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ORIGINAL ARTICLE

Separate and Combined Effects of Silicon and Potassium on Growth and Nitrogen Uptake in Okra Plants as Influenced by Salinity of Irrigation Water

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The aim of this pot experiment was to determine the impact of foliar spraying of silicic acid (Si) with or without potassium fertilizer amendment (K) on dry matter (DM), nitrogen uptake (TN), efficient use of N fertilizer (NUE) and pod yield of okra plants (*Abelmoschus esculentus* L.) as influenced by salinity in the irrigation water (Salt) using 15N isotope. Results showed that salt stress reduced growth and N uptake by okra plants. Si and/or K applications could reduce the negative effect of salinity to a certain extent depending on the way and the type of applied materials (i.e., separate or combined applications of Si and K). Solely Si application improved okra (DM) and N-nutrition (TN and NUE) under both saline (Salt+) and non-saline conditions (Salt-). This improvement was more pronounced in the former than the latter. However, Si+ did not have significant effect on DM and fresh weights of pods as compared with the control (Si-). Solely applied K fertilizer increased the growth, N uptake and ultimately pod yields. Moreover, the combined use of Si and K could significantly enhance total DM(TDM), TN, amounts of N derived from fertilizer (Ndff), soil (Ndfs) and %NUE in the entire okra plants as well as pod yield. In conclusion, solely applied K or in combination with Si could be considered as an effective agricultural practice to reduce salt stress in okra plants and increase the growth and ultimately pod yields.

Key words: Silicon, Potassium, Okra, Salinity, 15N

Okra (*Abelmoschus esculentus* [L.] Moench) is herbaceous annual plant belongs to the *Malvacea* family. It is one of the most important widely grown vegetable crops in many tropical, subtropical, and Mediterranean regions and is known as lady's finger. The local name of this plant species is known as "Bamya" and grown for its immature fruits which are consumed cooked in combination with some ingredients such as tomato, onion, garlic and coriander. This species has an important position among vegetable fruits due to its high nutritive and medicinal value (Kumar *et al.,* 2013), and shows a wide adaptability and is cultivated either as a home garden crop or on a commercial scale under various environmental conditions (Reddy *et al.,* 2012).

Salinity is one of the most important agricultural global problem causing inhibition and impairment of crop growth and development (Isayenkov and Maathuis 2019). Salt stress generally affects the okra germination rate, plant growth, development and yield as well as fruit quality (Ifediora *et al.,* 2014).Salinity can influence several physiological processes including photosynthesis, transpiration, stomatal conductance and water potential, growth and yield production (Abbas *et al.,* 2015; Azeem *et al.,* 2017).Okra is classified as a semi saline tolerant crop (Maas and Hoffman 1977), whereas Ayers and Westcot (1989) and Bresler *et al.,* (1982) classified it as salt sensitive plant. However, results of Ünlükara *et al.,* (2008) revealed that okra is moderately tolerant to salinity. Such difference in its tolerance may be related to the different genotypes used, plant parts and environmental conditions under which the crop is grown (Saima *et al.,* 2022).A number of research works have been done with the ultimate aim of reducing the effect of salt stress on plant growth using appropriate agronomical practices with an adequate balanced mineral nutrient management (Azeem *et al.,* 2017; El-Ramady *et al.,* 2018).

Fertilizers are important materials used to improve soil fertility and crop nutrition. Okra plant requires sufficient nutrients for growth enhancement, regular fruiting and subsequent pickings (Gayathri and Seran 2020).Potassium (K) is a key macro-element playing a crucial role in plant growth and development. It has a regulatory function in several biochemical (e.g., protein synthesis, carbohydrate metabolism and enzyme activation) and physiological (e.g., stomatal regulation and photosynthesis) processes, which eventually increase the yield and the quality of crops (Hasanuzzaman *et al.,* 2018). Increased evidence has shown that K is also an important determinant of plant adaptive responses to a wide-range of environmental stresses, and can involve osmotic adjustment of salt-stressed plants (Wang *et al.,* 2013; Ahanger *et al.,* 2017; Isayenkov and Maathuis 2019). Moreover, although silicon (Si) is not perceived as an essential element for higher plants, its useful effects have been observed in a widespread variety of plant species. It has been broadly reported that Si plays an important role in plant health management and recently received higher attention for improving plant nutritional content and agricultural productivity (Mastalerczuk *et al.,* 2020; Mehta *et al.,* 2020). Accumulating evidence from the last two decades showed that Si affects the increase of plants' resistance to adverse environmental conditions (Ma 2004; Guntzer *et al.,* 2012; Zhu and Gong 2014).Its beneficial effect in plants grown under stressed conditions postulated to be stimulation of plant antioxidant systems (Muhammad Zia-ur-Rehman *et al.,* 2017), which enhances membrane physical integrity, to protect plant photosynthetic apparatus, and to enhance nutrient uptake (Barreto *et al.,* 2018; Kurdali *et al.,* 2013&2019; Junior *et al.,* 2019). Amongst the abiotic stresses, Si is known to alleviate several stresses including salt and drought stress, metal toxicity, radiation damage, nutrient imbalance, high temperature and freezing (Ma 2004).Si application may be involved in metabolic or physiological activity of stressed plants. The mechanisms underlying Si-enhanced abiotic stress tolerance (e.g., salinity) are reported by Liang *et al.,* (2007) and Zhu and Gong (2014).

It is widely reported that application of Si seems to interact favorably with other nutrient elements such as N (Ashraf *et al.,* 2009; Kurdali and Al-Chammaa 2013); P (Eneji *et al.,* 2008), and K (Mali and Aery 2008).In a previous study conducted by Salem *et al.* (2022), the wheat crop supplied with potassium silicate (K_2SiO_3), particularly under water shortage is regarded as a crucial action to enhance the tolerance of plants with reducing yield losses. Proper plant nutrition is, therefore, one of the most important strategies to alleviate abiotic stresses in crop production. Accordingly, an effective nutrient management is an essential component for plant growth and offers the potential to achieve maximum yield (El-Ramady *et al.,* 2018).

Since K and Si are involved in many morphological, physiological and biochemical processes in plants for improving plant tolerance to abiotic stresses, information is still scarce regarding their synergistic effects on growth and nutrient uptakes of okra in response to salt tolerance. Hence, a better understanding of the interactions between Si&K applications and plant responses will contribute to more efficient agricultural practices, particularly under salt stress conditions. Keeping in view the importance of Si or K applications in plant growth and development, this study was designed to find out the effects of foliar sprays with silicic acids and/or soil amendment with potassium sulfate fertilizer on growth and nitrogen uptake in salt stressed okra plants using ^{15}Nisotope.

