

Impact of Salinity on the Radiation Use Efficiency of Quinoa (*Chenopodium quinoa* Willd.) in Semi-arid Area in Tunisia

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Abstract

The impact of three level of salinity ($T_0 = 1.2 \text{ dS m}^{-1}$, $T_1 = 9.2 \text{ dS m}^{-1}$ and $T_2 = 18 \text{ dS m}^{-1}$) on photosynthetically active radiation intercepted (PARabs), Radiation Use Efficiency at pre-anthesis and post-anthesis (RUE_{PR} and RUE_{PS}), Radiation Use Efficiency of total dry biomass (RUE_{TDM}) and Radiation Use Efficiency of Grain Yield (RUE_{GY}) at quinoa harvest were investigated during the growing season (2015). The RUE pre-anthesis (from transplanting to anthesis) has registered a decrease of 10.8 and 15.8% respectively in T_1 ($\text{RUE}_{\text{PR}} = 4.62 \text{ g MJ}^{-1}$) and T_2 ($\text{RUE}_{\text{PR}} = 4.36 \text{ g MJ}^{-1}$) compared to the control T_0 ($\text{RUE}_{\text{PR}} = 5.18 \text{ g MJ}^{-1}$). Likewise, the RUE post-anthesis was reduced by 8.9 and 32.1% in T_1 ($\text{RUE}_{\text{PS}} = 1.23 \text{ g MJ}^{-1}$) and in T_2 ($\text{RUE}_{\text{PS}} = 0.91 \text{ g MJ}^{-1}$), dissimilarity to T_0 ($\text{RUE}_{\text{PS}} = 1.35 \text{ g MJ}^{-1}$). The maximum RUE_{TDM} (3.2 g MJ^{-1}) was manifested in (T_0). However, the minimum RUE_{TDM} (2.8 g MJ^{-1}) was observed in T_2 ($S = 18 \text{ dS m}^{-1}$). A decline of 16.1% was observed in RUE_{TDM} due to the reduction on TDM from T_0 ($S = 1.2 \text{ dS m}^{-1}$) to T_2 ($S = 18 \text{ dS m}^{-1}$). As well, the RUE_{GY} declined when salinity increased. The highest RUE_{GY} (1.24 g MJ^{-1}) was registered in T_0 . However, the lowest RUE_{GY} (0.62 g MJ^{-1}) was obtained in T_2 . A decrease of 50% in RUE_{GY} due to the height reduction on yield was observed in the T_2 .

Keywords: irrigation saline water, radiation interception, total dry matter, yield, radiation use efficiency, quinoa

1. Introduction

Quinoa is proficient to tolerate different stresses such as drought, salinity and elevated radiation (Geerts et al., 2008). Bosque Sanchez et al. (2003) and Jacobsen et al. (2003) affirmed that quinoa yield is higher beneath moderate salinity than under fresh water. Similarly, Razzaghi et al. (2012b) observed that quinoa appears to be not influenced by salinity. Consequently, the smart modeling of growth relies on a sufficient description of LAI, the light extinction coefficient for PARabs and RUE.

In unstressed experiments, the major canopy features of grain crops are distinguished, in maize (Kiniry et al., 1989); in wheat (Siddique et al., 1989), in soybean (Sinclair & Shiraiwa, 1993); in Peanut (Kiniry et al., 2005) and in sorghum (Sivakumar & Virmani, 1984; Kiniry et al., 1989).

The RUE is as well predisposed by the quantity of nutrients in plants, mainly by nitrogen (Scott Green et al., 2003). The water shortage reduces the PARabs due to the leaves curling (Müller, 2001). Similarly, Collinson et al. (1999) observed under prolonged water stress, the number and size of leaves may be reduced.

Several researchers have studied the RUE of quinoa (Razzaghi et al., 2012b) and the impact of salinity on yield of quinoa (Martínez et al., 2009; Peterson, 2013). However, only few studies concern the effect of irrigation water salinity on radiation use efficiency before and after quinoa grain filling.

