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Genotype and Drought Effects on Morphological, Physiological and Yield Traits of Quinoa (*Chenopodium quinoa* Willd.)

A. M. M. Al-Naggar[1*], R. M. Abd El-Salam[1], A. E. E. Badran[2] and Mai M. A. El-Moghazi[2]

[1]Department of Agronomy, Faculty of Agriculture, Cairo University, Egypt.
[2]Plant Breeding Unit, Department of Genetic Resources, Desert Research Center, Cairo, Egypt.

Authors' contributions

This work was carried out in collaboration between all authors. Author AMMA designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors AMMA, RMAE and AEEB supervised the study and managed the literature searches. Author MMAE managed the experimental process and performed data analyses. All authors read and approved the final manuscript.

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ABSTRACT

Studying genotypic variation in quinoa germplasm is a prerequisite to start a breeding program aiming at improving its productivity under water stress conditions. The objectives of this investigation were: (i) to evaluate the effects of drought stress on morphological, physiological and yield characteristics, (ii) to assess the variability among five quinoa genotypes in such traits and (iii) to identify the best adapted quinoa genotype(s) to the newly reclaimed sandy soils in Egypt. A two-year experiment was conducted at New Salhiya, Sharqiya Governorate, where the soil is sandy. A split plot experiment with five replications was used. The main plots were devoted to three irrigation regimes, *i.e.* well watering (WW), water stress (WS) and severe water stress (SWS), achieving a field capacity of 95, 65 and 35%, respectively, and sub plots to five quinoa genotypes. Results showed that water stress caused a significant decrease for all studied traits, except for root length and water use efficiency (WUE), which showed a significant increase. Reductions or increases due

**Corresponding author: Email: medhatalnaggar@gmail.com;*

to water stress increased as water stress increased, but differed from genotype to another and from trait to another. Under SWS, maximum reduction reached 56.75% for inflorescence weight and maximum increase reached 147.4% for WUE. A significant variability among quinoa genotypes was observed for all studied traits. Ranges of variability became wider as water stress increased for most studied traits. The quinoa variety CICA-17 proved the highest yield under SWS followed by CO-407 and Chipaya. On the contrary, the lowest yield was exhibited by Ollague under WS and QL-3 under SWS. Our study recommended using CICA-17 variety in New Salhiya and similar newly reclaimed locations in Egypt, which suffer from soil moisture deficit.

Keywords: Chenopodium quinoa; water stress; water use efficiency; yield traits.

1. INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) has recently gained worldwide attention because of its ability to grow in various stress conditions like soil salinity, acidity, drought, frost, etc. [1-4]. Apart from this, its grain is a rich source of a wide range of minerals, vitamins, oil containing large amounts of linoleate, linolenate and natural antioxidants [5,6] and high quality protein containing ample amounts of sulphur rich amino acids [5]. However, in Egypt, quinoa is under-researched, under-supported and considered a neglected crop; it has not been provided due importance.

The increasing population in Egypt demands an increase in food production along with a shift towards environmentally sound sustainable agriculture. Expansion of agriculture is only available in the newly reclaimed lands in desert areas of Egypt. There is a need for cultivation of crops or varieties that require minimum inputs including soil moisture availability. Quinoa can be termed 'underutilized', especially for Egypt, since in spite of its wide adaptability and nutritional superiority, its commercial potential has remained untapped. Quinoa's highly proteinaceous grain can help to make diets more balanced. Quinoa's ability to produce high protein grains under ecologically extreme conditions makes it important for the diversification of future agricultural systems.

The main aim of quinoa breeders is the development of cultivars with high grain yield and quality components, adapted to diverse agro-climatic regions. In spite of the immense nutritive importance of the crop, not much work has been done for its genetic improvement leading to lack of information on many aspects. Breeding a crop for new and targeted environments requires the use of a range of cultivars/genotypes since it allows us to quantify intraspecific variability for different traits and their interactions. Genetic variability in the base population plays a very important role in any crop-breeding program. The extent of diversity present in the germplasm determines the limits of selection for improvement.

The characters of economic importance are generally quantitative in nature and exhibit considerable degree of interaction with the environment. Thus, it becomes imperative to compute the variability present in the material. Improvement of yield requires an in-depth knowledge of the magnitude of variation present in the available germplasm and the extent of environmental influence on these factors. Reports on variability in different traits of quinoa are rare, based on few yield components and are based on experiments carried out in America and Europe [3,7,8]. Detailed experimental results on qualitative and qualitative variability of quinoa under Egyptian desert conditions are absent.

In arid and semiarid agroecosystems, drought and salinity are the main abiotic stresses damaging the potential yield and causing yield instability in quinoa [9-11]. The effect of drought on yield varies depending on the stage of plant development. Geerts et al. [12] found that drought occurring in early growing stages improved overall water use efficiency. When drought occurred during the pre-flowering stage up until the dough stage, significant decreases in yield were seen. Jensen et al. (2000) also found decreases in yield when drought was applied during flowering and seed fill. However, contrasting responses have been reported. Razzaghi et al. [13] found that yield did not significantly decrease when simulated drought was applied during the seed filling stage. Darwinkel and Stolen [14] reported greater drought tolerance in later growth stages. Jacobsen and Stolen [15] note that in Denmark, the greatest impact from drought occurs during the vegetative stage.

The present study was conducted with the following objectives: (i) to evaluate the effects of drought stress on morphological, physiological and yield characteristics, (ii) to assess the variability among five quinoa genotypes in such traits and (iii) to identify the best adapted quinoa genotype(s) to the newly reclaimed sandy soils in Egypt.

2. MATERIALS AND METHODS

This study was carried out in the two successive growing seasons 2014 /2015 and 2015/2016 at New Salhiya station, Sharqiya Governorate, Egypt. The station is located at 30° 18' 24" N latitude and 31° 6' 47" E longitude with an altitude of 20 meters above sea level.

