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Carrot productivity and its physiological response to irrigation methods and regimes in arid regions

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ABSTRACT

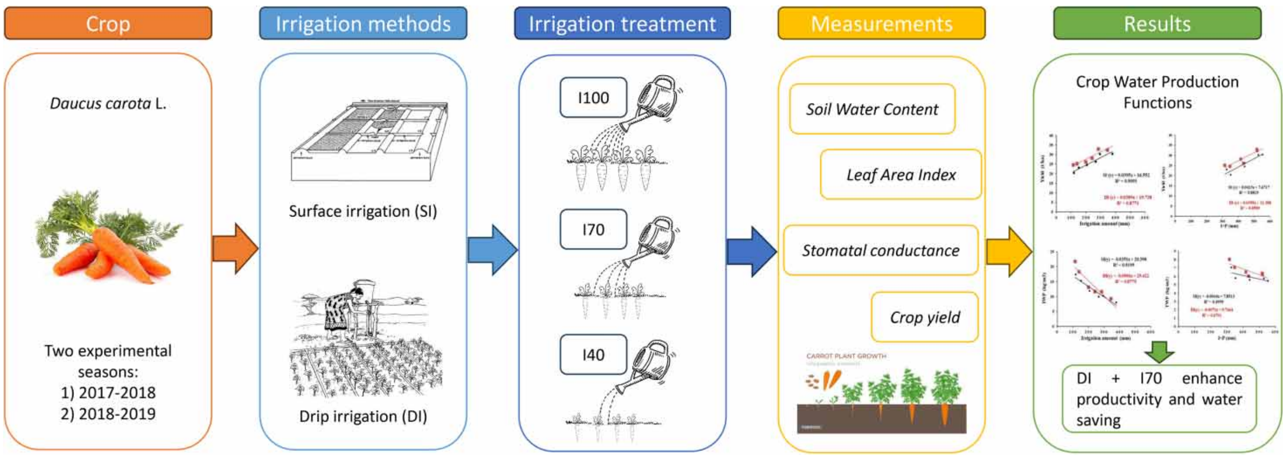
The aim of this study is to optimize water irrigation management for improving carrot productivity and water-saving in arid regions of southern Tunisia. Field studies were conducted over two seasons (2017–2019) to evaluate the effects of drip irrigation (DI) and surface irrigation (SI) methods coupled with three irrigation regimes on agronomic parameters of carrot crops. Irrigation regimes consisted of water replacements of cumulated crop evapotranspiration (ETc) at levels of 100% (I100), 70% (I70), and 40% (I40) when the readily available water in I100 treatment was depleted. Results showed a reduction in carrot yield by 13–22% and 22–32% with I70 and I40 treatments compared to I100, respectively. Yield is affected by the irrigation method with a reduction of around 6–7% under the surface method for both years. The water productivity (WP) was found to significantly vary among regimes and methods, where the highest values were observed for the I40 regimes and drip method. Drip and I100 irrigation techniques seem to optimize carrot production. Under situations of water shortage, adopting deficit irrigation treatment (DI70) could be an alternative for managing carrot irrigation and improving water productivity.

Key words: arid regions of Tunisia, carrot crop, irrigation techniques, water productivity, yield

HIGHLIGHTS

- The adoption of suitable irrigation methods coupled with effective irrigation scheduling becomes a priority for farmers to face water shortages in arid regions and to improve productivity.
- Adopting deficit irrigation coupled with drip irrigation (DI70) could be an alternative for managing carrot irrigation and improving water productivity.

GRAPHICAL ABSTRACT



INTRODUCTION

Tunisia is among the Mediterranean countries that suffer from poverty in terms of water resources. The pressure on irrigation water use is increasing as the demand for food production increases due to population growth. Hence, Tunisian food production depends primarily on irrigated agriculture where irrigation can represent up to 70% of water use. In addition, the phenomenon of the drought caused by the climate change impacts intensifies this problem in several areas (Autovino *et al.* 2018). The study of Jabal *et al.* (2022) showed a clear impact of some climatic factors on crop production in the arid region of Iraq.

In this context, optimizing water use of irrigated land in arid areas is considered a priority task. Therefore, the using of more efficient irrigation systems and optimizing irrigation programs could be a good alternative to on-farm water management. Provenzano *et al.* (2014) mentioned that the researches in optimization water-saving strategies associated with irrigation scheduling assure an appropriate reaction between findings and practices. The pathway to achieve efficient irrigation water use imposes the need to systematically optimize the soil and water management practices and the irrigation equipment (Knox *et al.* 2012).

Drip irrigation is one of the most effective methods allowing accurate application of irrigation in small amounts directly to the root zone (Bhunia *et al.* 2015). However, surface irrigation methods characterized by low efficiency may not easily control the irrigation amount per application (Sezen *et al.* 2006). The drip irrigation system is very effective for water saving compared to surface or sprinkler irrigation (Jensen *et al.* 2014; Abdul Rajak 2022). It provides more efficient water use for crops than surface because the drip method applies frequent irrigation and localized water application to only part of the crop's potential root zone and reduces adverse effects of over-irrigated and water stress commonly caused by surface irrigation (Nagaz & Mechlia 2008).

A promising management strategy for improving water use efficiency (WUE) is deficit irrigation, which is defined as the application of water below full crop requirements for evapotranspiration. The effects of this practice on carrot crop production are well documented in several researches. Carvalho *et al.* (2016) found that the carrot crop was influenced by different water depths applied, and the highest WUE was obtained with an average replacement of 63.4% of soil water. The study of Abdel-Mawly (2004) showed that the highest root yields were obtained with 100% evaporation replenishment and maximum water use value were recorded at 75% level of evaporation replenishment. Prabhakar *et al.* (1991) determined that a higher carrot root production, total dry matter and WUE with a water application level of 100% Epan.