Therefore, this study was undertaken to investigate the impact of salinity on quinoa particularly during flowering and resolve the tolerance of quinoa with reverence to: (i) PARabs, (ii) RUE pre-anthesis and RUE post-anthesis and (iii) Radiation use efficiency of total dry biomass and grain yield at harvest.

2. Methodology

2.1 Location

The study was conducted at INRGREF, located in Cherfech, Ariana (Tunisia, 10° Est, 37° N, Alt. 10.5 m), during the growing season 2015. The climate of the region is semi arid.

The annual average rainfall is about 450 mm with unequal distribution.

The highest and least temperatures were 33 ± 4 °C and 20 ± 3 °C, and the most and lowest percentage of relative humidity were $44 \pm 3\%$ and $22 \pm 1\%$, respectively. The texture was clay-loam and characterized by a hydraulic conductivity at saturation of 1 m d^{-1} .

The water content at field capacity varies from 45.2 to 47.9% and at the wilting point ranges from 25.7 to 27.1% from the surface to the depth. The total available water was 188 mm m^{-1} . The bulk density varied from 1.56 to 1.67.

2.2 Plant Material

Plant material consisted of one quinoa variety (*Chenopodium Quinoa Willd*). The planting was carried out on March 02, 2015.

2.3 Experimental Design and Irrigation Treatment

Three levels of water salinity were applied; T_0 : irrigation with low salt water ($T_0 = 1.2 \text{ dS m}^{-1}$); T_1 : treatment with medium salt water ($T_1 = 9.2 \text{ dS m}^{-1}$) and T_2 : irrigation with salt water ($T_2 = 18 \text{ dS m}^{-1}$).

All irrigation treatments (T_0 , T_1 and T_2) received 100% of ET_c . Salt application was initiated on April 15, 2015. The experimental design adopted was a complete randomized block with three replicates.

Each elementary plot had 2.5 m length and 5 m width (Figure 1). Indeed, each treatment (T_0 , T_1 and T_2) was composed with 6 lines of 2.5 m length (Figure 1). The distance among plants was 0.33 m and 1 m between crop lines.

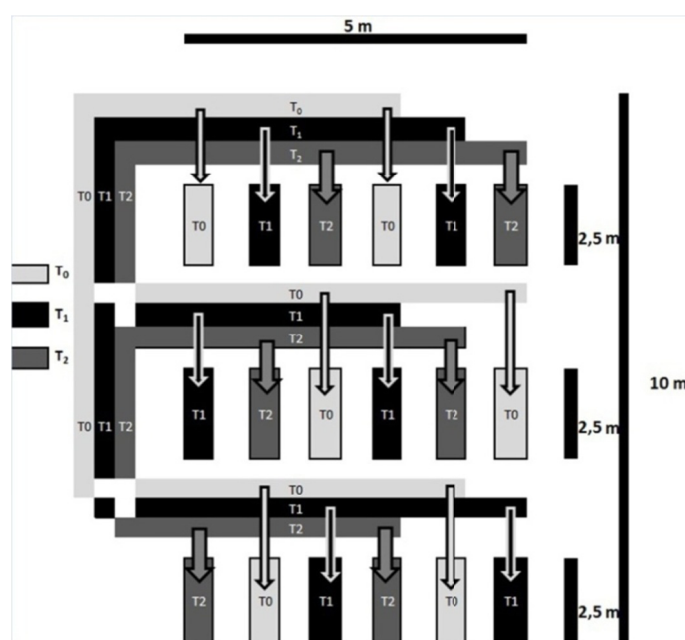


Figure 1. Experimental plot

2.4 Field Measurements

2.4.1 Climatic Data

Climate information was registered by agro meteorological station and composed of temperatures (T_{\min} and T_{\max}), air relative humidities (HR_{\min} and HR_{\max}), wind speed (V) and rainfall (P).

Reference evapotranspiration (ET_0) and radiation (R_s , $\text{MJ m}^{-2} \text{d}^{-1}$) were calculated by the CROPWAT 8.0 software using the FAO-Penman-Monteith approach (Allen et al., 1998).