2.1 Plant Materials

Seeds of five quinoa (*Chenopodium quinoa* Willd.) genotypes were obtained from Madison University, Wisconsin, USA. The pedigree and origin of these genotypes are presented in Table 1.

2.2 Experimental Procedures

2.2.1 Field experiments

On the 19th of November the seeds were planted along the irrigation pipes of drip irrigation system. Each pipe (row) length was 90 meter and keeping row to row distance of 60 cm and hill to hill of 60 cm. Seeds (7-10) were sown in each hill, thereafter (after 35 days) were thinned to three plants/hill to achieve a plant density of 35,000 plants/fed (83,300 plants/ha). Each experimental plot included three rows of 0.6 meter width and 12.0 meters long (plot size = 21.6 m^2) with a 1.0 meter ally between irrigation treatments.

2.2.2 Experimental design

A split-plot design in randomized complete block (RCB) arrangement with five replications was used. Main plots were allotted to three irrigation regimes, i.e. well watering (WW), water stress (WS) and severe water stress (SWS). Sub plots were devoted to five quinoa genotypes.

2.2.3 Irrigation system

The irrigation method used in this study was drip irrigation system which gives the chance to supply a specific amount of water for each plant separately. The main irrigation lines were allotted to the irrigation pipes, each main line is operated by a pressure reducing valve to control the water pressure in the irrigation system and to control the water regime application during the season.

2.2.4 Water regimes

The following three different water regimes were used:

1. **Well watering (WW)**, where the field capacity (FC) was about 95%. Irrigation in this treatment (WW) was given each three days; with 40 irrigations during the whole season. The water meter recorded at the end of each irrigation about 205 m^3 water/ha; thus, the total quantity of water given in the whole season for WW treatment was 8200 m^3 per ha.
2. **Water stress (WS)**, where the field capacity (FC) was about 65%. Irrigation in this treatment (WS) was given each six days; with 20 irrigations during the whole season. The water meter recorded at the end of each irrigation about 250 m^3 water/ha; thus, the total quantity of water given in the whole season for WS treatment was 2050 m^3 per ha.
3. **Severe water stress (SWS)**, where the field capacity (FC) was about 35%. Irrigation in this treatment (WW) was given each nine days; with 10 irrigations during the whole season. The water meter recorded at the end of each irrigation about 236.8 m^3 water/ha; thus, the total quantity of water given in the whole season for WW treatment was 2368 m^3 per ha.

Fertilization regimes: were practiced as follows:

First: Organic fertilizer: A Compost locally made of plant and animal wastes of the farm at New Salhiya was added to the soil with the rate of 12 tons/fed and was well mixed with the soil two weeks before sowing at a depth of 10-15 cm.

Second: Mineral fertilizers: The following mineral fertilizers were applied:

1- Nitrogen fertilizer at the rate of 70 kg N / fed was applied through irrigation system after 25, 50 and 75 days from sowing in three equals doses as ammonium nitrate (33.5% N).
2- Triple Superphosphate Fertilizer (46% P_2O_5) at the rate of 30 kg P_2O_5/fed was added as soil application in two equals

doses, the first (15 kg P_2O_5/fed) before sowing during preparing the soil for planting and the second (15 kg P_2O_5/fed) after 25 days from sowing.

3- Potassium fertilizer at the rate of 25 kg K_2O/fed was added as soil application in two doses; before planting (15 kg K_2O/fed) and after 25 day from sowing (10 kg K_2O/fed) as Potassium Sulfate (48% K_2O).
4- Calcium Sulfate or Gypsum (22% Ca, 17% S) at the rate of 20 kg /fed was added as soil application in two equal doses, the first time during preparing the soil for planting and the second time 75 days after sowing.
5- Trace elements (Chelated iron 3%, Chelated zinc 2%, Boron 0.5%, Magnisium 3%) were added through irrigation system at a rate of half liter/month.
6- Phosphoric acid (52:60% P_2O_5) at a rate of two Liters every 15 days was added through irrigation system when needed to open closed drippers.

2.2.5 Soil and water analysis

Full analyses for the soil and water were performed by Central Lab for Soil and Water Analysis, Desert Research Center, Cairo Egypt. The soil type was sandy and consist of silt (9.9%), fine sand (63.4%) and coarse sand (26.7%); soil pH was 8.1 and EC was 0.2 dSm^{-1}. Soluble cations of soil in mEqu/l were Ca (2.45), Mg (5.8), Na (8.5), K (6.8). Soluble anions of soil in mEqu/l were Cl (5.3), CO3 (0.0), SO4 (2.39). Irrigation water EC was 0.67 dSm^{-1}. Soluble cations of water in mEqu/l were Ca (1.4), Mg (0.4), Na (4.9), K (0.3). Soluble anions of water in mEqu/l were Cl (3.0), CO3 (0.0), SO4 (0.0).

2.3 Meteorological Data

The weather data for the experimental site are presented in Table 2.

