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Research Article
Morpho-Physiological Responses of Quinoa (*Chenopodium quinoa* Willd.) Varieties to Salinity in a Hydroponic System

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Abstract

Background and Objective: Among the abiotic stresses, salinity probably has the most deleterious effect on plant growth and productivity. This study was aimed to assess the responses of eight *C. quinoa* varieties to different NaCl concentrations (200, 300, 400 and 500 mM NaCl) and CK (control) in hydroponics. **Materials and Methods:** Morphological features assessed were relative growth (height), dry biomass of shoots and roots, relative chlorophyll content, yield while the physiological parameters were stomatal conductance, net photosynthesis, transpiration rate, intrinsic water use efficiency, intercellular CO_2 concentration and relative water content. Application of one-way ANOVA and Tukey analysis determined the significance of the responses among the treatments and varieties. **Results:** The results indicated that a significant difference (p = 1.48E-10) existed in relative growth (height) among the varieties with a consistent increase in salinity as compared to the CK at $p<0.05$. A >50% reduction in stomatal conductance was observed between the CK and 500 mM NaCl and a significant difference (p = 9.84E-12) was identified among the treatments. The highest respiratory and net photosynthesis rates were found in CKs for all the varieties with a significant difference (p = 7.86E-07) among the treatments at $p<0.05$. Moreover, yield decreased significantly after 200 mM NaCl with ~ 80% at 300 and 400 mM NaCl relative to the CK. **Conclusion:** The varieties displayed tolerance to high salinity concentration, even though their responses were differential, they all produced viable seeds. Hence, they can be used in future breeding programs to enhance the growth and development of other varieties in highly saline soils.

Key words: Quinoa, salinity, stomatal conductance, productivity, plant growth, hydroponics

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

C. quinoa is a unique pseudocereal crop with an Andean origin that has evolved incredible physiological and morphological adaptive mechanisms to withstand extreme environmental conditions[1-8]. Stress imposed from salinity is critically important because it limits plant growth and productivity[9-14]. Quinoa is a facultative halophyte and recognized as one of the most salt-tolerant crops known[13,15-18]. With the increase in soil salinization resulting from the effects of global warming and anthropogenic activities and in addition to over 96% of the world's water being categorized as saline, it is imperative to focus on identifying and introducing more crops with higher tolerance to salinity[4,19]. Furthermore, quinoa is a highly nutritious crop with adequate amount of nutrients to supplement our dietary needs and has been identified by United Nations (UN) through the Food and Agriculture Organization (FAO) and subsequently declared 2013 as 'International Year of Quinoa'. Quinoa is special because of its ability to adapt naturally to the different abiotic stresses, namely saline, drought and frost[18,20-23].

Generally, for plants to survive in saline conditions they must overcome several inevitable constraints such as accretion and depletion of ions, decrease in soil water potential and oxidative processes which can potentially exert excessive pressure on metabolism[1,24-27]. Hence, plants have evolved different mechanisms to avoid significant injurious impacts of salinity stress by mitigating osmotic stress through the prevention of water loss and increase intake. They also developed epidermal bladder cells that compartmentalize a significant amount of salt[28-30]. Besides, plants also excude salt through their tissues and loading sodium ions into vacuoles both internally and externally[4,27,31].

Quinoa has such extraordinary adaptations to salinity that some varieties have the potential to grow in salt concentrations even higher than that of seawater[22,24]. Moreover, when exposed to different levels of salinity, their yield was highest between 100 and 200 mM NaCl[8]. During a study, quinoa was exposed to six levels of salinity and it was observed that the optimal growth and biomass accumulation achieved was between 100 and 200 mM NaCl. Also, at 500 mM NaCl even though germination was <25%, those plants that survived, showed a significant decrease (50%) in their shoot length but nevertheless completed their life cycle[8,32]. Additionally, 182 quinoa accessions were screened for salt tolerance in which 25% exhibited greater than 60% germinability at 250 mM NaCl. These 15 accessions were further assessed at 300 and 340 mM NaCl with 13 accessions showing a reduction in growth while two grew 1.79-11% higher than the CK[33]. A study was also done with cultivars Chipaya and Ollague in which a decrease in fresh weight was noted, while at 450 mM NaCl they sustained a 50 and 40% higher transpiration rate than the CK, respectively[20]. Based on these differential responses to salinity, this study was designed to determine morphological and physiological responses of eight previously untested varieties of quinoa at four salinity levels and CK in the hydroponic system.