Therefore, the adoption of suitable irrigation methods coupled with effective irrigation scheduling to improve WUE has become increasingly necessary. Several researchers have studied the effects of this combination on water and crop productivity. Webber *et al.* (2006) found that alternate furrow irrigation can save water by close to 25% compared to conventional furrow irrigation and the combination with deficit irrigation scheduling water savings can reach 50% with no yield reductions. Irrigating at moderate soil water content with low irrigation amounts under drip irrigation not only optimizes water use but also boosts the use of soil water and precipitation, thereby increasing winter wheat yield and WUE (Kumar Jha *et al.* 2019). Rodrigues *et al.* (2013) and El-Wahed & Ali (2013) indicated that drip and deficit irrigation are selected as alternative irrigation techniques for water saving compared to sprinklers and full irrigation systems for maize production. The study of Malash *et al.* (2005) on tomato production showed that the drip irrigation system produced the highest marketable yield whatever the water management strategies used compared to the surface irrigation.

Under the arid conditions of Tunisia, some farmers are using surface irrigation for carrot crops and they are opting always to maximize yields through maximizing water supply. However, other farmers have adopted efficient irrigation systems. In fact, the majority of them are using localized irrigation systems and their farms are equipped with storage basins having a capacity of 20–100 m^3, which allows them to irrigate several crops simultaneously. In this context, irrigation is applied by farmers using empirical knowledge without scheduling and the application of water often exceeds crop requirements (Nagaz *et al.* 2017).

Carrot (*Daucus carota* L.) is a root vegetable crop with a short cycle and is grown for fresh market food. It is grown in arid regions of Tunisia during autumn and winter periods, which coincide with the rainy season and is commonly irrigated with drip irrigation or surface irrigation (Nagaz *et al.* 2012). Because carrot crop has a high economic value, and thus it is necessary to optimize the irrigation programs for enhancing the production crop Carvalho *et al.* (2016).

For this region, Nagaz *et al.* (2012, 2017) and El-Mokh *et al.* (2013, 2017) have studied the effects of different irrigation regimes on yield and water productivity (WP) of drip-irrigated carrots but the studies of the combined effect of different irrigation methods coupled with different irrigation regimes for carrot crop is lacking.

Under this compromise of water limitation and the necessity to grow food, there is a need to evaluate our current practices and study the possible integration of different tools and techniques in order to improve WP and ensure the sustainability of our system. Therefore, a 2-year study was conducted with the objective of investigating the impact of different irrigation regimes and methods on carrot yield and WP in an arid region of Tunisia.

MATERIALS AND METHODS

Field experiments were conducted for 2 years (2017/2018) and (2018/2019) in the experimental field of the Agricultural Training Center of El Fje situated in the Southern East of Tunisia (33°45′ N, 10°63′ E; altitude 12 m) in the region of Médenine. The climate is typical of arid areas, with mean annual rainfall of 200 mm distributed mainly during autumn to early spring, November to February being the wettest months of the year, and reference evapotranspiration of about 1,400 mm/year.

The experiment site soil is sandy textured with 80.6% sand, 6.3% silt, and 13.1% clay and low organic matter content (<0.8%). The field capacity and permanent wilting point, of the top 60 cm depth soil, were 0.2 and 0.062, respectively, and bulk density was 1.45 g/cm^3 (Table 1). The available water holding capacity of the 60 cm carrot rooting depth was 75 mm

The carrots were sowed on October 20 and 23, respectively, for 2017–2018 and 2018–2019. The experimental design was split into 18 plots. Main plots and sub-plots were assigned with three replications to irrigation methods (drip and surface irrigation), and to irrigation regimes (I100, I70, and I40), respectively. Nagaz *et al.* (2012) initiated to study of the effect of different irrigation regimes 100, 80, and 60% on carrot production from 2007. In this study, the choice of these irrigation regimes is a continuity for those previous studies that aimed to develop quantitative specific information for arid regions of Tunisia on yield and water use of carrots under different irrigation water regimes.

All plots were irrigated with water from a well having an electrical conductivity of 7.4 dS/m. For the drip irrigation system, each dripper had a 4 L h^{-1} flow rate. A control mini-valve in the lateral permits the use or non-use of the dripper line. Irrigation water quantity applied through drip irrigation was measured by the water meter. For surface irrigation, each plot was prepared as a basin and fed individually/ manually. Measured amounts of water were delivered to the basin using a hosepipe and water meter implied in the irrigation system.

Fertilizers were supplied for the cropping period in the same amounts; nutrient supply included N, P, and K at rates of 300, 250, and 250 kg/ha, respectively, which were adapted to the local practices. The P and K fertilizers were applied as basal doses before planting. Nitrogen was divided and delivered with the irrigation water in all treatments during early vegetative growth.

Three irrigation regimes were considered: the full irrigation (I100) consists of delivering a total of cumulated crop evapotranspiration (ETc) when readily available water in the root zone is depleted, the deficit irrigation regimes supplying 70% (I70) and 40% of ETc (I40) with the same frequency. The ETc was estimated for daily time steps by using reference evapotranspiration (ETo) combined with carrot crop coefficient (Kc). ETo is estimated using daily climatic data collected from the climatic station located close to the field experiment and the FAO-56 Penman–Monteith method (Allen *et al.* 1998). The Kc was computed following the single crop coefficient approach for surface irrigation and the double crop coefficient approach for drip irrigation. The dual crop coefficient, the sum soil evaporation (Ke) and basal crop coefficient (Kcb) reduced by any occurrence of soil water stress (Ks) provides separate calculations for transpiration and soil evaporation ($Kc = KsKcb + Ke$). The soil water balance (SWB) method was adopted for irrigation scheduling using the FAO-56 guidelines (Allen *et al.* 1998). To this end, a SWB model was developed by means of a spreadsheet program for Excel. The model computes the soil water depletion on a daily basis and projects the next irrigation event based on the target depletion (35% of total available water (TAW)). The root depth starts with a value of 0.15 m at planting and increases linearly with the increase of carrot coefficient up to 0.60 m. These values were assumed from those presented in the FAO-56 manual for carrots.