Table 1. Name, origin and seed color of quinoa genotypes under investigation

Name	Origin	Seed color
QL-3	Bolivia	Light yellow
Chipaya	Altiplano Salares, Bolivia	Mixed (white & Paige color)
CICA-17	Peru	Yellow
CO-407	Colorado, USA	Mixed (light yellow & white)
Ollague	Altiplano Salares, Bolivia	Yellow

Table 2. Meteorological data during the two growing seasons of the experiment

Month	Max. Temp. (°C)	Avg. Temp. (°C)	Min. Temp. (°C)	RH %	Wind speed (km/h)	Precipitation (mm)
Season 2014/2015						
November	27.6	24.6	14.5	50.1	16.3	94
December	21.9	21.3	11.2	61.0	11.9	4.8
January	20.3	19.6	16.5	62.4	11.1	0
February	20.9	18.1	9.9	57.8	12.8	8.1
March	26.5	26.1	12.9	51.6	14.9	0.3
Total						107.2
Season 2015/2016						
November	26.8	25.4	14.2	65.0	9.6	0
December	22.1	21.5	11.0	67.6	12.0	99.3
January	20.5	20.1	10.5	60.8	13.1	14.7
February	23.1	21.7	10.2	53.1	17.3	0.5
March	28.5	26.1	15.5	50.1	16.3	14.3
Total						128.8

Source: Central Lab for Agricultural Climate, Agricultural Research Center at Salhiya, Sharqiya Governorate, Egypt. R.H. = Relative humidity, Temp. = Temperature, Aver. = Average, Max. = Maximum, Min. = Minimum

2.4 Data Recorded

1. **Days to flowering (DTF)** measured as the number of days from the date of emergence to the date at which about 50% of the plants in a plot showed blooming).
2. **Days to maturity (DTM)** measured as the number of days from the date of emergence to the date when the crop was ready for harvesting, i.e. seeds had become mature and the plant had started drying
3. **Plant height (PH) in cm** measured on 10 guarded plants plot^{-1} as the average height from the ground level to the tip of the inflorescence on the main stem at the time of harvest.
4. **Leaf area (LA) in cm^2** measured on the 3rd leaf from the top of the plant using the leaf area meter Model Li-3100 Series No. LAM-1059, USA, when the plant was in full bloom.
5. **Chlorophyll concentration index (CCI) %** measured on five guarded plants/plot by Chlorophyll Concentration Meter, Model CCM-200, USA, as the ratio of transmission at 931 nm to 653 nm through the 3rd leaf from the top of the plant.
6. **Root length (RL) in cm** measured on 10 guarded plants/plot at harvest time by lifting the plant from the sandy soil with the help of shovel and washing it with running water.
7. **Branches/plant (BPP)** measured as the total number of primary branches growing from the main stem at different node positions, including the basal branches on 5 guarded plants plot^{-1}.
8. **Inflorescences/plant (I/P)** measured as number of inflorescences per plant at the time of harvest on 5 guarded plants plot^{-1}.
9. **Inflorescence diameter (ID) in cm** measured as the diameter of the middle of inflorescence (maximum diameter).
10. **Inflorescence length (IL) in cm** measured as the mean length of three inflorescences taken randomly from different positions, from the lowest branch to the top of the inflorescence
11. **Inflorescence weight (IW) in g** measured as the weight of inflorescence from the lowest branch to the top of the inflorescence.
12. **Seeds/plant (S/P)** measured as number of seeds/plant on 5 guarded plants plot^{-1} by multiplying number of inflorescences per plant x number of seeds per inflorescence.
13. **Thousand seed weight (TSW) in g:** Five samples of 1000 seeds from the bulked seed of each genotype were weighed and averaged.
14. **Seed yield/plant (SYPP) in g** measured as weight of seeds per plant on 10 guarded plants/plot.
15. **Seed yield/hectare (SYPH) in kg** estimated by converting seed yield per plot to seed yield per hectare (ha).
16. **Water use efficiency (WUE) in kg seed/1 m^3 water:** This was calculated by the following formula: WUE = (Seed yield/ha in kg)/(quantity of irrigation water/ha in m^3 given during the whole season).

2.5 Biometrical and Genetic Analyses

Analysis of variance of the split-split plot design in randomized complete block (RCB) arrangement was performed on the basis of individual plot observation using the MIXED procedure of MSTAT ®. Combined analysis of variance across the two growing seasons was also performed if the homogeneity test was non-significant. Moreover, combined analysis for each environment separately across seasons was performed as RCB design. Least significant difference (LSD) values were calculated to test the significance of differences between means according to Steel et al. [16].

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance

Combined analysis of variance across two growing seasons (S) of the split-plot design for the studied traits of five genotypes (G) of quinoa under three irrigation regimes (T) is presented in Table 3. Mean squares due to seasons were significant ($P \leq 0.05$ or 0.01) for all studied traits, except for days to flowering (DTF), days to maturity (DTM), branches/plant (BPP), inflorescence diameter (ID), inflorescence weight (IW), seed yield/ha (SYPH) and water use efficiency (WUE), indicating significant effect of climatic conditions on most studied traits of quinoa (Table 2).

Mean squares due to irrigation regimes (T) and quinoa genotypes (G) were significant ($P \leq 0.05$ or 0.01) for all studied traits, indicating that irrigation regime and genotype had significant effects on all studied traits. Significant differences among studied quinoa genotypes suggest that improvement of these traits are possible *via* breeding procedures.

Table 3. Combined analysis of variance of split plot for studied traits of quinoa genotypes under three irrigation regimes (treatments) across two seasons

