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Enhancing Grain Yield Quality of Alkalinized Sorghum *(Sorghum bicolor L.*) Plants with Exogenous Application of Silicon

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Abstract

Alkalinity stress is a major constraint for crop production in arid and semiarid regions, such as Egypt. Alkaline stress is more harmful than saline stress, and this is mainly due to its additional high pH stress. Silicon has beneficial effects on many crops, mainly under biotic and abiotic stresses. Silicon can affect biochemical, physiological, and photosynthetic processes and, consequently, alleviates alkalinity stress and enhancing yield. However, the effects of Si on sorghum (*Sorghum bicolor L.*) plants under alkalinity stress are still unknown. The objective of this study was to evaluate the effect of Si supply as sodium meta-silicate ($Na_2Sio_3.5H_2o$ at 1.5 mM) on sorghum yield and some biochemical characteristics of yielded components, either exposed or not exposed to alkalinity stress (Na_2CO_3). The experiment was conducted in pots to evaluate the beneficial effect of grain presoaking in Si on two sorghum (*Sorghum bicolor L.*) cultivars (alkalinity sensitive cultivar Giza 15 and alkalinity tolerant one ICSR 92003). The present study was carried out in a greenhouse at the Faculty of Science, Mansoura University, Egypt, through the two successive seasons (2016/2017) and (2017/2018). Alkalinity stress was imposed by various alkaline salt concentrations of 0 (control), 25, 50, and 75 mM Na_2CO_3, with fifteen replications.

Keywords: Sorghum; Alkalinity; Silicon Yield; Protein; Polysaccharides; Harvest index; Crop index; Mobilization index; Relative grain yield

Abbreviations: Si: Silicon; Cont: Control; DW: Dry Weight; HI: Harvest Index; ANOVA Analysis of Variance; S: Sensitive; T: Tolerant.

Introduction

Sorghum is grown around the world and ranks fifth in global cereal production after maize, rice, wheat and barley. It is a major contributor to the staple diets of local populations. Sorghum also has decreased starch and protein digestibility in vitro, and is high in dietary fiber and resistant starch and this array of qualities may play a role in mechanisms that reduce disease risk [1]. The important value of sorghum grain has been considered to be slightly inferior as compared to other cereal grains on the basis of lower protein and starch digestibility and consequently, reduced metabolizable energy. Yield is the

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most important economic trait of Sorghum plants, and grain production is the main selection criteria for alkalinity resistance. Yield is the ultimate outcome of all the processes involved at all stages in growth and development of a crop, any one of which may limit the yield of a particular crop [2].

Alkalization and salinization induce severe effects on the natural grasslands and farming lands in Egypt nowadays. The presence of alkaline salts (Na_2CO_3 or $NaHCO_3$) in the soil caused mainly alkaline stress [3], which is one of the most crucial abiotic stressors. Many studies have been showed that alkaline stress is more harmful than saline stress, and this is mainly due to its additional high pH stress [4].

Alkalinity stress is well known to cause disturbance in metabolites transport to grains, reduce the number of reproductive tillers which limit their contribution to grain yield and cause pollen sterility. Furthermore, water stress during grain growth could have a sever effect on final yield compared with stress during the other stages [5]. Stressing plants resulted in significant and gradual decline in all yield components, such as number of tillers, number of spikes per plant, number of grains per plant, straw yield, grain yield and weight of 1000 grains [6]. Moreover, the yield components, like grain yield, grain number, grain size, and floret number, were decreased under pre-anthesis water stress treatment in sunflower [7].

In addition, the stressed yielded grains contained less nitrogen, phosphorus, potassium, calcium and magnesium contents, but higher sodium content when compared with control plants [8]. In connection, yield components of water-stressed mustard plants were generally reduced, while total seed protein content showed significant increase [9].

Silicon (Si) has been verified to play an important role in enhancing plant resistance to abiotic stress [10]. Si plays an important role in plant-environment relationships because it can enhances plants' abilities to withstand edaphoclimatic and/or biological adversities by acting as a "natural anti-stress" mechanism that enables higher yields and a better-quality end product. Silicon has a large number of diverse roles in plants, and does so primarily when the plants are under stressful conditions, whereas under precious conditions, its role is often minimal or even nonexistent [11]. Silicon (Si) has been verified to play an important role in enhancing plant resistance to abiotic stress [10]. Silicates most often benefit plants grown in Si-poor soils and during adverse years, including prolonged periods of drought, frost, high incidence of pests and/or diseases [12].

Materials and Methods

Plant material and experimental design

A homogenous lot of *Sorghum bicolor L.* (i.e. either alkalinity sensitive cultivar Giza 15 or alkalinity tolerant cultivar ICSR 92003) grains were selected. The grains were separately surface sterilized by soaking in 0.01 M $HgCl_2$ solution for three minutes, then washed thoroughly with distilled water. The sterilized grains from each cultivar were divided into two sets (≈ 300 g per set for each cultivar). Grains of the 1st set were soaked in distilled water to serve as control, while those of the 2nd were soaked in 1.5 mM of freshly prepared Si (as sodium meta-silicate $Na_2O_3Si.5H_2O$) solution for 6 hrs, thereafter air-dried. The grains of both groups were sown in plastic pots (ten seeds/pot) filled with 5.5 kg of dried soil (clay/sand 2/1, v/v). The pots were arranged in completely randomized design in factorial arrangement. At the time of sowing, the grains were irrigated at field capacity with various alkaline salt concentrations of 0 (control), 25, 50, and 75 mM Na_2CO_3 .The Na_2CO_3 concentrations used were equivalent to 0 (control), 0.528, 1.056, and 1.584 g Na_2CO_3 kg^{-1} soil, respectively.