MATERIALS AND METHODS

Growth condition: The experiment was conducted (~90-day) in greenhouse at the Center for Horticultural Biology and Metabolomics, Haixia Institute of Science and Technology, Fujian Agriculture and Forestry University, China during the period of March to July (2018) in ambient light, temperature range of 24-26°C and average relative humidity of ~65%. Except for grain yield, all other measurements and sampling were done during the vegetative period of the plants (~70-day).

Plant pre-screening and selection: Seeds were sown to amplify and to obtain fresh seeds to enhance consistency in standard and accuracy of the experimental result. New seeds were then tested for viability using filter paper and water[33]. These seeds were then subjected to *in vitro* preliminary screening in different salinity levels 0-500 mM NaCl in MS/2 medium[34], with 0 being the CK) and were assessed on germinability, survival and height after 21 days. Germinability, survival and height of the seedlings were the criteria used for selection of the eight varieties, namely A (PT-ROB), B (PT-1), C (PT-2), D (PT-3), E (PT-TR), F (PT-Gaoxing) G (PT-4) and H (PT-Taoyuan). The Fujian Agriculture and Forestry University, Plant Transformation Unit provided these varieties.

Plant growth and treatments: These seeds were then sown in pindstrup substrate until two-true leaf seedling stage and then transferred into the hydroponic system containing water. After day one, Hoagland solution was added and then five days later salt was added incrementally at 50 mM NaCl day to avoid osmotic shock and damage to root until the maximum concentration was achieved for the respective treatment threshold[32,35-37]. Treatments consisted of the hydroponic solution with NaCl added to reach concentrations of 200, 300, 400 and 500 mM NaCl with 0 mM NaCl serving as the control treatment (CK). The culture solution was changed with the final salt increment and weekly thereafter and as the plants grew, the nutrient solution with respective salt concentrations, as necessary[32,38]. The plants were arranged in a complete randomized block design in the hydroponic box, with 6 biological replicates per treatment.

Plant growth measurements: To have an accurate perspective of the morphological features, 3 plants were harvested at the vegetative stage to determine their shoot and root lengths, shoot and root dry biomass, stem diameter and dry biomass of the entire plant because, at maturity, quinoa exhibits excessive dehiscence. Dry weight (DW) was determined by apportioning the plant into shoot and root. Samples were weighed and then wrapped with aluminium foil and oven-dried at 105°C for 19 min followed by 80°C for 24 h. After constant mass was achieved, samples were removed and the dry weight of shoot and root were measured. Shoot biomass and root biomass ratios were calculated by the dry mass at the respective salinity/dry mass at the CK for each variety and concentration, respectively[39-41]. Relative plant growth (height) was determined:

$$\text{Relative plant growth (\%)} = \frac{\text{Height at a specific concentration}}{\text{Height at CK for the same concentration}} \times 100$$

Before harvest, the net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration and transpiration rate were determined using the LI-COR (6800) Portable Photosynthesis System. Intrinsic water use efficiency (iWUE) was taken as the ratio of net photosynthesis and transpiration rate[42,43]. The relative chlorophyll content was determined during the vegetative stage with a Soil Plant Analysis Development (SPAD) chlorophyll meter, Konica Minolta[44,45]. All measurements and data were taken from three leaves of each plant with 3 readings per leaf in treatment and CK.

For relative water content (RWC), leaves were sampled from plants and the fresh weight (FW) measured. Leaves were then floated in H_2O for 4 h and reweighed to determine the turgid weight (TW). Leaves were then wrapped with aluminium foil and oven-dried at 105°C for 19 min and followed by 80°C for 24 h. After the expiry of this period or constant mass was achieved, samples were removed and the dry weight (DW) determined. The relative water content (RWC) was then calculated using the formula[40,46,47]:

$$\text{RWC (\%)} = \frac{\text{FW-DW}}{\text{TW-DW}} \times 100$$

Statistical analysis: The experiment was conducted in a completely randomized block design with three biological replicates per treatment. The data were subjected to one-way analysis of variance test (ANOVA) and expressed as the mean of the 3 replicates (Mean±SD) and the significance among treatments and varieties for morphological and physiological responses was checked at $p<0.05$ and $p<0.001$. Where ever a significant difference was identified, Tukey HSD test was employed to identify where such occurred. The Statistical Package for Social Sciences (Version 21 for Windows, SPSS Inc., New York, NY, USA) and GraphPad Prism (version 7.00 for Windows, GraphPad Software, La Jolla California, USA) were used to perform the analysis.

