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Water Requirements, Soil Moisture Availability, and Their Effects on Quinoa (*Chenopodium quinoa* Willd.) Development and Yield

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Abstract - **Throughout the world, about 70% of the total water is used for irrigation. Reports show that there will be a significant increase in irrigation requirements, as irrigation is an important factor affecting water footprint and productivity worldwide [45]. The experiment described in this article was carried out at the Agricultural Research Station, Ministry of Agriculture, Iraq, in 10 kg pots to evaluate the effects of soil moisture availability on water requirements, water productivity, and quinoa crop productivity under different irrigation treatments. These treatments maintained the soil at different levels of soil water tension (-0.05, -0.10, -0.15, -0.30, and -0.40 MPa) during the vegetative and/or reproductive periods of growth. The study analyzed water consumption, plant growth, yield components, and water productivity of the quinoa crop. The data showed that evapotranspiration decreased with increasing soil moisture tension during both the vegetative and reproductive periods of development. The maximum water productivity was consistently recorded at the lowest soil moisture tension, highlighting moisture efficiency. It was concluded that quinoa is relatively tolerant to soil moisture stress during the vegetative period compared to the reproductive period. The number of grains per ear was identified as a limiting factor for grain yield.**

Keywords: **Irrigation Requirements, Soil Moisture Tension, Water Productivity, Quinoa Crop, Evapotranspiration**

I. INTRODUCTION

As little information is available in Iraq regarding the impact of water stress on the productivity, growth, and production of quinoa (Chenopodium quinoa Willd.), which belongs to the Amaranthaceae family, it remains a relatively new crop in many consuming countries. Limited information, particularly in regions like Iraq, addresses the impact of water stress on water use efficiency, development, and production of this crop. This promising crop is known for its resistance to abiotic stresses such as drought [19] and salinity [33], [21]. Quinoa has been observed to thrive under high salt conditions similar to those of seawater crops [8], [20]. Additionally, quinoa can grow across a wide range of soil textures, from sandy to clay, and within a soil pH range of 4.5 to 9. Quinoa is classified as a C3 plant [27].

Water requirements for quinoa vary depending on the planting season and the development stage of the plant. While it can survive on rainwater, crops planted during the summer require light irrigation, and saltwater can be utilized [17], [42], along with NPK fertilizer [44]. Water stress is one of the most significant factors leading to the disruption of biochemical processes [29]. Water stress at various stages of plant growth diminishes the biological yield of genotypes, which exhibit diverse responses to water stress. Drought-resistant varieties are characterized by a high accumulation of dry matter during vegetative growth [24], [26], [27]. Chenopodium sp. is part of a complex comprising two species - *C. album* and *C. quinoa* - cultivated in the Himalayan regions of Punjab, specifically at high altitudes [1700–2700 m] in the Ravi River basin, as well as in higher regions of Kashmir and Ladakh. Initially cultivated for its leaves and used as a potherb, these Chenopodium species are now primarily grown for their grains, which are considered superior to buckwheat [15], [35], [28].

Drought and salinity are prevalent environmental stressors that impede plant development, dictate the global distribution of vegetation, and limit crop yields in agriculture [16], [13], [22], [23], [37]. Enhancing crop production in arid and semi-arid regions, including Iraq, may be achieved through the diversification of crop production and the introduction of new strains and varieties with stress tolerance, such as *Chenopodium quinoa Willd.*, a resilient plant with the potential to become a significant crop in the region and in the expanding global market [19], [20]. This is a major challenge in Iraq, as substantial areas are lost annually due to salinity and drought [38]. The wide range of salinity tolerance in quinoa offers an excellent opportunity for promoting resilience. Several researchers [18], [10] suggest that increasing yield or reducing water usage can be achieved through various means. Notably, significant improvements in irrigation and water productivity have been observed in the quinoa-rice system in Asia and Australia over recent decades, attributable to improved varieties and enhanced management of irrigation, nutrients, bushes, and water.

According to a report by the Food and Agriculture Organization of the United Nations [14], quinoa is recognized as an annual crop favoring short days and low temperatures. It encompasses a range of varieties adapted to diverse agro-ecological systems and climatic conditions, thriving at temperatures between 4 °C and 35 °C and at various altitudes, starting from sea level. The stages of ear formation and flowering exhibit the highest tolerance to water stress. Conversely, branching and maturity are critical stages during which yield reductions occur under stress [42]. The aim of this study was to investigate the response of quinoa (*Chenopodium quinoa Willd.*) to different irrigation treatments.