Table 1 | Hydro-physical properties of the experimental site soil

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	ρb (g cm^{-3})	Θs (cm^3/cm^3)	ΘFc (cm^3/cm^3)	Θ Wp (cm^3/cm^3)
0–20	85.75	3.25	11	Sandy	1.48	0.41	0.22	0.057
20–40	81.5	5.25	13.25	Sandy	1.46	0.39	0.20	0.058
40–60	74.5	10.5	15	Sandy	1.43	0.37	0.20	0.072
Avarege	80.58	6.33	13.08	Sandy	1.45	0.39	0.21	0.062

ρb: bulk density, Θs: soil water content at saturation, ΘFc: soil water content at field capacity, Θ Wp: soil water content at witting point.

Tube access probes based on time domain reflectometry (Handheld Device HD2 IMKO Micromodultechnik GmbH) were used to measure soil water content. The probes were installed vertically at three depths (0–20, 20–40 and 40–60 cm) below the dripper for the drip irrigation system and at the center of gravity of each plot for the furrow irrigation system. Measured values were collected before and after each irrigation and significant rainfall events throughout the growing season.

Plants in an area of 1 m^2 per plot were used to monitor changes in leaf area during the growing period. The leaf area was determined by the Li-Cor Area Meter (Model LI 3100 Li-Cor). The stomatal conductance rates were measured at mid-day to characterize physiological activity using a portable gas analyzer (Li-Cor 6400).

At physiological maturity, carrot fresh root yield, root number/m and root weight were collected. Three replicates were randomly selected from each plot for yield measuring. For each replicate, the plants of 1 m^2 were harvested. The performance of water application was evaluated based on total water productivity (TWP (kg/m^3) = Yield (kg/ha)/irrigation and precipitation water applied (m^3/ha)) and irrigation water productivity (IWP (kg/m^3) = Yield (kg/ha)/irrigation water applied (m^3/ha)), irrigation of 75 mm applied before seeding date is not included in the total amount. According to Ghazouani (2016), the IWP is considered an appropriate indicator of irrigation scheduling, and could be influenced by the irrigation system performance and the related water losses.

The analysis of variance (ANOVA) for the two factors irrigation methods and irrigation regimes was conducted using XLSTAT. All treatments were compared based on statistical significance using the Fisher least significant difference (LSD) test at a 5% ($\alpha = 0.05$) significance level.

RESULTS AND DISCUSSION

Weather conditions

The daily ETo and precipitation (P) registered during the growing period of carrot for both years (2017–2019) is shown in Figure 1. The cumulative precipitations during the growing period of carrots were 234 and 176 mm for 2017/2018 and 2018/2019, respectively. During the first season, 6 days of rain were recorded. Average rainfall ranged from 5 to 159.25 mm/day. Precipitation events occurred more frequently (12 days) in the second season, even though they were characterized by lower daily amounts which ranged from 4 to 49.4 mm/day. ETo was 377 mm in 2017/2018, and 386 mm in 2018/2019 during the investigated seasons. For both years, ETo tends to decrease during the initial phase of the growth cycle and stabilizes in December and January at relatively low values. A slight increase in ETo values is observed at the end of the growing period.

Soil water content

Considering the irrigation treatments and the two irrigation methods, the temporal variability of the mean soil water content in the root zone during the two seasons is shown in Figure 2.

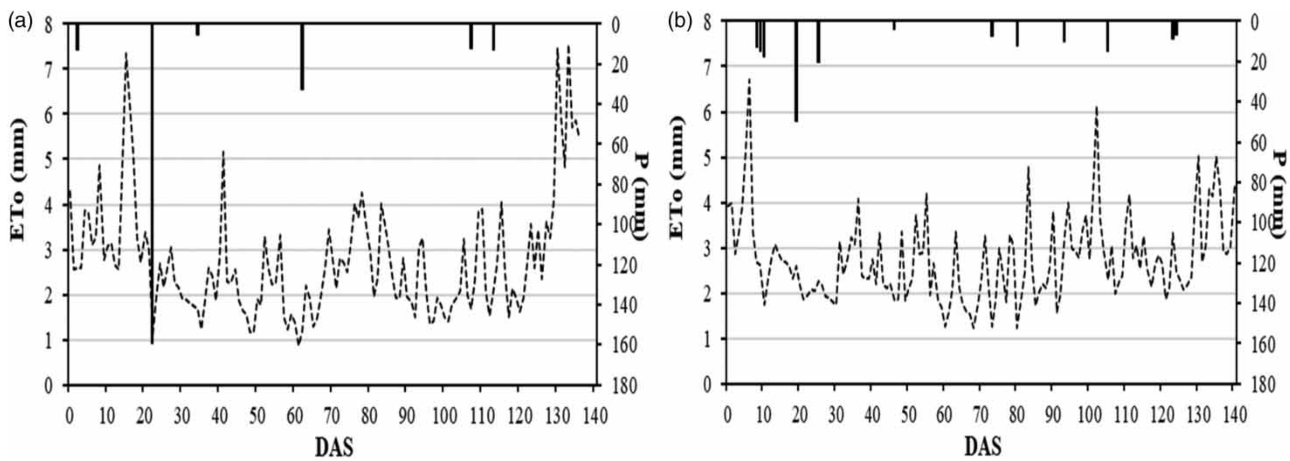


Figure 1 | Daily values of reference evapotranspiration (ETo) and precipitation (P) during 2017–2018 (a) and 2018–2019 (b) throughout the growing periods of carrot.