SOV	df	Mean squares							
		Days to 50% flowering	Days to 50% maturity	Plant height	Leaf area	Chlorophyll-Concent. index	Root length	Branches /Plant	Inflorescence /plant
Season (S)	1	0.06	0.027	195.4**	68.6**	221.0**	0.5*	0.5	3.53**
R(S)	8	0.76	0.16	5.6	0.1	7.1	0.2	0.4	2.66
Treatment (T)	2	130.21**	777.31**	18739.4**	319.6**	4659.2**	164.4**	619.6**	781.82**
T x S	2	0.78**	0.83*	421.9**	33.1**	305.8**	0.0	1.0*	3.21**
Error (a)	16	0.35	0.45	7.3	0.2	6.2	0.4	0.4	1.08
Genotype (G)	4	31.44**	63.24**	125.6**	39.8**	354.2**	85.4**	174.6*	54.21**
G x S	4	3.24**	0.677	32.8**	13.9**	53.2**	0.6*	0.8	6.31**
G x T	8	8.77**	25.99**	118.4**	13.7**	91.4**	110.2**	42.5**	55.77**
G x S x T	8	1.46**	1.75**	125.6**	7.2**	16.4**	0.5	1.5**	4.24**
Error (b)	96	0.6	0.72	3.3	0.3	4.4	0.3	0.5	1.46
		Inflorescence diameter	Inflorescence length	Inflorescence weight	Seeds /plant	1000-seed weight	Seed yield/plant	Seed yield/ha	Water use efficiency
Season (s)	1	0.3	0.4*	0.0001	137350*	0.54*	0.91*	5.1	98.64
R(S)	8	0.3	0.2	0.019	102274	0.51	0.37	369.3	104.4
Treatment (T)	2	752.5**	381.2**	12.86**	9833577**	18.54**	1200.6**	789450**	1809739*
T x S	2	0.1	0.3*	0.24**	2055197**	0.350	0.66*	411.4*	285.4**
Error a	16	0.4	0.1	0.024	97066	0.353	0.44	179.1	76.55
Genotype (G)	4	202.0**	109.8**	4.3**	1401183**	2.28**	199.8**	194892**	100965**
G x S	4	1.8**	0.6*	0.36**	1774849**	0.60**	1.19**	585.1**	258.5**
G x T	8	12.4**	11.2**	1.57**	1168931**	3.65**	111.96**	75591.5**	65680.8**
G x S x T	8	1.01**	0.2	0.18**	1414597**	0.45**	0.39	145.2	184.8**
Error b	96	0.4	0.3	0.024	109826	0.23	0.33	124.3	53.87

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

Mean squares due to the 1st order interaction, *i.e.* T×S, G×S and G×T were significant (P ≤ 0.05 or 0.01) for all studied traits, except for root length (RL), ID and 1000-seed weight (TSW) for T×S and days to maturity (DTM) and branches/plant (BPP) for G×S (Table 3). Significance of G×T indicates that genotype's rank differed from one irrigation regime to another and selection would be efficient for all studied traits under a specific water stress environment, as previously reported by several investigators [17-21].

Mean squares due to the 2nd order interaction, *i.e.* G×S×T were significant (P ≤ 0.05 or 0.01) for all studied traits, except for RL, inflorescence length (IL), SYPP and SYPH, indicating that quinoa genotype's performance differed from a combination of treatment and season to another combination for most studied traits.

It is observed from Table 3 that variance due to irrigation treatments was the largest contributor to the total variance in this experiment for all studied traits. Comparing irrigation with season effect, it is clear that irrigation variance showed larger contribution to total variance than season variance for all studied traits, indicating that water stress had more effect than season effect on such traits.

Combined analysis of variance of randomized complete blocks design for studied traits of five quinoa genotypes under three environments (WW, WS and SWS); representing well watering (95% FC), water stress (65% FC) and severe water stress (35% FC) is presented in Table 4. Mean squares due to genotypes, were significant (P ≤ 0.01) for all studied traits, indicating the significance of differences among studied quinoa genotypes for all studied traits under all water stress environments and selection would be efficient under all studied environments.

Mean squares due to the interaction genotype × season (G × S) were significant (P ≤ 0.05 or 0.01) for all studied traits under all environments, except RL and WUE under WW, DTF, RL, BPP, IL, SYPP, SYPH and WUE under WS and ID and IL under SWS environment.

It is observed from Table 4 that genotypes are the largest contributor to total variance for all studied traits in all environments, except chlorophyll concentration index (CCI) under WW, plant height (PH) under WS and LA, CCI and CCI under SWS, where seasons were the largest contributor and SPP under SWS, where G×S interaction variance was the largest contributor to total variance.

3.2 Mean Performance

3.2.1 Effect of water stress on quinoa traits

The effects of soil moisture stress levels on the means of studied traits across all quinoa genotypes in the two growing seasons are presented in Table 5. The environment WW represents the non-stressed one (95% FC), while WS represents water stressed environment (65% FC) and SWS represents severe water stress (35% FC). Mean seed yield/plant (SYPP) was significantly decreased due to water stress by 13.8 and 30.1%, respectively. Effects of soil moisture stress on the mean performance of seed yield/plant were approximately in the same trend to effects on seed yield/ha (10.5 and 28.6%, respectively). Consistent to these results, several studies reported reductions in grain yield due to drought stress [22-25].

Significant reductions in seed yield of quinoa was accompanied with significant reductions in seeds/plant (10.4 and 12.8%), 1000-seed weight (16.39 and 16.93%), inflorescence weight (23.9 and 56.2%), inflorescence length (16.9 and 28.6%), inflorescence diameter (8.7 and 33.3%), inflorescences/plant (17.6 and 36.8%) branches/plant (22.5 and 37.0%), plant height (10.2 and 41.7%), chlorophyll concentration index (3.7 and 34.4%) and leaf area (10.7 and 28.1%) due to water stress (WS) and severe water stress (SWS), respectively. For days to flowering and days to maturity, severe water stress caused a significant reduction (earliness) by 2.5% (1.5 day) and 5.1% (4.5 day), respectively.

On the contrary, irrigation at 65 and 35% field capacity (FC) caused a significant increase in root length (11.2 and 21.2%, respectively) and water use efficiency (47.0 and 147.4%, respectively) (Table 5). Elongation of the root due to soil moisture stress is because the quinoa plant is forced to search for water deep in the soil. Increase of WUE due to decreasing the soil moisture level from 252.7 m^3 at WW to 371.5 m^3 at WS and 625.1 m^3 is logic, because the reduction in quantity of irrigation water (from 3440 to 2010 and 995 m^3) was much greater than the reduction in seed yield/ha. This increase in WUE by decrease of quantity of irrigation

water was reported by Geerts *et al.* [12]. They found that drought occurring in early growing stages of quinoa improved overall water use efficiency. When drought occurred during the pre-flowering stage up until the dough stage, significant decreases in yield were seen. Jensen et al. (2000) also found decreases in yield when drought was applied during flowering and seed fill. On the contrary, Razzaghi et al. [13] found that yield did not significantly decrease when simulated drought was applied during the seed filling stage. Darwinkel and Stolen [14] reported greater drought tolerance in later growth stages. Jacobsen and Stolen [15] noted that in Denmark, the greatest impact from drought occurs during the vegetative stage.