MATERIALS AND METHODS

Soil properties, plant materials and agricultural practices

Seeds of a local genotypeof okra plant (*Abelmoschus esculentus* L.) were sown in 8-L, bottom-perforated plastic pots containing thoroughly mixed soil (7 kg) collected from the field at the depth of 0 to 20 cm., during 2019 growing season. The pots were placed outdoor under natural climatic conditions in the research station of the agriculture department, located south east of Damascus, Syria (33°20'13.3"N 36°26'16.2"E; altitude 617 m).The site is located within a dry Mediterranean semiarid area with hot-dry summer and cold winter. The total annual rainfall is about 120 mm, and most precipitations occur between November and early April.The sowing date was on the 20th of April, while the harvesting date was at the end of July. For the last ten years, the average minimum temperature in winter was 1.3°C in January, while it increased to the average maximum temperature of 38.3 °C in July. Some climatic data of the experimental site during the growing period are shown in Table 1.

Soil was air dried before being ground and sieved (2 mm) to remove small rocks and plant litter. The main physical and chemical soil properties were: pH 7.85, EC_e 0.52 dSm^{-1}, organic matter 0.54%, cations (Ca^{++} 4.08, Mg^{++}13.21 , K^{+}0.01 and Na^{+}0.08 mmol L^{-1}), anions (SO_4^{--} 1.27, HCO_3^{-}4.0 and Cl^{-} 1.02 mmol L^{-1}), available P (Olsen) 5.6 mg g^{-1}, total N 0.02%, NO_3^{-}8.9 mg g^{-1}, NH_4^{+}19.2 mg g^{-1}. Exchangeable cations (Ca^{++} 46.08 and Mg^{++} 6.33 meq 100 g^{-1} soil). The soil is classified as a clay loam, with average54.2% clay, 32.5% silt, and 13.3% sand.

After emergence of the first true leaves, the number of plants per pot was maintained at two and irrigated with tap water for a week, and thereafter, saline water treatments were started. At the beginning of the experiment, pots were saturated with tap water to determine the field capacity, and the water content held in the soil after excess water has drained away was assumed as a field capacity. The amount of water applied to each pot was determined by calculating the difference at the field capacity and weight of each pot before irrigation. Each pot was weighted, before each irrigation, and soil moisture content was maintained around 70% of field capacity throughout the experimental period. Since soil contained a small amount of available phosphorus (P), an equivalent amount of 75 kg P_2O_5 ha^{-1} in the form of phosphoric acid (H_3PO_4) was applied to each pot prior to planting to all treatments.

Experiment design and treatments

The design was a split plot, with salinity being the main plots. Si and K fertilizer treatments were randomized within salinity treatment as a 3 factorial (2× 2× 2) design, with 5 replications. Salinity stress was induced by sodium chloride (NaCl) added to the irrigation water. The main plot, salinity, had two levels: irrigation with saline water “Salt+” (EC_{iw}≈7dS m^{-1}) and irrigation with non-saline water “salt-“(EC_{iw}≈ 1 dS m^{-1}).Within each of saline treatment, two levels of potassium (K) fertilizer were used: K+ (with K)and K- (without K). Potassium nutrition was provided to the soil in the form of potassium sulfate (K_2SO_4) at an equivalent rate of 100 K_2O ha^{-1} prior planting. Within every potassium treatment, foliar silicon fertilizer was applied in the form of silicic acid $Si(OH)_4$, manufacture by (ROTH) company; Carl Roth Gmbh + Co. KG (Art- Nr. 0201.2), at two levels: application of 150 mg L^{-1} as foliar spray (Si+) and the control. For non-Si treated okra plants, leaves were sprayed with distilled water and set as control(Si-). One hundred mL per plant of Si solution (pH 6.7) were applied with a manual sprayer early in the morning, a week after the induction of salt stress, even full wet. First spray of silicic acid was given two weeks after emergence of the first true leaves, and further three sprays were given regularly at fifteen day intervals. For the salinity treatment, the plants were adapted to salinity by irrigation with tap water ($EC_{iw} \approx 1$ dS m^{-1})for one week, to avoid osmotic shock. Then, plants were subjected to the desired salinity level (i.e., $EC_{iw} \approx 7$dS m^{-1}).Total number of pots was 40 (i.e., 2 saline treatments x 2 K levels x 2 Si levels x 5 replicates). The various combinations of the used treatments and their justifications are listed in Table 2.

^{15}Nitrogen Fertilizer

^{15}N isotope technique was employed to estimate the fractional contribution of nitrogen derived from soil (Ndfs) and from fertilizer (Ndff).An equivalent fertilizer rate of 100 kg N ha^{-1}(Firoz 2009) in the form of urea enriched with 5% ^{15}N atom excess was applied to all plants. The N-fertilizer was split in two applications (50% at 4-5 leaves stage and50% at the beginning of flower bud initiation).

Plant Harvest, Analysis and Calculations

Tender green pods of okra were carefully harvested from each pot early in the morning, at three day intervals, with small scissors and weighed. The harvested okra pods were between 5 and 6 cm in length. Cumulative pod yield over nine harvests was used to assess fruit yield. At the end of the experiment, okra plants were harvested 12 weeks after planting by cutting 1 cm from the base of the stem. Fresh weight of different parts of shoots (pods, leaves and stem) was recorded, while the roots were carefully separated from the soil and washed before fresh weights were recorded. The harvested plant materials were oven dried at 70 °C until constant weight to determine the moisture content and dry weight (DM).Total dry matter weight (TDM) per pot was determined as the sum of dry weights of pods, leaves, stems and roots. Samples were then ground to a fine powder using a mill having a 0.5 mm sieve. Total nitrogen was determined by Kjeldahl procedure, and $^{15}N/^{14}N$ isotope ratio was measured with an emission spectrometer (Jasco-150, Japan).

Percent (%) and amount (mg N pot^{-1}) of N derived from fertilizer (Ndff), from soil (Ndfs) and nitrogen fertilizer use efficiency (%NUE) were calculated using the ^{15}N isotopic data by applying equations previously described (Zapata 1990).

Statistical Analysis

Collected data were subjected to analysis of variance (ANOVA) using the statistical program Statview, 4.57® Abacus Concepts, Berkley, Canada. Means were compared using the least significant difference (Fisher’s LSD) test at a probability level of $P<0.05$.

RESULTS

Dry matter yield

The effect of Si and/or K fertilizer on dry matter production (DM) of different parts of okra plants subjected to salt stress is shown in Table 3. Data of the whole plant (TDM) are presented in Fig.1. Salt stress significantly reduced DM yield. Such reduction was influenced by the fertilization treatments as well as by the plant part. In the non-fertilized control treatment (K-Si-), irrigation with saline water reduced TDM of okra by 46%. However Si and/or K applications reduced the negative effect of salinity to 38, 37, and 41% in the K-Si+, K+Si- and K+Si+ treatments, respectively, as compared with the control (Salt-K-Si-). The negative effect of salinity on DM was high in leaves (68%), followed by stem (38%), roots (33%), and pods (8%). Nevertheless, Si and/or K applications could reduce the negative effect of salinity on DM production of different plant parts, particularly the pods.