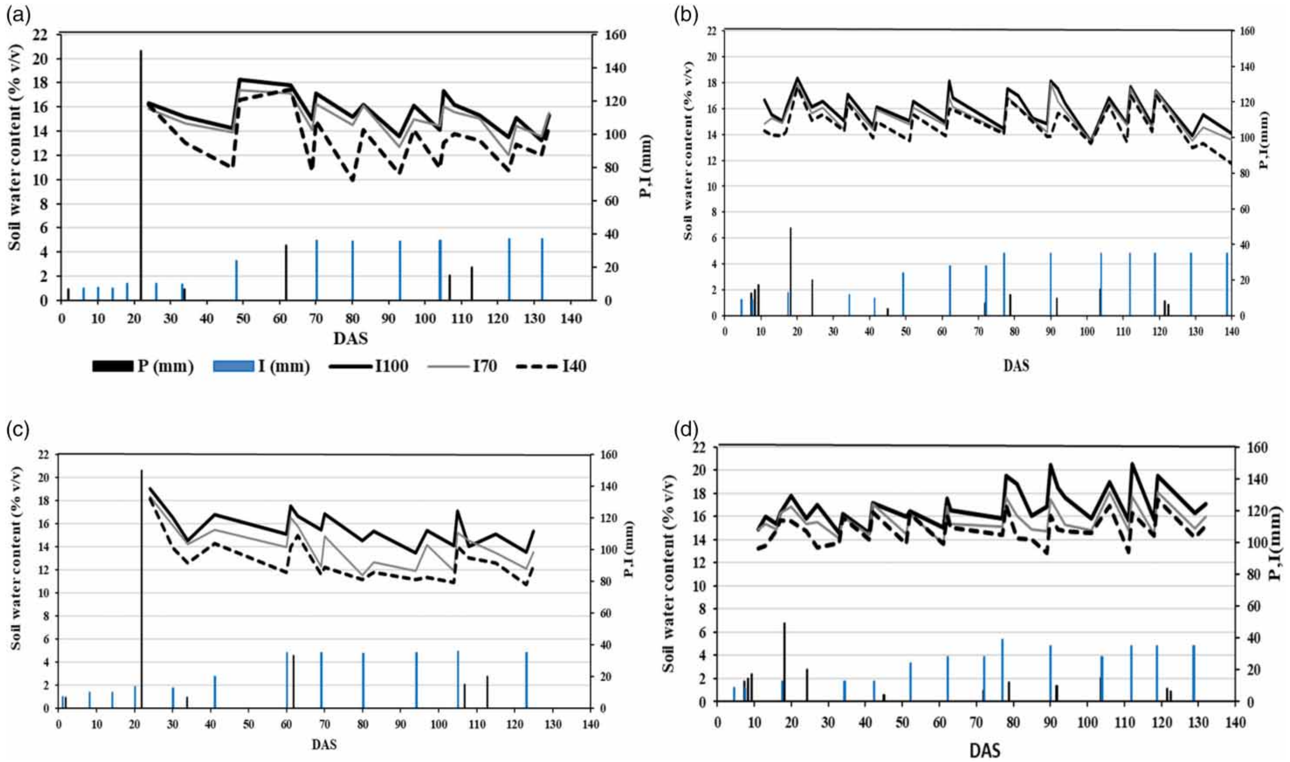


Figure 2 | Temporal variability of the average of soil water content in response to the different irrigation treatments under surface (a: 2017/2018, b: 2018/2019) and drip (c: 2017/2018, d: 2018/2019).

Results show that the full treatment (I100) maintains the highest soil water content level compared to I70 and I40 treatments during the considered period. The lowest soil water content is observed with the I40 treatment. However, the patterns of soil water content are similar for I100 and I70 treatments with small differences in peaks occurring after each watering or rainfall event because of the greater irrigation volumes. For the deficit irrigation, excepting the surface irrigation method, these peaks are not well observed. Furthermore, due to the different amounts of water that had been applied in both cropping seasons, The average soil water content fluctuations for the drip and surface method were 14–20% and 13–18% for I100, 12–18% and 13–16% for I70, 11–15% and 10–14% for I40.

Moreover, the occurrence of rainfall allowed for keeping the soil water contents close to field capacity and resulted a similar values of mean soil water content for all treatments, especially in the second year where the precipitation events were well distributed during the growing season.

The results show also that the drip-irrigated plots had higher values of soil water content than surface-irrigated plots. In fact, drip irrigation maintains a greater level of moisture in the root zone and reduces losses of water by evaporation or drainage. However, with the surface method, the surface soil is completely wetted resulting in an increase of soil evaporation.

Malash *et al.* (2008) and Tagar *et al.* (2012) found that drip irrigation generally balanced soil moisture in the active root zone with minimum water losses.

Crop growth and physiological activity

Figures 3 and 4 show the mean values of leaf area index (LAI) and stomatal conductance rate during the crop period under different treatments for both years.

For both years statistical analyzes showed significant differences between the treatments for both parameters. This difference is mainly clear in full vegetation (80 DAS) and during the last period of the growing cycle (110 DAS) where the water requirements are maximum.

The irrigation regime represents the main factor of difference between the I100, I70, and I40 regimes compared to the irrigation method factor and seems to induce for carrot crop significant disturbances in growth and physiological activity.

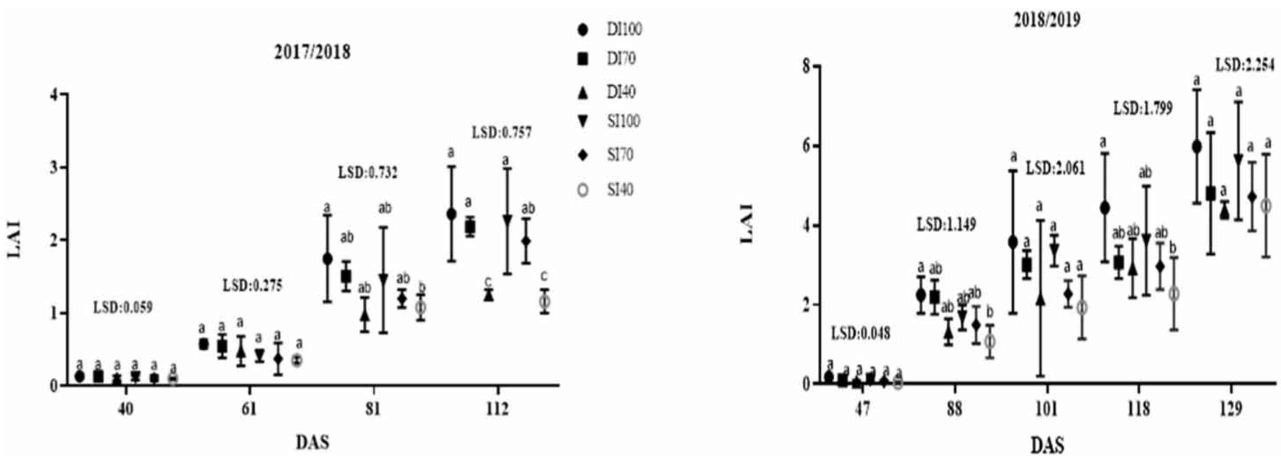


Figure 3 | The influence of irrigation treatments on the LAI at different periods of the carrot development cycle during the two seasons 2017/2018 and 2018/2019.