Fghire et al. [26] investigated physiological and growth responses of six genotypes of *Chenopodium quinoa* to water stress in field conditions under four irrigation treatments (100% ETc, 50% ETc, 33% ETc and rainfed). Their results showed that the six genotypes displayed different levels of tolerance to water stress. Tolerant genotypes responded to the increase of water stress by decreasing leaf water potential, stomatal conductance, leaf area index and the chlorophyll a and b. They added that under the half irrigated treatment (50% ETc) quinoa plant present an interesting tolerance to water stress, so using just half water requirement they can get comparative results to the control.

Water is a key limiting factor for agriculture, especially in semi-arid regions. Drought stress affects plant N nutrition by reducing N bioavailability (i.e. N mineralization) and N uptake (i.e. lowering the diffusion and mass flow from soil solution to root surface). These processes influence crop N acquisition, shoot growth, leaf gas exchange rates and biomass partitioning [27]. Effects vary according to the type and moment of drought stress. Drying–rewetting events have higher probability to occur in semi-arid environments, and for quinoa, flowering is the most critical stage [12, 28]. The mechanisms used by plants to survive and maintain productivity under drought can be classified as stress avoidance, stress tolerance and efficiency mechanisms [27]. Quinoa is able to establish equilibrium between water uptake and transpiration to avoid dehydration under soil water deficit. The plant enhances water uptake through the accumulation of solutes in cells to lower root water potential [1]. Hormonal signaling through ABA is involved in the regulation of stomatal aperture, turgor maintenance and osmotic adjustment during drought [29, 30].
Crop development in plants grown under limited moisture conditions is greatly disturbed [31]. A significant reduction of size and leaf area is generally observed [32]. The reduced leaf surface can come from a reduction in leaf expansion and/or an accelerated senescence of the leaf. Leaf growth is stopped quickly by water deficit, since it occurs at water potentials of -0.4 MPa [33]. Thus, plants subjected to water deficit generally exhibit a significant loss in leaf size and area and leaf senescence accelerated (Lebon et al. 2006).

3.2.2 Effect of genotype on quinoa traits

Genotypes of quinoa under investigation showed significant differences, expressed in ranges (differences between minimum and maximum values) for all studied traits under each of the three studied water treatments (Table 5). The ranges became wider as water stress increased for all studied traits, except inflorescence length, chlorophyll concentration index and days to maturity, where ranges became narrower as water stress increased. Wider ranges of most studied traits of quinoa under water stress and severe water stress than well watering suggest that selection for favorable values of traits would be more efficient under water stressed than non stressed environments. Water use efficiency, seed yield/ha and number of seeds/plant traits showed the widest ranges, but DTF, DTM and leaf area traits exhibited the narrowest ranges.

Means of studied traits of each of the five quinoa genotypes under each environment and combined across the three environments (WW, WS and SWS) and across the two seasons are presented in Table 6. The high means of all studied traits were considered favorable, except earliness traits (DTF and DTM), where high means were considered unfavorable.

Combined data across environments and seasons showed that quinoa genotypes varied greatly in SYPH (from 2024.7 kg for CICA-17 to 1524.2 kg for Ollague), SYPP (from 31.5 g for CICA-17 to 24.8 g for Ollague), WUE (from 488.8 g/m^3 for CICA-17 to 640.4 g/m^3 for Ollague), TSW (from 3.8 g for CICA-17 to 2.8 g for Ollague), SPP (from 8838 for Ollague to 8359 for CO-407), IW (from 2.5 g for QL-3 and Ollague to 2.0 for CO-407), IL (from 18.3 cm for CO-407 to

Table 4. Combined analysis of variance across seasons of randomized complete blocks design for studied traits of five quinoa genotypes under well watering (95% FC), water stress (65% FC) and severe water stress (35% FC)

SOV	df	Mean squares							
Well watering (95% FC)									
		Days to 50% flowering	**Days to 50% maturity**	**Plant height**	**Leaf area**	**Chlorophyll concent. index**	**Root length**	**Branches /Plant**	**Inflorescence /plant**
Season (S)	1	0.02	0.32*	10.0**	2.2**	367.2**	0.13	0.5	2
Error	8	0.21	0.31	3.8	0.2	17.3	0.1	0.4	2.65
Genotype (G)	4	10.95**	21.55**	86.2**	6.0**	218.8**	34.61**	32.2**	5.75**
G x S	4	3.27**	0.27*	33.9**	1.8**	34.7**	0.21	1.9**	8.75**
Error	32	0.44	0.25	3.1	0.2	10.2	0.21	0.3	2.34
		Inflorescence diameter	**Inflorescence length**	**Inflorescence weight**	**Seeds /plant**	**1000-seed weight**	**Seed yield /plant**	**Seed yield /ha**	**Water use efficiency**
Season (S)	1	0.26*	0.03	20.5**	59030.5	0.10*	0	113.1	0.61
Error	8	0.17	0.2	0.6	106053.9	0.08	0.3	78.5	0.21
Genotype (G)	4	64.84**	42.5**	22.4**	135550.9**	0.13*	31.1**	75261.36**	6156.9**
G x S	4	1.06*	0.23*	2.9**	894667**	0.28**	0.7**	100.8**	0.198
Error	32	0.5	0.18	0.7	57358.8	0.08	0.3	71.95	0.222
Water stress (65% FC)									
		Days to 50% flowering	**Days to 50% maturity**	**Plant height**	**Leaf area**	**Chlorophyll concent. index**	**Root length**	**Branches /Plant**	**Inflorescences /plant**
Season (S)	1	1.28*	1.28*	937.5**	35.5**	330.8**	0.2	0.5*	0.72**
Error	8	0.4	0.4	15.2	0.2	1	0.8	0.3	0.07
Genotype (G)	4	9.17**	8.97**	167.5**	16.9**	190.5**	55.6**	120.2**	1.97**
G x S	4	0.53	1.43*	199.7**	13.0**	18.5**	0	0.9	2.37**
Error	32	0.54	0.71	6.2	0.3	2.2	0.3	0.6	0.27