RESULTS

Morphological parameters

Relative plant growth-height: The untreated plants showed much proclivity to grow higher than the treated plants with all the varieties displaying the tallest plants at CK. In this instance, variety H had the highest relative growth with 91.9% at 200 mM NaCl, while variety A had the lowest relative growth at 38.6, 31.49 and 20.57% at 200 mM NaCl, 400 mM NaCl and 500 mM NaCl, respectively. At 300 mM NaCl, the relative growth was highest in variety H at 89.9% and this trend continued at 400 mM NaCl and 500 mM NaCl with 69.59 and 53.05%, respectively in Fig. 1. In summary, a significant difference ($p = 1.48E-10$) existed in relative growth among the plants in the different treatments and between the CK and the 500 mM NaCl ($p = 0.005$). Moreover, Tukey analyses identified significant differences between and among the different concentrations at $p<0.05$.

Shoot biomass and root biomass ratios: Variety D (2.28±0.23) at 200 mM NaCl displayed the highest shoot biomass ratio and variety C (0.47±0.44) at 500 mM NaCl was

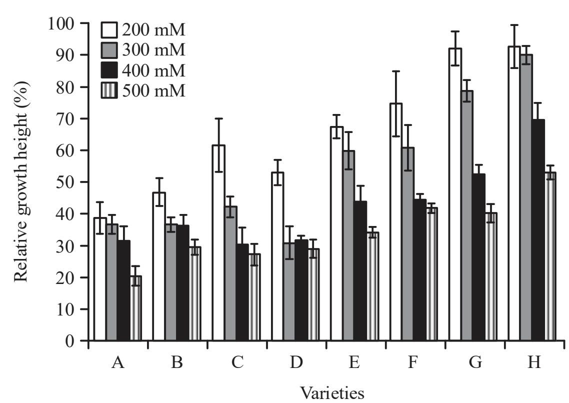

Fig. 1: Effect of NaCl on relative growth (height) between the CK and the various NaCl concentrations on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

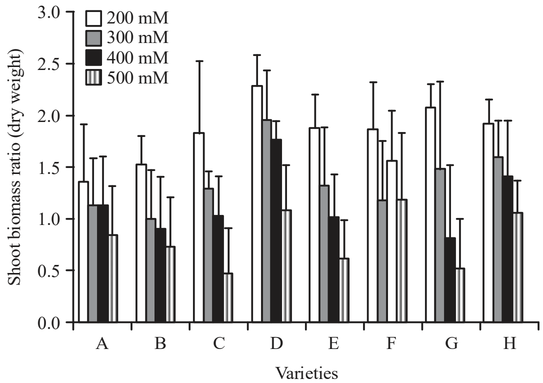

Fig. 2: Effect of NaCl on the relative dry shoot biomass between the CK and NaCl concentrations on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

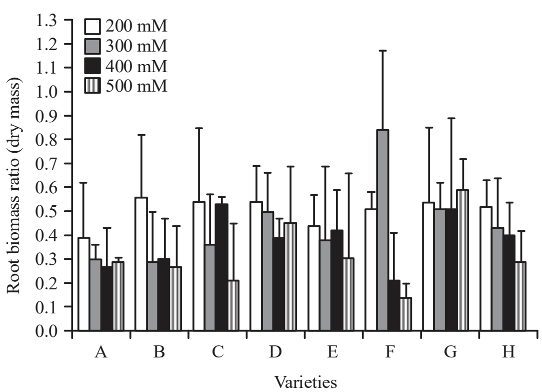

Fig. 3: Effect of NaCl on the relative dry root biomass between the CK and NaCl concentrations on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

the lowest among the varieties and concentrations. The highest shoot biomass ratio was observed between the CK and 200 mM NaCl for all the varieties and treatments with lowest and highest being variety A (1.36±0.47) and variety D (2.28±0.30) (Fig. 2). At the 500 mM NaCl concentration, the shoot dry biomass was highest in F (1.18±0.65) and lowest in C (0.47±0.41). A significant difference was identified by one-way ANOVA among the varieties at $p<0.05$.

For root biomass ratio, variety F had the highest (0.84±0.3) and the lowest (0.14±0.06) at 300 mM NaCl and 500 mM NaCl among the varieties and concentrations, respectively. Varieties A (0.30±0.23), B (0.56±0.26), C (0.54±0.31), D (0.54±0.15), E (0.44±0.13) and H (0.52±0.11) all had the highest root biomass ratios at 200 mM NaCl among the different concentrations (Fig. 3).