2.4.2 Leaf Area Index, Total Dry Matter Production

The observations were made on leaf area index (LAI) and total dry biomass (TDM). For this reason, twelve samples were taken during the quinoa crop cycle. At each sample, three plants per treatment ($T_0 = 1.2 \text{ dS m}^{-1}$, $T_1 = 9.2 \text{ dS m}^{-1}$ and $T_2 = 18 \text{ dS m}^{-1}$) were taken from each plot, a total of nine plants per sample. After separation of the various parts, the quantity of fresh material was determined immediately. The dry biomass was calculated after drying at 80°C to a constant weight. Leaf area was measured using planimeter type CID Inc-CI-202.

2.5 Theoretical Formulations

2.5.1 Estimation of the Daily Photosynthetically Active Radiation Intercepted

The radiation interception (RI) was calculated from measurements of LAI using the relation recommended by Monteith and Elston (1983).

$$RI = 1 - e^{-k \cdot LAI} \quad (1)$$

Where, k is the extinction coefficient for total solar radiation ($k = 0.60$) (Razzaghi et al., 2012a).

Photosynthetically active radiation intercepted by quinoa (PARabs) was calculated using the formula of Beer (Manrique et al., 1991):

$$PAR_{abs} = PAR_0 \cdot RI \quad (2)$$

PAR_0 is photosynthetically active radiation incident, which is equal to half of the solar radiation (Monteith & Unsworth, 1990).

2.5.4 Estimation of the Radiation Use Efficiency

RUE of total dry biomass (RUE_{TDM}) and RUE of grain yields (RUE_{GY}) were calculated using the following equations:

$$RUE_{TDM} (\text{g MJ}^{-1}) = TDM (\text{g m}^{-2}) / PAR_{abs} (\text{MJ m}^{-2}) \quad (3)$$

$$RUE_{GY} (\text{g MJ}^{-1}) = GY (\text{g m}^{-2}) / PAR_{abs} (\text{MJ m}^{-2}) \quad (4)$$

2.6 Statistical Analysis

The outcome was analyzed with General Linear Model (GLM). It was performed using SPSS 20.0 software and was completed by multiple comparisons of means with Student Newman Keuls test (S-N-K).

3. Results

3.1 Impact of Salinity on Leaf Area Index (LAI)

Figure 2 shows that at all the three treatments T_0 , T_1 and T_2 , the LAI curves illustrate the same pace. Indeed, from the emergence to the 71st day after quinoa transplanting (DAT), a rapid LAI increase was observed (period of vegetative growth).

Next to, from the 71st to the 85th DAT, the LAI remains stable. Then from 85th to harvest we can see a decline phase.

In fact, the variance analysis proves insignificant differences ($p > 0.05$) between the T_0 , T_1 and T_2 . The S-N-K test illustrates that the T_0 , T_1 and T_2 were statically homogeneous and have the same classification.

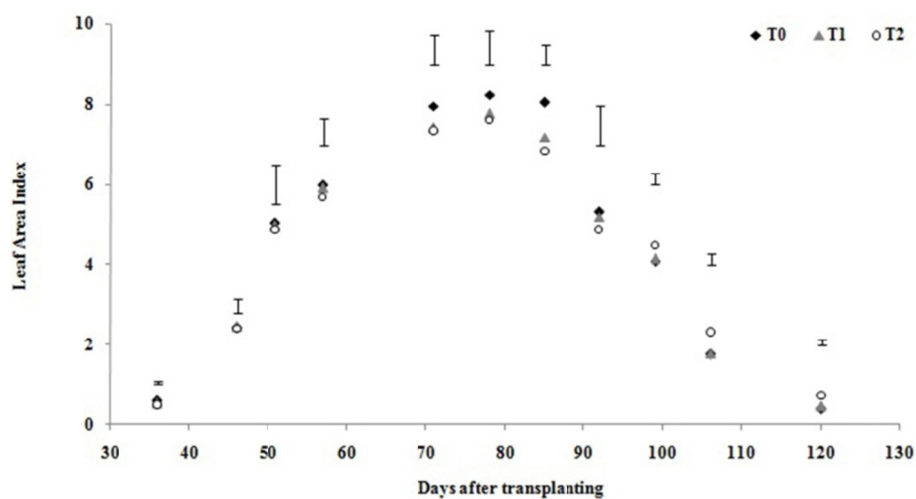


Figure 2. The Leaf Area Index (LAI) of quinoa in (T_0 , T_1 and T_2). The vertical bars represent the least significant difference at 5% (LSD)