Leaching was avoided by maintaining soil water below field capacity at all times. The Si and Na_2CO_3 concentrations were selected according to on our preliminary tests. The pots were then irrigated at field capacity with normal water through the whole experimental period. The pot of the 1st set was allocated to eight groups (64 pots per each group) as follows: control (Cont.), control silicon, 25% Na_2CO_3, silicon + 25% Na_2CO_3, 50% Na_2CO_3, silicon + 50% Na_2CO_3, 75% Na_2CO_3, silicon + 75% Na_2CO_3 (for sensitive cultivar). The 2nd set groups were allocated to eight groups as follows: control (Cont.), control silicon 25% Na_2CO_3, silicon + 25% Na_2CO_3, silicon + 50% Na_2CO_3, silicon + 75% Na_2CO_3 (for tolerant cultivar). After thinning and at heading, the plants received 36 kg N ha^{-1} as urea and 25 kg P ha^{-1} as superphosphate. Moreover, triplicates samples were taken from each treatment for the biochemical analyses. Data were obtained and the mean values were computed for each treatment.

Yield analyses

Harvest index = Economic yield / Straw yield [13]
Crop index = Grain yield / Biological yield [13]
Mobilization index = Crop yield / Straw yield [14]
Relative grain yield = (Yield in treatment / Yield in control) X 100 [13]

Evapotranspiration efficiency = Water use efficiency for grain/ Harvest index [15]

Estimation of protein

Protein content was determined spectrophotometrically according to the method adopted by [16].

Estimation of polysaccharides

The method used for estimation of polysaccharides in the present study was that of [17].

Estimation Na^+, K^+ and ca^{+2}

Flame spectrophotometry was used for determining Na^+ and K^+, while ca^{+2} was measured by atomic absorption spectrophotometry according to the method described by [18].

Estimation of phosphorus

Phosphorus content was determined according to the method adopted by [19].

Statistical analysis

It should be mentioned that the sample numbers which were taken for investigation were as follows: ten for growth parameters, ten for agronomic traits and three for all chemical analyses and only the mean values were represented in the respective figures. The data were subjected to one-way analysis of variance (ANOVA), and different letters indicate significant differences between treatments at $p \leq 0.05$, according to CoHort/CoStat software, Version 6.311.

Results

Yield components and biochemical aspects of yielded grains

This experiment was planned to assess up to what extent grain priming with silicon could ameliorate the stress imposed by alkalinity stress. For that, this part concerned with yield and yield attributes of alkalinity sorghum plants and biochemical aspects of the yielded grains of alkalinity sorghum cultivars. The experimental design was previously mentioned in the section of materials and methods (See chapter 2). Measurements were carried out at harvest (i.e. 90 days from sowing).

Changes in yield components

To study the impact of grain priming with silicon on yield components of both sorghum plants grown under alkalinity stress, the panicle length, panicle weight, number of panicles per plant, number of spiklets per panicle, number of panicles per plant, number of grains per panicle, number of grains per plant, grain yield per panicle, grain yield per plant, individual grain biomass, 100-kernel weight, straw yield per main panicle, straw yield per plant, crop yield per panicle, crop yield per plant, mobilization index, crop index, harvest index, as well as relative grain yield and evapotranspiration efficiency were estimated. Ten plants from each treatment were randomly taken to estimate yield and yield components of sorghum plants. The obtained results were tabulated and represented in suitable figures.

The data in figures 1a up to 5.c revealed that alkalinity stress caused significant reduction ($p \leq 0.05$) in all yield components of sorghum plants. With regard to the sorghum cultivar, the sensitive one was more affected by alkalinity stress than the tolerant one. In consequence to the previous determinations, silicon induced additional increase ($p \leq 0.05$) in yield components of stressed sorghum plants. Moreover, the treatment of silicon improved all yield components.

Changes in biochemical aspects of yielded grains

The present work was undertaken to investigate the impact of grain presoaking in silicon on biochemical aspects of the yielded grains of both sorghum cultivars under alkalinity stress by measuring polysaccharides and total protein as well as ions (Na^+, K^+ , Ca^{2+} and p^{+3}) contents. Triplicate samples from powdered grains were taken to estimate biochemical aspects of the yielded grains.

Changes in polysaccharides and total protein

In relation to sorghum cultivar, the developed grains of tolerant plants had higher polysaccharides and total protein content than those of the sensitive one (Figure 6.a, 6.b). Alkalinity stress led to marked decrease ($p \leq 0.05$) in polysaccharides and total protein content in the developed grains of the two sorghum cultivars as compared to control values. In general, application of silicon induced marked increase significant ($p \leq 0.05$) in polysaccharides and total protein content in the well-developed grains of the two sorghum cultivars under stressed and controlled conditions except at high alkalinity concentration (75%) in both cultivars.

Changes in ionic content

It appeared from figures 7.a up to 7.b that, alkalinity stress induced significant increase ($p \leq 0.05$) in Na^+, K^+ , Ca^{+2} and P^{+3} contents in mature grains. As compared to control values, in the majority of cases, silicon appeared to induced additional increase in k^+, ca^{+2} and p^{+3} in the developed grains of both sorghum cultivars. On the other hand, silicon appeared to decrease Na^+ in well -developed grains of alkalinity stressed plants.

