Impact of Irrigation Deficit on Yield, and Water Productivity of Quinoa

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ABSTRACT: A field experiment was carried out to ivestigat the impact of irrigation deficit on Quinoa (*chenopodium quinoa* Willd) variety *Chipaya*. The sowing date was Nov. 11, 2018, and the harvesting date was March. 17, 2019.The irrigation regimes (irrigation deficit) were in the rate of 40, 60, 80, and 100% of the reference evapotranspiration (ET_0) as compared with rainfed irrigation as control. The experimental design was a Randomized Complete Block Design with three replicates. The results indicated that the irrigation regimes had a significant effect on Quinoa productivity. The best effect of irrigation regimes on the gross seed yield of quinoa was recorded with 100% of ET_0 irrigation regime corresponding to an increase by 155.56% over the rainfed irrigation. Seed yield reached the highest values of 0.616 ton/fed at 100% of ET_0,.Also, there were no significant differences between irrigation at 100 and 80 % of the ET_0 irrigation regime. Seed weight per plant, and per m^2 had the highest values with 100% of ET_0. It increased by about 216.70 and 216.68% over the rainfed irrigation. The total applied water (TAW) were 931.4, 796.6, 658.0, 523.3, and 285.6 m^3/fed for irrigation treatments of 100, 80, 60, and 40% of ET_0 and rainfed irrigation, respectively. The irrigation water-use efficiency (IWUE) or water productivity (WP) as kg grain/m^3 of applied water reached the values of 0.681, 0.655, 0.806, 0.778, and 0.712 kg/m^3 for 100, 80, 60, 40% of $ET_{0,}$ and rain-fed treatments, respectively.Irrigation at 100 or 80% of ET_0 gave the highest seed yield. Nevertheless, irrigation at 60% of ET_O gave the highest water productivity (IWUE).

KEYWORDS: Quinoa, rain-fed irrigation, irrigation deficit, seed yield, growth, water productivity, characterization.

INTRODUCTION

The quinoa plant belongs to the genus Chenopodium and the family Chenopodiaceae.**(Iqbal, 2015).** It is well adapted to arid and semi-arid regions. It can be planted on high land up to 4000 m above sea level. Quinoa is a C3 annual dicot of 0.5 to 2 m height, terminating in a panicle consisting of small flowers, and with only one seed of around 2 mm produced per flower. **(Geerts and Garcia, 2012).** Quinoa seed has an excellent balance of carbohydrates, lipids, and protein for nutrition **(Maradini-Filho *et al*., 2017).** Quinoa protein has all essential amino acids found in wheat. ln addition to lysine and sulfur amino acids **(Escuredo *et al*., 2014).** Besides, it contains a considerable amount of fiber and minerals, such as calcium and iron **(Ando et al., 2002).** Grains of quinoa is used instead of wheat grains in bread and other bakeries production **(Abou-Zaid *et al*., 2012 and Koehler *et al*., 2014).**Quinoa plants are resistant to various stresses such as salinity, cold air, high solar radiation, low temperature, and can be planted in different soil types with the broad range of pH values **(Jacobsen *et al*., 1998).** Drought stress reduces plant growth in terms of shoot and root fresh as well as dry weights along with chlorophyll a and b contents and relative water contents (RWC) while a considerable increase was observed in hydrogen peroxide (H_2O_2), malondialdehyde (MDA), proline and total sugar contents in some quinoa cultivars **(Naz *et al*., 2020).** Under water-scarce conditions, tolerance of plants is highly associated with accumulation of proline, which is an amino acid (non-protein), produces in leaf tissues **(Ashraf and Foolad, 2007). Jensen *et al*. (2000)** observed yield reduction when water stress was applied during the flowering stage and grain filling stage, while application of water stress during the vegetative stage led to increased yield. Drought in early vegetative stages may prolong its life cycle, allowing the plant to make up for growth lost during the early drought if water is available later. The plant also avoids the negative effects of drought through fast and deep rooting, particularly in dry soils. Quinoa also reduces its leaf area by controlled leaf senescence under drought. The Food and Agriculture Organization of the United Nations (FAO) has identified Quinoa as an important alternative crop to contribute to future global food security and declared the year 2013 as the international year of quinoa **(FAO, 2012).** Therefore, the present research was conducted to investigate the impact of different irrigation deficits on Quinoa production as compared with rain-fed irrigation.