For non-salt stressed plants (Salt-), TDM of the non-fertilized control treatment (K-Si-) was 18.2 g/pot, which increased to 20, 20.8, 21 g/pot in the K-Si+, K+Si- and K+Si+ treatments, respectively. Hence, the percent increments were10, 14 and 15% of the control, respectively (Fig. 2), indicating that Si or K could relatively have a similar impact as application of Si and K together on TDM of okra under non saline stress.

For salt stressed plants (Salt+), TDM of the non-fertilized control treatment (K-Si-) was 9.8 g /pot, which increased to 12.4, 13.2, 12.3 g/pot inthe K-Si+, K+Si- and K+Si+ treatments, respectively. Comparing with the control, the percent increments were thus, 26, 34 and 25%, respectively (Fig. 2). This result could indicate that the beneficial effect of silicon and/ or potassium fertilizer on TDM of okra was more pronounced under saline than under non-saline conditions, particularly when plants were fertilized with K alone.

As shown from the TDM data (Fig. 1), DM yield in different plant parts were also increased by K and Si applications both under saline and normal conditions (Table 3). For non-salt stressed plants (Salt-), solely applied Si (K-Si+) resulted in slight increments of DM yield, over the control (K-Si-), which was only significant in roots (8%) as well as in the whole plant (10%). However, solely applied K (K+Si-) resulted in significant increments of TDM (14%) as well as the different plant parts, particularly the pods (32%). The combined application of Si and K (K+Si+) could significantly enhance TDM by 15% and pod's DM by 59% indicating that the use of K together with Si is an important strategy for growth and pod yield improvements of okra plants grown under non-stressed conditions.

In salt stressed plants (Salt+), separate application of Si (K-Si+) had no effect on pod DM (+3% over the control), whereas, solely applied K (K+Si-) or in combination with Si (K+Si+) significantly increased pod DM by 36 and 27%, respectively. This result may indicate that, under saline conditions, the best treatment could be (K+Si-) due to its highest TDM as well as pod's DM (Fig. 2). On the other hand, the percent increments of root DM due to Si and/or K applications were higher in plants grown under saline than under normal conditions, particularly for solely applied K (Fig. 2).

Fresh weight (FW) of pods

In the control treatment (K-Si-), fresh weights of pods were 10.8 and 9.5 g/ pot for plants grown under non-saline and saline conditions, respectively. The greatest fruit yield (16.5 g/ pot) was obtained from the (salt-, K+Si+) treatment, which was significantly different from those of the other treatments. Whereas, the greatest value (13.25 g/ pot) under saline condition was obtained in the (K+Si-) treatment (Fig. 3). Comparing with the control (K-Si-), K had a more obvious effect than Si in improving the pod yield of plants. Solely applied Si (K-Si+) had no significant effects on pod's fresh weight (FW) neither under saline nor under normal conditions. However, solely applied K (K+Si-) or in combination with Si (K+Si+) significantly increased pod's FW by 32 and 52% under non-saline conditions, and by 40 and 28% under saline conditions, respectively.

Nitrogen yield

The effect of Si and/or K fertilizer on nitrogen uptake (mg N/pot) in different parts of okra plants subjected to salt stress is shown in Table 4. Data of the whole plant (TN) are presented in Fig. 1.As shown from DM data, salt stress induced significant reduction in TN yield in okra plants which was influenced by the fertilization treatments as well as by the plant part. In the non-fertilized control treatment (K-Si-), salt stress reduced TN of okra by 39%where it was relatively similar to values obtained from K-Si+ (36%) and K+Si+ (37%) treatments. However, solely applied K (K+Si-) significantly reduced the negative effect of salinity from 39% to 21%. Therefore, salt stressed plants amended only with potassium sulfate (i.e. K+Si-) showed less reduction in plant nitrogen as well as plant biomass than those of the other used treatments. Regardless of the fertilization treatments, the negative effect of salinity on N yield was high in leaves, followed by roots and pods. No significant decreases in stem N yield were recorded (Table 4). Si and/or K applications could reduce the negative effect of salinity in the different plant parts, particularly in pods.

For non-salt stressed plants (Salt-), total nitrogen yield (TN) of the non-fertilized control treatment (K-Si-) was 348 mg N/pot, and increased to 418, 391, and 437 mg N/pot in the K-Si+, K+Si- and K+Si+ treatments, respectively. Hence, the percent increments were 20, 12 and 26% of the control, respectively (Fig. 4). Accordingly, the plants irrigated with non-saline water and treated with K plus Si showed more increment in plant nitrogen (TN) than those of the other treatments.

For salt stressed plants (Salt+), TN of the non-fertilized control treatment (K-Si-) was 211mg N/pot, which increased to 266, 308 and 276 mg N/pot in the K-Si+, K+Si- and K+Si+ treatments, respectively. In comparison with the control (K-Si-), the percent increments were thus, 26, 46 and 30%, respectively (Fig. 4). Hence, the plants irrigated with saline water and treated only with K showed more increment in plant nitrogen (TN) than those of the other treatments.

As shown from TN data, N- yield in different plant parts were also increased by K and Si applications both under saline and normal conditions. For the non-salt stressed plants (Salt-), maximum increment of total N was observed in the K+Si+ treatment. The combined application of Si and K could significantly enhanced TN by 26% and pod's N by 66% which were higher than those of the other treatments.

In salt stressed plants (Salt+), separate application of Si (K-Si+) had no effect on pod's DM (+9% over the control), whereas, solely applied K (K+Si-) or in combination with Si (K+Si+) significantly increased pod's N by 37 and 20%, respectively. This result may indicate that, under saline conditions, the best treatment was(K+Si-) due to the highest N yield of the different plant parts, particularly the pods (Fig 4).

Soil and fertilizer nitrogen uptake

The effects of Si and/or K fertilizer on percent (%) and amounts (mg N/pot) of nitrogen derived from fertilizer (Ndff) and from soil (Ndfs) in the whole okra plants are shown in Fig. 5.

Solely applied Si or K to the non-stressed plants caused significant decreases in %Ndfs with no significant difference being observed between the control (K-Si-) and the K+Si+ treatment. For plants grown under saline conditions, the highest %Ndfs value (68%) was obtained from solely applied K (K+Si-).

Total amount of Ndfs in the non-stressed control treatment (Salt$^-$K$^-$Si$^-$) was 230 mg N/pot, which was significantly increased to 288 mg N/pot in the K+Si+ treatment (26% increment). No significant differences in the total amount of Ndfs were observed between the control (K$^-$Si$^-$) and plants treated either with Si or with K. For salt stressed plants, total amount of Ndfs in the control treatment (Sal$^+$K$^-$Si$^-$) was 140 mg N/pot and increased by 27, 50 and 27% in K-Si+, K+Si- and K+Si+ treatments, respectively. The actual amounts of the aforementioned treatments were 178, 208 and 176 mg N/pot, respectively.