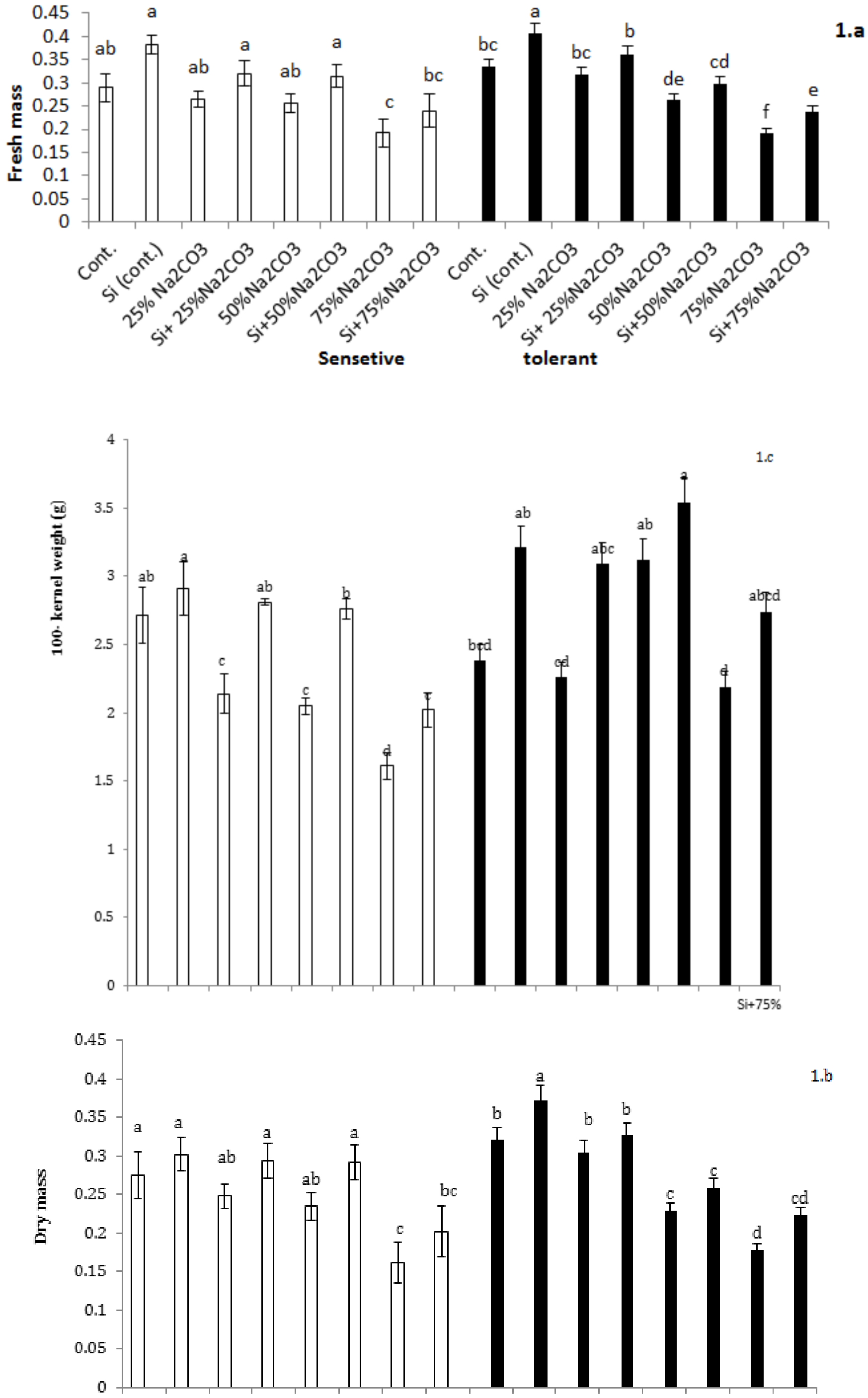

Figure 1: Effects of sodium meta-silicate grain biomass on fresh mass 1.a. , dry mass 1.b. and 100- kernel weight 1.c. of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