II. MATERIALS AND METHOD

A greenhouse experiment was conducted in 10 kg pots filled with top clay loam soil to examine the effects of maintaining the soil at different levels of soil water tension (-0.05, -0.10, -0.15, -0.30, and -0.40 MPa) during the vegetative and/or reproductive periods of development on water consumption, plant growth, yield components, and water productivity of the quinoa crop.

A. Location

The experiments were conducted at the Office of Field Research, Ministry of Agriculture, Iraq, located at 32°N, 43°E, at an elevation of 32 meters above sea level.

B. Soils used in the Experiment

1. Clay loam soil was used.
2. The soil types were analyzed to determine their basic physical and chemical properties using samples prepared by passing the soil through a 2 mm sieve. The results of these analyses are presented in the tables.

C. Physical Properties of Soil

Soil moisture retention characteristics were determined for the clay loam at -0.05, -0.15, and -0.40 MPa tension, and for the sandy loam at -0.05, -0.15, and -0.30 MPa tension using the WC4p device (Fig. 1).

The bulk density of soil aggregates was determined using the gravimetric method. Field capacity and permanent wilting points were also determined, and the results are presented in Table I.

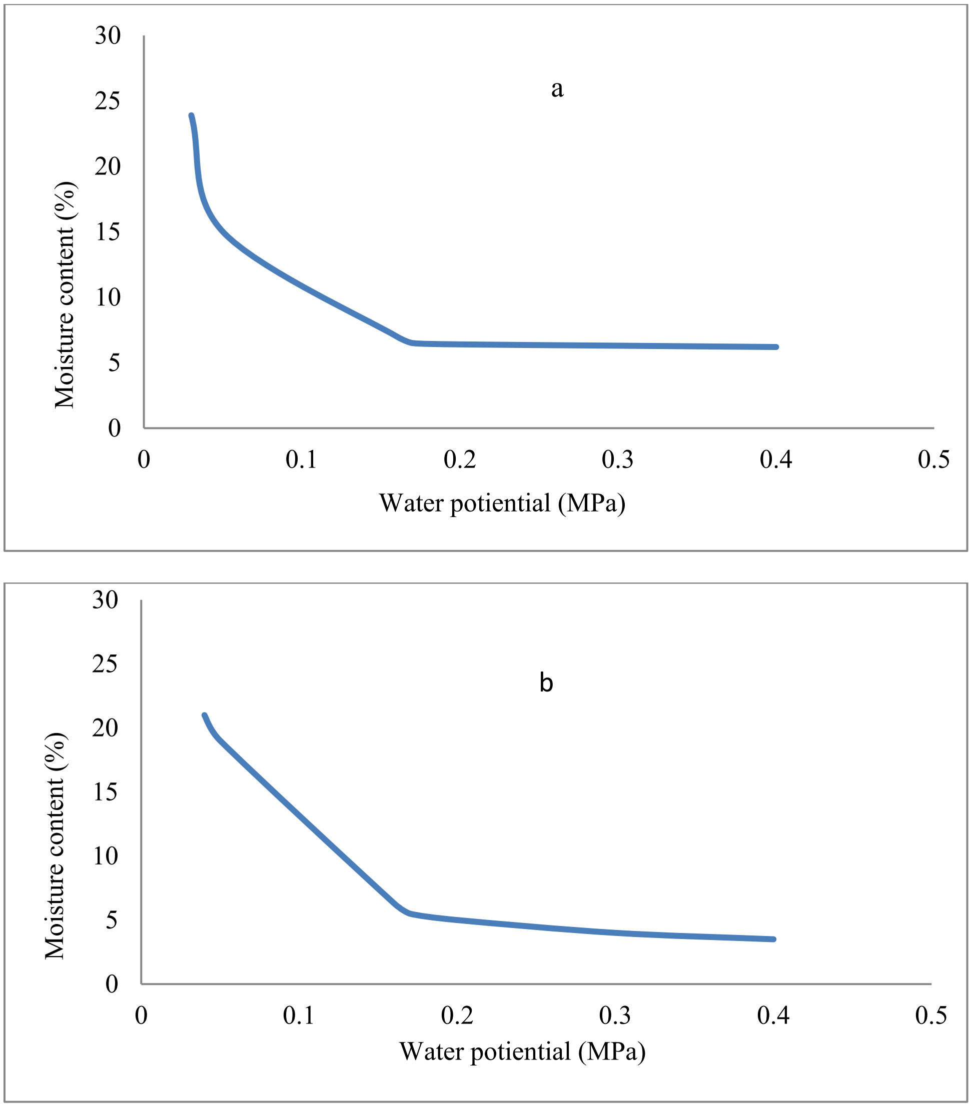

Fig. 1 Soil moisture characteristics curve for clay loam (a) and sandy loam (b) soil

D. Mechanical Analysis of Soils

The results of the mechanical analysis of the soil using the pipette method are presented in Table I.

E. Chemical Composition of Soils

The chemical composition of the soils is presented in Table I. The NH_4HCO_4–DTPA method [Soltanpour and Schwab, 1977] was used to extract plant-available P and K. Phosphorus (P) was determined spectrophotometrically, and potassium (K) was measured using a flame photometer [MAFF, 1981].

Nitrogen was determined using the method of Jackson [1958]. Total soil organic matter was determined by the loss-on-ignition method. A pH meter with a glass electrode was used to determine soil pH [41].

TABLE I THE PHYSICAL AND CHEMICAL PROPERTIES OF SOIL

