.52g	0.362h	1.29g
	Si 2Mm	1.71f	0.387g	1.41f
	Si 4Mm	1.87e	0.430f	1.60e
	Si 6Mm	1.95e	0.447ef	1.63e
	Si 8Mm	2.05d	0.463e	1.77d
40%FC	**DW**	0.84j	0.191l	0.714j
	Si 2Mm	0.92j	0.213k	0.757j
	Si 4Mm	1.05i	0.236j	0.85i
	Si 6Mm	1.17h	0.250j	0.95h
	Si 8Mm	1.25h	0.278i	1.02h
P-value	**drought**	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0000	0.0000
	drought × Foliar	0.0000	0.0000	0.0012
		2nd season		
80%FC	**DW**	2.13de	0.518d	1.88d
	Si 2Mm	2.21cd	0.543cd	2.01c
	Si 4Mm	2.30c	0.569c	2.09c
	Si 6Mm	2.61b	0.608b	2.31b
	Si 8Mm	2.87a	0.674a	2.495a
60%FC	**DW**	1.59i	0.380g	1.33h
	Si 2Mm	1.68h	0.406g	1.52g
	Si 4Mm	1.91gi	0.441f	1.67f
	Si 6Mm	2.00fg	0.460ef	1.70ef
	Si 8Mm	2.09ef	0.484e	1.78e
40%FC	**DW**	0.86m	0.198k	0.742m
	Si 2Mm	0.97l	0.225j	0.822l
	Si 4Mm	1.03l	0.257i	0.930k
	Si 6Mm	1.14k	0.281hi	1.01j
	Si 8Mm	1.26j	0.307h	1.10i
80%FC	**drought**	0.0000	0.0000	0.0000
	Foliar	0.0000	0.0000	0.0000
	drought × Foliar	0.0007	0.0010	0.0005

Data are means (n=3) ± SE. Means followed by the same letter in each column are not significantly different according to the LSD test ($P \leq 0.05$). DW: distilled water, N: Nitrogen, P: Phosphorus and K: Potassium.

4. Conclusion

In conclusion, drought stress represents a major environmental limitation that severely impairs the growth, physiological performance, and productivity of the common bean (*Phaseolus vulgaris* L., cv. Bronco). However, the exogenous foliar application of potassium silicate (K_2SiO_3) demonstrated a profound mitigating effect against drought-induced adversities. The treatment effectively enhanced leaf relative water content (RWC) and relative water loss (RWL), and supported photosynthetic pigments under water-deficit conditions. Furthermore, potassium silicate upregulated antioxidant enzymes (SOD and CAT) to scavenge reactive oxygen species (ROS). Additionally, the application successfully restored the leaf nutritional status by mitigating nutrient starvation (N, P, and K) caused by severe drought. Overall, foliar application of potassium silicate particularly at the highest concentration (8 mM) serves as a highly effective, sustainable, and multifaceted biostimulant strategy to fortify drought tolerance and safeguard the yield of common bean crops cultivated under water-limited

4. References

[1] **Barrs, H. D., & Weatherley, P. E. (1962).** A reexamination of the relative turgidity technique for estimating water deficits in leaves. Australian Journal of Biological Sciences, 24(3), 519–570. https://doi.org/10.1071/BI9620519

[2] **Bates, L. S., Waldren, R. P., & Teare, I. D. (1973).** Rapid determination of free proline for water stress studies. Plant and Soil, 39(1), 205–207. https://doi.org/10.1007/BF00018060

[3] **Broughton, W. J., Hernández, G., Blair, M., Beebe, S., Gepts, P., & Vanderleyden, J. (2003).** Beans (Phaseolus spp.) – model food legumes. Plant and Soil, 252(1), 55–128. https://doi.org/10.1023/A:1024646215694

[4] **Chance, B., & Maehly, A. C. (1955).** Assay of catalase and peroxidases. Methods in Enzymology, 2, 764–775. https://doi.org/10.1016/S0076-6879(55)02300-8

[5] **Chapman, H. D., & Pratt, F. P. (1982).** Determination of minerals by titration method. In Methods of analysis for soils, plants and water (pp. 169–170). Agriculture Division, University of California, Riverside.