MATERIALS AND METHODS:

1.The site of the experiment:

The present investigation was carried out at the experimental farm of the City of Scientific Research and Technological Applications SRTA-City, Old Borg El-Arab, Alexandria Governorate, Egypt. Geographically, the experimental farm is located at 30° 53’N and 29° 32’E, with an elevation of about 28 meters above sea level.

2. Climatic conditions:

The climatic conditions were extracted from NASA web-meteorological free data **(power.larc.nasa.gov)** and the new Borg El-Arab station**.** The values of climatic parameters during the growing season (2018 – 2019) i.e. temperature (T °C), relative humidity (RH %), rainfall (Pe mm), wind speed (U2 m/s at 2m height), and atmospheric pressure (P kPa) are presented in Table (1).

Table (1). Climatological data for the experimental site during the growing season

Months	Temperature (C°)			RH (%)	Pe mm	U_2 m/s	P kPa	ET_0 mm
	Max.	Min.	Mean					
Nov. 2018	24.46	16.06	19.69	63.13	18.74	2.62	101.16	47.03
Dec. 2018	19.38	12.60	15.52	67.21	33.43	3.51	101.39	63.93
Jan. 2019	17.08	7.82	11.83	61.45	10.13	3.98	101.15	70.39
Feb. 2019	18.79	8.78	13.15	64.22	11.71	3.29	101.25	69.62
March 2019	20.80	10.54	15.10	63.40	4.64	3.48	101.16	50.13

3. Field experiment:

3.1. Planting The field experiment was planted with a Quinoa crop. Quinoa (*chenopodium quinoa* Willd) variety *Chipaya*. The sowing date was Nov. 11, 2018, and the harvesting at Mar.17, 2019. The growing season was 126 days. The soil type was sandy clay loam and some soil physical and chemical properties are illustrated in Table (2). The seeds were sowed in a soil bed with 0.5 m width and 10.5 m length with 0.2 m between plants(2 seeds per hole) . The number of plants per m^2 was 20 plants.

3.2. Irrigation

The drip irrigation system was constructed as 0.5 m between rows and 10.5 m in length. The irrigation practice was done weekly using a drip irrigation system with a capacity of 6.0 L/hr.

3.3. Fertilization

The experiment was fertilized with recommended doses of ammonium nitrate (33.5% N) as 100 kg/fed, superphosphate (15.5% P_2O_5) as 50 kg/fed and potassium sulfate (48% K_2O) as 50 kg/fed.

3.4. Experimental treatments

The experiment was designed to investigate the effect of irrigation regimes as 40, 60, 80, and 100% of the reference evapotranspiration (ET0) as compared with rainfed irrigation. The experimental design was a Randomized Complete Block Design with three replicates.

4. Soil analysis

The soil samples were collected from the experimental site at two depths; surface 0 – 30 cm and subsurface 30-60 cm before planting to determine the soil's physical and chemical properties. Soil samples were air-dried and sieved through a 2-mm sieve and analyzed according to the methods described **by Carter and Gregorich (2008)** and presented in Table (2).

4.1. Physical properties of soil

Particle-size distribution is determined by the hydrometer method according to **Carter and Gregorich (2008).**

4.2. Chemical properties of soil

Soil Electrical conductivity (EC) (1:1 w/v) was measured using a conductivity meter according to **Jackson (1973).** Organic carbon OC, Organic Matter OM %, CaCO3 %, cations and anions, CEC meq/100 gm soil and available macronutrients NPK (ppm) were laboratory determined according to **Jackson (1973), Richards (1972) and Carter and Gregorich (2008).**

5. Water analysis:

The following parameters of irrigation water were determined; pH, Electrical conductivity (EC), soluble cations (Na, K, Ca, and Mg), and soluble anions (CO_3, HCO_3, Cl, and SO_4) in Table (3).

Table (2). Some soil physical and chemical properties

Soil characteristics	0 – 30 cm	30 – 60 cm
Particle-size distribution(%)		
Sand%	63.05	64.11
Silt%	16.31	15.21
Clay%	20.64	20.72
Textural Class	SandyClay Loam	SandyClay Loam
pH(1:1, water suspension)	8.14	8.09
EC (1:1, water extract) dSm^{-1}	10.00	6.00
$CaCO_3$ (%)	48.51	48.51
Soil water content (%)	3.82	3.42
OM (%)	1.34	1.57
Soluble Cations (meq l^{-1})		
Ca^{++}	10.34	7.51
Mg^{++}	14.52	8.35
Na^{+}	73.15	41.60
K^{+}	2.49	2.54
Soluble Anions (meq l^{-1})		
CO_3^{--}	-	-
HCO_3^{-}	8.19	7.46
Cl^{-}	57.90	27.76
SO_4^{--}	34.01	24.93
Available nutrients $mgkg^{-1}$ soil		
Nitrogen (N)	42.58	33.44
Phosphorus (P)	61.00	35.00
Potassium (K)	600.00	500.00

