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Ameliorating effects of foliar potassium silicate application on dry beans under salinity stress

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ABSTRACT

In recent years, research on reducing salinity stress in plants using potassium silicate (K_2SiO_3) has been increasing. However, there is no scientific research which shows the positive or negative impacts of this molecule on dry beans in decreasing salinity stress. Therefore, the aim of this study is to investigate the possible effects of foliar K_2SiO_3 application on dry beans growth and yield in attenuating the adverse effects of salinity. Four different salinity levels of irrigation water (control-0.6 dS m^{-1}, low-1.6 dS m^{-1}, medium-3.0 dS m^{-1} and high-4.8 dS m^{-1}) and three different foliar K_2SiO_3 application doses (0, 2 and 4 mM) were tested simultaneously as two different factors. In general, the results showed that the salinity of irrigation water significantly raised soil salinity and drainage water salinity, however it decreased consumption of plant water, efficiency of water use and growth and yield parameters of dry beans. In addition, a foliar K_2SiO_3 application had a slightly positive effect on the efficiency of water use, plant height, pod number and dry biological, pod and seed yields. The salinity threshold value was slightly and moderately increased by the 2 and 4 mM K_2SiO_3 applications, respectively. Overall, the results suggest that foliar K_2SiO_3 application at the applied concentrations has an insignificant effect in ameliorating the salinity stress tolerance on dry beans.

1. Introduction

Although it can be grown in almost any soil, many abiotic stresses in addition to biotic stress factors negatively affect the performance and productivity of beans (*Phaseolus vulgaris* L.). Considering the increased salinity problems in both soil and water resources, it is thought that the most critical threat to the production of dry beans in the future will be salinity stress (Cokkizgin 2012). It is reported that the bean plant is very sensitive to salinity because the salinity threshold ($EC_{ex\text{-}thresh}$) is as low as 1.0 dS m^{-1}, and the relative yield reduction per unit increase in EC_{ex} beyond the threshold reaches 19%. In addition, the yield loss for bean plants at 0.7, 1.0, 1.5, 2.4 and 4.2 dS m^{-1} irrigation water salinities (EC_{iw}) were 0%, 10%, 25%, 50% and 100%, respectively (Ayers and Westcot 1985).

Currently, significant research is planned to examine the effects of potassium and calcium in terms of increasing the tolerance of plants to environmental stress (Bybordi 2016), while there is also data based on the positive effects of foliar spraying with micronutrients to enhance the plans resistance to salinity stress (Van Bockhaven et al. 2013). Although considered a "non-essential" plant mineral nutrient, silicon has been shown to improve plant tolerance to abiotic stresses such as nutrient toxicity or deficiency (Das et al. 2019) and also salinity and drought (Coskun et al. 2016). Possible mechanisms by which potassium and silicon alleviate salt stress include maintaining plant water status, reducing ion toxicity and oxidative damage, regulating plant hormone levels and facilitating biosynthesis of solutes (Tantawy et al. 2015). Therefore, foliar applications of potassium silicate (K_2SiO_3) in liquid form could be used as a promising alternative to reduce the damage caused by abiotic stress. However, the significance of K_2SiO_3 for plant growth and development remains debated due to the large differences in plant uptake capacity.

In the last decade, the effectiveness of K_2SiO_3 applications on plants such as wheat (Osman et al. 2017), tomatoes (Oztekin et al. 2018), chickpeas (Garg and Bhandari 2016), strawberries (Yaghubi et al. 2016), cucumbers (Ouzounidou et al. 2016), canola (Bybordi 2016), pepper (Manivannan et al. 2016), grass (Esmaeili et al. 2015), mung bean (Mahmood et al. 2017), onion (Bybordi et al. 2018), and zucchini (Savvas et al. 2009) have been investigated to raise their resistance to salinity stress. To date, no studies have been reported in the literature on the effects of K_2SiO_3 applications on the dry bean growth, yield, and quality parameters under salt stress. Therefore, the aim of this study was to investigate the possible effects of foliar K_2SiO_3 application on dry beans growth and yield in attenuating the unfavourable effects of salinity.

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2. Materials and Methods

2.1. Experimental area and plant material

To study the possible ameliorating effects of K_2SiO_3 on dry beans grown under salinity stress, a two-year study was performed under a polyethylene-covered rainout shelter (temperature 16.8-36.4°C, relative humidity 52.3-62.0%) at the Agricultural Research Area (36°53'15"N; 30°38'53"E) of Akdeniz University, Türkiye, located at 54 m above mean sea level. In both years the experiment started in August and continued until November. In the experiment, uniformly well-grown Elkoca-05 dry bean cultivars were used. This cultivar has a high tolerance to bacterial and viral diseases and matures in approximately 90-100 days (Elkoca and Kantar 2005). The seeds of Elkoca-05 dry bean variety used in the experiment were supplied by Prof. Dr. Faik Kantar (Atatürk University, Faculty of Agriculture, Erzurum, Türkiye), who is the breeder of this variety.