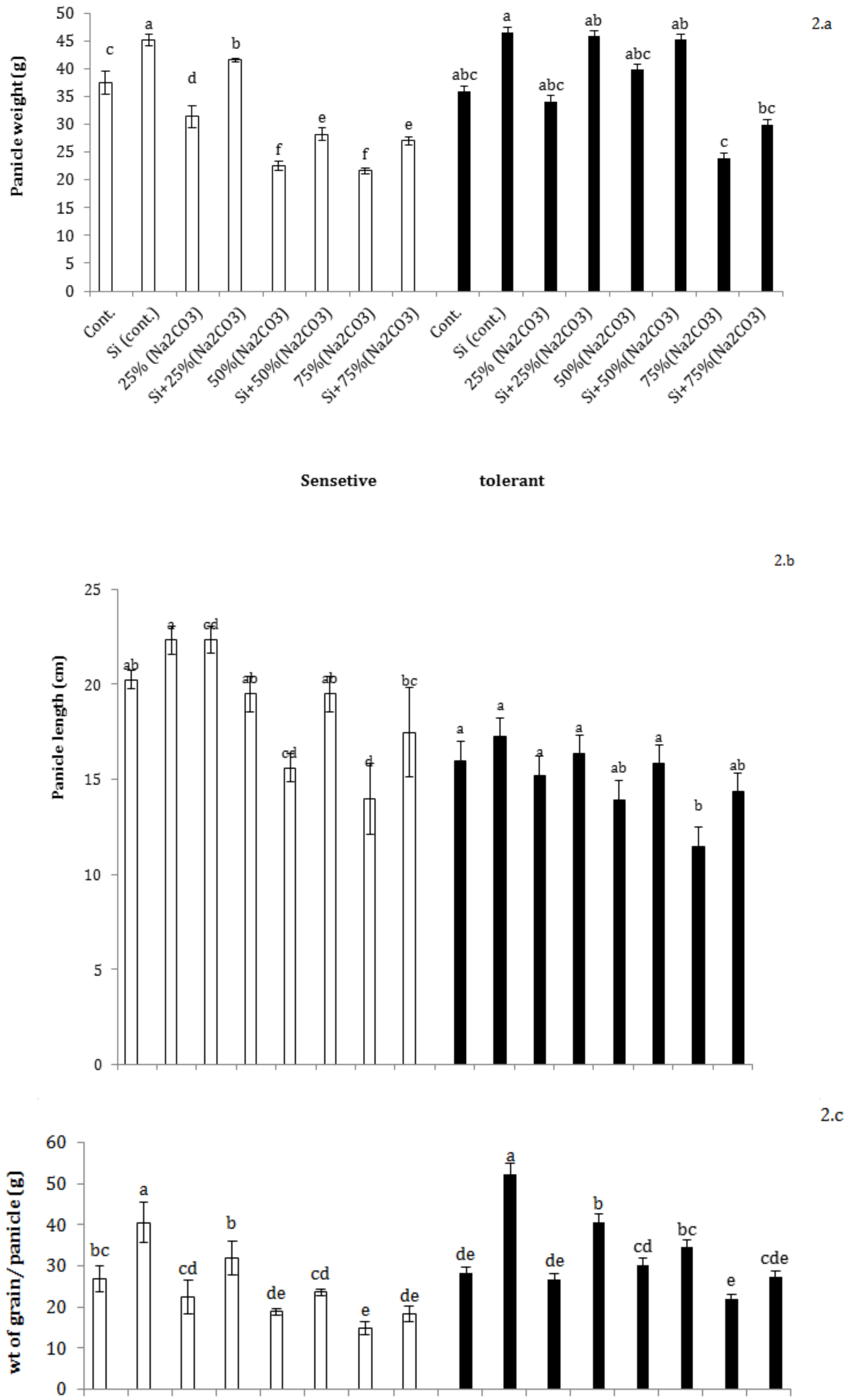

Figure 2: Effects of sodium meta-silicate on main panicle weight 2.a., main panicle length, 2.b., and wt of grain/main panicle 2.c. of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

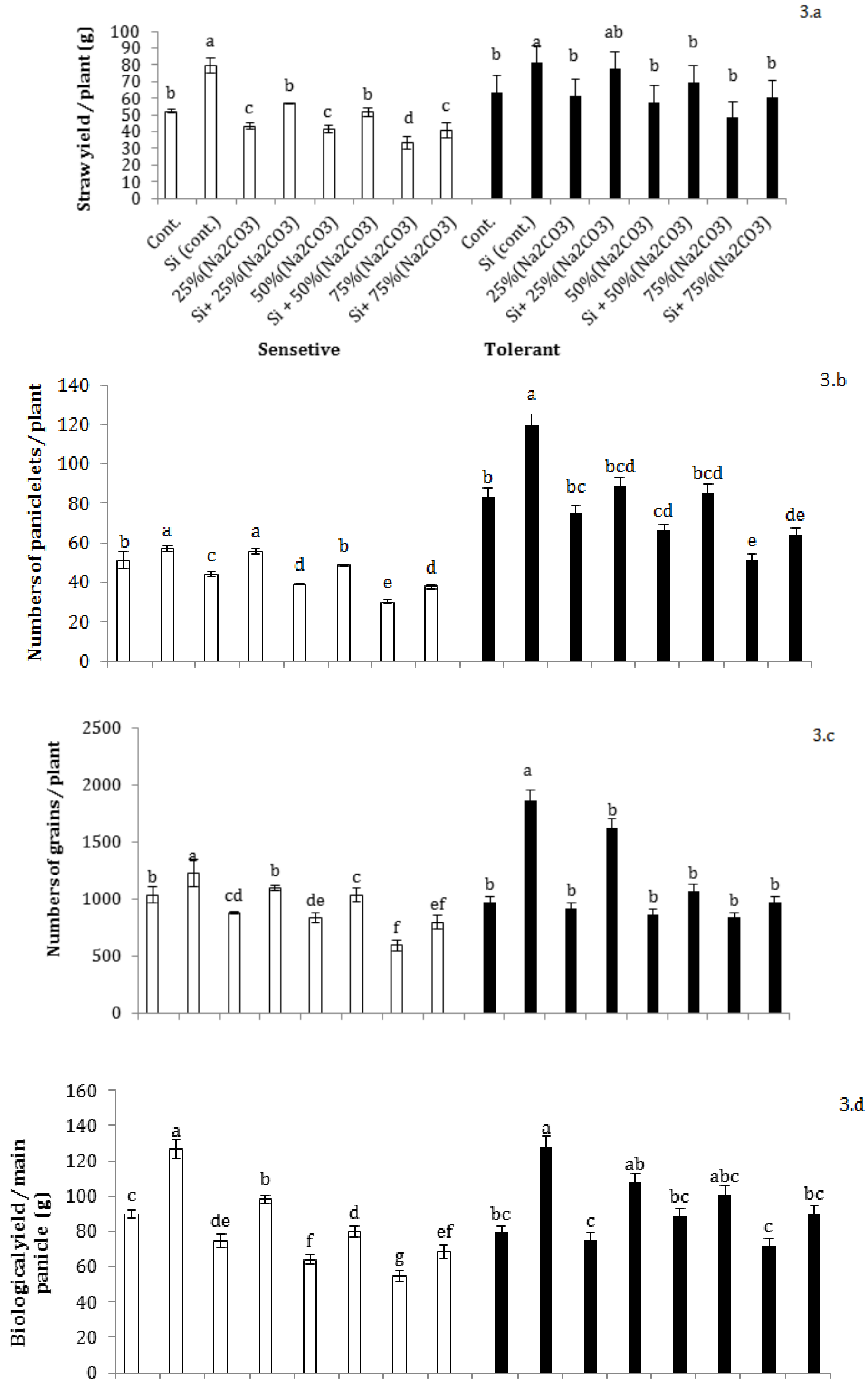

Figure 3: Effects of sodium meta- silicate on straw yield / plant 3.a. , number of paniclelets / plant 3.b., number of grains / plant 3.c. and biological yield / main panicle 3.d of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