The %Ndff value in the control treatment (K-Si-) was the same under both saline and non-saline conditions (34%). In non-stressed plants, separate applications Si and K resulted in significant increases of %Ndff to 43 and 39%, respectively. However, no significant difference in %Ndff was observed between the control (K-Si-) and the K+Si+ treatment. However, the latter treatment showed the highest %Ndff value (36%) amongst the other treatments subjected to salt stress.

The amount of Ndff in the non-stressed control treatment (Salt$^-$K$^-$Si$^-$) was 118 mg N/pot which was less than those noted in the other treatments where their actual values were 179, 151 and 149 mg N/pot in theK-Si+, K+Si- and K+Si+ treatments, respectively. Accordingly, the percent increments were 51, 28 and 26% relative to the control. For salt stressed plants, the amount of Ndff in the control treatment (Sal$^+$K$^-$Si$^-$) was 72 mg N/pot which increased to 89, 100 and 100 mg N/pot in the K-Si+, K+Si- and K+Si+ treatments, respectively. Hence, the percent increments were 24, 39 and 39% relative to the control.These results indicate that solely added Si could be more important than K in enhancing fertilizer N uptake under non-stressed conditions. However, the opposite was true under salt stressed conditions. Also, combined application of Si and K was more beneficial under stressed than under normal conditions.

Salt stress significantly reduced amounts of Ndff which was influenced by the Si and K input. In the non-fertilized control treatment (K-Si-), salt stress reduced the amount of Ndff by 39%. However, Si and/or K applications could reduce the negative effect of salinity on fertilizer N uptake to 25, 15, and 15% in the K-Si+, K+Si- and K+Si+ treatments respectively, as compared with the control (Salt-K-Si-).

Nitrogen use efficiency (%NUE)

The nitrogen use efficiency (%NUE) is expressed as a ratio of N output (total Ndff) and input (N-fertilizer applied). Regardless of treatments used, NUE ranged between 3 and 7%, 7-9%, 6-15% and 8-32%, in roots, stems, pods and leaves, respectively (Table 5). For a more complete picture of measuring NUE, the entire plant should be considered (Congreves *et al.,* 2021). The efficient use of the applied nitrogen fertilizer in okra plants was affected by the experimental treatment combinations used (i.e., K and/or Si application) as well as by salt stress, ranging from 24% in the Salt+K-Si- to 59% in Salt-K-Si+ treatment (Fig. 6). %NUE in the non-stressed control treatment (K-Si-) was 38%. Whereas, it increased to 59, 50 and 49% in K-Si+, K+Si- and K+Si+ treatments, respectively. The corresponding values in plants subjected to salt stress were, 24, 29, 33 and 33% (Fig. 6). Although NUE in the whole plant of solely applied Si grown under normal condition was the highest amongst treatments (Fig. 6) , the highest NUE in pods was occurred in the combined application of Si and K (11.3%) whereas, it was only 8.7% in Salt-K-Si+ treatment (Table 5).

Table 1: Some climatic data during the growing season of the experimental site

Variable	April	May	June	July
T_{mean} (°C)	17	22.5	25.6	30
T_{min} (°C)	9.7	13.4	16.5	20
T_{max} (°C)	24.3	31.6	34.7	40
RH (%)	62.8	56.6	55.6	59.0
ET_0 (mm day^{-1})	5.82	8.23	9.01	10.47
Rain (mm)	6.7	3	0	0

T_{mean}= average temperature, T_{min}= minimum temperature, T_{max}= maximum temperature, RH=Relative air humidity, ET_0= *reference evapotranspiration*

Table 2: List of experimental treatment combinations used

Abbreviations	Related Explanations	Research justification
(Salt-, Si-, K-)	Non-salt stressed plants without Si, without K fertilizers	Control : to be compared with the other below treatments (i.e., Si and /or K applications, under saline or non -saline conditions)
(Salt-, Si+, K-)	Non-salt stressed plants with Si, without K application	The effect of Si alone under non-saline conditions
(Salt-, Si-, K+)	Non-salt stressed plants with K, without Si application	The effect of K alone under non-saline conditions
(Salt-, Si+, K+)	Non -salt stressed plants with Si and K applications	Dual effect of Si plus K, under non- saline conditions
(Salt+, Si-, K-)	Salt stress plants without Si, without K fertilizers	The effect of salt stress without fertilizer (K or Si) amendments
(Salt+, Si+, K-)	Salt stress plants with Si, without K application	The effect of Si alone on salt stressed plants
(Salt+, Si-, K+)	Salt stress plants with K application, without Si	The effect of K alone on salt stressed plants
(Salt+,Si+, K+)	Salt stress with Si plus K applications	Dual effect of Si plus K on salt stressed plants

Table 3: Effect of silicon (Si) and/ or potassium fertilizer (K) on dry matter yield (g pot-1) of different parts of okra plants grown under saline (Salt+) and non-saline (Salt-) conditions.

Leaves					
Treatments	**K-Si-**	**K-Si+**	**K+Si-**	**K+Si+**	**L.S.D**
Salt-	7.08±0.21 A, b	7.80±0.18 A, ab	7.93±0.28 A, a	7.80±0.28 A, ab	*0.75*
Salt+	2.28±0.11 B, c	3.68±0.09 B, ab	4.03±0.17 B, a	3.25±0.21 B, b	*0.46*
LSD 0.05	*0.58*	*0.48*	*0.80*	*0.85*	
Stems					
Salt-	6.08±0.17 A, b	6.68±0.16 A, ab	6.80±0.24 A, a	6.70±0.24 A, ab	*0.63*
Salt+	3.75±0.12 B, b	4.33±0.19 B, a	4.03±0.11 B, ab	4.28±0.14 B, a	*0.44*
LSD 0.05	*0.51*	*0.61*	*0.64*	*0.68*	
Roots					
Salt-	3.35±0.07 A, b	3.63±0.04 A, a	3.85±0.04 A, a	3.76±0.11 A, a	*0.22*
Salt+	2.26±0.03 B, c	2.79±0.07 B, b	3.02±0.04 B, a	2.83±0.12 B, ab	*0.23*
LSD 0.05	*0.18*	*0.20*	*0.13*	*0.41*	
Pods					
Salt-	1.71±0.06 A, c	1.92±0.06 A, c	2.26±0.08 A, b	2.72±0.13 A, a	*0.27*
Salt+	1.56±0.12 A, b	1.61±0.09 B, b	2.12±0.10 A, a	1.98±0.12 B, a	*0.33*
LSD 0.05	*n.s*	*0.26*	*n.s*	*0.44*	

Means ±SE within a row (small letter) and within a column (capital letter) followed by the same letter are not significantly different ($P<0.05$)

Table 4: Effect of silicon (Si) and/ or potassium fertilizer (K) on nitrogen yield (mg N pot-1) of different parts of okra plants grown under saline (Salt+) and non-saline (Salt-) conditions.