Physical Content	**Clay Loam**	**Sand (%)**	**Silt (%)**	**Clay (%)**
		42.4	29.1	28.5
Field capacity (%)	23.4	Organic matter (%)		5.9
Permanent wilting point (%)	6.6	Nitrogen content(mg/kg)		3.2
Available soil moisture (%)	16.8	Phosphorous content(mg/kg)		3.75
Water holding capacity	50.7	Potassium content(mg/kg)		34.0
Bulk density (g/cc)	1.82	Soil pH		7.5

F. Soil Sterilization

Soil sterilization was done by heating the soil to 90°C for 72 hours to kill any contaminants of mycorrhizal fungi

G. Fertilization

Commercial fertilizers were used in the experiment. Nitrogen was applied in two doses: a basal dose of 50 kg/ha (0.25 g per pot) as ammonium nitrate, 50 kg P_2O_5/ha (0.25 g per pot) as triple superphosphate, and 50 kg K_2O/ha (0.25 g per pot) as potash. The remaining 50 kg N/ha was applied 30 days after planting.

H. Meteorological Data

Table I (A) presents the mean monthly maximum and minimum temperatures during the experimental periods, which were calculated from daily maximum and minimum temperatures recorded. This table also provides the mean monthly relative humidity during the experimental periods, calculated from daily measurements using the wet-bulb thermometer method.

TABLE I (A) SHOWS SOME METREOROLOGICAL DATA OF THE TRIAL LOCATION

WS avgm/s	**SLRt Mj m^{-2}**	**RH min %**	**RH avg%**	**Tmin C°**	**Tmax C°**	**Date**
2.32	9.83	19.7	39	7.74	19.35	30/11-9/12
1.98	9.74	15.56	42.29	6.82	17.65	10/12-19/12
2.44	9.51	15.25	37.86	4.53	15.39	20/12-29/12
2.48	10.49	15.18	36.04	3.33	15.9	30/12-8/1
1.94	9.71	22.32	49.13	5.49	15.11	9/1-18/1
2.51	12.33	22.48	50.76	2.85	12.51	19/1-28/1
2.02	12.15	21.17	45.41	2.81	15.58	29/1-7/2
1.97	15.28	15.15	41.36	5.34	19.98	8/2-17/2
2.53	15.04	15.33	38.84	8.72	21.12	18/2-27/2
2.49	14.81	15.16	35.31	8.16	22.1	28/2-9/3
2.98	16.66	20.87	47.27	5.42	17.63	10/3-19/3
3.16	17.61	22.9	51.53	5.2	19.17	20/3-29/3
2.68	20.3	22.11	46.4	12.84	31.06	30/3-8/4
3.93	17.58	16.21	38.85	15.11	31.21	9/4-18/4
2.82	19.83	16.08	38.98	13.61	29.97	19/4-28/4

Trial was conducted in field of Center of Desert Studies using quinoa (*Chenopodium* Quinoa Willd.) as test crop.