2.2. Plant growing medium

In the experiment, weighable drainage-type lysimeters (48 cm in diameter and 70 cm in height) were used. The lysimeters were able to collect the leachate water in a drainage container located at the bottom. All lysimeters were filled with approximately 170 kg of air-dried soil sieved with a 4 mm fine screen. The texture of the experimental soil was sandy loam. The weight-based field capacities and wilting points of soil were 20.1 and 9.92% in 2019, and 21.9 and 9.95% in 2020, respectively. Similarly, the initial saturated paste extracts electrical conductivities of the soil (EC_{ex}) were 0.70 and 0.72 dS m^{-1}, respectively.

2.3. Experimental design and treatments

Since two different factors, including irrigation water salinity levels (WSL) and K_2SiO_3 application doses, were investigated in the study, a factorial experiment was conducted in a randomized complete block with three replications. The factorial combination of four WSL including control (WSL_0= 0.6 dS m^{-1}), low (WSL_1= 1.6 dS m^{-1}), moderate (WSL_2= 3.0 dS m^{-1}) and high (WSL_3= 4.8 dS m^{-1}) with three K_2SiO_3 application doses including control (0 mM), 308.56 ppm K_2SiO_3 (2 mM) and 617.12 ppm K_2SiO_3 (4 mM) were used as treatments. The selection of treatments for WSL and K_2SiO_3 were based on the salinity threshold values and bean relative yield losses (Ayers and Westcot 1985), and suggested K_2SiO_3 doses for various plants (Esmaeili et al. 2015, Bybordi et al. 2018), respectively.

Additional sodium, calcium and magnesium salts were used to prepare the saline waters at different concentration levels. Thus, the SAR (sodium adsorption ratio) value was kept similar to that of the control salinity level in order to explore only the influences of the total salinity but not the prevailing effect of a certain ion (Hancioglu et al. 2019). In the experiment, the required K_2SiO_3 dosages were prepared by dissolving the required grams of K_2SiO_3 salt in pure water. 0.1% concentration of Tween-20 was transferred to the prepared solutions as a surfactant to reduce the surface tension.

2.4. Cultural practices and applications

Fertilizers were applied based on the soil analyses and crop needs (20 kg N ha^{-1} for, 60 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}) (Elkoca and Kantar 2005). The total amount of P and K, in addition to half of N were applied just before the seed sowing, and the remaining half of nitrogen was applied at the flowering phase. Four seeds were sown at a depth of 3 cm in August. Only control water was applied until the seedling establishment. After the seedling establishment, thinning application was performed to leave one plant per lysimeter.

Irrigation scheduling was determined by monitoring the change in soil water status in the control treatments by weighing the lysimeters every other day throughout the growing period in 2019 and 2020. Irrigation practices were performed in all treatments whenever the available water decreased to 45-55% in the soil of the control lysimeters (Doorenbos and Kassam 1986). The volume of irrigation water (AIW in L) that should be applied to each lysimeter was calculated by using the lysimeter weights at field capacity (W_{fc} in kg) and right before irrigation (W_a in kg) in addition to a leaching fraction (LF) of 18% (Hancioglu et al. 2019):

$$AIW = \left(W_{fc} - W_a\right) / \left[(1 - LF) \times \rho_w\right] \quad [1]$$

Where, ρ_w is the water bulk density (1 kg L^{-1}).

A hand-operated sprayer was used to spray the targeted doses of K_2SiO_3 onto the plant leaves. Only pure water was sprayed onto the control K_2SiO_3 (0 mM) plants (Esmaeili et al. 2015, Osman et al. 2017).

2.5. Data measurements

After each irrigation cycle the quantity of leachate drainage water (DRW in L) collected in each lysimeter container was calculated and an EC analysis of the drainage water (EC_{drw}) was realized in situ. The amount of drainage water was used to estimate the crop evapotranspiration and as feedback to monitor the targeted leaching fraction. The following water balance equation was considered to estimate the volumetric crop water use or evapotranspiration (ET_v in L) between two consecutive irrigation cycles:

$$ET_v = \left[\left(W_n - W_{n+1}\right) / \rho_w\right] + (AIW - DRW) \quad [2]$$

where: W_n and W_{n+1} are the weights determined by lysimeter at two consecutive irrigations (kg), ρ_w is water bulk density (1 kg L^{-1}). Then ET_v was converted to depth based on daily ET (ET_d in mm day^{-1}) by considering the lysimeter surface soil area and time in days between the two consecutive irrigation cycles. At the end of each growing period the seasonal ET (ET_s in mm $season^{-1}$) was calculated.

Right before harvest, stem diameters, plant heights and pod lengths were calculated accurately. After harvest, the seed and pod numbers were counted, and yield parameters (dry vegetative, dry biological, dry pod and dry seed) were measured in the analytical laboratory. Soil samples from each lysimeter were obtained to determine the soil salinity status by the saturated soil paste extract method.

The water use efficiencies (WUE) were calculated by using the following equation (Howell et al. 1990).

$$WUE = Y / ET_s \quad [3]$$

where: ET_s: seasonal evapotranspiration (mm $season^{-1}$) and Y: dry seed yield (mg).