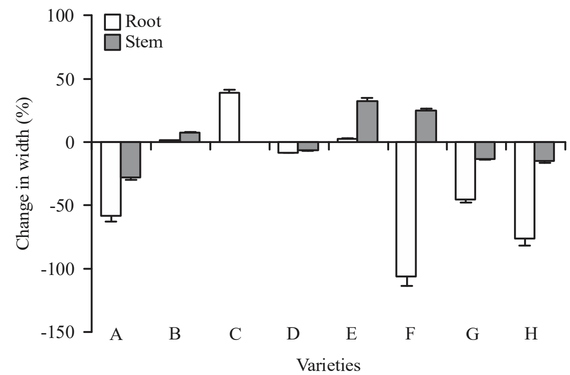

Fig. 4: Percentage change between 500 mM NaCl and CK on root length and stem width on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

Variety H seemed to be the most salt-tolerant with respect to root biomass even though its relative root length reduced by 75% between the CK and 500 mM NaCl (Fig. 4). One-way ANOVA identified significant differences among the varieties ($p = 0.041$) but no significant difference among the treatments ($p = 0.61$) at $p<0.05$.

Root and stem morphology: Root length depicted a decrease with A (57.93%), D (8.46%), F (106.65%), G (45.45%) and H (76.41%) at 500 mM NaCl as compared to the CK. Moreover, B (1.59%) and E (2.84%) had slightly longer roots and with C (39%) having the highest increase between the CK and 500 mM NaCl. In addition, the stem diameter has shown differential responses to salinity among the genotypes, considering the change between the CK and 500 mM NaCl. Stem diameter increased in B (8.13%), E (32.72%) and F (24.86%) while the reduction was observed in A (27.90%), D (6.39%), G (12.53%) and H (15%) with C neither being decreased nor increased. Hence, the largest increase in stem diameter was observed in variety E (32.72%) and the most significant reduction being observed in variety A (27.90%) (Fig. 4). ANOVA and Tukey post-hoc analyses identified significant differences between the CK and 500 mM NaCl and among the varieties at $p<0.05$.

Physiological response

Net photosynthetic rate: Except for variety C, all the other varieties have displayed a reduction in the net photosynthesis. Variety G (11.13±1.17 µmol CO_2 m^{-1} sec^{-1}) expressed the highest rate of net photosynthesis while variety C (6.60±0.46 µmol CO_2 m^{-1} sec^{-1}) was the lowest at the CK. At 500 mM NaCl, variety H (9.91±1.37 µmol CO_2 m^{-1} sec^{-1})

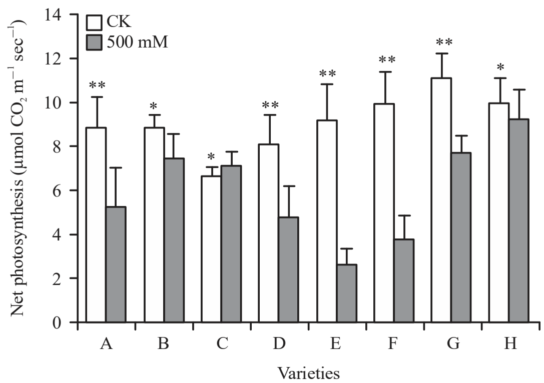

Fig. 5: Effect of NaCl between 500 mM NaCl and CK on the net photosynthetic rate on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates, **Significant difference at $p<0.05$, *$p<0.001$ between CK and 500 mM NaCl

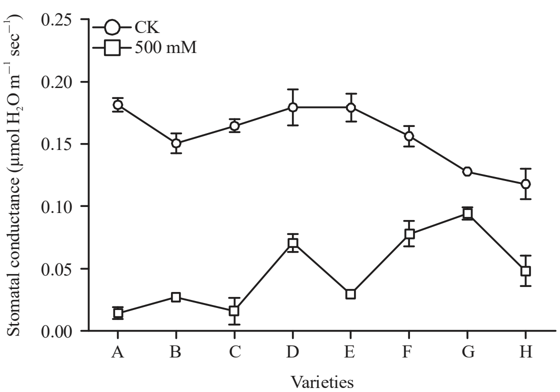

Fig. 6: Effect of NaCl at 500 mM NaCl and CK on stomatal conductance on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