3.2 Effect of Saline Water Irrigation (SWI) on Photosynthetically Active Radiation Intercepted (PAR_{abs})

Figure 3 shows the daily evolution of active radiation incident (PAR_0) and the PAR_{abs} in T_0 , T_1 and T_2 .

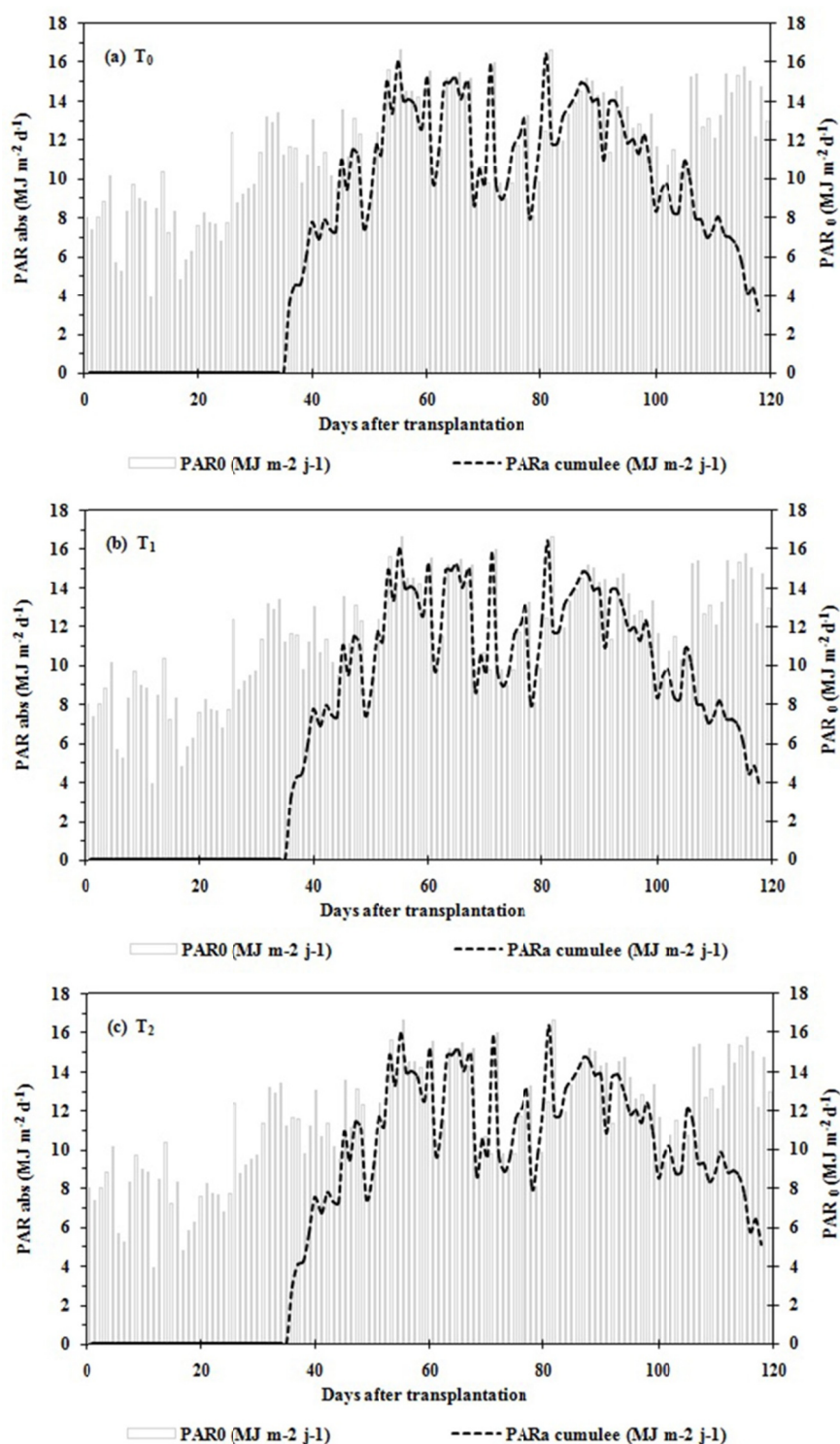


Figure 3. The Daily Photosynthetically active radiation incident (PAR_0) and intercepted by quinoa (PAR_{abs}) under the three treatments (T_0 , T_1 and T_2)

It was observed that the quinoa daily PAR_{abs} in T_0 , T_1 and T_2 were low at the growth stage and then increased during the mid-season stage and decreased at the end of the cycle but remained higher compared to the beginning of the transplant cycle. The increased PAR_{abs} at the flowering and ripening stages was necessary for the seeds filling.

In fact, the cumulative PARabs in the T_0 treatment has increased from (3.56 MJ m^{-2}) at 36th DAT to (803.7 MJ m^{-2}) at the end of the cycle. Similarly, for both T_1 and T_2 treatments, the PAR abs has progressed respectively from (3.2 and 2.9 MJ m^{-2}) to (801.2 and 802.5 MJ m^{-2}). Variance analysis demonstrated insignificant differences ($p > 0.05$) between the T_0 , T_1 and T_2 . The S-N-K test proves that the treatments T_0 , T_1 and T_2 are statically homogeneous and have the same classification.

3.3 Impact of Salinity on Radiation Use Efficiency (RUE)

The Radiation Use Efficiency pre-anthesis and post-anthesis (RUE_{PR} and RUE_{PS}) of quinoa in the T_0 , T_1 and T_2 were illustrated in Figure 4.