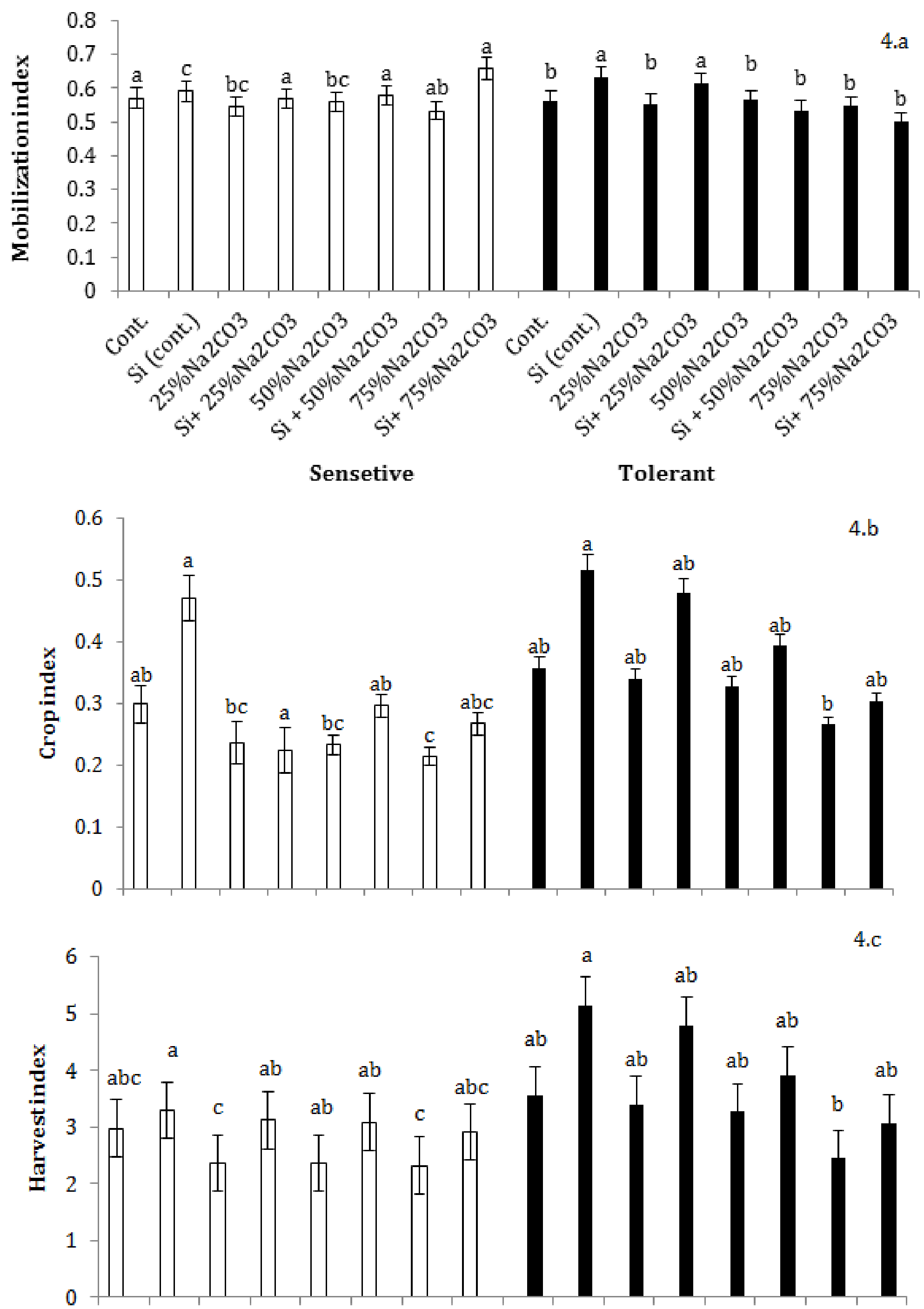

Figure 4: Effects of sodium meta silicate on mobilization index 4.a., crop index 4.b. and harvest index 4.c. of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