Table (3). Chemical properties of the irrigation water

Parameters	Value
pH	8.2
EC (dS/m)	3.6
Soluble cations (meq/l)	
Ca^{++}	2.87
Mg^{++}	6.56
Na^{+}	24.35
K^{+}	0.71
Soluble anions (meq/l)	
$CO_3^{--} + HCO_3^{-}$	5.25
Cl^{-}	13.73
SO_4^{--}	17.13
Soluble nutrients (mg/l)	
N	1.42
P	1.32
B	0.8

6. Plant chracteristics

At harvest time (126 days after sowing), the following parameters were recorded:

6.1. yield and seed characteristics: foliage yield (ton/fed), total yield (ton/fed), seed weight (g/plant), seed weight (g/m^2), weight of 1000 seeds, seed yield (ton/fed), harvest index(%), and seed water content(%).

6.2. water characteristics Qiunoa water requriments(m^3/fed), and irrigation water use efficiency (water productivity), kg/m^3.

7. Statistical analysis

All obtained data of the present study were, statistically, analyzed according to the design used by the **Statistix (2019)** computer software program and were tested by analysis of variance. The revised least significant difference test at 0.05 level of probability was used to compare the differences among the means of the various treatment combinations as illustrated by **Duncan (1955) and Gomez and Gomez (1984).**

RESULTS AND DISCUSSION

1. Quinoa yield and seed characteristic

The irrigation regime treatments had a highly significant effect on foliage and total yield (Table 4). The highest values were attained at 100% of the ET_o irrigation regime. It accounted for 2.82 and 2.72 times increase over the rainfed irrigation treatment, respectively. Seed weight per plant and seed weight per m^2 reached a maximum value at 100% of ET_0. It increased by about 216.70 and 216.68% over the rainfed irrigation regime, respectively. There were no significant differences between 100 and 80 % of ET_0 treatments. Seed weight per plant was 10.185 and 8.781 g/plant at 100 and 80% of $ET_{0,}$respectively; as well, seed weight per m^2 was 203.69 and 175.62 g/m^2 at 100 and 80 % of $ET_{0,}$ respectively. The weight of 1000-seeds reached the highest value at 60% of the ET_0 irrigation regime (3.43 g). It increased by 18.28 % over the rainfed irrigation regime. Seed yield per fed recorded the highest value at 100% of the ET_0 irrigation regime (0.616 ton/fed). The increase over the rainfed irrigation treatment was 155.56%. There were no significant differences between irrigation at 100 and 60% of the ET_0 irrigation regime as shown in Table 4 and Figure 1. The harvest index reached the highest value at 40% of ET_0 irrigation treatment (45.81%). It increased by about 39.96% over the rainfed irrigation regime (32.73%). In addition, the seed water content reached its maximum value at 100% of ET_0treatment and decreased with other irrigation regimes (Table 4).

Table (4). Quinoa seed yield and seed quality as affected by irrigation regime

Treatments % of ET_0	Foliage yield ton/fed	Total yield ton/fed	Seed weight g/plant	Seed weight g/m^2	Weight of 1000-seeds(g)	Seed yield ton/fed	Harvest Index, %	Seed moisture content, %
100	1.171 a	1.787 a	10.185 a	203.69 a	3.32 a	0.616 a	35.23 ab	11.16 a
80	0.899 b	1.419 b	8.781 ab	175.62 ab	3.33 a	0.520 ab	37.10 ab	10.68 a
60	0.795 b	1.310 b	8.658 ab	173.15 ab	3.43 a	0.515 ab	39.70 ab	9.50 ab
40	0.483 c	0.887 c	6.868 b	137.36 b	2.77 a	0.404 bc	45.81 a	10.01 ab
Rainfed	0.415 c	0.656 c	3.216 c	64.32 c	2.90 a	0.241 c	32.73 b	8.14 b