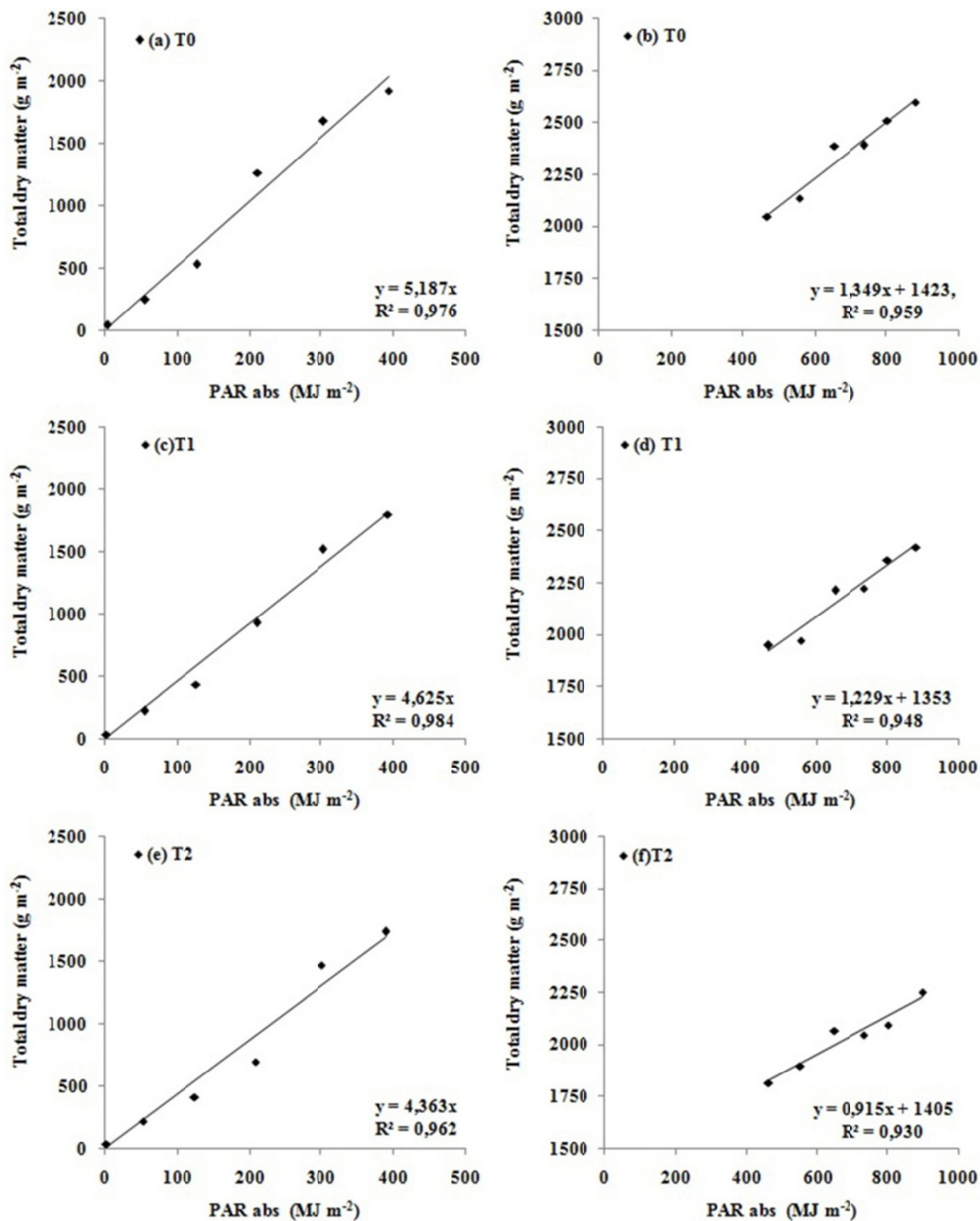


Figure 4. The RUE_{PR} and RUE_{PS} of quinoa under the T_0 (a and b), T_1 (c and d) and T_2 (e and f)

Data analysis (Figure 4) shows that the throughout quinoa growing cycle the relation between PARabs and total dry biomass (*i.e.*, radiation use efficiency) aren't linear. Moreover, we observed that it has an inflection point at the anthesis stage and divides the curve into two separate lines, one pre-anthesis and the other post-anthesis. The slope of each line expresses the RUE for the total dry biomass before and after anthesis.

In detail, the RUE_{PR} was equivalent to 5.18 g MJ⁻¹ in T₀ (Figure 4a) and 4.62 g MJ⁻¹ in T₁ (Figure 4c). The lowest RUE_{PR} (4.36 g MJ⁻¹) was obtained in treatment T₂ (Figure 4e).

Regarding the RUE_{PS}, it was equal to 1.35 and 1.23 g MJ⁻¹ respectively for the two treatments T₀ (Figure 4b) and T₁ (Figure 4d). However, for the treatment T₂, it has been reduced to 0.91 g MJ⁻¹ (Figure 4f).

The RUE_{TDM} and the RUE_{GY} in T₁, T₂ and T₃ were exposed in Table 1.

Table 1. The RUE_{TDM} and the RUE_{GY} in T₀, T₁ and T₂ at harvest

Treatments	PARabs	TDM	GY	RUE _{TDM} (g MJ ⁻¹)	RUE _{GY} (g MJ ⁻¹)
T ₀	803.7 a	2598.5 a	999.7 a	3.2 a	1.24 a
T ₁	801.2 a	2423.1 b	703.7 b	3.0 ab	0.88 b
T ₂	802.5 a	2251.3 c	498.2 c	2.8 b	0.62 c
LSD (5%)	59	107.3	98	0.20	0.3

Note. TDM: Total dry matter; GY: Grain yield; LSD: Least Significant Difference (5%).