[6] **Cooke, J., & Leishman, M. R. (2016).** Consistent alleviation of abiotic stress with silicon addition: A meta-analysis. Functional Ecology, 30(8), 1340–1357. https://doi.org/10.1111/1365-2435.12713

[7] **Coskun, D., Deshmukh, R., Sonah, H., Menzies, J. G., Reynolds, O., Ma, J. F., ... & Belzile, F. (2019).** The controversies of silicon's role in plant biology. New Phytologist, 221(1), 67–85. https://doi.org/10.1111/nph.15343

[8] **Dalal, V. K., & Tripathy, B. C. (2012).** Modulation of chlorophyll biosynthesis by water stress in rice seedlings during chloroplast biogenesis. Plant, Cell & Environment, 35(9), 1685–1703. https://doi.org/10.1111/j.1365-3040.2012.02520.x

[9] **Debona, D., Rodrigues, F. A., & Datnoff, L. E. (2017).** Silicon's role in abiotic and biotic plant stresses. Annual Review of Phytopathology, 55, 85–107. https://doi.org/10.1146/annurev-phyto-080516-035312

[10] **Etesami, H., & Jeong, B. R. (2018).** Silicon (Si): Review and future prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants. Ecotoxicology and Environmental Safety, 147, 881–896. https://doi.org/10.1016/j.ecoenv.2017.09.063

[11] **Fadeel, A. A. (1962).** Location and properties of chloroplasts and pigment determination in roots. Physiologia Plantarum, 15(1), 130–147. https://doi.org/10.1111/j.1399-3054.1962.tb07994.x

[12] **Fielding, J. L., & Hall, J. L. (1978).** A biochemical and cytochemical study of peroxidase activity in roots of Pisum sativum. Journal of Experimental Botany, 29(4), 969–981. https://doi.org/10.1093/jxb/29.4.969

[13] **Foyer, C. H., Baker, A., Wright, M., & Sparkko, M. (2020).** Reactive oxygen species, oxidative signaling and the regulation of photosynthesis. Environmental and Experimental Botany, 172, 103946. https://doi.org/10.1016/j.envexpbot.2020.103946

[14] **Gavuzzi, P., Rizza, F., Palumbo, M., Campanile, R. G., Ricciardi, G. L., & Borghi, B. (1997).** Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. Canadian Journal of Plant Science, 77(4), 523–531. https://doi.org/10.4141/P96-129

[15] **Gong, H., Zhu, X., Chen, K., Wang, S., & Zhang, C. (2005).** Silicon alleviates oxidative damage of wheat plants in pots under drought. Plant Science, 169(2), 313–321. https://doi.org/10.1016/j.plantsci.2005.02.023

[16] **Gupta, A., Rico-Medina, A., & Caño-Delgado, A. I. (2020).** The physiology of plant responses to drought. Science, 368(6488), 266–269. https://doi.org/10.1126/science.aaz7614

[17] **Hasanuzzaman, M., Bhuyan, M. H. M. B., Zulfiqar, F., Raza, A., Mohsin, S. M., Mahmud, J. A., ... & Fotopoulos, V. (2020).** Reactive oxygen species and antioxidant defense in plants under abiotic stress:

Revisiting the crucial role of a universal defense regulator. Antioxidants, 9(8), 681. https://doi.org/10.3390/antiox9080681

[18] **Hu, Y., & Schmidhalter, U. (2005).** Drought and salinity: A comparison of their effects on mineral nutrition of plants. Journal of Plant Nutrition and Soil Science, 168(4), 541–549. https://doi.org/10.1002/jpln.200420516