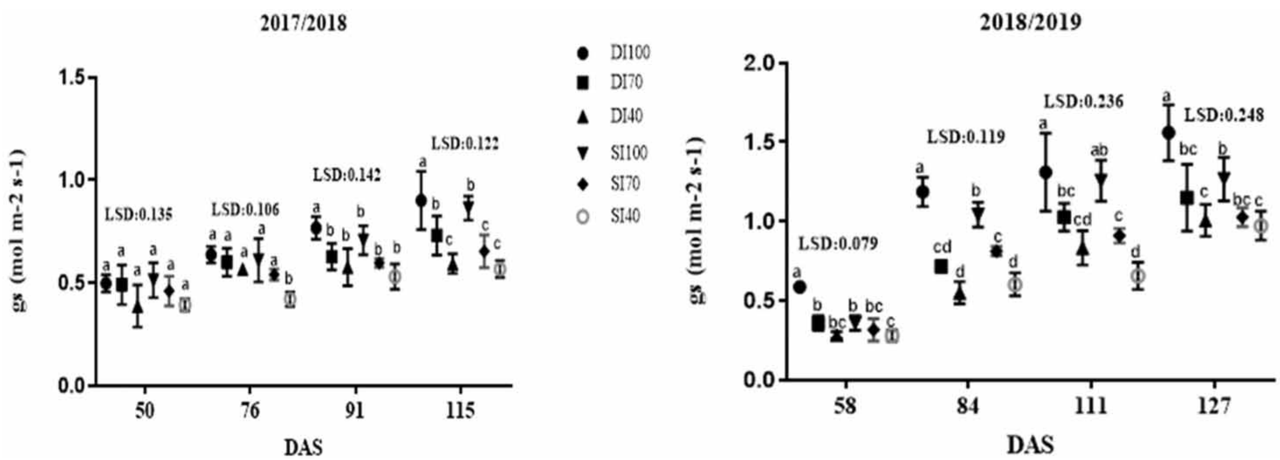


Figure 4 | The influence of irrigation treatments on stomatal conductance at different periods of the carrot development cycle during the two seasons 2017/2018 and 2018/2019.

Carrot growth was analyzed by measuring the LAI in different periods of the development cycle. A similar trend was indicated in Figure 3 for all treatments in the two seasons. The carrot crop shows a rapid and important vegetative development.

The results of statistical analysis show a significant difference between the irrigation regimes. The values obtained with the I100 treatment are higher than those obtained with the I70 and I40 treatments. The lowest values were recorded with the I40 treatment. The deficit irrigation treatments (I70 and I40) limit crop canopy expansion throughout the vegetative cycle. The observed differences could be explained by the effect of water stress that seems to limit leaf expansion. Indeed, several studies have shown the effect of water stress on plant development. Gibberd *et al.* (2003) showed that a low irrigation amount resulted in a high restriction of leaf biomass for carrots.

The analysis of irrigation method's effects on carrot growth demonstrated that the highest LAI values were obtained with the drip method, but no statistically significant differences ($p \leq 0.05$) were found. Moreover, the carrot harvest for the surface method was retarded by 15 days compared to the drip one. It seems that the surface method reduces the leaf area and retard the root growth.

Generally, the difference between the DI100 treatment and the SI100 is not significant although plants irrigated with DI100 have the highest leaf area. However, the DI40, SI70, and SI40 treatments present a significant difference with the DI100 and SI100 treatment but are not with the DI70 treatment. Liu *et al.* (2011) also found that the LAI negatively responded to water restriction lower than 50% under sprinkler irrigation.

The values of stomatal conductance under the different treatments are presented in Figure 4. In general, the stomatal conductance tends to increase throughout the growth cycle.

The stomatal conductance is affected by the irrigation regimes. Indeed, for both methods, the stomatal conductance values obtained with the treatments irrigated with 100% of ETc are higher than those irrigated at 70 and 40% of ETc during the whole period of measurement. Thus, deficit treatments reduce the stomatal conductance rates. These reductions are more important as the level of water restriction is higher. Similar results obtained by Quezada *et al.*(2011)

The figure shows also that there was no effect of the irrigation method on the stomatal conductance. However, the highest values were obtained with the drip method.

The water status of the plant seems to be influenced by the water status of the soil and by the weather conditions at the time of the measurements. Ludong (2008) found that environmental and internal soil factors, such as air and canopy temperature, and soil water status influence the photosynthesis rate and the stomatal conductance directly or indirectly.

Under deficit water conditions, the rates of growth are influenced both by the allocation of biomass to the different organs and by the physiological and morphological properties of these organs (Zltako & Lidon 2005). Gibberd *et al.* (2003) found that carrot plants effectively reduced leaf growth to match the daily transpiration with the water available under deficit irrigation.

Crop yield

Tables 2 and 3 present the carrot yield and yield components under three irrigation regimes for DI and SI methods in the two seasons.

Considering the effect of irrigation regimes on crop yield, the data shows that in both years the average yields in full irrigation regime (I100) were higher than in deficit one (I70 and I40) for both methods. Yield values were 32.96 and 30.31 t/ha in the first year and 32.45 and 30.42 in the second year under DI and SI methods, respectively. However, from a statistical point of view, the differences in crop yield were significant only between I100 and I40 but not for I100 and I70 or I70 and I40. Yields decreased as the level of deficit irrigation increased. Similar results are presented by Léllis *et al.* (2017). The higher yield obtained with the I100 can be attributed to the greater amount of water applied and to the higher root numbers and weight (Table 3) within this treatment. These results are in agreement with those found Nagaz *et al.* (2012) and Quezada *et al.* (2011).