I. Experiment

Quinoa plants, three per pot, were grown in 25 cm-diameter plastic pots, each containing 6 kg of clay. The pots were arranged in a randomized block design with three replicates for each treatment, resulting in a total of 27 pots in the experiment.

The following irrigation treatments were maintained by frequently weighing the whole pots (after allowing for the increase in fresh weight of plants from the destructive sampling of three additional quinoa plants on four dates during the growing period) and adding measured quantities of water to the surface of the pots. Water was added when the following predetermined tensions were reached.

1. High moisture tension: -0.40 MPa (stress)
2. Medium moisture tension: -0.15 MPa (slight stress)
3. Low moisture tension: -0.05 MPa (no stress)

The experimental treatments consisted of maintaining plants at one of three irrigation levels throughout the reproductive period, resulting in a total of nine treatment combinations. All 27 pots in the experiment were grown to maturity and harvested before being separated for measurement at the end of the experiment.

The crossover point for irrigation levels at the end of the vegetative development period and the beginning of the reproductive period was uniformly imposed across all treatments and occurred when tassel emergence was observed at maturity. The water requirement over successive time intervals was calculated from the loss in weight of soil moisture.

Results will be expressed as cm depth of soil water per unit area of soil surface (ET_a). Water productivity (WP) will also be calculated. Measurement of total fresh weight, grain yield, number of grains per ear, 100-grain weight, and water productivity calculated as follows:

$$WP = \frac{weight\ of\ grains(\frac{g}{plant})}{ETa(mm)}.$$

At the end of the experiment, measurements were made for each plant on total fresh weight, grain yield, number of grains per ear, 100-grain weight, and water requirement. Data for each of the above variables were analyzed separately using an analysis of variance for a randomized block design with Mstat-C software. Tests of significance were conducted at a 95% confidence level (p = 0.05).

III. RESULTS OF THE STUDY

A. Evapotranspiration

The data in Table I (A) show that the total water consumption (ET_a) of quinoa ranged from 292 to 450 mm at various stages and that the mean daily ET_a decreased with increasing soil moisture tension during both the vegetative and reproductive stages.

TABLE II THE MEAN DAILY AND TOTAL SEASONAL WATER REQUIREMENT (ET_a) IN VARIOUS IRRIGATION TREATMENTS (mm day^{-1})

Treatment	Jul.	Aug.	Sep.	Oct.	Nov.	Average (mm day^{-1})	Total (mm)
1.1	0.80	3.20	4.40	2.20	0.90	2.30	292
1.2	0.80	3.20	5.00	3.00	1.30	2.66	337
1.3	0.80	3.20	5.50	3.40	1.50	2.88	365
2.1	1.10	3.85	4.90	2.0	0.90	2.59	328
2.2	1.10	3.85	5.75	3.00	1.30	3.00	380
2.3	1.10	3.85	6.00	3.40	1.50	3.17	402
3.1	1.60	4.65	5.20	2.20	0.90	2.91	369
3.2	1.60	4.65	5.90	3.00	1.30	3.29	417
3.3	1.60	4.65	6.63	3.40	1.50	3.55	450

The results in Table II clearly illustrate how the water requirement consistently decreased with increasing soil moisture in all months. Compared to the low-tension treatment (-0.05 MPa), the water requirement in the medium and high-tension treatments was reduced by 10.2% and 19.5% during the vegetative stage and by 6.3% and 18.6% during the reproductive stages, respectively.

It can be seen from Figures 2, 3, and 4 that ET_a increased with the stage of development, reaching a peak value during the flowering (tasseling) period before declining subsequently.