was the highest with variety E the lowest (2.61±0.725 µmol CO_2 m^{-1} sec^{-1}). Variety E exhibiting the highest difference between the CK and 500 mM NaCl at (9.16±1.17 µmol CO_2 m^{-1} sec^{-1}) and (2.61±0.725 µmol CO_2 m^{-1} sec^{-1}) is representing a 71.5% reduction. Variety H showed the least difference between the CK and 500 mM NaCl at 9.95±1.16 and 9.19±1.37 µmol CO_2 m^{-1} sec^{-1}, respectively. Interestingly, variety C increased from 6.60±0.42 to 7.1±0.64 µmol CO_2 m^{-1} sec^{-1} between the CK and 500 mM NaCl (Fig. 5). ANOVA analysis of the results revealed a highly significant difference among the treatments (p = 7.86E-07) while no significant difference existed among the varieties (p = 0.459) for the net photosynthetic rate at $p<0.05$. Except for varieties B, C and H, all the others exhibited significant differences ($p<0.001$) between the CK and 500 mM NaCl.

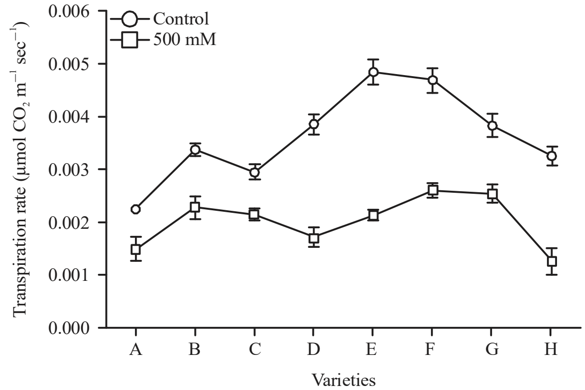

Fig. 7: Effect of 500 mM NaCl and CK on transpiration rate on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

Stomatal conductance: All varieties showed >50% decline in the stomatal conductance between the control and final treatment except for variety G (26%). The largest reduction was observed in variety A (0.187±0.005 µmol H_2O m^{-1} sec^{-1}) followed by C (0.16±0.005 µmol H_2O m^{-1} sec^{-1}) with G (0.118±0.012 µmol H_2O m^{-1} sec^{-1}) with the lowest (Fig. 6). However, this markedly increased was only noticed from the perspective of the CK to the final threshold. Hence, stomatal conductance is sensitive to saline condition. Further, analysis of variance identified no significant difference among the varieties (p = 0.56) while a significant difference (p = 9.84E-12) was observed among the treatments at $p<0.001$.

Transpiration rate: Transpiration rate showed a consistently decreasing trend among the varieties with higher values being recorded at the CK as compared to 500 mM NaCl. Variety E showed the highest transpiration rate with 0.00483 µmol CO_2 m^{-1} sec^{-1} while the lowest was variety A with 0.0022 µmol CO_2 m^{-1} sec^{-1} at the CK. At the 500 mM NaCl, variety F had 0.00259 µmol CO_2 m^{-1} sec^{-1} and variety H 0.00125 µmol CO_2 m^{-1} sec^{-1} being the highest and lowest, respectively (Fig. 7). No significant difference was identified among the same treatments (p = 0.24) and varieties (p = 0.62) at $p<0.05$. Likewise, when comparing the transpiration rate between the CK and the 500 mM NaCl, no significant difference was identified.

Water use efficiency: Intrinsic Water use Efficiency (iWUE) decreased as the NaCl concentration increased. At the CK, varieties H and F exhibited the highest and lowest iWUE with 4.01±0.20 and 2.12±0.10 µmol CO_2 mmol H_2O^{-1}, respectively. At 500 mM NaCl, varieties H and E showed the highest and lowest with 2.63±0.18 and

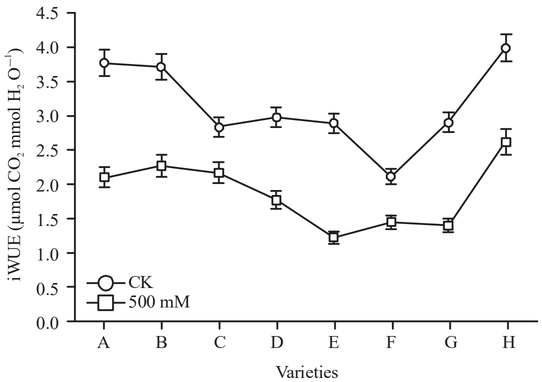

Fig. 8: Effect of the between 500 mM NaCl and CK on the intrinsic water use efficiency
Data include (Mean±SD) 3 biological replicates