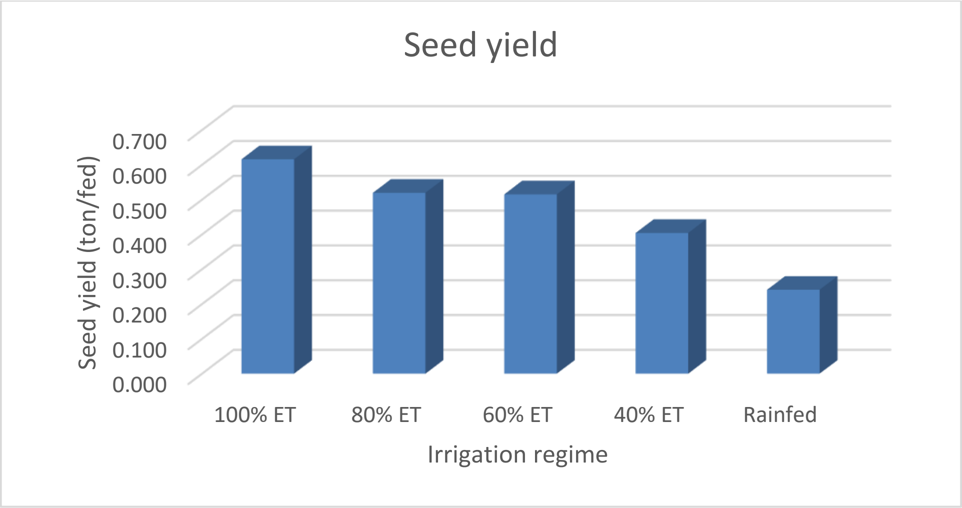

Figure (1): Effect of irrigation deficit on seed yield of quinoa

. Quinoa water requirements and water productivity

The water use efficiency calculated as:

$$IWUE\ (kg/m^3) = \frac{Seed\ Yield(ton/fed)}{TAW(m^3/fed)}$$

$$CWUE(kg/mm) = \frac{Seed\ Yield(ton/fed)}{ETc(mm/fed/season)}$$

The total applied water (TAW) were 931.4, 796.6, 658.0, 523.3, and 285.6 m^3/fed for irrigation treatments of 100, 80, 60, and 40% of ET_0 and rainfed irrigation, respectively (Table 5). The calculated crop evapotranspiration reached 229.0, 183.2, 137.4, 91.6, and 50.2 mm/season, respectively. The irrigation water-use efficiency (IWUE) or water productivity (WP) as kg seeds/m^3 of applied water reached the values of 0.681, 0.655, 0.806, 0.778, and 0.712 kg/m^3 for 100, 80, 60, 40% of ET_0, and rainfed treatments, respectively. The maximum value was obtanid for 60% of ET_0 (Table 5 and Figure 2). The consumptive water-use efficiency (CWUE) reached its maximum value at 40% of the ET_0 irrigation regime. Its values were 2.769, 2.847, 3.858, 4.443, and 4.053 kg/mm of applied water, respectively. Irrigation at 60% of $ET_0$was the best treatment resulting in the highst water productivity (IWUE). It increased by about 13.20% over the rainfed irrigation treatment. At this treatment, it is possible to save about 273.4m^3/fed of applied water; which accounted for 29.35% of water-saving.

Table (5). Quinoa water requirements of Quinoa as affected by irrigation regime

Treatments % of ET_0	ETc mm/season	TAW m^3/fed	CWUE kg/mm	IWUE kg/m^3
100	229.0	931.4	2.769	0.681
80	183.2	796.6	2.847	0.655
60	137.4	658.0	3.858	0.806
40	91.6	523.3	4.443	0.778
Rain	50.2	285.6	4.053	0.712
LSD 0.05			1.462 ns	0.278 ns

