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Effects of surface and subsurface drip irrigation regimes with saline water on yield and water use efficiency of potato in arid conditions of Tunisia

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Abstract: Field experiments were conducted on a sandy soil during spring of 2009 and autumn of 2010 in southern Tunisia for evaluating the effects of two drip irrigation methods and three irrigation regimes on soil moisture and salinity, yield and water use efficiency of potato (*Solanum tuberosum* L.). The surface drip (SDI) and subsurface drip (SSDI) irrigation methods were used. Irrigation regimes consisted in replacement of cumulated ETc when readily available water is depleted with levels of 100 % (FI100), 60 % (DI60) and 30 % (DI30). FI100 was considered as full irrigation while DI60 and DI30 were considered as deficit irrigation regimes. Well water with an ECi of 7.0 dS/m was used for irrigation. Findings are globally consistent between the two experiments. Results show that soil moisture content and salinity were significantly affected by irrigation treatments and methods. Higher soil moisture content and lower soil salinity were maintained with SSDI than SDI for all irrigation treatments. For both irrigation methods, higher salinity and lower moisture content in the root zone are observed under DI60 and DI30 treatments compared to FI100. Potato yields were highest over two cropping periods for the SSDI method although no significant differences were observed with the SDI. Irrigation regimes resulted in significant difference in both irrigation methods on yield and its components. Yields were highest under FI100. Compared to FI100, considerable reductions in potato yields were observed under DI60 and DI30 deficit treatments resulting from a reduction in tubers number/m² and average tuber weight and size. Water use efficiency (WUE) was found to vary significantly among irrigation methods and treatments and varied between 5.9 and 20.5 kg/m^3. WUE of SSDI method had generally higher values than SDI. The lowest WUE values were observed for the FI100 treatment, while the highest values were obtained under DI30 treatment for both methods. SSDI method provides significant advantage on yield and WUE and reduces the soil salinity compared to the SDI in potato production under experimental conditions. The SSDI and FI100 irrigation techniques seem to optimize the use of saline water in potato production and to control soil salinity. Under situations of water shortage, adopting deficit irrigation treatment (DI60) could be an alternative for irrigation scheduling of spring and autumn potato under the arid conditions of southern Tunisia.

Keywords: potato, yield, water use efficiency, drip irrigation, deficit irrigation, salinity

Introduction

Dwindling supplies of quality water for irrigation and increasing demand from other users are forcing farmers to use saline irrigation waters (Rhoades *et al.*, 1992; Shani and Dudley, 2001). Several workers (Oron *et al.*, 2002; Katerji *et al.*, 2003) have indicated that when saline waters are used for irrigation due attention should be given to minimize root-zone salinity. Others have indicated the need for use of appropriate irrigation systems and practices that will supply just sufficient quantity of water to the root-zone to meet the evaporative demand and minimize salt accumulation in the root-zone (Fisher, 1980; Munns, 2002). Therefore, the efficient use of saline water for irrigation is to undertake appropriate management of irrigation to preserve water resources and prevent the development of excessive soil salinization for crop production. Effective irrigation scheduling and the use of modern irrigation systems are two possible options to improve water use efficiency in arid regions.

Potato species is considered relatively susceptible to salinity (Maas and Hoffman, 1977) and normally is not suited for stressful conditions. During the last few years, irrigated potato has been expanding rapidly in the arid part of Tunisia around shallow wells having a salinity of 2 to 6 dS/m. The reason of this new development is an easy access to subsidized drip irrigation equipment made possible recently, and because temperature conditions allow to produce potato over the autumn and spring seasons.