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The salt tolerance model as indicated by (Maas and Hoffman 1977) was used to calculate the soil salinity level and slope values for dry seed yields:

$$Y_a/Y_m = 1-(EC_{ex} - EC_{ex-thresh})\times b/100 \qquad [4]$$

where: Y_m and Y_a are the maximum and actual dry seed yields (gr) under the control (non-saline) and the saline applications, respectively, EC_{ex} is soil salinity beyond the threshold value (dS m^{-1}), $EC_{ex\text{-}thresh}$ is threshold soil salinity, and b is the slope value (% per dS m^{-1}).

2.6. Data analysis

All experimental data were subjected to a two-way ANOVA for variance analysis. In the statistical analysis, WSL in four levels (0.6, 1.6, 3.0 and 4.8 dS m^{-1}) was the first factor and K_2SiO_3 application doses in three levels (0, 2 and 4 mM) was the second factor. All statistical analyses were fulfilled at $P\leq0.01$ level of significance unless stated otherwise. The mean values were compared to the Duncan test at a $P\leq0.05$ level of significance by SAS software (Version 13.0). In the presence of a significant interaction among the factors for any parameter, statistical evaluations of that parameter were performed by the factorial level (WSL x K_2SiO_3); otherwise the main factors (WSL and K_2SiO_3) were evaluated individually.

3. Results

3.1. Salinities of soil and drainage water, and evapotranspiration

Meaningful interactions for salinity of the soil between the main factors (WSL x K_2SiO_3) were found both in 2019 ($P\leq0.05$) and 2020. The maximum EC_{ex} values were found under high WSL with 4 mM and 0 mM K_2SiO_3, while the minimum values were found for each K_2SiO_3 under WSL_0 and WSL_1 in 2019, (Table 1). The EC_{ex} values under K_2SiO_3 with WSL_2 and WSL_3 were 5.3-9.0 and 13.4-18.9 times, respectively, higher than those

Table 1. Effects of water salinity and potassium silicate on salinities of soil and drainage water, evapotranspiration of crop and water use efficiency

Parameter	Year	K_2SiO_3 (mM)	Salinity level (dS m^{-1}) 0.6		1.6		3.0		4.8		P > F	Mean	
Soil salinity (dS m^{-1})	2019	0	0.66	†e#	2.28	de	3.76	cd	7.15	ab			
		2	0.52	e	2.10	de	4.68	c	6.98	b			
		4	0.53	e	1.73	de	2.75	cd	9.84	a			
	2020	0	0.78	e	2.16	d	4.11	c	6.37	b			
		2	0.85	e	2.17	d	4.37	c	6.48	b			
		4	0.91	e	2.28	d	4.16	c	7.24	a			
Average drainage water salinity (dS m^{-1})	2019	0	1.07	B‡	1.84	AB	2.36	A	2.43	A	*	1.93	
		2	1.06	C	1.51	BC	1.90	AB	2.05	A	**	1.61	
		4	1.12	B	1.61	AB	2.25	A	2.16	A	*	1.78	
		P > F	ns		ns		ns		ns			ns	
		Mean	1.09	C	1.65	B	2.16	A	2.21	A	**		
	2020	0	0.67	B	1.09	B	1.69	A	2.15	A	**	1.40	
		2	0.63	C	1.06	C	1.62	B	2.42	A	**	1.43	
		4	0.66	C	1.20	B	1.43	B	1.88	A	**	1.29	
		P > F	ns		ns		ns		ns			ns	
		Mean	0.65	D	1.12	C	1.58	B	2.15	A	**		
Evapotranspiration (mm season^{-1})	2019	0	496.9		530.5		465.7		437.3		ns	482.6	
		2	554.8	A	472.8	B	436.2	BC	410.7	C	**	468.6	
		4	523.5	A	509.6	A	481.9	A	415.3	B	*	482.6	
		P > F	ns		ns		ns		ns			ns	
		Mean	525.1	A	504.3	A	461.3	B	421.1	C	**		
	2020	0	623.7	A	545.0	B	469.9	C	390.8	D	**	507.3	
		2	598.0	A	538.4	AB	469.1	BC	419.9	C	*	506.4	
		4	630.9	A	592.2	A	415.9	B	370.2	B	**	502.3	
		P > F	ns		ns		ns		ns			ns	
		Mean	617.5	A	558.5	B	451.6	C	393.6	D	**		
Water use efficiency (mg mm^{-1})	2019	0	4.9	bc	7.1	bc	1.2	c	0.0	c			
		2	35.6	a	2.2	bc	5.6	bc	0.0	c			
		4	12.3	b	5.5	bc	12.6	b	0.4	c			
	2020	0	23.2	Ab£	17.9	B	12.8	C	10.1	C	**	16.0	b
		2	29.4	Aa	22.7	AB	15.1	BC	8.8	C	*	19.0	b
		4	32.0	Aa	30.2	A	20.3	B	10.0	C	**	23.1	a
		P > F	*		ns		ns		ns			**	
		Mean	28.2	A	23.6	B	16.1	C	9.6	D	**		

*: $P<0.05$, **: $P<0.01$, ns: non-significant, #: within each year, no significance on values with the same italic lowercase letter, ‡: within each row, no significance on values with the same uppercase letter, £: within each column, no significance on values with the same lowercase letter.