TABLE III EFFECT OF IRRIGATION AT DIFFERENT SOIL MOISTURE TENSIONS AND STAGES OF DEVELOPMENT ON THE WATER REQUIREMENTS OF QUINOA CROP (mm day^{-1})

Tension (Mpa)	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Average (mm day^{-1})**	**Total (mm)**
ET$_a$ Vegetative Stage							
-0.05	1.60	4.65	5.83	2.86	1.23	3.24	412
-0.15	1.10	3.85	5.55	2.86	1.23	2.91	370
-0.40	0.80	3.20	4.69	2.86	1.23	2.61	331
ET$_a$ Reproductive Stage							
-0.05	1.16	3.90	5.69	3.40	1.50	3.18	405
-0.15	1.16	3.90	5.55	3.00	1.30	2.98	378
-0.40	1.16	3.90	4.83	2.20	0.90	2.59	330
ET$_a$ Mean of Stages							
-0.05	1.38	4.27	5.90	3.13	1.36	3.21	408
-0.15	1.13	3.87	5.55	2.93	1.26	2.94	374
-0.40	0.69	3.55	4.89	2.53	1.06	2.60	330
LSD (p=0.05) =0.8247							

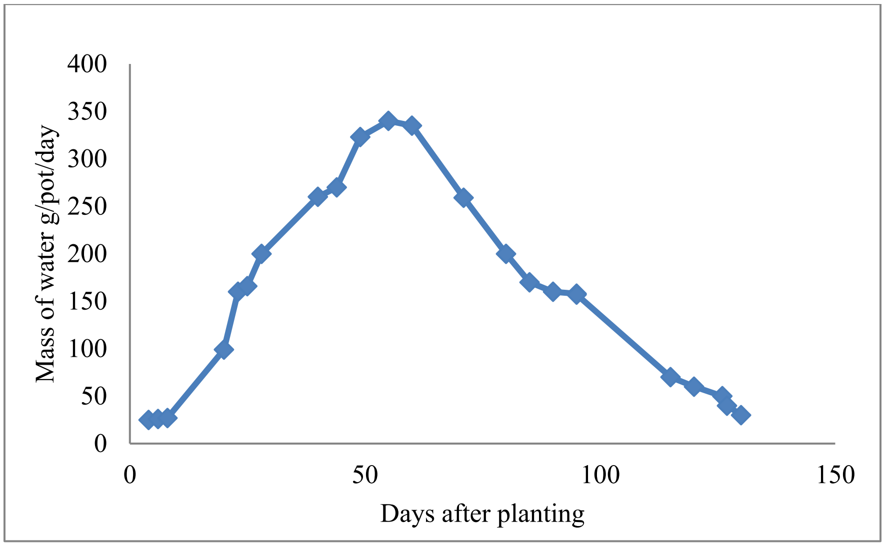

Fig. 2 Evapotranspiration of Quinoa for treatment 2.2. (bar) represent the standard deviation from means

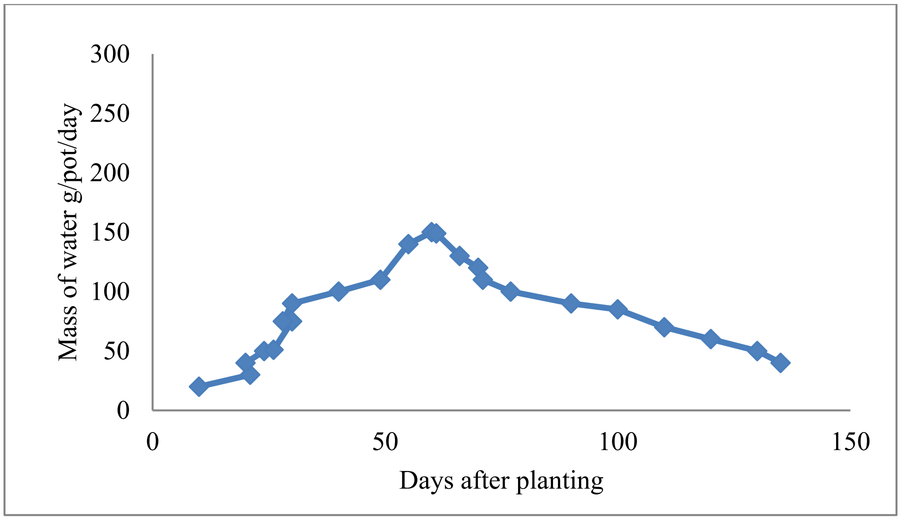

Fig. 3 Evapotranspiration of Quinoa for treatment 1.1 (bar) represent the standard deviation from means