Furthermore, comparing the yield data in Table 2 with LAI data in Figure 3 revealed that the crop yield increased linearly with the irrigation amount. Indeed, The reduced vegetative growth (LAI) over crop development stages was a reason for the decrease in crop yield for the deficit irrigation treatments. Gibberd *et al.* (2003) and Abdel-Mawly (2004) reported that this decrease was largely influenced by the decrease of root size, sheet growth and less photosynthetic surface (LAI) which resulted in lower dry matter accumulation.

In both seasons, root yield obtained with the DI method was found to be superior to the SI method; under the same irrigation level. Carrot yield was reduced under the surface method from 8 to 6% in the I100 regime, 6.63 to 5.93% in the I70 regime and 17.16 to 8.51% in the I40 regime compared to drip one for the seasons 2017/2018 and 2018/2019, respectively.

Table 2 | Carrot yields under different irrigation methods (DI and SI) and treatments (I100, I70 and I40) during the two cropping periods of carrot

	2017/2018				2018/2019			
	Irrigation regime				Irrigation regime			
Irrigation method	I100	I70	I40	Mean	I100	I70	I40	Mean
DI	32.96 a	26.13abc	24.64bc	27.91	32.45a	28.17ab	25.25ab	28.63
SI	30.31ab	24.58bc	20.41c	25.10	30.42ab	26.3ab	23.1b	26.61
Mean	31.64	25.36	22.53		31.44	27.24	24.18	
LSD (5%)	irrigation regime (IR)			5.6				5.569
	irrigation method (IM)			4.57				4.547
	IR*IM			7.92				7.876

LSD (5%) indicates the least significant difference values at 5% level.

Table 3 | Yield components under different irrigation methods (DI and SI) and treatments (I100, I70 and I40) during the two cropping periods of potato

	Root weight G/ROOT		Root number/m^2	
	2017/2018	2018/2019	2017/2018	2018/2019
Irrigation method				
DI	49.030	57.201	58	51
SI	46.934	49.763	52	53
LSD (5%)	9.24	6.23	11.976	9.707
Irrigation regime				
I100	55.76	57.028	58	56
I70	45.46	55.267	55	53
I40	42.72	48.151	53	48
LSD (5%)	11.31	7.635	14.667	11.889

LSD (5%) indicates the least significant difference values at 5% level.

The results indicated that drip irrigation improves crop yield under the same level of irrigation compared to surface irrigation. This improvement in yield was related to the maintenance of a high level of soil water content at the root zone during the growing stages and the reduction of water losses through soil evaporation compared to surface irrigation. These results are in congruity with those obtained by Malash *et al.* (2008) who reported that drip irrigation maintained ideal water levels in the soil in the root zone and resulted in an 11% yield advantage when compared with the furrow-irrigated plots for tomato crops.

The combined effects of the irrigation regimes and methods on root carrot yield are presented in Table 2. In both cropping seasons, carrot yield was enhanced under DI irrigation compared with SI irrigation and the maximum yield was obtained with treatment I100. The tubers yield produced under DI with I100 treatment was 32 t/ha which is higher than that obtained under SI and I100 (30 t/ha). That yield is not significantly different from the yield obtained with DI and I70 (26.13–28.17). The root yield obtained with DI and I40 treatments (24.64–25.25 t/ha) was similar to the yield obtained with SI and I70 (24.58–26.30 t/ha). The lowest tuber yield values (20.41–23.1 t/ha) were produced with SI and I40.

The findings of Kharrou *et al.* (2011), Fang *et al.* (2018) and Kumar Jha *et al.* (2019) also confirm these results. The high yields obtained with the DI method and I100 under the prevailing climatic conditions indicate its high potential to manage the irrigation of carrots.

Table 2 shows also there was no significant difference in the yield of carrots between the two seasons only with a slight increase in yield for I70 and I40 under the second year.

Water productivity

The water supplies from sowing to harvest under different irrigation methods (DI and SI) and regimes (I100, I70, and I40) during the two cropping periods of carrots are given in Table 4. Indeed, irrigation water applied before sowing for the two seasons (75 mm) is not included in the total. Total rainfall amounts were 234 and 176 mm in the first and second years, respectively.

In the first year, irrigation amounts under drip irrigation were 283, 198, and 113 mm for I100, I70, and I40, respectively. Under surface irrigation, the amounts were 294, 206 and 118 mm for I100, I70, and I40, respectively (Table 4). In the second year, there was an increase in these amounts by 61, 42, and 25 mm under the drip method and by 84, 59, and 33 under surface one for I100, I70, and I40, respectively. This increase is related principally to the reduction of the precipitation amount this year. The amount of irrigation water for I100 irrigation treatment was comparable to that reported by Nagaz *et al.* (2012). The DI method reduces the irrigation amounts compared to SI by 11, 8, and 5 mm in the first year and 34, 25, and 13 mm in the second year for I100, I70, and I40, respectively.

The TWP and IWP of each treatment expressed as the ratio of carrot yield to irrigation and total water received from sowing to harvest are given in Table 5.