		Inflorescence diameter	Inflorescence length	Inflorescence weight	Seeds /plant	1000-seed weight	Seed yield /plant	Seed yield /ha	Water use efficiency
Seasons (S)	1	0	0.9**	0.28**	1522512**	0.01**	0.07	103.7	48.06
Error	8	0.2	0.1	0.01	67758	0.002	0.6	470.6	76.41
Genotype (G)	4	85.8**	46.4**	2.37**	3187435**	0.39**	75.7**	60581**	13820.9**
G x S	4	2.6**	0.3	0.44**	2637323**	0.04**	0.6	177.2	27.10
Error	32	0.3	0.3	0.02	102753	0.01	0.4	178.5	37.95
Severe water stress (35% FC)									
		Days to flowering	**Days to maturity**	**Plant height**	**Leaf area**	**Chlorophyl concent. index**	**Root length**	**Branch /Plant**	**Inflorescence /plant**
Seasons (S)	1	0.32	0.08	91.66**	97.2**	134.6**	0.2	1.6**	7.22*
Error	8	0.62	0.35	11.24	0.16	1.1	0.2	0.5	2.1
Genotype (G)	4	28.87**	74.72**	108.1**	44.3**	127.7**	215.5**	107.9**	158.0**
S x G	4	2.37**	2.48*	50.40**	13.36**	32.8**	1.3**	1.1*	3.67*
Error	32	0.83	1.21	0.73	0.34	0.75	0.4	0.5	1.76
		Inflorescen. diameter	**Inflorescen. length**	**Inflorescen. weight**	**Seeds /plant**	**1000-seed weight**	**Seed yield /plant**	**Seed yield /ha**	**Water use efficiency**
Seasons	1	0.3	0	0.19**	2666202**	1.122	2.1**	611.1*	620.789
Error	8	0.6	0.2	0.03	122594	1.14	0.4	178.5	180.861
Genotype (G)	4	76.1**	43.3**	**4.49	425060**	**9.05	316.9*	**210233**	212349.1**
S x G	4	0.2	0.5	0.122**	1072052**	*1.19	0.7*	597.4**	600.77*
Error	32	0.4	0.4	0.04	169367	0.618	0.3	122.5	123.43

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively*

Table 5. Summary of means ± standard error (SE), reduction (Red%) from well watering (WW) to water stress (WS) and severe water stress (SWS), minimum (Min) and maximum (Max) values for all studied traits across all quinoa genotypes across seasons

Stress	Mean± SE	Red%	Max	Min	Mean± SE	Red%	Max	Min
	Days to 50% flowering				Days to 50% maturity			
WW	60.8 ± 0.3	-	62.5	59.7	126.4 ± 0.3	-	129.4	121.5
WS	60.7 ± 0.4	0.2	62.1	59.2	126.6 ± 0.3	-0.2	127.9	124.6
SWS	59.3 ± 0.4	2.5*	63.3	56.6	119.9 ± 0.3	5.1*	123.9	116.5
	Plant height (cm)				Leaf area (cm^2)			
WW	88.9 ± 0.4	-	93.9	86.6	17.8 ± 0.2	-	18.6	16.8
WS	79.8 ± 1.1	10.2**	82.8	73.8	15.9 ± 0.3	10.7**	17.7	14.2
SWS	51.8 ± 0.4	41.7**	56.9	48.8	12.8 ± 0.3	28.1**	15.5	10.1
	Chlorophyll concentration index (%)				Root length (cm)			
WW	51.8 ± 1.43	-	58.1	46.2	17.0 ± 0.2	-	19.8	14.9
WS	49.9 ± 0.66	3.7*	55.9	45.9	18.9 ± 0.3	-11.2**	22.1	16.0
SWS	34.0 ± 0.39	34.4**	39.3	30.1	20.6 ± 0.3	-21.2**	26.6	15.1
	Primary branches/pplant				Inflorescences/ plant			
WW	17.3 ± 0.3	-	20.0	13.6	13.6 ± 0.3	-	20.1	10.4
WS	13.4 ± 0.4	22.5**	17.4	8.2	11.2 ± 0.3	17.6**	18.7	6.8
SWS	10.9 ± 0.3	37.0**	15.5	7.0	8.6 ± 0.3	36.8**	16.5	5.1
	Inflorescence diameter(cm)				Inflorescence length(cm)			
WW	21.9 ± 0.3	-	25.1	19.1	18.9 ± 0.2	-	22.1	17.0
WS	20.5 ± 0.2	8.7**	23.9	16.9	15.7 ± 0.3	16.9**	17.8	13.0
SWS	14.6 ± 0.3	33.3**	18.7	11.9	13.5 ± 0.3	28.6**	16.0	11.1
	Inflorescences weight (g)				Seeds/plant			
WW	2.40 ±0.1	-	2.88	1.74	9554±96	-	9767.0	9153.0
WS	2.51 ±0.2	13.8**	3.51	1.68	8558±94	10.4**	9264.0	8024.0
SWS	2.65 ±0.2	30.1**	2.88	1.81	8329±98	12.8**	9313.0	7872.0
	1000-seed weight (g)				Seed yield/plant (g)			
WW	3.66 ± 0.03	-	4.1	2.9	32.6 ± 0.2	-	34.9	30.0
WS	3.06 ± 0.03	16.39**	3.8	2.5	28.1 ± 0.3	13.8**	31.4	23.9
SWS	3.04 ± 0.03	16.93**	4.3	1.8	22.8 ± 0.3	30.1**	29.9	14.7
	Seed yield/ha (kg)				Water use efficiency (g/m^3)			
WW	2074.4 ± 9.0	-	2234.6	1709.8	252.7±0.38	--	271.2	209.0
WS	1855.7 ± 14.0	10.5**	2044.2	1551.1	371.5±5.03	-47.0	409.0	310.4
SWS	1480.4 ± 11.9	28.6**	1883.5	985.6	625.1±9.1	-147.4	795.3	416.2