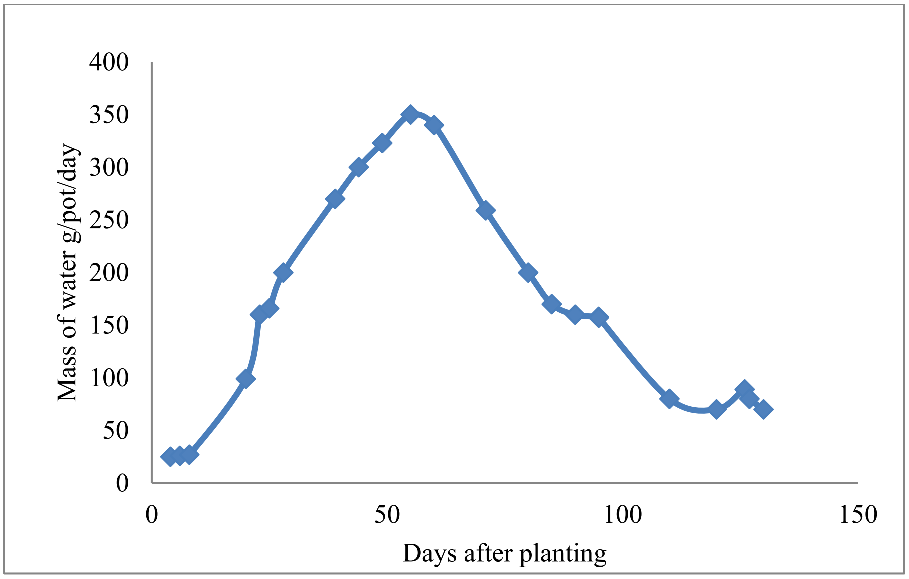

Fig. 4 Evapotranspiration of Quinoa for treatment 3.3 (bar) represent the standard deviation from means

B. Development and Yield

The numbers of grains per ear, 100-grain weight, grain yield, stalk yield, and their ratios resulting from the irrigation of the quinoa crop at low, medium, and high soil moisture tensions during the two stages of development are shown in Table IV.

TABLE IV EFFECT OF SOIL MOISTURE TENSION (Mpa) TREATMENT ON THE YIELD COMPONENT OF QUINOA CROP

Treatment	**No of Grains/Ear**	**100 Grain Yield (tones/ha)**	**Grain Yield (tones/ha)**	**Stalk Yield (tones/ha)**
3.3	432	25.3	5.8	25.0
3.2	329	22.2	4.7	24.3
3.1	247	17.8	3.1	21.4
2.3	385	23.5	5.2	23.8
2.2	300	21.8	3.9	23.3
2.1	210	15.6	2.6	20.7
1.3	272	20.7	3.7	17.1
1.2	222	16.2	2.9	16.0
1.1	180	14.1	2.4	10.9
LSD ($p \geq 0.05$)	89.189	4.154	2.558	5.026

From the data in Table IV, it can be concluded that the number of grains per year decreased with increasing soil moisture tension at both the vegetative and reproductive stages.

TABLE V EFFECT OF IRRIGATION AT DIFFERENT SOIL MOISTURE TENSIONS AND STAGES OF DEVELOPMENT ON THE NUMBER OF GRAINS PER EAR

Tension (MPa)	**Vegetative Stage**	**Reproductive Stage**
-0.05	336	363
-0.15	298	283
-0.40	244	212
LSD ($p \geq 0.05$) for comparison treatment means= 84.525		

The data in Table V show that the reduction in quinoa yield resulting from drier soil moisture treatments was greater at the reproductive stage than at the vegetative stage.

TABLE VI EFFECT OF IRRIGATION AT DIFFERENT SOIL MOISTURE TENSIONS AND STAGES OF DEVELOPMENT ON THE NUMBER OF GRAINS AND YIELDS OF QUINOA (TON/HA)

Tension (MPa)	**Vegetative Stage**	**Reproductive Stage**	**Mean of Stages**
-0.05	4.52	4.89	4.71
-0.15	3.91	3.84	3.88
-0.40	3.02	2.72	2.87
LSD ($p \geq 0.05$) for comparison treatment means= 1.180			

The data in Table VII also show that the 100-grain weight decreased with increasing soil moisture tensions at both stages.