Table 4 | Water supply from sowing to harvest under different irrigation methods (DI and SI) and regimes (I100, I70, and I40) during the two cropping periods of carrot

	Irriagtion (mm)			Total water supply (mm)	
Irrigation Regimes	DI	SI	Rainfull (mm)	DI	SI
2017/2018					
I100	283	294	234	517	528
I70	198	206	234	432	440
I40	113	118	234	347	352
2018/2019					
I100	344	378	176	520	554
I70	240	265	176	416	441
I40	138	151	176	314	327

Table 5 | IWP and TWP under different irrigation methods (DI and SI) and regimes (I100, I70 and I40) during the two cropping periods of carrot

	IWP (kg/m3)				TWP (kg/m3)			
	I100	I70	I40	Mean	I100	I70	I40	Mean
	2017/2018							
DI	11.64c	13.19bc	21.76a	15.54	6.37a	6.04a	7.09a	6.51
SI	10.31c	11.94c	17.36ab	13.21	5.74a	5.58a	5.80a	5.71
mean	10.98	12.57	19.56		6.06	5.82	6.45	
LSD%								
IR	3.45				1.33			
IM	2.81				1.09			
IR*IM	4.87				1.89			
	2018/2019							
DI	9.43bc	11.70b	18.35a	13.16	6.23b	6.75ab	8.04a	7.01
SI	8.04c	9.93bc	15.27a	11.09	5.48b	5.96b	7.05ab	6.17
mean	8.74	10.82	16.82		5.86	6.36	7.55	
LSD%								
IR	2.01				1.19			
IM	1.64				0.97			
IR*IM	2.84				1.68			

LSD (5%) indicates the least significant difference values at 5% level.
Treatment means within each column, by each year, followed by the same letter are not significantly different according to Least Significant Difference (LSD) test at $P \leq 0.05$.

For both years, WP was significantly affected by the irrigation regimes. Clearly, the fully irrigated plots (I100) showed a decrease in WP compared to the deficit-irrigated ones (I70 and I40). Moreover, WP with the I100 regime was not significantly different from those obtained with the I70 treatment but statistically different from those obtained with the I40 regime. This difference is well shown in the second year. The highest TWP ranging between 6.45 and 7.54 kg/m^3 for the first and second year, respectively, was obtained in the I40 regime. As shown in the table, the highest IWP was obtained under the I40 regime with an average of 19.56 and 16.81 kg/m^3 for the first and second years, respectively. Conversely, the lowest IWP was obtained under I100 with an average of 10.97 and 8.74 kg/m^3 for the first and second years, respectively. Whereas, the I70 occupies an intermediate position with an average of 12.56 and 10.82 kg/m^3 for the first and second years, respectively. The average values are similar to those found by Nagaz *et al.* (2017).

Carvalho *et al.* (2016) found that the Carrot crop was influenced by different water depths applied, and the highest WUE was obtained with an average replacement of 63.4% of soil water.

Generally, in the deficit irrigation treatments lower amounts of water applied and lower crop yield have higher WP values.

For both years, the drip irrigation method showed a higher WP compared with the surface irrigation method under the same level of irrigation. Tagar *et al.* (2012) found that higher WUE was obtained in the drip irrigation method compared to the furrow one for tomato crops. The low WP for the surface method during the two experiments can be attributed not only to reduced yields but also to higher irrigation water use.

The interaction effects of irrigation regimes and methods were significant during both years (Table 5). The WP of carrot decreased as applied irrigation water increased. Indeed, the WP obtained with the I40 regime and DI method was higher than the I40 and SI method. The values of WP with the DI method and I100 and I70 were considerably higher than the WP obtained with SI and I100 and I70. These results demonstrate that the DI method enhanced the WP compared to SI in carrot production under experimental conditions, especially with I40 and I70 deficit treatments.

Over the 2 years, there was a slight increase in TWP values in the second year. For all treatments, yield was similar for the 2 years but the irrigation amount increased in the second year. Values of IWP reflect this difference; they decreased typically under the second year by 22, 17, 12, 20, 11, and 16%, respectively, for I100, I70, and I40 regimes under SI and DI methods. These results demonstrate that DI method provides a significant advantage on WP compared to SI in carrot production under experimental conditions, especially with I70 deficit treatment and the potential of DI in water management and use.

Crop water production function

The analysis of the relationship between carrot crop yields in response to different levels of water input is represented in Figure 5. For a fixed amount of water, crop yield was evidently influenced by irrigation amount (I), as well as by the total amount of water supplied (P + I). The figure showed that with a total amount of water of 520 mm (DI method), the highest root carrot yield was achieved (32 t/ha). While increasing the total water amount to 554 mm (SI method) resulted in the reduction of carrot yield to 30 t/ha. El-Mokh (2016) found that water amount supplies between 400 and 420 mm for carrots produced 28 to 30 t/ha root yield and increasing water amount by 100 mm affected yield with 24% reduction. Furthermore, the reduction of total water amount by 30% caused a relatively small yield reduction (20% for the first year and 13% for the second year). Moreover, for each 100 mm decrease of applied water, crop yield decline ranges between 12 and 22%.

Figure 6 analyzed the relationship between WP and the water amount applied.

Considering TWP, the ratio remains constant for the first year. This was explained by the consequence of the compensatory effect exerted by irrigation compared to the rainfall and that the increases in yield are proportional to the amount of the

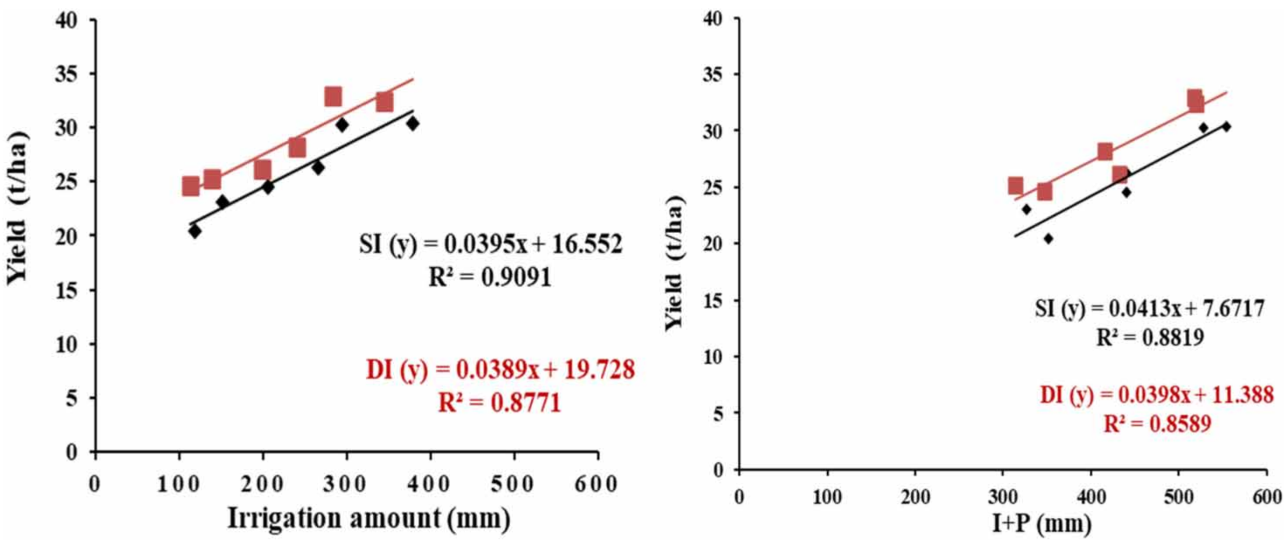


Figure 5 | Carrot crop yield as a function of seasonal irrigation depth, total amount, and I of water applied, P + I, for all treatments during the two seasons.