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of the minimum value. Similarly, the maximum EC_{ex} value (7.24 dS m^{-1}) in 2020 determined under WSL_3 with 4 mM K_2SiO_3 treatment and the minimum EC_{ex} values occurred under WSL_0 with all K_2SiO_3 doses (between 0.78 and 0.91 dS m^{-1}) (Table 1). The EC_{ex} values under K_2SiO_3 with WSL_1, WSL_2 and WSL_3 were 2.8-2.9, 5.3-5.6, and 8.2-9.3 times, respectively, higher than those of the minimum EC_{ex} value.

The seasonal mean EC_{drw} did not illustrate a significant difference statistically in terms of WSL x K_2SiO_3 interaction. On the other hand, EC_{drw} showed significant differences for the main factor WSL in 2019 and 2020, however not for K_2SiO_3 treatments. With respect to WSL_0, EC_{drw} values were 1.50, 1.98, and 2.03 times in 2019 and 1.72, 2.43, and 3.31 times in 2020 under WSL_1, WSL_2 and WSL_3, respectively. There was no significant difference for EC_{drw} among K_2SiO_3 under any WSL, but differences were observed among WSL under each K_2SiO_3 at the 1% or 5% level of significance in both seasons. The maximum EC_{drw} values were observed with WSL_3 in both 2019 and 2020 but this value was not found significantly different from those with WSL_2 under 2 mM K_2SiO_3; with WSL_1 and WSL_2 under 0 and 4 mM K_2SiO_3 in 2019 and from that with WSL_3 under 0 mM K_2SiO_3 in 2020 (Table 1).

WSL x K_2SiO_3 interaction and main factor K_2SiO_3 did not show significant differences for crop ET in both seasons. On the other hand, significant differences in both years under WSL were detected for ET. Crop ET values varied between 421 (under WSL_3) and 525 (under WSL_0) mm $season^{-1}$ in 2019, and between 394 (under WSL_3) and 618 (under WSL_0) mm $season^{-1}$ in 2020. With respect to WSL_0, ET declined by 12% and 20% under WSL_2 and WSL_3, respectively, in 2019, and by 10%, 27%, and 36% under WSL_1 WSL_2 and WSL_3, respectively, in the second year. In both seasons, ET values did not show significant differences among K_2SiO_3 under any WSL. However, increasing irrigation water salinity under each K_2SiO_3 (except 0 mM K_2SiO_3 in 2019) generally caused a decline in ET values (Table 1).

A statistically significant WSL x K_2SiO_3 interaction for WUE was found in 2019 ($P \leq 0.05$), but not in 2020. In 2019, the maximum WUE value was found under WSL_0 with 2 mM K_2SiO_3 application, while the minimum WUE values were obtained for all K_2SiO_3 under WSL_0 (except 2 and 4 mM K_2SiO_3), WSL_1, WSL_2 (except 4 mM K_2SiO_3), and WSL_3 application (Table 1). With respect to the maximum WUE, the declineranged between 80% and 100%. In 2020, the WUE data showed significant differences statistically under both main factors (WSL and K_2SiO_3). With respect to WSL_0, declines in WUE values were 16%, 43%, and 66% under WSL_1, WSL_2 and WSL_3, respectively. Similarly, with respect to 0 mM K_2SiO_3, WUE values declined by 44% under 4 mM K_2SiO_3 treatment in 2020. Among WSL treatments, WUE statistically differed under each K_2SiO_3 treatment at the 1% or 5% significance level. Under these K_2SiO_3 applications, the maximum WUE was generally determined from WSL_0 and WSL_1. In addition, increasing K_2SiO_3 applications, only under the control WSL in 2020, caused a significant increment in WUE (Table 1).

3.2. Growth parameters

In both seasons, the interaction of the two factors was not significant for plant height values. Plant height values exhibited significant differences statistically under each main factor in 2020, but only under WSL in 2019. With respect to WSL_0, plant heights declined by 85% under WSL_3 in 2019, and by 14%, 24%, and 37% under WSL_1, WSL_2 and WSL_3 applications, respectively, in the second year. Likewise, with respect to 0 mM K_2SiO_3, plant heights increased by 24% and 20% under 2 and 4 mM K_2SiO_3 in 2020. In both seasons, plant heights did not differ significantly among K_2SiO_3 under any WSL. In addition, the increase of irrigation water salinity under each K_2SiO_3 generally caused a decline in this parameter in both seasons ($P \leq 0.05$ in 2020) (Table 2).

For stem diameter values, the interaction of the two factors, in addition to K_2SiO_3 were not significant in both seasons. On the other hand, this parameter in both years exhibited significant differences under WSL. With regard to WSL_0, stem diameters under WSL_3 declined by 73% and 9% respectively, in 2019 and 2020. Stem diameter did not show a significant difference among K_2SiO_3 treatments under any WSL in both 2019 and 2020. However, this parameter declined by WSL_3 under 2 and 4 ppm ($P \leq 0.05$) K_2SiO_3 in 2019 and under only 4 mM K_2SiO_3 ($P \leq 0.05$) in 2020 (Table 2).