Leaves					
Treatments	**K-Si-**	**K-Si+**	**K+Si-**	**K+Si+**	**L.S.D**
Salt-	188.38±5.5A,c	214.68±6.1 A,ab	197.48±5.4A, bc	219.85±6.0 A, a	*17.69*
Salt+	65.78±2.6 B, b	98.65±5.0 B, a	111.58±4.6 B, a	99.78±4.6B, a	*13.23*
LSD 0.05	*14.98*	*19.15*	*17.31*	*18.47*	
Stems					
Salt-	63.00±1.66 A, c	84.50±3.50 A, a	73.05±3.14 A, b	79.80±3.65 A, ab	*9.52*
Salt+	65.25±1.81 A, b	76.10±3.07 A, a	80.00±2.78 A, a	73.70± 1.81 A, a	*7.5*
LSD 0.05	*n.s*	*n.s*	*n.s*	*n.s*	
Roots					
Salt-	42.43±0.41 A, c	53.38±0.84 A, a	46.68±0.89 A, b	48.15±0.79 A, b	*2.34*
Salt+	30.33±0.34 B, d	36.93±0.32 B, c	48.33±0.79 A, a	42.08±1.26 B, b	*2.40*
LSD 0.05	*1.30*	*2.20*	*n.s*	*3.64*	
Pods					
Salt-	53.88±1.38 A, d	65.33±1.45 A, c	73.70± 0.70A, b	89.43±1.45 A, a	*3.95*
Salt+	50.00±2.15 A, c	54.60±1.60 B, c	68.43±1.82 B, a	60.20±0.77 B, b	*5.12*
LSD 0.05	*n.s*	*5.27*	*4.76*	*4.01*	

Table 5: Effect of silicon (Si) and/ or potassium fertilizer (K) on nitrogen use efficiency of added fertilizer (%NUE) of different parts of okra plants grown under saline (Salt+) and non-saline (Salt-) conditions.

Leaves					
Treatments	**K-Si-**	**K-Si+**	**K+Si-**	**K+Si+**	**L.S.D**
Salt-	21.29±0.62 A, c	31.82±0.82 A, a	25.81±0.73 A, b	24.25±0.74 A, b	*2.25*
Salt+	7.68±0.34 B, c	10.72±0.59 B, ab	11.99±0.59 B, ab	12.54±0.65 B, a	*1.71*
LSD 0.05	*1.74*	*2.46*	*2.30*	*2.41*	
Stems					
Salt-	6.74±0.22 B, c	11.54±0.55 A, a	9.17±0.39 A, b	8.76±0.45 A, b	*1.29*
Salt+	7.80±0.27 A, c	8.61±0.37 B, ab	9.26±0.36 A, a	9.04±0.29 A, a	*1.00*
LSD 0.05	*0.86*	*1.62*	*n.s*	*n.s*	
Roots					
Salt-	4.06±0.05 A,c	6.77±0.15 A, a	4.75±0.05 A, b	4.72±0.11 A, b	*0.30*
Salt+	2.94±0.03 B, c	3.56±0.03 B, b	4.77±0.14 A, a	4.74±0.19 A, a	*0.37*
LSD 0.05	*0.15*	*0.37*	*n.s*	*n.s*	
Pods					
Salt-	6.76±0.21 A, d	8.74±0.32 A, c	9.91±0.17 A, b	11.30±0.28 A, a	*0.77*
Salt+	5.15±0.16 B, c	6.21±0.22 B, b	6.97±0.23 B, a	6.37±0.07 B, b	*0.55*
LSD 0.05	*0.64*	*0.94*	*0.69*	*0.71*	

Tables 4, 5: Means ±SE within a row (small letter) and within a column (capital letter) followed by the same letter are not significantly different (*P*<0.05)

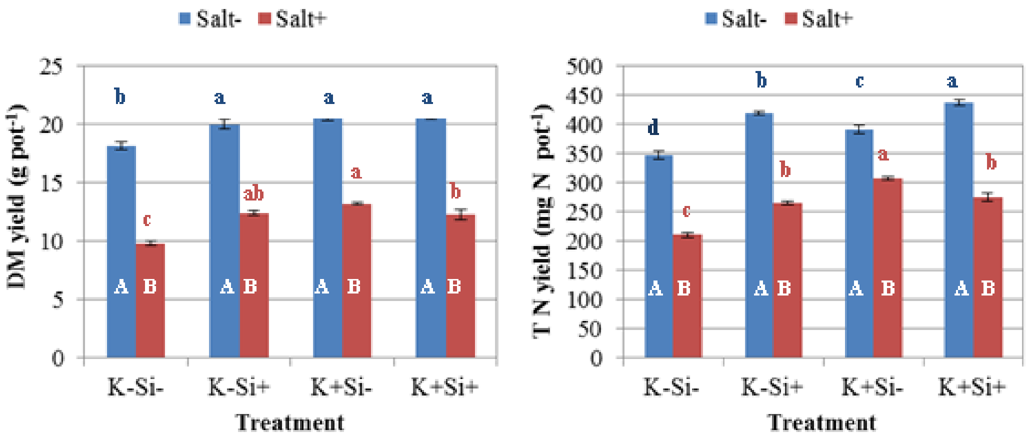

Figure 1: Effect of separate and combined applications of silicon (Si) and potassium fertilizer (K) on dry matter (DM) and total N yield (TN) in the whole plant of okra grown under saline (Salt+) and non-saline (Salt-) conditions. Columns followed by the same letter are not significantly different (P<0.05). Small letters indicate comparisons amongst Si and/or K applications for each salinity treatment. Capital letters denote the effect of salt stress in each treatment (i.e. K and/or Si).