Earlier reports by Ayers *et al.* (1986), Saggu and Kaushal (1991), Goldberg and Shamueli (1970), Bernstein and Francois (1973) and Fereres *et al.* (1985) show that saline water can be efficiently used through drip irrigation. Moreover, it results in considerable saving in irrigation water (Tan, 1995; Yohannes and Tadesse, 1998; Cetin and Bilgel, 2002). Drip irrigation provides more efficient water use for crops than surface irrigation because drip method applies frequent irrigation and localized water application to only part of the crop's potential root zone. Many studies and reports have addressed that yield and quality of potato (*Solanum tuberosum* L.) tubers could be improved with drip irrigation (Singh *et al.*, 1977; Sammis, 1980; Sener *et al.*, 1994; Weatherhead and Knox, 1997; Waddel *et al.*, 1999; Erdem *et al.*, 2006; Nagaz *et al.*, 2008). However, the continuous use of saline water with conventional on-surface drip irrigation (SDI) might result in salt accumulation close to soil surface (Ayers and Westcot, 1985; DeMalach and Pasternak, 1993; Oron *et al.*, 1995; Hachicha *et al.*, 2006) due to increased evaporation before migrate and reach the main root zone and thus causing adverse effects on the crop growth and yield (Hanson and Bendixen, 1995).

Besides, salt accumulation in the root zone under conventional on-surface drip irrigation can be partially avoided by using subsurface drip irrigation (SSDI) (Oron *et al.*, 1990, 1991, 1992; Phene 1993). Saline irrigation water can be successfully used with SSDI in commercial fields, while maintaining yields and improving water use efficiency compared to surface irrigation (Cahn and Ajwa 2005; Siefert *et al.*, 1975; Tingwu *et al.*, 2003), because SSDI can result in suitable root-zone salinity (Hanson *et al.*, 2009). Previous research shows that crop marketable yields and quality and water use efficiency have been improved through the use of SSDI (Phene *et al.*, 1987, 1991; Camp, 1998; Ayars *et al.*, 2001; Al-Omran *et al.*, 2005; Alam *et al.*, 2000; Alexiou *et al.*, 2003; Hanson and May, 2004; Patel and Rajput, 2008; Patel and Pandey, 2008; Hassanli *et al.*, 2009).

A recent positive approach to attain the goal of improving water use efficiency in agriculture is conventional deficit irrigation. Deficit irrigation (DI) is a water saving strategy under which crops are exposed to a certain level of water stress either during a particular period or throughout the whole growing season (English and Raja, 1996; Pereira *et al.*, 2002). The expectation is that any yield reduction will be insignificant compared with the benefits gained deriving from the save of water (Eck *et al.*, 1987). The goal of deficit irrigation is to increase crop water use efficiency (WUE) by reducing the amount of water applied (Kirda, 2002). The effects of DI have been widely investigated for potato crop (Foti *et al.*, 1995; Karafyllidis *et al.*, 1996; Dalla Costa *et al.*, 1997; Fabeiro *et al.*, 2001; Yuan *et al.*, 2003; Kashyap and Panda, 2003; Onder *et al.*, 2005). However, little information is available about the water use efficiency, and yield of potato crop with on farm drip and subsurface drip irrigation in arid conditions of Tunisia.

Due to chronic water shortage and soil degradation hazards in irrigated areas, there is a need to develop strategies that may help to save water and control salinity. Under conditions of high evaporative demand and chronic shortages of water, techniques based on irrigation restrictions during the whole growing period without substantially affecting yields seem to be reasonably appropriate. Thus, various deficit irrigation strategies will be applied to potato crop. The objective of this study was to evaluate the effects of surface and subsurface drip irrigation and irrigation regimes with saline water on soil salinity, yield and water productivity of potato under the arid Mediterranean conditions of southern Tunisia.

Materials and methods

Field experiment was conducted during the spring and fall seasons of 2009 and 2010 in a commercial farm situated in the Southern East of Tunisia (33°50' N, 10°64' E; altitude 30 m) in the region of Médenine. The climate is typical of arid areas and the rainfall during the spring and autumn cropping periods of potato is reported in Figure 1.