Similar to stem diameter, the interaction of the two factors, in addition to K_2SiO_3 were not significant for pod length values in both seasons, but WSL showed significant differences ($P \leq 0.01$ in 2019 and $P \leq 0.05$ in 2020) for this parameter. With respect to WSL_0, pod lengths declined under WSL_2 and WSL_3 by 48% and 85% in 2019, and 6% and 8% in 2020, respectively. Pod length under only WSL_1 showed a significant difference among K_2SiO_3 treatments ($P \leq 0.05$) in 2020. Similarly, this parameter declined by WSL_2 and WSL_3 under only 0 mM K_2SiO_3 in 2019 (Table 2).

Statistically significant interaction of the two factors for the number of pods was found in both years ($P \leq 0.05$). The maximum number of pods was counted for WSL_0 with 2 mM K_2SiO_3 treatment (11.3 pods $plant^{-1}$) in 2019 and for WSL_0 and WSL_1 with 4 mM K_2SiO_3 (15.0 and 14.1 pods $plant^{-1}$, respectively) in 2020 (Table 2). The decline in the number of pods were between 47% and 100% in 2019, and 20% and 78% in 2020.

Statistically significant interaction of the two factors for the number of seeds was obtained in 2019, but not in 2020. In 2019, the maximum number of seeds were obtained under WSL_0 with 2 mM K_2SiO_3 (34.5 seeds $plant^{-1}$) (Table 2). The reductions in the number of seeds were between 58% and 100%. In 2020, the number of seeds showed significant differences statistically under both main factors (WSL and K_2SiO_3). With respect to WSL_0, the number of seeds declined by 20%, 47% and 74% under WSL_1, WSL_2 and WSL_3, respectively. Similarly, with respect to 0 mM K_2SiO_3, the number of seeds increased by 37% under the 4 mM K_2SiO_3 treatment in 2020. Among WSL treatments, the number of seeds differed statistically under each K_2SiO_3 treatment. Under these K_2SiO_3 applications, the maximum values were generally obtained from WSL_1 and WSL_2 treatments. In addition, the number of seeds indicated a significant increment with the 4 mM K_2SiO_3 treatment only under WSL_0 (Table 2).

3.3. Yield parameters

For dry vegetative yield, WSL x K_2SiO_3 interaction was meaningful in 2020 however not in 2019. In 2019, dry vegetative yields exhibited significant differences statistically under WSL but not under K_2SiO_3. With respect to WSL_0, dry vegetative yields decreased by 37%, 28% and 89% under WSL_1, WSL_2 and WSL_3, respectively. Additionally, dry vegetative yield did not differ significantly among K_2SiO_3 under any WSL. However, this parameter significantly declined especially under WSL_3 with each K_2SiO_3 in 2019. In 2020, WSL_0 with 4 mM K_2SiO_3 yielded

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Table 2. Effects of water salinity level and potassium silicate dosage on some growth parameters of dry beans

Parameter	Year	K_2SiO_3 (mM)	Salinity level (dS m^{-1})				$P > F$	Mean
			0.6	1.6	3.0	4.8		
Plant height (cm)	2019	0	86.17†A‡	85.17A	66.33A	23.00B	**	65.17
		2	88.00A	78.00A	77.33A	0.00B	**	60.83
		4	92.17A	82.33A	86.66A	18.33B	**	69.87
		P > F	ns	ns	ns	ns		ns
		Mean	88.78A	81.83A	76.78A	13.77B	**	
	2020	0	88.44A	78.22AB	69.11B	60.22B	*	74.00b£
		2	111.67A	98.72AB	85.06BC	72.89C	*	92.08a
		4	113.33A	92.89AB	83.11BC	64.67C	*	88.50a
		P > F	ns	ns	ns	ns		**
		Mean	104.48A	89.94B	79.09B	65.92C	**	
Stem diameter (mm)	2019	0	6.41	7.10	6.73	3.77	ns	6.01
		2	7.46A	7.10A	6.31A	0.00B	**	5.21
		4	7.09A	6.89A	7.05A	2.00B	*	5.75
		P > F	ns	ns	ns	ns		ns
		Mean	6.98A	7.03A	6.70A	1.91B	**	
	2020	0	7.03	6.91	6.79	6.52	ns	6.81
		2	6.64	7.31	6.88	6.78	ns	6.90
		4	7.22A	7.17A	6.73A	5.69B	*	6.70
		P > F	ns	ns	ns	ns		ns
		Mean	6.97A	7.13A	6.80A	6.33B	**	
Pod length (cm)	2019	0	11.84A	11.31A	3.33B	0.00B	**	6.62
		2	13.27	4.78	8.98	0.00	ns	6.76
		4	11.26	6.93	6.91	4.22	ns	7.31
		P > F	ns	ns	ns	ns		ns
		Mean	12.13A	7.67AB	6.37B	1.41C	**	
	2020	0	11.08	10.40b	10.33	9.81	ns	10.41
		2	11.00	11.10a	10.87	10.04	ns	10.75
		4	11.48	10.45b	10.21	11.01	ns	10.79
		P > F	ns	*	ns	ns		ns
		Mean	11.19A	10.7 65AB	10.47B	10.29B	*	
Number of pods (per plant)	2019	0	3.83*bc*#	4.33*bc*	1.00*bc*	0.00*c*		
		2	11.33*a*	1.00*bc*	3.50*bc*	0.00*c*		
		4	4.50*bc*	4.00*bc*	6.00*b*	1.00*bc*		
	2020	0	11.56*bcd*	9.22*de*	6.55*ef*	4.77*fg*		
		2	12.00*bc*	111.1*cd*	7.67*e*	4.74*fg*		
		4	14.11*ab*	15.00*a*	8.22*e*	3.33*g*		
Number of seeds (per plant)	2019	0	8.83*bc*	12.66*bc*	1.00*bc*	0.00*c*		
		2	34.50*a*	4.00*bc*	10.67*bc*	0.00*c*		
		4	12.00*bc*	10.00*bc*	14.33*b*	2.00*bc*		
	2020	0	31.11Ab	22.67B	16.67C	10.11D	**	20.13b
		2	35.00Ab	28.89A	18.67B	9.34B	**	22.97b
		4	42.78Aa	36.11A	22.55B	8.78C	**	27.56a
		P > F	*	ns	ns	ns		**
		Mean	36.30A	29.22B	19.30C	9.41D	**	