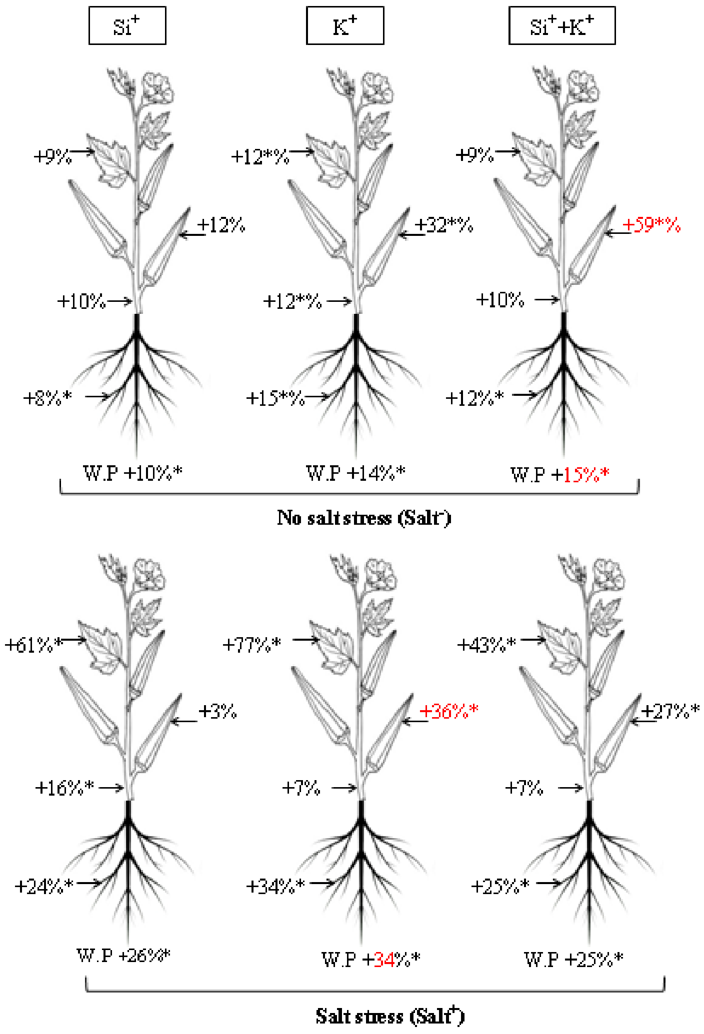

Figure 2: Scheme representing the effects of silicic acid (Si) and /or potassium fertilizer (K) on percent increments of dry matter yield of the different parts and of the whole plant (W.P) of okra grown under saline and non-saline conditions, as compared with the un-treated control treatment (Si-K-). Values indicated by the symbol * are significant (p<0.05).

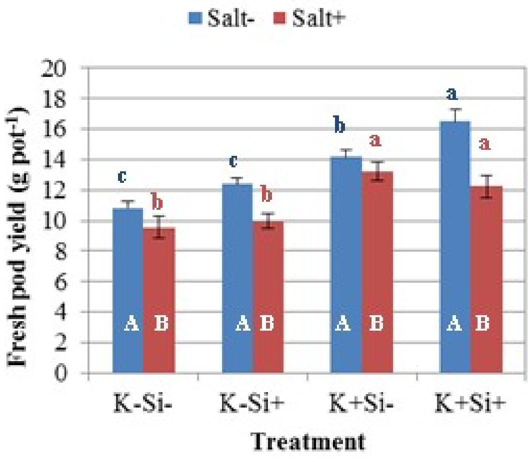

Figure 3: Effect of separate and combined applications of silicon (Si) and potassium fertilizer (K) on pod's fresh weight (FW) of okra plants grown under saline (Salt+) and non-saline (Salt-) conditions. Columns followed by the same letter are not significantly different (P<0.05). Small letters indicate comparisons amongst Si and/or K applications for each salinity treatment. Capital letters denote the effect of salt stress in each treatment (i.e. K and/or Si).

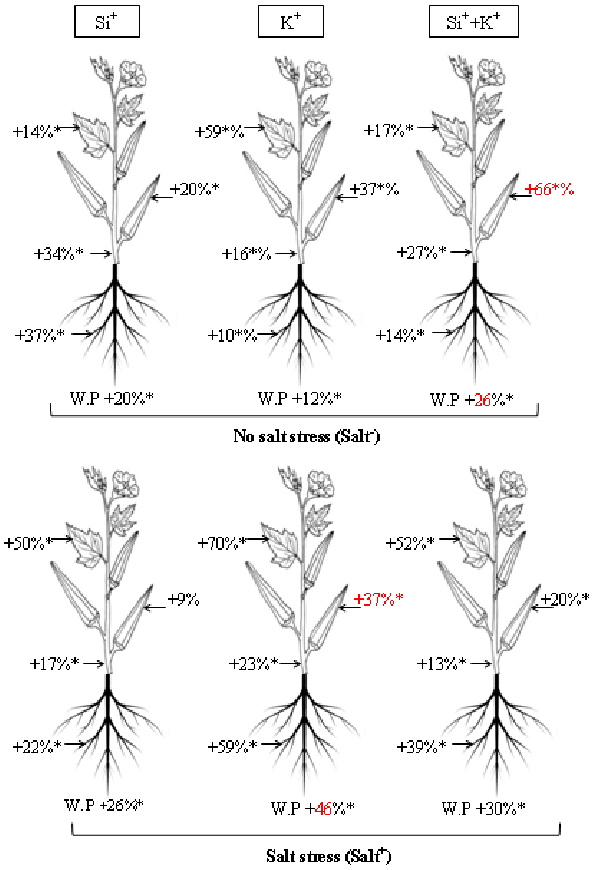

Figure 4: Scheme representing the effects of silicic acid (Si) and /or potassium fertilizer (K) on percent increments of total nitrogen yield of the different parts and in the whole plant (W.P) of okra grown under saline and non-saline conditions, as compared with the un-treated control treatment (Si-K-). Values indicated by the symbol * are significant (p<0.05).

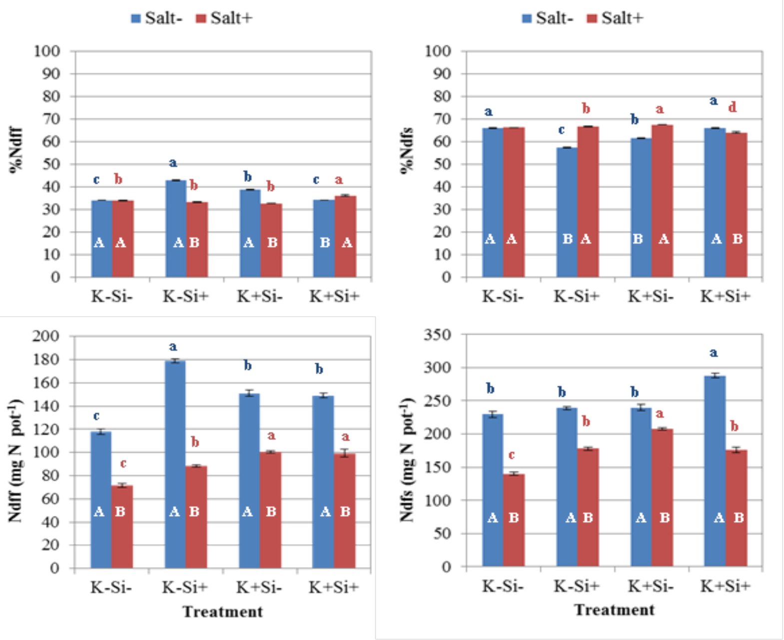

Figure 5: Effect of separate and combined applications of silicon (Si) and potassium fertilizer (K) on percents and amounts of nitrogen derived from fertilizer (Ndff) and soil (Ndfs) in the whole plant of okra grown under saline (Salt+) and non-saline (Salt-) conditions. Columns followed by the same letter are not significantly different (P<0.05). Small letters indicate comparisons amongst Si and/or K applications for each salinity treatment. Capital letters denote the effect of salt stress in each treatment (i.e. K and/or Si).