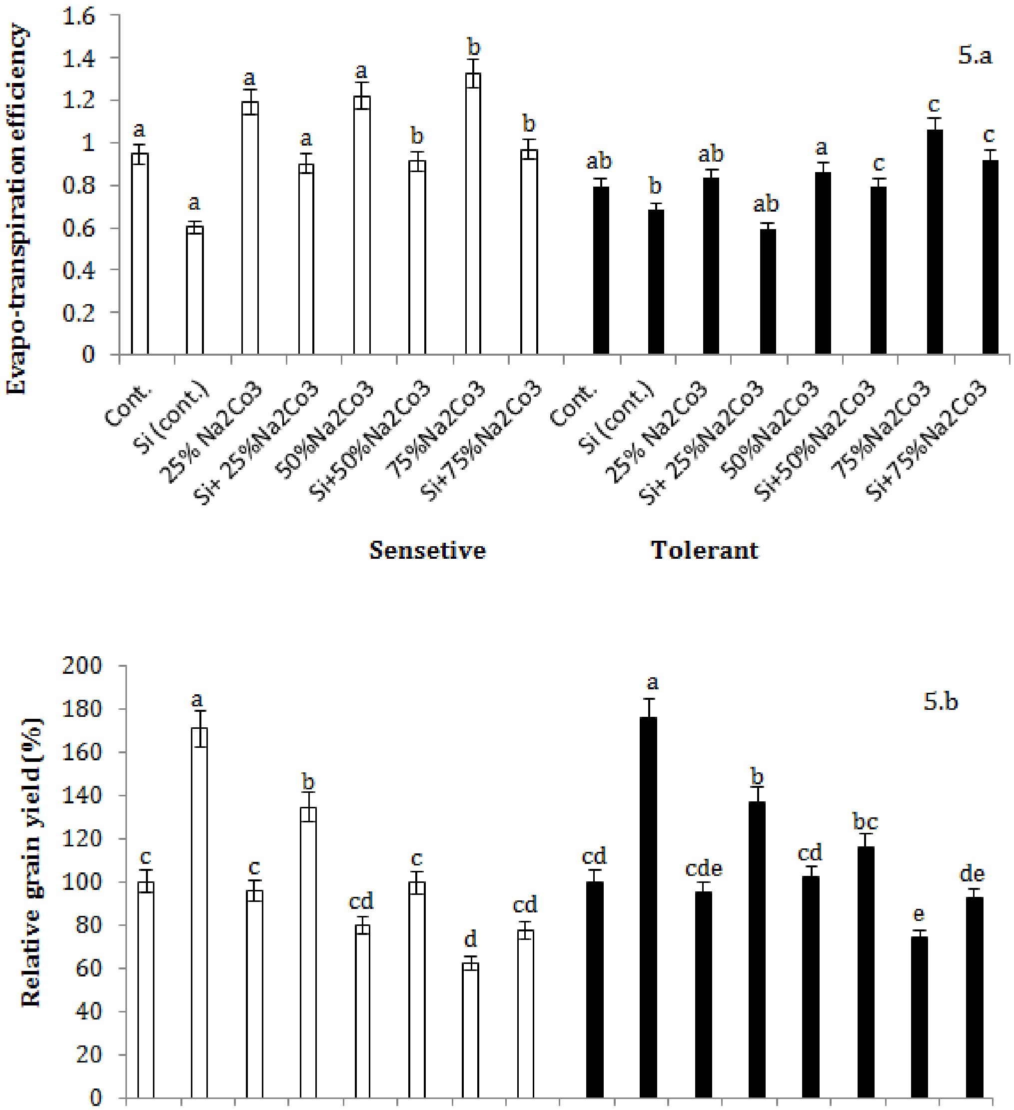

Figure 5: Effects of sodium meta-silicate on 5.a. evapo-transpiration efficiency and 5.b relative grain yield of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

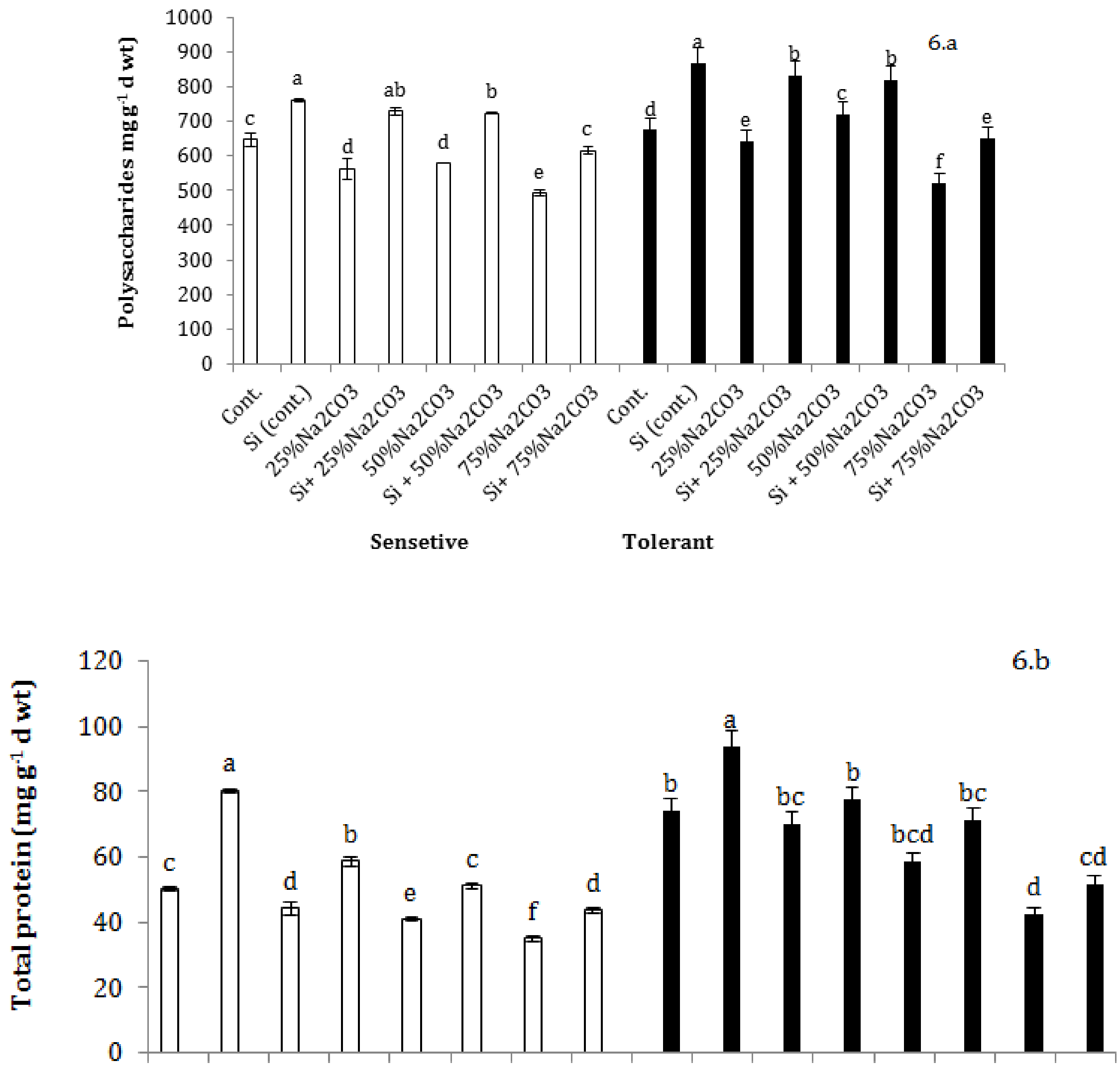

Figure 6: Effects of sodium meta-silicate on polysaccharides 6.a. and total protein 6.b. of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