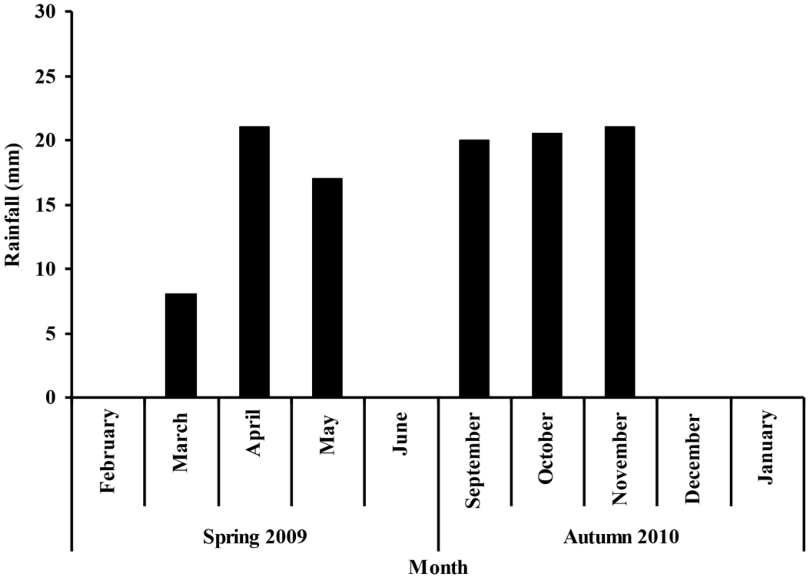

Figure 1- Monthly values of rainfall received during the potato cropping periods for 2009 and 2010.

The soil of the experimental area is sandy soil with low organic matter content (<7 g/kg). Average values in the 60 cm topsoil of field capacity (0.33 bar, pF 2.5) and permanent wilting point (15 bar, pF4.2), determined by the membrane method, are respectively 12.69 and 4.3%. The bulk density of soil was 1.47 g/cm^3. The total soil available water calculated between field capacity and wilting point for an assumed potato root extracting depth of 0.60 m, was 74 mm. The electrical conductivity (ECe) values measured before planting of potato are, respectively, 2.7 and 5.9 dS/m for spring and autumn seasons.

The field experiment consisted of three irrigation regimes and two drip irrigation methods: surface drip (SDI) and subsurface drip (SSDI) irrigation methods. The considered irrigation regimes were: full irrigation (FI100) treatment irrigated when readily available water in the root zone had been depleted and plants in that treatment received 100% of accumulated crop evapotranspiration (ETc), two additional treatments were irrigated at the same frequency as treatment FI100, but with quantities equal to 60 and 30% of accumulated ETc (40% deficit (DI60) and 70% deficit (DI30)).

A split-plot design with three replications was used with irrigation methods as main plots and irrigation regimes as subplots. Each subplot had six rows with 4.2 m width and 26.0 m length. The subsurface drip lines with 70 cm spacing were buried at a depth of 15 cm below the soil surface (Camp, 1988) in each row. The surface drip

Table 1- Chemical composition of irrigation water (meq/l).

ECi (dS/m)	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$CO_3^{2-}+HCO_3^{-}$	SO_4^{2-}	Cl^{-}	SARiw
7.0	16.0	18.4	34.8	0.8	3	28.5	38.5	8.4

lines with 70 cm spacing were laid on the soil surface beside the plant rows. Drip irrigation lines having a diameter of 16 mm were used. The drip laterals for both the SSDI and SDI systems were 16 mm diameter polyethylene pipes with in-line emitters 40 cm apart. The drippers had 4 l/h flow rate at 1.0 atm pressure in both methods. A drip line for each plant row and an emitter for each potato plant were used in the experiment.

Water for each main plot passed through a water meter, gate valve, before passing through laterals placed in every potato row. A control mini-valve in the lateral permits use or non-use of the dripper line. The irrigation water for the experiment was obtained from a well with electrical conductivity (ECi) of 7.0 dS/m (Table 1).