Table 1 shows that at harvest, the RUE_{TDM} and RUE_{GY} were significantly ($P < 0.05$) affected by the IWS (T₀ = 1.2 dS m⁻¹, T₁ = 9.2 dS m⁻¹ and T₂ = 18 dS m⁻¹). However, insignificant difference ($P > 0.05$) was observed between (T₀ and T₁) and between (T₁ and T₂) in the RUE_{TDM}. In consequence, the maximum RUE_{TDM} was marked under T₀ (3.2 g MJ⁻¹). Nevertheless, the minimum was observed under T₂ (2.8 g MJ⁻¹).

So far, for RUE_{GY} statistical analysis showed significant ($P < 0.05$) difference between the T₀, T₁ and T₂. The maximum RUE_{GY} was marked in T₀ (1.24 g MJ⁻¹) after that by T₁ (0.88 g MJ⁻¹). The minimum RUE_{GY} (0.62 g MJ⁻¹) was registered in T₂.

4. Discussion

The impacts of three levels of salinity for quinoa on the TDM, LAI, PARabs, RUE_{TDM} and RUE_{GY} at harvest were investigated.

The results in (Figure 2) affirmed that the SWI (T₁ = 9.2 dS m⁻¹ and T₂ = 18 dS m⁻¹) reduced the LAI. Indeed, in the end of mid-season phase (85 DAT), the reduction in the LAI has varied from 10.8 to 15.3%. However, the statistical analysis showed insignificant differences ($p > 0.05$) between the T₀, T₁ and T₂.

LAI is the site of photosynthetic activity; this parameter is of major importance in the selection of salt tolerant varieties and could be considered more reliable than the vegetation height (Ben Naceur et al., 2001). Our outcomes are in accord with those of El Youssfi (2013), Algosaibi et al. (2015), and Stikic et al. (2015). Those authors declared that increased NaCl concentration in water decreased the leaf area of quinoa and consequently decreased LAI. Peterson and Murphy (2015) reported that SWI affects negatively the LAI for four varieties of quinoa. Indeed, LAI decreased by (50.1; 45.9; 43.2 and 40.8) respectively with increasing concentration of NaCl (0; 8; 16 and 32 dS m⁻¹). Similarly, irrigation of these four varieties of quinoa by another type of salt water (Na₂SO₄) and with the same concentrations decreased the LAI compared to the control (50.1, 47.4, 47.4 and 47). Likewise, Algosaibi et al (2015) reported that the leaf area of quinoa declined from 19 to 15.1 cm² with growing salinity from 4 to 16 dS m⁻¹.

El Youssfi (2013) found that saline water affects the leaf area of three varieties of quinoa according to growth stages and that the increasing concentration of NaCl reduced the leaf area.

In Figure 3, the SWI (T₁ = 9.2 dS m⁻¹ and T₂ = 18 dS m⁻¹) has no consequence on the evolution of PARabs. Otherwise, the accumulation of Na⁺ and Cl⁻ only perturbs photosynthetic activity under extreme conditions where the influx of NaCl exceeds the cell's ability to compartmentalize toxic ions in the vacuole (Downton & Milhouse, 1985; Schröppel & Kaiser, 1988).

This seems to be confirmed by the experiments of Eckardt (1972) on (*Salicornia fruticosa*) which has been shown to reduce photosynthesis only from relatively high salinities, of the order of 30 g l⁻¹ of NaCl. Baumelstwer and Schmidt (1962) explained this phenomenon by the fact that sodium could replace, sometimes

even advantageously, potassium with regard to photosynthesis, but not in its role in protein synthesis. Similarly, Munns (1993) showed that salt affected carbon uptake by reducing leaf area more than by reducing photosynthesis rates. Also, Abdelly et al. (1995) reported that salinity affected the leaf area without affecting the photochemical process of photosynthesis. In addition, James et al. (2006) observed that photosynthetic activity per leaf area unit may remain unchanged even in the case of stomatal closure.

As well, other authors have reported that at moderate salinity the photochemical activity is insensitive to salt (Kingsbury et al., 1984a, 1984b, Kyparassis et al., 1995). The ability to maintain appreciable photosynthesis under stress appears to be a major component of stress tolerance (O'Toole & Turner, 1984; Turner, 1986).