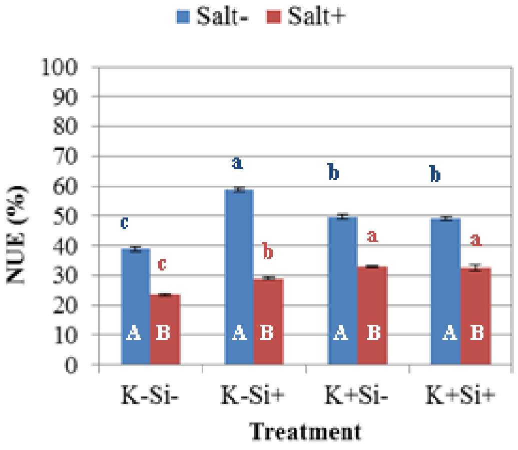

Figure 6: Effect of separate and combined applications of silicon (Si) and potassium fertilizer (K) on nitrogen use efficiency (%NUE) in the whole plant of okra grown under saline (Salt+) and non-saline (Salt-) conditions. Columns followed by the same letter are not significantly different (P<0.05). Small letters indicate comparisons amongst Si and/or K applications for each salinity treatment. Capital letters denote the effect of salt stress in each treatment (i.e. K and/or Si).

DISCUSSION

A number of agricultural management strategies have been considered for alleviating the negative effect of salinity in plants (Zaman *et al.,* 2018). An adequate balance mineral nutrition is found one of the best strategies to mitigate salt stress in plants (Rengel and Marschner 2005). The present experiment aimed at investigating the effects of silicic acid (Si) and /or potassium fertilizer (K) on growth and nitrogen uptake of okra plants as influenced by salinity in the irrigation water. In light of the presented work, it is obvious that salt stress reduced growth and nitrogen uptake by okra plants. Total dry matter yield (TDM) and total nitrogen uptake (TN) in the control (K-Si-) treatment reduced by 46 and 39%, respectively, due to irrigation with saline water. However, Si and/or K applications could reduce the negative effect of salinity in various portions of plants to a certain extent, depending on the type and the method of applied materials (i.e., separate or combined applications of Si and K).

Effect of foliar application of silicic acid on growth and nitrogen uptake of okra plants

In non-stressed plants, foliar application of Si (K-Si+) enhanced total dry matter (TDM) by 10% as compared with the control (K^-Si^-). However, it increased up to 26% when plants were submitted to salt stress. Total nitrogen uptake was also increased by 20% and 26% in Si treated plants grown under non-saline and saline conditions, respectively. These results indicated that exogenous application of silicon improved okra growth and N-nutrition both under saline and non-saline conditions. This improvement was more pronounced in the former (Salt+) than the latter (Salt-). Similarly, Abbas *et al.* (2015) showed that exogenous application of silicon reduced the impact of salt stress with a positive effect of Si on some in physio-biochemical parameters of two okra genotypes grown under saline and non-saline conditions. They suggested that Si is an excellent stress-mitigating agent for protecting plants from NaCl induced toxicity in okra. Our results also indicated that Si markedly improved root growth of okra plants grown under saline conditions by 24% which was higher than the value obtained in plant grown under non saline conditions (only 8%). Similarly, Mastalerczuk *et al.* (2020) reported that Si mainly had a beneficial impact on the plant roots mass by encouraging the development of a large root system, especially under water deficiency. As suggested by Guntzer *et al.* (2012), the improvement in root DM of okra plants by the exogenous application of Si could allow for a better absorption of nutrients. Siddiqui *et al.* (2010) reported that N uptake is usually low under salt stress conditions. However, foliar application of Si may reduce the effect of salt stress and enhance the growth of the plants through increasing the uptake of N which lead to improving growth and productivity of plants (Garg and Chandel 2011). Our results showed that TN (Fig. 1), amounts of Ndff (Fig. 5) and their use efficiencies (NUE), (Fig. 6) in the entire okra plants were significantly higher in the Si treated plants (K-Si+) than the control (K-Si-), both under saline and non-saline conditions. Regarding to pod yield, silicon foliar application did not have significant effect on dry matter and fresh weights as compared with the control (Si-). However, N yield in pods was significantly increased by 20% in non-stressed plants, but only 9% in salt stressed plants (indicating that Si had an ameliorating effect on pod quality particularly in plant grown under non-stressed condition.

Overall, although Si had positive effects on whole plant DM yield and TN uptake as well as NUE, its impact on pod yield was not noteworthy. Therefore, it can be concluded from the prevailing experimental conditions that the separate application of Si at a rate of 150 mg L^{-1} as foliar spraying should not be considered as an ideal treatment for okra plants due to insignificant increments of pod yield, both under saline and non-saline conditions.

Effect of potassium sulfate on growth and nitrogen uptake of okra plants

Okra plant performance (e.g., plant growth and nitrogen uptake) due to the application of potassium sulfate fertilizer at rate of 100 K_2O ha^{-1} prior planting was affected by salinity in the irrigation water. Separate application of potassium (K+Si-) enhanced TDM and TN by 14 and 12% in non-stressed plants, and by 34 and 46% in salt stressed plants, respectively. This result indicated that K improved okra growth and N-nutrition, both under saline and non-saline conditions. The ameliorating effect of K was more pronounced in the former (Salt+) than the latter (Salt-). Many research works have shown that K nutrition enhances growth performance of plants under normal as well as stress conditions by regulating the biosynthesis, conversion, and allocating of metabolites which helps to increase the dry matter accumulation and ultimately increase the yields (Hasanuzzaman *et al.,* 2018). Our results also showed that K markedly increased root growth of okra plants grown under saline conditions by 34% which was higher than the value obtained in plant grown under non-saline conditions (15%). Such increments could allow a better N uptake which increased by 46% in the whole plant under salinity stress as compared with the control (K-), **(**Fig.3). Moreover, our results showed that amounts of Ndff (Fig.5) and their N use efficiencies (NUE), (Fig.6) in the entire plant were significantly higher in the K fed plants (K+Si-) than the control (K-Si-), both under saline and non-saline conditions. Thus, it can be concluded that K helps to increase the N uptake as well as N use efficiency of added N- fertilizer that help in increasing okra yield. As a result, dry matter yield of okra pod increased by 36 and 32% under saline and non-saline conditions, respectively. In this context, Omotoso and Johnson (2005) reported that the increase in okra fruit weight from potassium fertilizer application could be as a result of higher dry matter production and chlorophyll content coupled with higher nutrient uptake, which makes assimilates got synthesized and trans-located to fruits and thereby increased the yield. Moreover, Khan *et al.* (2019) suggested that the combined application of potassium at a rate of 80 kg K_2O ha^{-1} and nitrogen fertilizers can be used successfully for commercial okra production (i.e., green pods). On the other hand, it is worth mentioning that pod fresh weights were significantly higher in K fed plants as compared with the control, both under saline and non-saline conditions which did not differ from each other indicating that pod yield might be more tolerant to salinity than vegetative and root growth of okra (Ünlükara *et al.,* 2008).Overall, it can be concluded that fertilization with potassium sulfate at a rate of 100 K_2O ha^{-1} under salt stress condition could be considered as an effective agricultural practice to alleviate salt stress in okra plants and increased the growth, N uptake and ultimately pod yields.