TABLE VII EFFECT OF IRRIGATION AT DIFFERENT SOIL MOISTURE TENSIONS AND STAGES OF DEVELOPMENT ON THE 100-GRAIN WEIGHT OF QUINOA

Tension (MPa)	Vegetative stage	Reproductive stage
-0.05	21.8	23.2
-0.15	20.3	20.0
-0.40	17.0	15.8
LSD (p≥0.05) for comparison treatment means= 3.975		

TABLE VIII EFFECT OF IRRIGATION AT DIFFERENT SOIL MOISTURE TENSIONS AND STAGES OF DEVELOPMENT ON STALK YIELD (TON/HA)

Tension (MPa)	Vegetative stage	Reproductive stage
-0.05	23.5	21.9
-0.15	22.5	21.1
-0.40	14.6	17.6
LSD (p≥0.05) for comparison treatment means= 1.8813		

*(Yield per pot converted to tones/ha. Assuming a plant population of 41660 plants/ha)

The results in Table VIII also show that the stalk yield was reduced by higher soil moisture tensions at both stages.

The relationship between ET_a and crop yield for all treatments is shown in Table IX. It demonstrates that the grain yield of quinoa increased with increasing ET_a up to a certain value. A slight reduction in yield was observed in the treatment where the crop was irrigated at medium tension during the vegetative stage and at low tension during the reproductive stage, while a slightly greater yield was obtained when the crop was irrigated at a low tension of -0.05 MPa throughout.

Upon examining the data in relation to soil moisture tension and their corresponding ET_a, irrespective of the development stage, it was found that crop yield was linearly related to ET_a. When calculating the relative decrease in yield (1 - Y_a/Y_m) and the relative evapotranspiration deficit (1 - ET_a/ET_m) for quinoa at both stages, it is evident (Table 18) that the relative reduction in yield due to the evapotranspiration deficit was greater at the reproductive stage than at the vegetative stage.

The yield response factor $K=\frac{1-\frac{Y_a}{Y_m}}{1-\frac{ET_a}{ET_m}}$ was found to be 1.6, 1.6 and 1.7 respectively.

Consequently, the relative reduction in yield was 1.6 times greater than the reduction in the ET_a value, as influenced by moisture stress at the reproductive stage.

TABLE IX EFFECT OF IRRIGATION AT DIFFERENT SOIL MOISTURE TENSIONS AND STAGES OF DEVELOPMENT ON THE RELATIVE YIELD DECREASE AND RELATIVE EVAPOTRANSPIRATION DEFICIT

Treatment	$(1-\frac{Y_a}{Y_m})$	$(1-\frac{ET_a}{ET_m})$	$\frac{1-\frac{Y_a}{Y_m}}{1-\frac{ET_a}{ET_m}}$
3.3	0.000	0.000	0.0
3.2	0.185	0.074	2.5
3.1	0.466	0.180	2.5
2.3	0.105	0.100	1.0
2.2	0.326	0.155	2.1
2.1	0.539	0.271	1.9
1.3	0.355	0.188	1.8
1.2	0.493	0.251	1.9
1.1	0.584	0.351	1.6
LSD (p≥0.05)	0.1821	0.0976	0.520

IV. DISCUSSION OF THE STUDY

The variation in the water consumption rates of the genotypes is due to the fact that the quantities of irrigation water added to the control treatment were higher than those in the treatments exposed to irrigation cutbacks and close to field capacity. This includes genotype susceptibility and efficiency in extracting higher quantities of groundwater, differences in growth time, and dry matter [1], [16], [19], [20], [25], [31]. This makes quinoa suitable for growth in arid and semiarid regions where farmers can rely on monsoon rains [4]. Additionally, [12] pointed to a positive correlation between total water used, total dry matter, and the number of days required to mature under normal irrigation conditions. Water stress at various stages of development reduced the amount of water added and the actual water consumption (ET) for quinoa genotypes compared to the S0 treatment (without stress). The actual water requirement reduction percentage for water stress treatments ranged from 11% to 17% for the control treatment. The actual plant water requirement increased as development progressed under normal irrigation conditions (S0) (Tables III and IV). The water consumption values were very low at the beginning of the development stage (from emergence to the beginning of branching) due to the lack of plant need for water because of low development rates in these stages, small plant size, limited surface area, and low evaporation rates due to low temperatures and high humidity from rain. Water consumption increased gradually during the branching stage (S2) and ear stage (S3) as the number of irrigations decreased [43]. As the temperature started to rise, the effective growth of the plants began to increase, leading to the growth and expansion of leaves and stems, increased root depth throughout the soil, and the accumulation of dry matter [39], [40]. The highest water consumption of the crop is achieved at the ear stage due to the plants reaching maximum surface area and the increased need for nutrients to meet the requirements of flowering, seed formation, and transporting carbohydrates toward the grain [6], [30].