Radiation use efficiency indicates the rate of the biomass accumulation to the quantities of radiation interception (Sinclair & Muchow, 1999). This efficiency varied with the stage of plant development (juvenile, vegetative or reproductive) as well as on the stresses to which it is subjected (Lebonvallet, 2008).

It has been demonstrated through our findings (figure 4) that the SWI declined the RUE pre-anthesis by 10.8 and 15.8% respectively for T_1 ($RUE_{PR} = 4.62 \text{ g MJ}^{-1}$) and T_2 ($RUE_{PR} = 4.36 \text{ g MJ}^{-1}$) compared to the control T_0 ($RUE_{PR} = 5.18 \text{ g MJ}^{-1}$). Likewise, the RUE post-anthesis was reduced by 8.9 and 32.1% for T_1 ($RUE_{PS} = 1.23 \text{ g MJ}^{-1}$) and T_2 ($RUE_{PS} = 0.91 \text{ g MJ}^{-1}$), contrast to the control T_0 ($RUE_{PS} = 1.35 \text{ g MJ}^{-1}$).

The RUE_{TDM} reduced when salinity augmented. The maximum RUE_{TDM} (3.2 g MJ^{-1}) was marked in T_0 . However, the minimum RUE_{TDM} (2.8 g MJ^{-1}) was registered under T_2 ($S = 18 \text{ dS m}^{-1}$). A decline of 16.1% was observed on RUE_{TDM} due to the reduction on TDM from T_0 ($S = 1.2 \text{ dS m}^{-1}$) to T_2 ($S = 18 \text{ dS m}^{-1}$).

As well, The RUE_{GY} was declined when salinity augmented. The highest RUE_{GY} (1.24 g MJ^{-1}) was recorded in T_0 . However, the lowest RUE_{GY} (0.62 g MJ^{-1}) was obtained in T_2 . A decrease of 50% was marked on RUE_{GY} due to the height reduction on yield in the T_2 treatment. These results were reliable with those of Peterson and Murphy (2015). They affirmed that yield assessment at different concentrations of NaCl showed that quinoa yield decreased by (14.5; 13.5; 12.3 to 7.9 g plant^{-1}) by increasing the salinity of (0; 8; 16 and 32 dS m^{-1}). Similarly, Algosaibi et al. (2015) showed that quinoa yield declined (34; 27.6 and $17.1 \text{ g plant}^{-1}$) with increasing salinity (4; 8 and 16 dS m^{-1}). Also, Talebnejad and Sepaskhah (2015) showed that the yield of quinoa decreased from (23.1; 17.1; 12.2 to $5.6 \text{ g column}^{-1}$) with increasing doses of NaCl (10; 30 and 40 dS m^{-1}).

However, Razzaghi et al. (2012a, 2012b) found that salt stress did not affect the RUE which is in order of $1.40 \text{ g TDM MJ}^{-1}$ for all treatments. The values of RUE reported by (Razzaghi et al., 2012a, 2012b) are lower than those reported by Ruiz and Bertero (2008) which equals 1.75 g MJ^{-1} and both are inferior than that illustrate by Monteith (1977) which is equal to $2.8 \text{ g TDM MJ}^{-1}$ for some C3 plant. Razzaghi et al. (2012b) attribute the absence of the negative effect of salt on the RUE to the high resistance of PARabs to high NaCl concentrations. In contrast, Wang et al. (2001) observed in soybean the RUE reduced significantly with increasing salinity in the greenhouse than in the open field. The possible explanation for this decrease is due to the decrease in LAI and a decrease in the interception of PARabs and consequently a reduction in RUE.

5. Conclusions

The results indicated that the SWI affects significantly the TDM and the grain yield. However, non-significant difference was observed for LAI. The cumulative PARabs was not affected with elevate salinity. However, the RUE pre-anthesis and RUE post-anthesis decreased with increased salt concentration of the SWI respectively for T_1 and T_2 next to the control T_0 . Likewise, at harvest, the RUE_{TDM} and the RUE_{GY} were reduced due to the reduction respectively on TDM and grain yield.

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