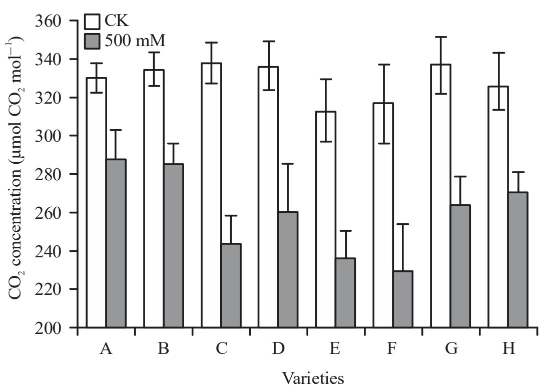

Fig. 9: Effect of salinity between 500 mM NaCl and CK on the intercellular CO_2 concentration on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

1.22±0.08 μmol CO_2 mmol H_2O^{-1}, respectively. However, the most significant difference between the CK and 500 mM NaCl was observed in varieties A (1.67 μmol CO_2 mmol H_2O^{-1}) and E (1.66 μmol CO_2 mmol H_2O^{-1}) while the lowest was exhibited at varieties C (0.67 μmol CO_2 mmol H_2O^{-1}) and F (0.67 μmol CO_2mmol H_2O^{-1}) (Fig. 8). One-way ANOVA identified no significant difference among the treatments and varieties but a significant difference was observed between the CK and 500 mM NaCl at $p<0.05$.

Intercellular carbon dioxide: Intercellular carbon dioxide reduced consistently with increasing NaCl concentrations. While the amount was very close with respect to the treatments among the different varieties, CK had the highest intercellular carbon dioxide content as compared to the 500 mM NaCl. At the CK, varieties C and E had the highest and

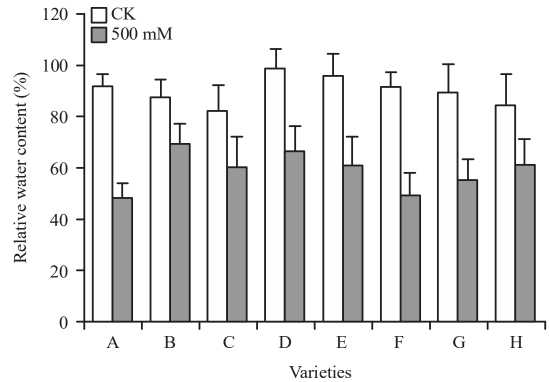

Fig. 10: Effect of the 500 mM NaCl and CK on the relative water content on the different quinoa varieties
Data include (Mean±SD) 3 biological replicates

lowest with 338.22±10.76 and 313.18±16.26 μmol CO_2 mol^{-1}, respectively. At 500 mM NaCl, the 287.42±15.74 and 229.27±24.58 μmol CO_2 mol^{-1} indicated the highest and lowest for varieties A and F, respectively (Fig. 9). Based on one-way ANOVA, a significant difference ($p = 3.034E-09$) was observed among the different treatments and varieties at $p<0.05$. Tukey (HSD) also identified a significant difference between the CK and 500 mM NaCl in the varieties.

Relative water content (RWC): Relative water content decreased with increasing salinity for all the varieties. Variety D had the highest (98%) and the lowest was observed in C (82%) in CK for 500 mM NaCl, D (64%) and A (48%) were the highest and lowest, respectively (Fig. 10). While the responses to salinity were minimally differential among the 200, 300 and 400 mM NaCl, the lowest and by all means, the most significant response was observed at the 500 mM NaCl level as identified by one-way ANOVA with a significant difference ($p<0.05$). The highest and lowest declines were observed between the CK and 500 mM NaCl in varieties A (57%) and E (34%), respectively.

Chlorophyll content: The highest average relative chlorophyll content was recorded at CK and 500 mM NaCl was 49.23 and 46.68, respectively. The lowest average was recorded at 200 mM NaCl at 41.54 among the varieties. After the decline at 200 mM NaCl, there were consistent decreases from 300 and 500 mM NaCl while at 400 mM NaCl it was higher than 500 mM NaCl in varieties A, B, C,D, F and G. With the exception of varieties E and H, all the other varieties have lower relative chlorophyll content at 500 mM NaCl (Fig. 11). Analysis of variance identified a significant difference among the varieties ($p = 6.17E-12$) and the treatments ($p = 4.65E-10$) at $p<0.05$.