*: $P<0.05$, **: $P<0.01$, ns: non-significant, #: within each year, no significance on values with the same italic lowercase letter, ‡: within each row, no significance on values with the same uppercase letter, £: within each column, no significance on values with the same lowercase letter.

the maximum dry vegetative yield (21.6 gr $plant^{-1}$) (Table 3). The decline in dry vegetative yields ranged between 21% and 61%.

Statistically significant interactions for the two factors for dry pod, dry biological and dry seed yields were obtained in 2019, however not in 2020. In 2019, WSL_0 with 2 mM K_2SiO_3 treatment yielded the maximum dry biological (60.5 gr $plant^{-1}$), pod (31.9 gr $plant^{-1}$), and seed (19.6 gr $plant^{-1}$) yields (Table 3). The decline for the treatment combinations were between 55% and 100% in dry biological yield, between 68% and 100% in dry pod yield, and between 81% and 100% in dry seed yield.

In 2020, dry biological, pod, and seed yields were significantly different under both main factors (WSL and K_2SiO_3). With respect to WSL_0, a decrease under WSL_1, WSL_2 and WSL_3 treatments were 22%, 49%, and 65% for dry biological yield; 24%, 57%, and 78% for dry pod yield; and 23%, 59%, and 79% for dry seed yield, respectively. Under 4 mM K_2SiO_3

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Table 3. Effects of water salinity level and potassium silicate dosage on some yield parameters of dry beans

Parameter	Year	K_2SiO_3 (mM)	Salinity level (dS m^{-1}) 0.6		1.6		3.0		4.8		*P* > F	Mean	
Dry vegetative yield (gr $plant^{-1}$)	2019	0	16.10[†]	A[‡]	11.93	AB	9.04	AB	3.94	B	*	10.26	
		2	28.66	A	14.64	AB	20.99	A	0.00	B	*	16.07	
		4	18.82	A	13.43	A	16.09	A	2.87	B	**	12.80	
		P > F	ns		ns		ns		ns			ns	
		Mean	21.20	A	13.33	B	15.37	B	2.27	C	**		
	2020	0	15.72	*bc*[#]	11.45	*efg*	9.62	*fg*	8.36	*g*			
		2	15.18	*bcd*	13.45	*cde*	12.09	*def*	10.06	*fg*			
		4	21.63	*a*	17.08	*b*	10.83	*efg*	8.67	*g*			
Dry biological yield (gr $plant^{-1}$)	2019	0	21.43	*b*	19.14	*bc*	10.44	*bcd*	3.95	*cd*			
		2	60.51	*a*	16.49	*bcd*	27.30	*b*	0.00	*d*			
		4	26.13	*b*	17.78	*bc*	26.30	*b*	3.66	*cd*			
	2020	0	35.79	Ab[£]	24.97	B	18.21	C	13.93	D	**	23.22	b
		2	39.64	Ab	31.05	AB	22.30	BC	15.26	C	*	27.06	b
		4	49.25	Aa	41.02	A	23.35	B	14.01	C	**	31.91	a
		P > F	*		ns		ns		ns			**	
		Mean	41.6	A	32.4	B	21.3	C	14.4	D	**		
Dry pod yield (gr $plant^{-1}$)	2019	0	5.33	*bc*	7.22	*bc*	1.40	*bc*	0.00	*c*			
		2	31.85	*a*	1.87	*bc*	6.31	*bc*	0.00	*c*			
		4	7.30	*bc*	4.36	*bc*	10.21	*b*	0.80	*bc*			
	2020	0	20.07	A	13.52	B	8.59	C	5.57	D	**	11.94	b
		2	24.46	A	17.59	AB	10.21	BC	5.20	C	**	14.37	b
		4	27.62	A	23.94	A	12.51	B	5.34	B	**	17.36	a
		P > F	ns		ns		ns		ns			**	
		Mean	24.05	A	18.35	B	10.44	C	5.37	D	**		
Dry seed yield (gr $plant^{-1}$)	2019	0	2.45	*bcd*	3.80	*bcd*	0.50	*d*	0.00	*d*			
		2	19.61	*a*	1.01	*cd*	2.57	*bcd*	0.00	*d*			
		4	6.70	*bc*	2.78	*bcd*	6.26	*bc*	0.17	*d*			
	2020	0	14.43	A	9.69	B	5.98	C	3.92	D	**	8.50	b
		2	17.55	A	12.43	AB	7.00	BC	3.71	C	**	10.17	b
		4	20.33	A	17.97	A	8.46	B	3.67	B	**	12.61	a
		P > F	ns		ns		ns		ns			*	*
		Mean	17.43	A	13.36	B	7.15	C	3.77	D	**		