[19] **Irigoyen, J. J., Einerich, D. W., & Sánchez-Díaz, M. (1992).** Water stress induced changes in concentrations of proline and total soluble sugars in nodulated alfalfa (Medicago sativa) plants. Physiologia Plantarum, 84(1), 55–60. https://doi.org/10.1111/j.1399-3054.1992.tb08764.x

[20] **Kubiś, J. (2008).** Exogenous spermidine differentially alters activities of some scavenging system enzymes, H_2O_2 and superoxide radical levels in water-stressed cucumber leaves. Journal of Plant Physiology, 165(4), 397–406. https://doi.org/10.1016/j.jplph.2007.02.005

[21] **Lachica, M., Aguilar, A., & Yañez, J. (1973).** Análisis foliar: Métodos utilizados en la Estación Experimental del Zaidín. Anales de Edafología y Agrobiología, 32(11–12), 1033–1047.

[22] **Luyckx, M., Hausman, J. F., Lutts, S., & Guerriero, G. (2017).** Silicon and plants: Current knowledge and technological perspectives. Frontiers in Plant Science, 8, 411. https://doi.org/10.3389/fpls.2017.00411

[23] **Meena, M., Divyanshu, K., Kumar, S., Swapnil, P., Zehra, A., Shukla, V., ... & Upadhyay, R. S. (2019).** Regulation of L-proline biosynthesis, signal transduction, transport, accumulation and its vital role in plants during variable environmental conditions. Heliyon, 5(12), e02952. https://doi.org/10.1016/j.heliyon.2019.e02952

[24] **Mukherjee, S. P., & Choudhuri, M. A. (1983).** Implication of water stress-induced changes in the levels of endogenous ascorbic acid and hydrogen peroxide in Vigna seedlings. Physiologia Plantarum, 58(2), 166–170. https://doi.org/10.1111/j.1399-3054.1983.tb04162.x

[25] **Rizwan, M., Ali, S., Ibrahim, M., Farid, M., Adrees, M., Bharwana, S. A., ... & Abbas, F. (2015).** Mechanisms of silicon-mediated alleviation of drought and salt stress in plants: A review. Environmental Science and Pollution Research, 22(20), 15416–15431. https://doi.org/10.1007/s11356-015-5305-x

[26] **Sairam, R. K., Rao, K. V., & Srivastava, G. C. (2002).** Differential response of wheat genotypes to long term salinity stress in relation to oxidative stress, antioxidant activity and osmolyte concentration. Plant Science, 163(5), 1037–1046. https://doi.org/10.1016/S0168-9452(02)00278-9

[27] Seleiman, M. F., Al-Suhaibani, N., Ali, N., Akmal, M., Alotaibi, M., Refay, Y., Dindaroglu, T., Abdul-Wajid, H. H., & Battaglia, M. L. (2021). Drought Stress Impacts on Plants and Different Approaches to Alleviate Its Adverse Effects. *Plants*, *10*(2), 259. https://doi.org/10.3390/plants10020259

[28] **Shen, X., Zhou, Y., Duan, L., Li, Z., Eneji, A. E., & Li, J. (2010).** Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. Journal of Plant Physiology, 167(15), 1248–1252. https://doi.org/10.1016/j.jplph.2010.04.011

[29] **Watanabe, F. S., & Olsen, S. R. (1965).** Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Science Society of America Proceedings, 29(6), 677–678. https://doi.org/10.2136/sssaj1965.03615995002900060025x

[30] **Wolf, B. (1982).** A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. Communications in Soil Science and Plant Analysis, 13(12), 1035–1059. https://doi.org/10.1080/00103628209367332

[31] **Zargar, S. M., Mahajan, R., Bhat, J. A., Nazir, M., & Deshmukh, R. (2019).** Role of silicon in plant stress tolerance: Opportunities to achieve a sustainable pathway for optimum food security. Frontiers in Plant Science, 10, 535. https://doi.org/10.3389/fpls.2019.00535