TAW: Total applied water CWUE: Consuming water use efficiency

IWUE: Irrigation water use efficiency ETc: crop evapotranspiration

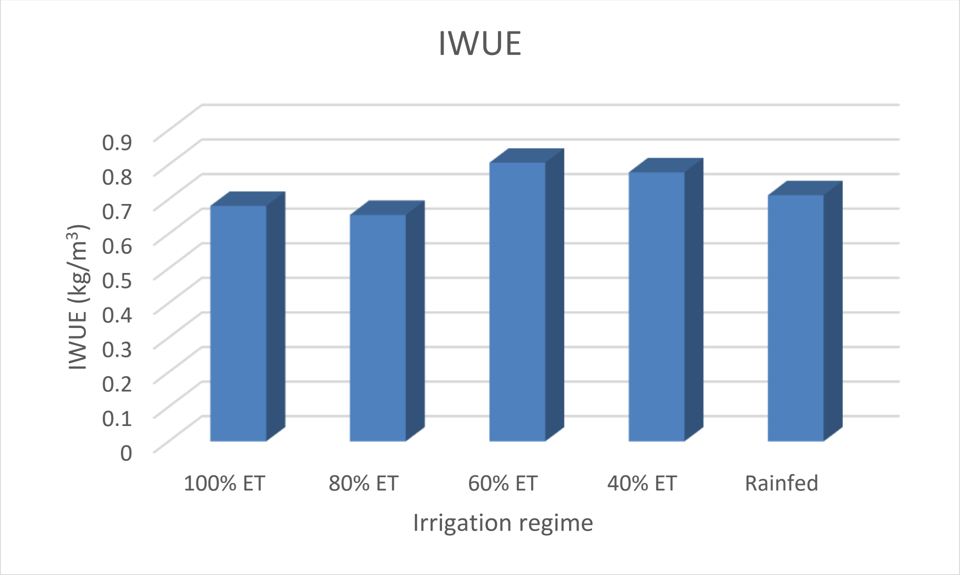

Figure (2). Effect of irrigation deficit on water productivity of quinoa

The present results indicated that if the farmers need the highest yield of quinoa, they must use 100% of ET_0 for irrigation. However, if the farmers need the efficient use of irrigation water, they must use 60% of ET_0 for irrigation. This treatment saves about 273.4m^3/fed, but the seed yield may be reduced by about 19.61% of the maximum yield at 100% of ET_0. Then the decision may be the comparison between the cost of saving water and the cost of reduced seed yield, the which is moor cost effective may be applied.

Deficit irrigation is defined as an optimization strategy in which irrigation is applied during the drought-sensitive growth stage of the crop **(Geerts and Raes, 2009)**. In this regard, several studies were performed to find out the most sensitive stage of quinoa growth to water stress. **(Jensen *et al.*, 2000)** did observe the yield reduction when water stress was applied during the flowering stage and grain filling stage, while application of water stress during the vegetative stage led to yield increase. In another study, **Geerts *et al.* (2008)** indicated that the milky grain stage of quinoa was most sensitive to water stress, followed by the flowering stage. Furthermore, **Hirich *et al.* (2014)** performed field trials in Morocco and concluded that the most tolerant stage to water stress is the vegetative stage, and deficit irrigation is most efficient when it is applied during this stage. Plant responses and mechanisms for dealing with low water availability can be divided into two major categories that are stress avoidance and stress tolerance **(Claeys and Inze, 2013).** Quinoa can tolerate water stress through a branched and deep root system (**Alvarez-Flores*et al*., 2014).**

Quinoa can resist water deficit based on its intrinsic low water requirement. Its skill to resume rapidly to its former photosynthetic level, and its specific leaf area after a period of water stress (**Jacobsen *et al*., 2009; Jensen *et al*., 2000).** This ability makes it suitable for growing in arid and semi-arid regions, where there is less water available for irrigation and farmers need to rely on seasonal rainfall **(Bhargava *et al*., 2006).** Quinoa's grain is a rich source of minerals, vitamins, high-quality oil, protein, and natural antioxidants **(Vega-Gálvez*et al*., 2010).** In recent years, the quinoa crop received a lot of attention, because of its adaptability to produce in unfavorable soils and under harsh climatic conditions (**Garcia *et al*., 2003; Jacobsen *et al*., 2013, and 2015)**.

Comparing the result of this study with other studies performed at other places suggested that the farmers in semi-arid regions have to be cautious for cultivating quinoa, as the produced seed yield was significantly lower than that obtained in other places under field conditions using a higher amount of applied irrigation water. Water scarcity, low rainfall, depletion of groundwater, the occurrence of drought, and poor water management in semi-arid regions makes the water much more valuable. Quinoa is a good candidate crop for agricultural diversification because of its extraordinary tolerance to various environmental stress conditions like drought and soil salinity. Therefore, decision-makers can consider this fact before promotingfarmers to cultivate new untraditional crops such as quinoa as a new applied land-use type that tolerant to drought conditions.

Plant root systems are essential for adaptation against different types of biotic and abiotic stresses. Different root features such as fine root diameter, specific root length and area, root angle, and root density are useful for improving a plant's productivity under water-stress conditions **(Wasaya et al., 2018). Forster et al., (2005)** indicated that plants having higher root density (RD) could extract sufficient water. This concept corresponding with high water stress. According to the present result, the quinoa RD (calculated as root weight over the soil volume per plant, g/cm3) indicating that one of the strategies of quinoa to overcome water stress is to increase its root growth **(Alvarez-Flores et al, 2014).** Variation in RD of different irrigation treatments showed that RD increased significantly by increasing deficit irrigation at all treatments.