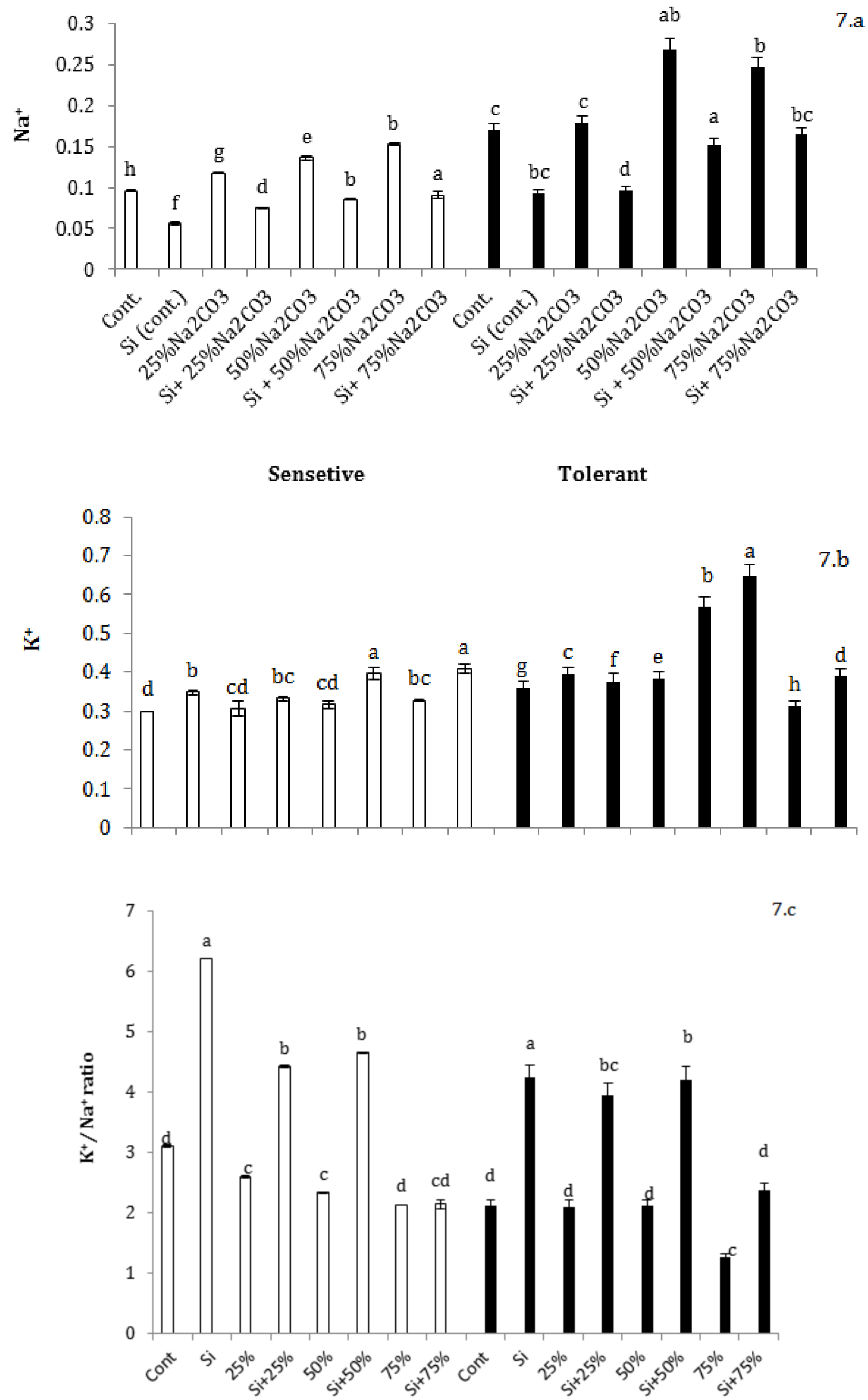

Figure 7: Effects of sodium meta-silicate on ionic content Na^+ 7.a., K^+ 7.b. and K^+/ Na^+ ratio 7.c. of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