The potato cultivar "Spunta" was planted with 0.10 m depth by hand on 11 February and 7 September in the 2009 spring and 2010 fall growing seasons, respectively, in 70 cm rows with tubers spaced 40 cm apart. Fertilizers were supplied for the cropping seasons in the same amounts; before planting, soil was spread with 17 t/ha of organic manure. Nutrient supply included N, P and K at rates of 300, 300 and 200 kg/ha, respectively, which were adopted from the local practices. The P and K fertilizers were applied as basal dose before planting. Nitrogen was divided and delivered with the irrigation water in all treatments during early vegetative growth. After tubers initiation stage, 120 kg/ha of potassium nitrate were applied.

The crop evapotranspiration (ETc) was estimated for daily time step by using reference evapotranspiration (ETo) combined with a potato crop coefficient (Kc). ETo is estimated using daily climatic data collected from the meteorological station, located at Médenine, Tunisia and the FAO-56 Penman-Monteith method (ETo-PM) given in Allen *et al.* (1998). The potato crop coefficient (Kc) was computed following the recently developed FAO-56 dual crop coefficient approach, the sum soil evaporation (Ke) and basal crop coefficient (Kcb) reduced by any occurrence of soil water stress (Ks), that provides for separate calculations for transpiration and soil evaporation (Kc=KsKcb+Ke).

For irrigation scheduling, the method used was the water balance, by means of a spreadsheet program for Excel, developed according to the methodology formulated by Allen *et al.* (1998). The spreadsheet program estimates the day when the target soil water depletion (readily available water, RAW) for the treatment FI100 would be reached and the amount of irrigation water needed to replenish the soil profile to field capacity. The program calculates the soil water depletion on daily basis using the soil water balance and projects the next irrigation event based on the target depletion (35 % of total available water in the root zone, 35 % of TAW). The soil depth of the effective root zone is increased with the program from a minimum depth of 0.15 m at planting to a maximum of 0.60 m in direct proportion to the increase in the potato crop coefficient.

For determining soil water content by the gravimetric method (θ_g), the weight of wet and dry soil has to be known. Samples were taken with a 4 cm auger from the middle row of every plot after planting and at intermediate dates between irrigation intervals during development and mid-season stages and at harvest. Each plot was sampled every 15 cm to a depth of 60 cm, at four sites perpendicular to the drip line at distances of 0, 10, 20 and 30 cm from the line, and at four sites between the emitters (0, 7, 15 and 20 cm from the emitter). After the sampling, the wet mass of the soil was immediately determined. Therefore, soil samples were dried for 48 h at 105°C and θ_g calculated. Undisturbed soil samples were taken at the beginning of the experiment in order to calculate the bulk density which was used for determining volumetric (θ_v) soil water content. The dried soil samples were ground to pass a mesh of 2 mm size and were analyzed for ECe.

Potato was harvested on June 5, 2009 for the spring crop and on December 30, 2010 for the autumn one. The middle four rows in each subplot were harvested by hand to determine potato yield (t/ha), tuber number/m², tuber weight (g) and size (mm).

Water-use efficiency (WUE) is defined as the yield obtained per unit of water consumed, whether from irrigation or total received, therefore including the precipitation. The WUE was calculated as follow:

$$\text{W.U.E (kg/ha/mm)} = \text{Yield (kg/ha)} / \text{TWR}$$

Where TWR is total water received (mm) from planting to harvest; an irrigation of 74 mm applied before planting is not included in the total.

Analysis of variance was performed to evaluate the statistical effect of treatments on potato yields, WUE and soil humidity and salinity using the STATGRAPHICS *Plus* 5.1 (www.statgraphics.com). LSD test at 5% level was used to find any significant difference between treatment means.