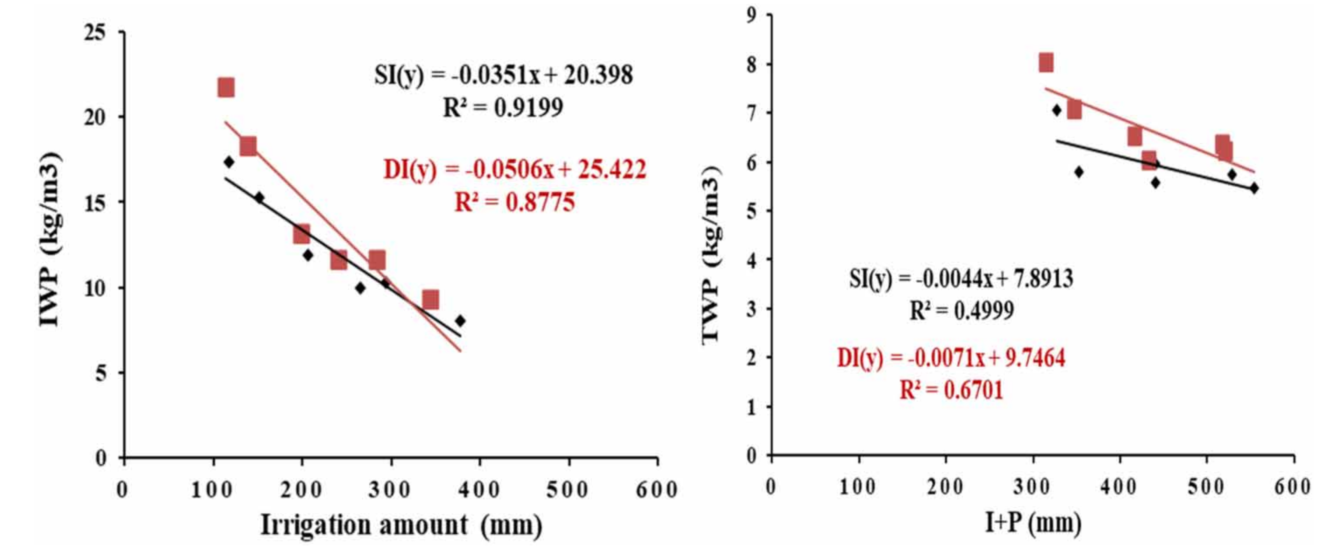


Figure 6 | IWP and TWP versus the seasonal irrigation depth, total amount, and I of water applied, P + I, for all treatments during the two seasons.

applied water. However, TWP decrease linearly with the increase in the amount of water. It can be observed also that providing more water around 600 mm under the surface method resulted in low TWP compared to the drip method.

Considering IWP, the equations (Figure 6) showed a negative linear relationship between irrigation productivity and irrigation amount. Limiting irrigation water amount determines a certain increase in IWP, consistent with the relationship found by Kumar Jha *et al.* (2019) for winter wheat crops and Ghazouani (2016) for potatoes. Compared with the surface irrigation method SI, the DI method saved 3.74%, 3.88% and 4.23% of irrigation water in 2017/2018, and 8.99%, 9.43% and 8.60% in 2018/2019, while increased IWP by 11.47%, 9.49% and 20.25% in 2017/2018, and 13.82%, 15.04% and 16.78% in2018/2019, at irrigation level of 100, 70 and 40% respectively.

These results showed that, under the drip method and I100 regime, irrigating with 283 mm in the first year and 344 mm in the second one achieved a similar yield but caused an IWP decline of about 24%. Similar variation was found for the other treatments. Indeed, the two seasons of this study are considered wet seasons, the amounts of rainfall combined with the amounts of irrigation determined the seasonal yield and WP. For the first year, more rainfall was received and less amount of water applied compared with the second year when the decrease of the amount of rainfall recompensed with more amount water applied.

CONCLUSIONS

The results revealed that despite the increase in irrigation amount resulting from surface irrigation method the carrot root yield decreased and the WP reduced, compared to the drip irrigation method. Differently, a suitable drip irrigation can optimize WP and crop yield but also, needs the adoption of an efficient irrigation scheduling.

Moreover, this study showed that the total irrigation regime (I100) seems to constitute an adequate irrigation strategy for carrot production. The relatively high yield and productivity with the I70 treatment shows a favorable response of the carrot to moderate water deficit. For limited water availability conditions, deficit irrigation control with water supply to 70% of needs (I70) could be adopted for the management of irrigation of the carrot crop and improving WP in arid areas of southern Tunisia.

Under water-scarce conditions of arid regions of south Tunisia, adopting optimized irrigation scheduling and efficient irrigation methods had the advantages of enhancing crop yield and WP and saving irrigation water. Consistent water savings, of close to 10%, are realized with drip irrigation over surface irrigation and when used in combination with deficit irrigation control with water supply to 70% of needs, water savings can be as large as 40% with an acceptable yield reduction and improvements of WUE.

On the other hand, further investigations have to consider other specific factors related to the soil, plant status and irrigation water quality, an economic analysis aimed to verify the costs associated with each method of irrigation and their benefits is also, indispensable in order to improve crops production and the sustainability of the system.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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