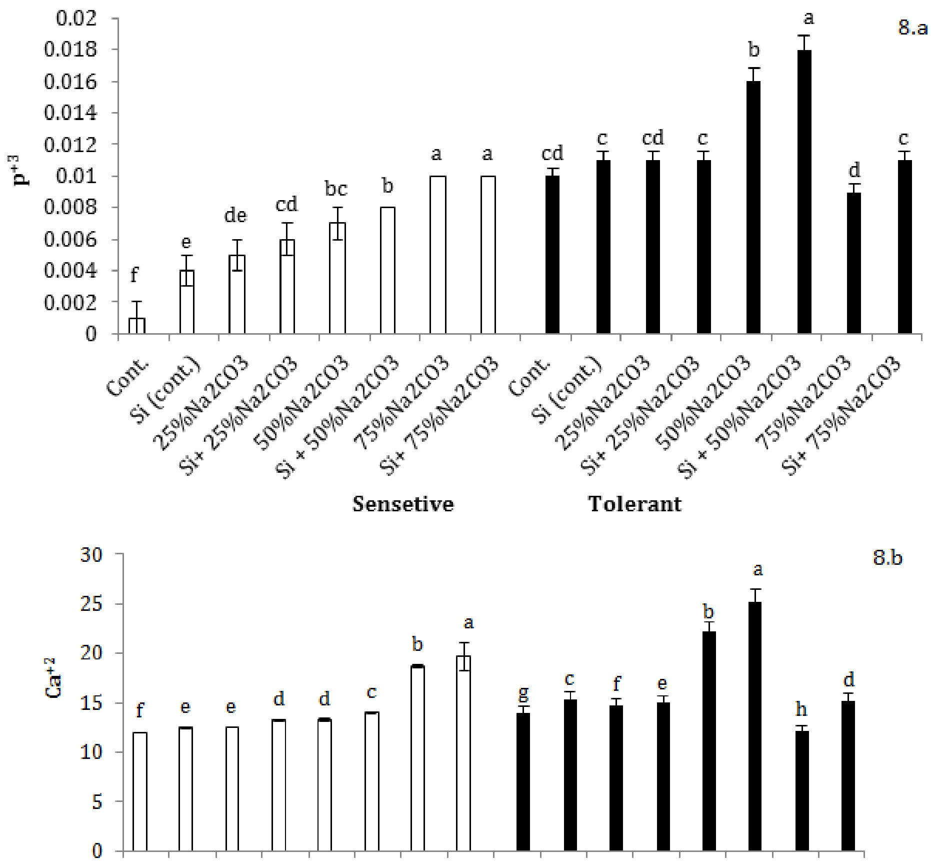

Figure 8: Effects of sodium meta-silicate on ionic content Ca^{+2} 8.a. and P^{+3} 8.b. of yielded grains of alkalinity stressed sorghum plants. Vertical bars represent standard error of the mean (n=10). Different letters indicate significant differences between treatments at $p \leq 0.05$.

Discussion

Alkalinity stress during the early stage of reproductive growth tends to reduce yield by reducing grain number. During grain development stress reduces yield by reducing grain size. The detrimental influences caused by alkaline on different growth parameters of sorghum plants could occur due to the raise in pH. Prolonged alkalinity stress during reproductive growth can severely reduce yield because of reduced grain number and grain size. The response and adaptation of plants to such conditions are very complex and highly variable. Exogenous application of Si is an effective method to alleviate the adverse effects of alkalinity stress on sorghum bicolor [10].

Yield is a result of the integration of metabolic reactions in plants; consequently any factor that influences this metabolic activity at any period of plant growth can affect the yield [20]. Hence, figures from 1 to 5 indicated that alkalinity stress significantly decreased all yield components (shoot length, panicle length, plant height, panicle weight, number of panicles per plant, number of spiklets per panicle and per plant, number of grains per panicle and per plant, grain yield per panicle and per plant, individual grain biomass, 100-kernel weight, grain yield, straw yield, crop yield, mobilization index, crop index, harvest index, as well as relative grain yield and evapotranspiration efficiency). The applied silicon appeared to alleviate the adverse impact of alkalinity stress on the yield components of sorghum plants.

The decrease in yield and yield components in different crops under similar conditions has also been reported by many workers [21]. These workers clearly indicated that drought tolerant genotypes showed less reduction in yield plants in respect of susceptible ones. Moreover, it is well known that drought can reduce the final grain yield by influencing wheat growth in different growth stages. Water stress during the early stage of reproductive growth tends to reduce yield by reducing seed number. During seed development stress reduces yield by reducing seed size. Prolonged moisture stress during reproductive growth can severely reduce yield because of reduced seed number and seed size [22].

Alkalinity stress reduced harvest, mobilization and crop indices in the two sorghum cultivars. This was in accord with Jalal [23] who reported that, water stress decreased harvest index, and biomass yield in two varieties of *Catharanthus roseus*. However, in crops, the detrimental effects of water deficits on the harvest index (HI) also minimize the impact of the water limitation on crop productivity and increase the efficiency of water use [24]. Therefore, increasing transpiration, transpiration efficiency and harvest index are three important avenues for the important of agricultural productivity [21].

Carbohydrates that represent one of the main organic constituents of the dry matter are well known to be affected by alkalinity stress (Figure 6). The results indicated that, alkalinity stress induced massive decrease in polysaccharides in yielded grains of both sorghum cultivars. This may probably be due to the fact that alkalinity stress stimulates the degradation of polysaccharides and at the same time increases the dark respiration during which a part of soluble sugars was consumed as a respiratory substrate. The other part of soluble sugars may explain the massive increase in total soluble sugars occurred within the developing grains as a result of water stress. From another point of view, alkalinity stress decreased the pigment concentration in sorghum leaves which results in inhibition of photosynthetic activity, in turn it leads to less accumulation of carbohydrates in mature leaves and consequently may decrease the rate of transport of carbohydrates from leaves to the developing grains, where there is a good relationship between source (leaves) and sink (grain) in cereal plants. Furthermore, the noticed decrease in polysaccharides of wheat grains as a result of water stress could be explained on the fact that, alkalinity stress impaired the utilization of carbohydrates [25].

Under alkalinity stress, protein content of the developed grains was significantly decreased in both sorghum cultivars (Figure 6). The decrease in protein contents in yielded grains was more pronounced in the sensitive cultivar than the tolerant one under alkalinity, this may probably be due to less transport of protein from source (flag leaf) to the sink (grain). In support of this finding, alkalinity stress induced remarkable decrease in soluble protein in flag leaf of both sorghum cultivars during grain filling. Similar results are obtained by EL-Tayeb [26].

Alkalinity stress induced marked reduction in biochemical aspects of yielded grains especially polysaccharides as well as total protein (Figure 7). Conversely, alkalinity stress induced increase in Na^{+}, K^{+} and Ca^{+2} and significantly increases P^{+3} contents in mature grains. Silicon induced significant increase in Na^{+}, K^{+} and Ca^{+2} contents in mature grains except at 75% in both cultivars (Figure 7). In general, application of silicon seemed to induce increase in K^{+}/Na^{+} ratio, K^{+} and Ca^{+2} of the developed grains of both sorghum cultivars.

Application of Si appeared to mitigate the deleterious effects of alkalinity stress on grain yield of the two sorghum cultivars. The repairing effect of Si may be attributed to the fact that Si reduces the rate of transpiration from leaves [27], which could possibly lead to the accumulation of excessive water, thus resulting consequently in an increase in grain fresh mass [28].

Conclusion

On conclusion sorghum plants with enough good supply of Si tolerate lack of water for a longer period because they efficiently use the absorbed water and lose it at a lower speed than plants with a low Si level. Si increases crop yield and improves technological quality, while the lack of this element can reduce the plants' biological ability to withstand alkalinity stress.

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