The advantages of deficit irrigation may be:

1- This resulted in maximization of the water productivity with good crop quality,

2- Creates a less wetted environment for crops and decreasing the riskof some diseases (such as fungi) in comparison with full irrigation, and

3- Reduces the leaching of plant nutrients due to the reduction of waterleaching in the root zone, and lower requirements of fertilizerapplication as for full irrigation conditions

To obtain the deficit irrigation advantages, there are some restrictionssuch as:

1- Know which crops respond to water deficit, and

2- More information about the crop-sensitive growing stages.

The deficit irrigation can be successful if farmers take action to avoid the risk of soil salinization due to insufficient leaching of the root zone when irrigating with poor water quality.

Generally, taking into account extreme caution when applying insufficient irrigation without prior knowledge of the plant's response to the deficit of water, taking into account the addition of leaching needs to remove salts in the root zone depth.

CONCLUSION

The present study investigates the comparison between irrigation deficit and rainfed irrigation. The obtained results concluded that irrigation at 60 % of the ET_0 irrigation regime resulted in high water-use efficiency. The best effect of irrigation treatment was recorded with 80 and 60 % of the ET_0 irrigation regime resulting in the highest seed yield. Therefore, it is recommended to apply the irrigation rate of Quinoa at 80 or 60% of ET_0 in regions that have such present conditions.

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الملخص العربي

أثر نقص الري على المحصول والانتاجية المائية للكينوا

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1 قسم تكنولوجيات الأراضى و المياه – معهد بحوث زراعة الأراضى القاحلة – مدينة الأبحاث العلمية و التطبيقات التكنولوجية – برج العرب – الإسكندرية

2 قسم الأراضي و الكيمياء الزراعية – كلية الزراعة سابا باشا – جامعةالإسكندرية

3 قسم الأنتاج النباتى – معهد بحوث زراعة الأراضى القاحلة – مدينة الأبحاث العلمية و التطبيقات التكنولوجية –برج العرب– الإسكندرية

يهدف البحث الحالي إلى دراسة تأثير نقص الري على الكينوا صنف (*chenopodium quinoa* Willd) Chipaya. كان تاريخ الزراعة 11 نوفمبر 2018 ، والحصاد في 17 مارس 2019. كان نظام الري (عجز الري) بمعدل 40 ، 60 ، 80 ، و 100٪ من البخر- نتح المرجعي (ET_0) مقارنة بالري المطري كمعاملة كنترول. كان التصميم التجريبي عبارة عن تصميم القطاعات كاملة العشوائية بثلاث مكررات. أشارت النتائج إلى أن نظام الري (نقص الري) له تأثير معنوي على إنتاجية الكينوا. تم تسجيل أفضل تأثير لنظام الري على محصول البذور الإجمالي للكينوا بنسبة 100٪ من نظام الري ET_0 وهو ما يقابل زيادة بنسبة 155.56٪ على الري المطري. وصل إنتاج البذور إلى قيم عالية بلغت 0.616 طن / فدان عند 100٪ من نظام الري ET_0 ، وهذا يعني ايضا عدم وجود فروق معنوية بين الري عند 100 و 80٪ من نظام الري ET_0. وزن البذرة لكل نبات ، و للمتر المربع لها أعلى قيم بنسبة 100٪ من ET_0. ويزداد بحوالي 216.70 و 216.68٪ عن الري المطري. تم حساب إجمالي المياه المضافة (TAW) بـ 931.4 و 796.6 و 658.0 و 523.3 و 285.6 متر مكعب / فدان لمعاملات الري بنسبة 100 و 80 و 60 و 40٪ من ET_0 والري المطري، على التوالي. بلغت كفاءة استخدام مياه الري (IWUE) أو إنتاجية المياه (WP) كيلوجرام من الحبوب / م 3 من المياه المطبقة قيم 0.681 و 0.655 و 0.806 و 0.778 و 0.712 كجم / م 3 لكل من 100 و 80 و 60 و 40٪ من ET_0 والمعاملة المطرية على التوالي. كان الري عند 100أو 80٪ من ET_0 هو أفضل معاملة نتج عنها إنتاجية عالية من البذور. ومع ذلك ، أدى الري بنسبة 60 ٪ من ET_0 إلى إنتاجية مائية عالية.