**and ** indicate significant at 0.05 and 0.01 probability levels, respectively. Red% = 100(WW-WS or SWS)/ WW*

14.2 cm for QL-3), ID (from 21.9 cm for CICA-17 to 16.0 cm for Ollague), IPP (from 14.70 for CICA-17 to 11.73 for Ollague), BPP (from 17.63 for CICA-17 to 11.13 for Ollague), RL (from 20.9 cm for CICA-17 to 17.0 cm for Chipay), CCI (from 49.4% for CICA-17 to 41.8% for Ollague), LA (from 17.2 cm^2 for CICA-17 to 14.1 cm^2 for QL-3), PH (from 75.4 cm for CICA-17 to 70.1 cm for Chipaya), DTF (from 61.4 for Chipaya to 58.6 for Ollague) and DTM (from 136.1 for CICA-17 to 132.1 for Ollague).

In general, combined data across all the three environments showed that the quinoa genotype CICA-17 had the highest (favorable) means for 11 out of 16 traits, namely WUE, SYPH, SYPP, IL, ID, IPP, BPP, RL, CCI, LA and PH. In the second highest place, came the quinoa genotype CO-407, for SYPH, SYPP, SPP, ID, IPP, BPP, CCI and PH, the genotype QL-3 for IW, RL and CICA-17 for IL and Chipaya for LA.

On the contrary, the lowest means across all environments were shown by the quinoa genotype Ollague for nine traits, namely SYPH, SYPP, IW, ID, IPP, BPP, CCI, DTF and DTM, QL-3 for LA, IL, WUE and CO-407 for SPP and IW. For earliness traits (DTF and DTM), the genotype Ollague was the earliest.

The variability among quinoa genotypes in all studied traits in the present investigation were in agreement with several investigations [3, 7, 8]. Quinoa's traditional range of cultivation stretches

as far north as Columbia and as far south as southern Chile. As a result of its wide distribution, the crop is adapted to a wide range of environments and forms a diverse range of ecotypes [7].

3.2.3 Effect of quinoa genotype × irrigation regime

The effect of the interaction (quinoa genotype × water stress) was clearly shown, where the rank of genotypes was changed from one environment (irrigation regime) to another; especially when comparing poor (SWS) with good (WW) environment (Table 6). The highest means of SYPH, SYPP and all yield components of the studied genotypes were generally obtained from the good environment (WW) where the optimum irrigation was given at all growth stages. The highest SYPH in this experiment (2234.6 kg) was obtained from the genotype QL-3 under well-watered environment (WW) followed by the genotype CICA-17 (2146.0 kg), C0-407 (2133.7 kg) and Chipaya (2133.0 kg) under the same environment (Table 6). These genotypes could therefore be considered responsive to this good environment (95% FC).

Table 6. Mean performance of studied traits of each quinoa genotype under well watering (WW), water stress (WS) and severe water stress (SWS) across two seasons

Genotype	WW	WS	SWS	Combined	WW	WS	SWS	Combined
	Days to 50% flowering				Days to 50% maturity			
QL-3	62.1	61.8	57.4	60.4	137.4	136.3	134.1	135.9
Chipaya	62.4	60.9	60.8	61.4	138.4	136.5	128.7	134.5
CICA-17	63.1	60.2	59.7	61.0	138.3	137.4	132.6	136.1
CO-407	61.6	60.3	58.9	60.3	139.4	137.8	129.3	135.5
Ollague	60.3	59.2	56.6	58.7	135.5	135.4	127.7	132.9
L.S.D. 0.05	0.5	0.5	0.6	0.5	0.3	0.6	0.8	0.6
	Plant height (cm)				Leaf area (cm^2)			
QL-3	94.0	77.3	48.8	73.3	18.1	14.2	10.1	14.1
Chipaya	87.4	73.8	49.1	70.1	18.6	16.6	12.4	15.9
CICA-17	86.6	82.6	57.0	75.4	18.4	17.7	15.5	17.2
CO-407	87.7	82.8	51.8	74.1	16.8	15.5	14.3	15.5
Ollague	88.8	82.7	52.2	74.6	17.2	15.5	11.8	14.8
L.S.D. 0.05	1.6	2.3	0.8	1.2	0.4	0.5	0.5	0.4
	Chlorophyll concentration index (%)				Root length (cm)			
QL-3	51.9	46.4	31.9	43.4	19.8	20.3	19.5	19.9
Chipaya	46.2	45.9	35.5	42.5	17.7	18.1	15.1	17.0
CICA-17	54.3	54.7	39.3	49.4	16.6	22.1	24.0	20.9
CO-407	58.1	55.9	33.1	49.0	15.9	17.9	17.9	17.2
Ollague	48.5	46.8	30.1	41.8	14.9	16.0	26.6	19.2
L.S.D. 0.05	2.9	1.3	0.8	1.4	0.4	0.5	0.5	18.8
	Branches/plant				Inflorescences/plant			
QL-3	18.9	13.4	8.9	13.7	16.6	15.4	4.1	12.0
Chipaya	15.7	12.6	10.4	12.9	15.3	14.9	8.9	13.0
CICA-17	20.0	17.4	15.5	17.6	17.0	14.3	12.8	14.7
CO-407	13.6	15.5	12.5	13.9	15.7	15.2	12.3	14.4
Ollague	18.2	8.2	7.0	11.1	15.4	14.6	5.2	11.7
L.S.D. 0.05	0.5	0.7	0.6	0.5	1.0	0.4	0.9	0.8
	Inflorescence diameter (cm)				Inflorescence length (cm)			
QL-3	20.0	19.3	12.2	17.2	17.8	13.0	11.8	14.2
Chipaya	21.3	19.2	14.9	18.5	17.9	14.0	13.5	15.1
CICA-17	23.8	23.1	18.7	21.9	19.9	17.8	16.0	17.9
CO-407	25.1	23.9	15.2	21.4	22.1	17.7	15.0	18.3
Ollague	19.1	16.9	11.9	16.0	17.0	15.8	11.1	14.6
L.S.D. 0.05	0.7	0.5	0.5	18.9	0.4	0.5	0.6	0.4
	Inflorescence weight (g)				Seeds/plant			