*: *P*<0.05, **: *P*<0.01, ns: non-significant, [#]: within each year, no significance on values with the same italic lowercase letter, [‡]: within each row, no significance on values with the same uppercase letter, [£]: within each column, no significance on values with the same lowercase letter.

treatment, dry biological, pod, and seed yields increased by 37%, 45%, and 48% with respect to 0 mM K_2SiO_3. None of these dry yield parameters differed significantly among K_2SiO_3 under any WSL. On the other hand, all of the dry yield parameters generally decreased with increasing irrigation water salinity for each K_2SiO_3 at a 1% or 5% level of significance in 2020 (Table 3).

3.4. Salt tolerance models

Salt tolerance model graphics for dry bean seed yields under various K_2SiO_3 foliar applications, shown in Figure 1, exhibit the threshold salinity and slope values. The threshold salinities under 0, 2 and 4 mM K_2SiO_3 application dosages were obtained for seed yield, to be 0.87, 0.20, and 1.23 dS m^{-1} in the first and 0.12, 0.42, and 0.88 dS m^{-1} in the second year, respectively. Similarly, slope values under the control, 2 and 4 mM K_2SiO_3 foliar application dosages were determined as 17.7, 16.1, and 11.0% per dS m^{-1} in 2019 and 12.7, 13.8, and 13.7% per dS m^{-1} in 2020, respectively (Figure 1).

4. Discussions

With respect to WSL_0, the crop ET especially under WSL_2 and WSL_3 declined relatively. The decrease in ET ranged from 12 to 20% in the first- and from 27 to 36% in the second-growing season. This difference between years can be attributed to the slight changes in climate parameters between the experimental years. Despite minor differences, leachate water salinities were similar in both seasons. Although the WSL x K_2SiO_3 interaction for soil salinity was significant in 2020, the results showed that increments in K_2SiO_3 application doses did not have an effect on soil salinity. These results agree with the findings of foliar potassium selenite application to dry beans under salinity stress carried out by Admasie et al. (2023).

No interaction was found for stem diameter, plant height and pod length in both seasons. On the other hand, the number of pods in both years; the number of seeds, dry pod yield, dry biological yield, and dry seed yield in 2019; and only dry vegetative yield in 2020 showed significant WSL x K_2SiO_3 interaction. These

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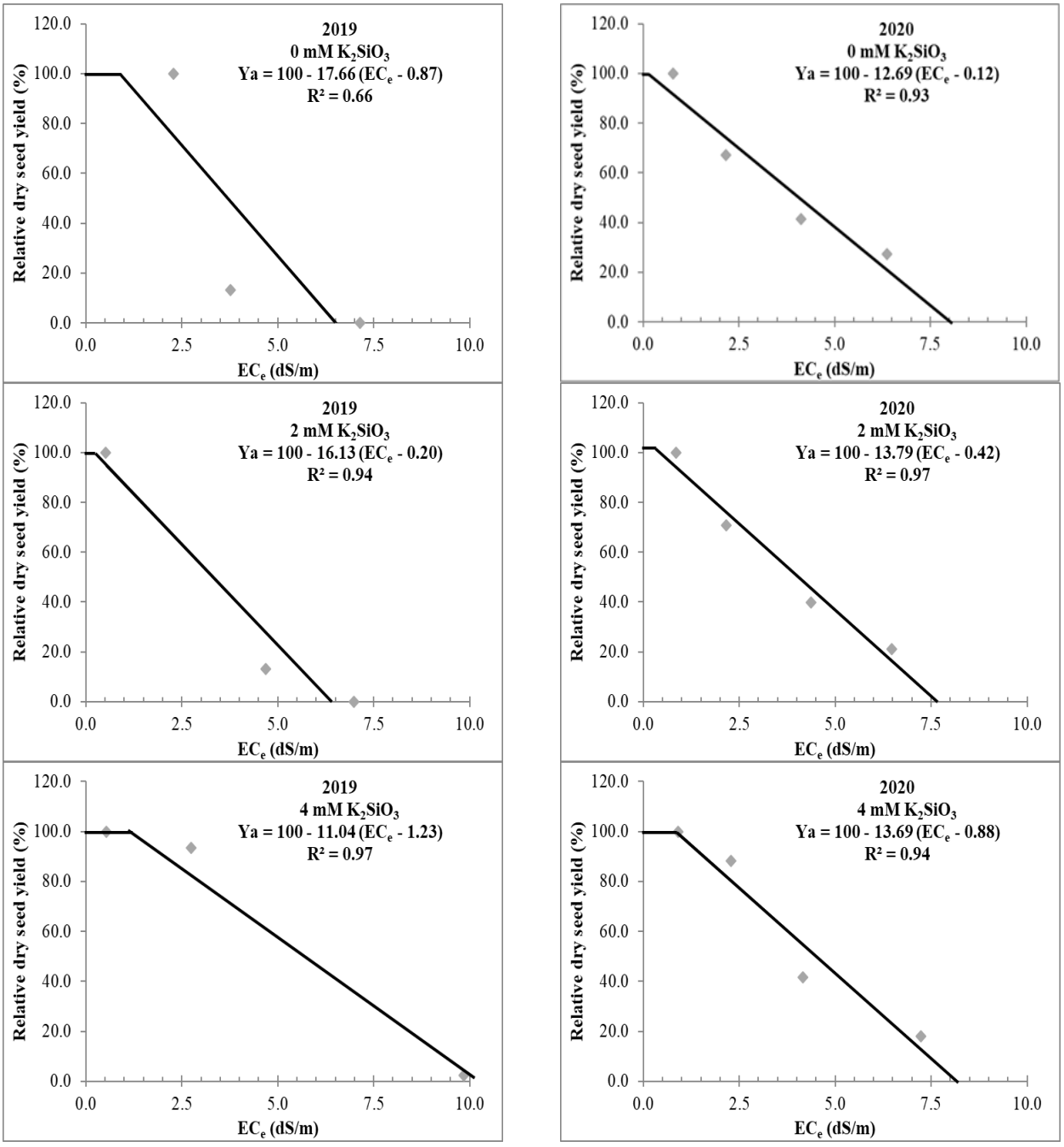