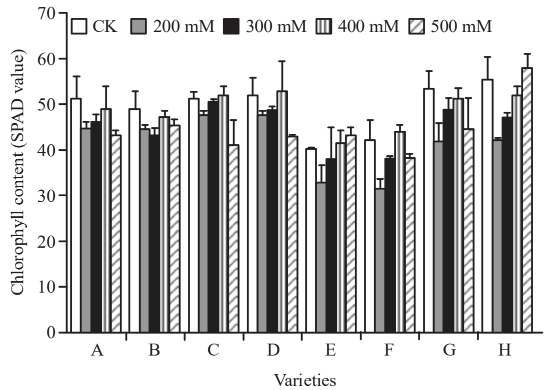

Fig. 11: Effect of the different concentrations of NaCl and CK on relative chlorophyll content
Data include (Mean±SD) 3 biological replicates

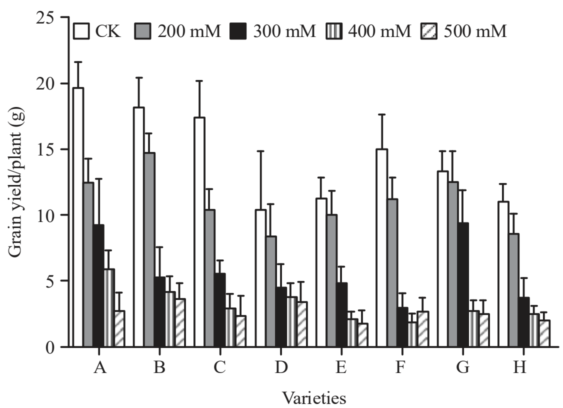

Fig. 12: Effect of the different NaCl concentrations and CK on grain yield of the genotypes
Data include (Mean±SD) 3 biological replicates

Yield productivity: The yield among the eight varieties decreased consistently with increasing salt concentration with 200 mM NaCl having the highest average (12.2 g) as compared with the CK at19.63 g, representing 15% reduction. Lowest yield for all the genotypes was recorded at 500 mM NaCl (Fig.12). Analysis of variance identified significant differences among the varieties (p = 0.003) and the treatments (p = 3.300E-13) at $p<0.01$. At the varietal level, a significant difference ($p<0.001$) was observed between the CK and 500 mM NaCl. While yield has decreased significantly with increasing salt concentration, it must be noted that the plants completed their life cycle and produced seeds at all the different concentrations, which are indicative of their tolerance to high salinity.

DISCUSSION

Generally, plants with high tolerance to salinity and other stress factors, have modified morphological and physiological structure to thrive in such condition with unique vacuolar enlargement to compartmentalize excess salt, development of salt bladders and highly cutinized epidermis[4,33,48]. Salt concentrations reduce plant height and hence lead to shorter plants with increasing concentration. In such condition, plants presumably expend more energy in trying to mitigate or compensate for the effects of the stress rather than growth. In this study, all plants exposed to salinity from 200 mM NaCl to 500 mM NaCl have exhibited continuous stunted growth with variety G having 56.41% reduction between CK and 500 mM NaCl and for the among the treatments, a highly significant difference ($p<0.001$) was identified through analysis of variance. Quinoa grown in 500 mM NaCl had a 50% reduction in height while optimal growth was achieved at 100 mM NaCl[32]. This is in concurrence with our results in which 2 varieties (G and C) exhibited >50% relative height while the other was over >35% between the CK and 500 mM NaCl. Evaluating the height and weight for two quinoa cultivars, Chipaya and KU-2 and compared them with *Thellungiella halophile* indicated that both quinoa cultivars outperformed the model halophyte (*T. halophila*), thus bestowing higher salinity tolerance for these agronomic features[2]. Wilson *et al.*[49], also posited that height reduced with increasing concentration in the quinoa cultivar 'Andean hybrid' when exposed at concentration exceeded 11 dS m^{-1}. Furthermore, height variations among quinoa varieties subjected to salt treatment were studied and observation revealed that while some varieties showed an increase in height, others remained stunted with increasing salinity[33]. Moreover, reduction in height due to increased salinity has been reported in many other plant species[27,50-53]. Evidence has shown that stress imposed from salinity results in stunted plants, such as in *Avicennia marina* (Forssk.) Vierh., *Bruguiera gymnorrhiza* (L.) Lam. ex. Savigny and *Vicia faba* L.[54-57]. Hence, salinity limits growth and other development in plants due to excess ion accumulation and low yield but may be an indication of a defensive response for halophytic potential[4,7,27,58-60]. In this study, shoot and root dry biomass decreased with increasing salinity which may have resulted from the deleterious effects of the accumulation of excess inorganic ions (Na^+, K^+, Cl^- etc.) on plant structural growth and deploying organic solutes as osmoprotectants instead[32]. In support, Wilson *et al.*[49] observed no significant reduction in leaf surface and dry mass in the quinoa cultivar 'Andean hybrid' until the concentration exceeded 11 dS m^{-1} as compared to lower levels but at higher salt concentration the results were in contradiction. This study also identified variety G as highly salt-tolerant because of the less variation and more consistency in the shoot dry biomass. A similar trend was also observed with 15 accessions studied in which a decrease in dry leaf weight observed as salinity increased, while others exhibited a decrease[33]. A decrease in dry biomass in response to salinity has been reported in *Saccharum officinarum* L., *Salvinia auriculata* Aubl., *Portulaca oleracea* L. and *Triticum aestivum* L.[61-66].