Genotype	WW	WS	SWS	Combined	WW	WS	SWS	Combined
QL-3	2.10	1.88	3.61	2.5	8589	9152	8208	8650
Chipaya	2.12	1.85	2.66	2.2	8517	9640	8071	8743
CICA-17	1.96	2.20	2.34	2.2	8409	8312	8412	8377
CO-407	2.05	1.90	2.03	2.0	8553	8653	7872	8359
Ollague	1.95	1.64	3.92	2.5	8729	9509	8277	8838
L.S.D. 0.05	0.1	0.0	0.2	0.1	163	218	279	219
	1000-seed weight (g)				**Seed yield/plant (g)**			
QL-3	4.1	3.2	1.8	3.0	34.9	28.9	14.8	26.2
Chipaya	3.8	2.9	2.9	3.2	32.5	27.6	23.7	27.9
CICA-17	4.0	3.8	3.6	3.8	33.3	31.4	29.9	31.5
CO-407	3.8	3.3	3.2	3.4	32.2	28.9	25.0	28.7
Ollague	3.4	2.5	2.5	2.8	30.0	23.9	20.4	24.8
L.S.D. 0.05	0.3	0.1	0.7	0.4	0.5	0.6	1.2	0.4
	Seed yield/ha (kg)				**Water use efficiency (g/m^3)**			
QL-3	2234.6	1921.9	985.6	1714.1	271.2	384.5	416.2	357.3
Chipaya	2133.0	1838.3	1553.4	1841.6	260.5	367.8	656.1	428.1
CICA-17	2146.0	2044.2	1883.5	2024.7	262.1	409.0	795.3	488.8
CO-407	2133.7	1921.4	1668.1	1907.8	260.6	385.9	704.4	450.3
Ollague	1709.8	1551.0	1311.6	1524.2	209.0	310.4	553.8	357.7
L.S.D. 0.05	18.3	29.0	24.0	17.6	0.4	5.6	10.1	6.5

The highest SYPH in this experiment was obtained from the genotype CICA-17 (2044.2 and 1833.5 kg) under the water stress (WS) and severe water stress (SWS) environments, respectively. This genotype was therefore considered tolerant to both stresses (65 and 35% FC) and the second responsive under the good environment (95% FC). It is clear that CICA-17 genotype might be considered as a source of drought tolerance alleles and of high potentiality under the optimum environment (WW), i.e. drought tolerant and responsive.

On the contrary, the lowest SYPH in this experiment was shown by QL-3 (985.6 kg) under SWS and Ollague (1311.6 kg) under WS (65% FC). For SYPP, the same genotypes showed a similar trend to that of SYPH. Under WW (95% FC), the highest means for SYPH, SYPP and IW were shown by the genotype QL-3, while for TSW, SPP, IW, I/P, B/P and PH were shown by the genotype CICA-17, for IL, ID and CCI by the genotype CO-407 and for RL were shown by the genotype Ollague. Under WS (65% FC) environment, the highest means were shown by the genotype CICA-17 for WUE, SYPH, SYPP, TSW, SPP, IW, IL, IPP, BPP, RL, LA and PH, by the genotype CO-407 for ID and CCI. Under SWS (35% FC) environment, the genotype CICA-17 exhibited the highest means for most studied traits (WUE, SYPH, SYPP, TSW, ID, CCI, IW, IL, IPP, BPP, RL, LA and PH) and QL-3 for SPP. The aforementioned genotypes could be considered useful quinoa germplasm in future breeding programs for improving respective traits of relation to drought tolerance. The quinoa variety CICA-17 proved to be the most drought tolerant genotype in the present experiment under water stress (65% FC) and severe water stress (35% FC) conditions followed by CO-407 and Chipaya.

4. CONCLUSIONS

Significance of variances due to quinoa genotype and its interaction with irrigation regime indicates that selection would be efficient for improving most studied traits of quinoa under a specific water stressed environment. Moderate water stress (65% FC) caused a slight but significant reduction in quinoa seed yield and its attributes, while severe water stress (35% FC) caused great and significant reduction in these traits. However, reduction in yield and its components due to water stress treatments differed significantly from quinoa genotype to another. The quinoa variety CICA-17 proved the highest yielding and the lowest yield reductions under both water stress treatments (35 and 65% FC) followed by CO-407 and Chipaya. The study therefore recommended using CICA-17 variety in Salhiya and similar newly reclaimed locations in Egypt, where the soil is sandy and suffers from soil moisture deficit.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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