Figure 1. Salt tolerance models for dry bean seed yield under foliar application of different potassium silicate dosages.

parameters with meaningful WSL x K_2SiO_3 interaction show a significant decline especially under WSL_2 and WSL_3. However, no meaningful conclusions were drawn about the effect of increasing K_2SiO_3 applications for all these parameters, especially in the 2019 growing season. In 2020, the number of pods and vegetative dry weight remained unaffected by increasing K_2SiO_3 doses under WSL_2 and WSL_3, but the plants responded positively to the maximum K_2SiO_3 application under WSL_0 and WSL_1. These results reveal that, in general, the contribution of K_2SiO_3 foliar application to dry beans in ameliorating high salinity stress were limited. Similarly, it was reported that the potassium selenite application to improve the salt tolerance of dry beans was limited (Admasie et al. 2023).

In general, increasing salinity stress adversely affected ET, WUE, growth and yield parameters of dry beans in 2019 and 2020. The number of seeds, plant height, dry biological yield, dry pod yield, dry seed yield and WUE in 2020 were positively affected especially under the 4 mM K_2SiO_3 foliar application dose. In related studies, it has been indicated that K_2SiO_3 treatment to canola plants was effective in raising the harvest index, seed number in silique, silique number, plant height and biological yield (Bybordi 2016). It was concluded that strawberry responded positively to K_2SiO_3 application in terms of shoot, root and whole plant dry matter under salinity stress conditions (Yaghubi et al. 2016). Also, it was reported that potassium humate and K_2SiO_3 increased the growth parameters and yield of wheat under salinity stress (Osman et al. 2017).

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Different K_2SiO_3 foliar application dosages caused changes in threshold soil salinities and slope values of dry beans in 2019 and 2020. In 2019, it was determined that the 2 mM K_2SiO_3 application had a significant negative effect on the salinity threshold, however a slightly positive effect on the slope value. On the other hand, it was revealed that the 4 mM K_2SiO_3 application had a positive significant effect on both the salinity threshold and slope values of dry beans. In 2020, it was concluded that the salinity threshold value was slightly and moderately affected by the 2 and 4 mM K_2SiO_3 applications, respectively, and the slope values were negatively affected, even at a very low level, by both K_2SiO_3 applications. The increment in WUE and salinity threshold values in the 2020 growing season can be attributed to the small positive effect, of especially 4 mM K_2SiO_3 application, on seed yield in beans. Similarly, it has been reported in other studies that silicon application increases plant yield under salt stress conditions (Li et al. 2015, Sapre and Vakharia 2017). In addition, it was also determined that the maximum seed weight and seed yield in canola plants were obtained from a 4 gr L^{-1} K_2SiO_3 application (Bybordi 2016).

5. Conclusions

In this study, the possible effects of 2 and 4 mM K_2SiO_3 foliar application in ameliorating salinity stress on dry beans were investigated. In summary, the 4 mM external K_2SiO_3 application to dry bean leaves partially improved plant responses by increasing threshold salinity to a limited extent. This minimal effect may be due to the K_2SiO_3 concentration perhaps being much lower than necessary for the bean plant or to decreases in the uptake of foliar applied K_2SiO_3 because of the sufficient potassium present in the soil. Since plants vary in their ability to absorb water or minerals from the leaf surface or roots, the effects of potassium silicate application levels can be investigated under direct soil applications and compared with the results under foliar application. Future experiments would benefit from investigating higher K_2SiO_3 concentrations and foliar application at multiple times at different periods.

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