The increase in temperature, rising evaporation rates, hot winds, and low humidity in the atmosphere all contribute to increased water consumption of the crop as it progresses toward maturity, as well as to increasing the water availability in the root zone of the quinoa plant, which is reflected in the water absorption rates from the root area. Evaporation occurs from the soil surface. These results are consistent with what Jensen [25] noted, stating that the availability of soil water depends on the type of soil, the amount of water available, and the requirements of daily evaporation, which controls the maximum rate of water extraction. Water requirement values decreased from the flowering stage to the maturity stage due to the low demand for water by the plant for the completion of tissue and the decrease in green surface area, as well as the high proportion of plant parts accelerating toward full maturity. Full coverage of the soil surface by the crop reduces evaporation rates and decreases the water requirement of the crop in later stages. The water consumption of quinoa was reduced during exposure to water stress at various growth stages due to the decrease in soil moisture and the lowering of available water for the plant (Tables II and III). The length of time required to reach the necessary stress level is determined as the plant progresses through the growth stages. This depends on the moisture depletion of the soil associated with the crop's water consumption, which is influenced by development characteristics and climatic conditions. This explains the increased demand for water in the advanced stages of plant life, which are critical stages that can cause damage to the crop when exposed to water stress for a long time [32], [36], [38].

Meteorological data show that the evaporation process can occur without interruption during daylight hours and at night due to the effects of weather conditions, like solar radiation, which provides water molecules with the energy needed to convert liquid to vapor, and wind, which removes the saturated layer and replaces it with a dry layer. Additionally, sensitive heat, relative humidity, and heat transfer across the sides of the pan affect the energy balance [9], [34]. The values of ETD and ET are related to temperature as well as light hours, as the transpiration process during daylight hours is influenced by solar radiation. At night, the stomata of the plant are closed, reducing or stopping water consumption. ET increased with the development stages and approached ETa at flowering and maturity stages, which were higher in the early stages. This may be due to the low values of aerodynamic resistance (ra) and rc resistance values during these stages in the modified Penman-Monteith equation [2], [3]. The values of evapotranspiration were estimated by [11]. The results showed a similar trend to the ETa values with an increase in the progress of the growing stages but were generally lower, and the differences remained clear between them.

V. CONCLUSION

An experiment was conducted to study the effect of soil moisture variability on the water requirement (evapotranspiration) of quinoa accessions. The experimental treatments consisted of various tensions (-0.40 MP_a, -0.15 MPa, and -0.05 MPa). The results obtained are summarized as follows. The mean daily ETa decreased with increasing soil moisture tension. The maximum daily values were recorded during tasseling, after which they declined sharply. ETa was reduced by about 6% and 20% in medium (-0.15 MPa) and high (-0.40 MPa) tensions, respectively, relative to that of low soil moisture tension (-0.05 MP_a) during both the vegetative and reproductive periods. The stage of plant growth had little effect on the soil moisture depletion pattern. Plants extracted relatively more but absolutely less soil water from the deeper soil layer in medium and high tensions compared to the low soil moisture tension. The number of grains per cob and seed yield decreased with increasing water stress. The reduction in seed yield was greater when the stress was applied during the reproductive period. The seed yield reduction was 2.2 times greater than the decrease in ETa. The relationship between ETa and seed yield was linear. The maximum water productivity (WP) was recorded at -0.05 MP_a and -0.40 MP_a soil moisture tensions. The effects were more pronounced when stress was imposed during the reproductive period compared to the vegetative period. Based on these results, it can be concluded that quinoa was relatively tolerant to soil moisture stress during the vegetative period compared to the reproductive period. Additionally, -0.40 MPa soil moisture tension was found to be severely detrimental, particularly during the reproductive period.

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