Synergistic effect of silicic acid and potassium sulfate on growth and nitrogen uptake of okra plants

In the present experiment, the combined use of Si and K (K+Si+) significantly enhanced TDM and TN by 15 and 26% in non-stressed, and by 25 and 30% in salt stressed plants, respectively. As shown from above data (separate applications of Si or K), the ameliorating effects of K plus Si on TDM and TN were more pronounced under salt (Salt+) than non-salt condition (Salt-). Our results also showed that K together with Si significantly increased root DM and N uptake of okra plants grown under saline conditions by 25% and 39%, respectively, which were significantly higher than values obtained in plant grown under non saline conditions (12% and 14%, respectively), (Fig.2 & Fig. 3). Likewise, dos Santos Sarah *et al.* (2021) demonstrated that Si supplied via foliar or root application to K fed common bean plants, significantly increased root dry matter yield. Also, amounts of Ndff and Ndfs (Fig.5) in addition to %NUE (Fig.5) in the whole okra plants were significantly higher in the K+Si treated plants than the control (K-Si-), both under saline and non-saline conditions. In comparison with the control (K-Si-), silicon foliar application together with potassium amendments (K+Si+) have significant effects on dry matter, fresh weight and N yield of pods. The percent increments of pod's dry matter yield and fresh weight as well as its N yield were 59%, 52% and 66% for plant grown under non-saline conditions, respectively. On the other hand, it is worth mentioning that NUE value in pods was the highest in the combined application of Si and K treatment (11.3%). Under saline conditions the observed values were, 27%, 28% and 20% for the above mentioned parameters, respectively. The increase in pod fresh weight from application of K and Si could be as a result of higher dry matter yield coupled with higher nitrogen uptake from soil and from fertilizer, which makes assimilates got synthesized, and translocate to pods and thereby increased the yield. Therefore, from the productivity viewpoint, it can be concluded that the combined application of silicon plus potassium (K+Si+) seem to be an effective agricultural strategy in enhancing yield and quality of okra pods, both under normal as well as stress conditions. Such enhancement was more pronounced in plants grown under non-saline than saline conditions. The (K+Si+) could be also considered as an effective treatment for reducing the negative effect of salinity in plants.

Many research works have shown that application of K or Si enhances growth performance of plant under normal as well as stress conditions. Ayub *et al.* (2018) reported that potassium silicate (K and Si) under salt stress condition was found to be very much effective to alleviate salt induced damages and increased the root length, shoot length, plant height, root and shoot fresh weight, root and shoot dry weight of okra. Kurdali *et al.* (2013) demonstrated that solely added K or in combination with adequate rate of Si were more effective in alleviating water stress and producing higher yield in barley plants than solely added Si. Applications of K or Si fertilizers to water stressed plants resulted in significant increments of fertilizer nitrogen uptake and its use efficiency. In chickpea, Si in combination with K was often more effective in enhancing N_2-fixation than solely added fertilizers (Kurdali *et al.,* 2013). Bybordi (2015) also found that there was a great interactive effect between Si and K, and the positive effect on the growth of wheat plants was more pronounced when these two elements were applied together. Also, Yuan *et al*. (2021) reported that applied Si (as H_2SiO_3) and/or K (as KNO_3) to ryegrass plants grown in pots containing vermiculite in presence of different salinity levels resulted in significant differences on the growth of plants. Under low saline stress, Si was superior to K on the growth of ryegrass plants as Si and K together. Under high salinity stress, the alleviating effect was more pronounced when Si and K were applied together as compared to their individual applications. However, our study showed that TDM and TN of okra grown under non-saline conditions were significantly improved when Si and K were applied simultaneously. Under saline stress, K was superior to Si or to Si+K on TDM and TN of okra. Likewise, Kurdali and Al-Chammaa (2013) found that solely added K (K_2SO_4) or in combination with adequate rate of Si (sodium metasilicate) was more effective in alleviating water stress and producing higher yields than the solely added Si. In the light of the above mentioned data it can be concluded that plantresponse to Si and/or K application could be related to plant species (i.e., Si accumulation capacity) (Pontigo *et al.,* 2021) as well as to the method (soil amendment or foliar spraying) and the form of applied potassium (e.g. KNO_3, K_2SO_4…) and was influenced by the plant organ (whole plant, fruits, roots...). On the whole, the previous results emphasized the advantage of combined use of Si and K on the growth of plants grown under stressed conditions and could suggest the importance of using Si-K fertilizer (e.g., K_2SiO_3) to be applied to abiotic stressed plants (Salem *et al.,* 2022).

CONCLUSIONS

Overall, this pot study implies that Si and K supplementation may mitigate the negative impacts of salinity on plant growth and N uptake in okra, and can be considered as an attractive approach for improving the growth and yield of plants. K and/or Si input to okra plants could reduce the negative effect of salinity to a certain extent depending on the mode and the type of applied materials as well as the plant part.The application of Si and/or K improved the plant growth and resulted in an increased N content in various portions of plants and ultimately in total N uptake as compared to control plants. The increased N uptake ultimately boosted NUE, showing more assimilation of N in okra plants.

From a productivity standpoint (i.e., pod yield), it can be concluded, that:

- Pods produced by solely applied Si gave lower yield than those applied with K or with K plus Si. As a result, separate application of Si could not be considered as an optimal treatment for okra plants due to insignificant increments of pod yield, both under saline and non-saline conditions.
- Fertilization of okra plants with potassium sulfate could be considered as an effective agricultural practice to alleviate salt stress in okra plants and to increase the growth and ultimately pod yields.
- Combined application of potassium and silicon (K+Si+) seems to be an attractive approach for improving yield and quality of okra pods, both under normal and salt stress conditions. Such improvement was more pronounced in plants grown under non-saline than saline conditions.
- Further field investigations are needed to confirm the potential of the agricultural practices (e.g., Si-K fertilizer) in improving the growth of okra plants grown under proper field conditions.

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CONFLICTS OF INTEREST

The authors declare that they have no potential conflicts of interest.

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