Interestingly, among the varieties studied, some showed a discrepancy in responses to root length. Survival of plant in saline condition mainly depends on how the root system manipulates the intake and distribution of salt as it is the first interface between the plant and that stressful abiotic condition. Some plants are very well adapted to exclude salt at the level of the root by developing salt filtration mechanism through enhancing hydrophobic barrier deposition, which prevents the absorption of non-selective apoplastic ions[14,67-69]. Salinity delay in the life cycle in all the varieties but interestingly, no significant difference among the species and treatment were identified. A previous study has revealed that increased in salinity alters the flowering and maturity period of cereals. Significant differential growth responses to the development of reproductive structures and in the delay in the advancement in the tolerant varieties in the floral initiation to salinity were also observed by Munns and Rawson[3]. Moreover, delay or altering flowering time was observed in Arabidopsis mutants and *Oryza sativa* L. at low salinity[70,71]. Additionally, given all the physiological disruptions resulting from plants being exposed to salinity, flowering can be delayed[5,27,72].

Stomatal conductance is sensitive to increasing salt concentration and accumulation. A decrease in stomatal conductance indicates a reduction of water loss in plants and can be tendered as an adaptive response to conserving water to recompense for the excess salt accretion and minimize osmotic pressure[73]. Stomatal conductance, density and size decrease in quinoa when exposed to 750 mM NaCl[74]. Photosynthetic rate is significantly affected with increasing salinity and hence, growth and development[19,32,49,74]. A decrease in net photosynthetic rate was reported with increasing salinity in a salt-sensitive and salt-tolerant wheat genotypes exposed to 4, 6 and 8 dS m^{-1} concentrations[6]. In this study, increase salinity has resulted in higher chlorophyll concentration in some varieties, which may deem to be a critical response in the production of more chlorophyll with the prospect of increasing photosynthetic rate. Additionally, varieties E and H had higher relative chlorophyll at 500 mM NaCl than at the CK while for variety. These 2 varieties are therefore more tolerant to salinity as they produced more chlorophyll at higher salinity levels. Interestingly, both of these varieties have higher relative chlorophyll content at 200, 300 and 400 mM NaCl, a further hint of their resilience to salinity stress. A study on rice concluded that those with less chlorophyll content are more sensitive to salinity and consistent decline is an early indication of the plant being subjected to stress[75,76]. At the forefront of crop growth, is output in the form of yield and hence, the need for plants that can withstand higher salinity. This study has identified a significant reduction in plant yield at higher salt concentration. At 100 and 200 Mm NaCl, no significant difference in yield was observed. However, as the concentration increased, the yield decreased significantly. Hence, salinity does influence plant productivity and yields as having been observed in numerous plant species that have been tested[1,4,8,77]. The results are significantly relevant to the future with a rapidly increasing global population and more of our arable lands becoming salinized because it identified quinoa varieties that can proliferate in highly saline condition.

CONCLUSION

This study indicates differential responses of quinoa varieties to varying salinity concentrations. It provides evidence to suggest that the growth and development of quinoa in saline conditions is dependent on the specific variety, even though it is characterized as a halotolerant plant. However, field evaluations will be invaluable to assess their performance in such conditions for the selection and researchers to enhance breeding to produce salt-tolerant varieties to sustain growth and productivity under saline condition.

SIGNIFICANCE STATEMENT

This study identifies quinoa varieties with tolerance to a highly saline condition in the hydroponic system. Results can be used to further investigate the genetic composition of these varieties and with the use of genetic engineering to advance this trait in other plants to bolster agronomic features.

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