Results and discussion

Climate conditions

The values of day's ETo-PM which define the weather conditions prevailing during the experiment are shown in Figure 2. These data, which only cover the period when experiment took place, are compared to the average values for the period 2004-2008. The autumn season from September to December is characterize by decreasing day's

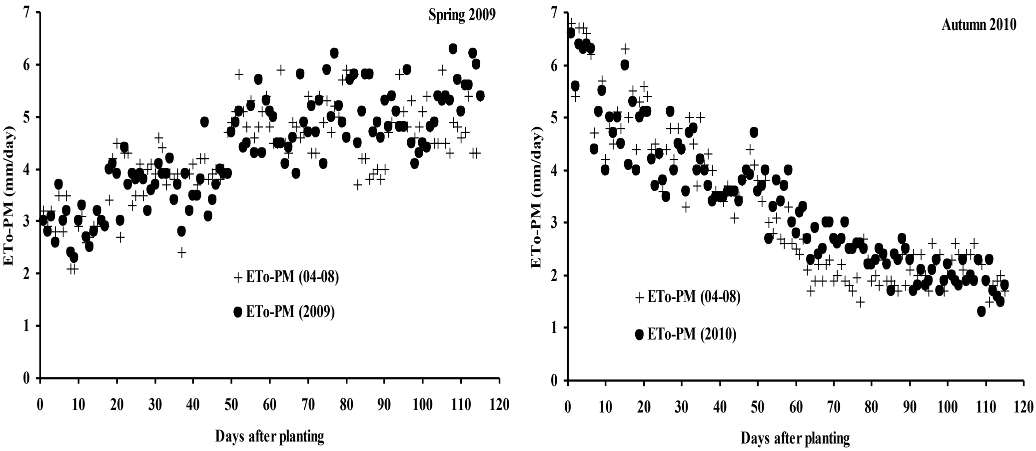

Figure 2 - Day's reference evapotranspiration computed following the FAO-56 Penman-Monteith method. (ETo-PM) during the cropping seasons of potato for spring 2009 and autumn 2010 and period 2004-2008.

ETo-PM values, whereas ETo-PM values increase in the spring season from February to June. The evolution of day's ETo-PM was similar, though with slightly higher values for the period under experiment for spring 2009, with a total of 502 mm as compared to 494 mm, the ETo-PM during the period 2004-2008. The total ETo-PM during the period under experiment for autumn 2010 was 384 mm as opposed to 377 mm in the period (2004-2008). The rainfall received during the spring and autumn cropping periods was, respectively, 46 and 61.5 mm (Figure 1). Most of the rainfall occurred during September, October and November for fall period and March, April and May for spring season.

Soil moisture content

The average soil moisture content values under different irrigation treatments for SDI and SSDI methods at planting, development, mid-season and harvest period of the spring and autumn potato crop are presented in Figure 3. Moisture was directly related to the amount of water applied at full or deficit-irrigated treatments and irrigation methods. Moisture in the soil profile initially showed higher moisture content in all the treatments due to the irrigation amount applied before planting to replenish the soil profile to field capacity. Initial soil moisture content in root zone area was averaged as 17.37 and 18.04% in spring season and 17.03 and 18.11% in autumn season, respectively, for SDI and SSDI. The results show that for all irrigation treatments significant differences were also observed between the soil moisture content of the subsurface irrigated plots and those irrigated with the surface drip system during the development, mid-season and harvest periods. SSDI had higher value of soil moisture content than SDI's. The reduction of the soil moisture content with regard to the field capacity (18.6%) was more important in the case of the SDI than that of SSDI. This is depend on reduce evaporation from soil surface by setting drip line under soil surface. With the subsurface drip method (SSDI) the surface soil layer is not completely wetted as in the case of the surface drip irrigation (SDI). Therefore, with the SSDI the first 10-15 cm below the soil surface remains relatively dry reducing thus the direct soil evaporation as compared to surface drip irrigation. Phene *et al.* (1983) and Solomon (1993) showed that with the SSDI the upper soil layer has a lower humidity resulting in a reduction of the direct soil evaporation.

For each irrigation method, the soil moisture content under FI100 was significantly higher than under deficit treatments for both irrigation systems ($p<0.05$). Soil moisture content at development, mid-season and harvest period of the surface (SDI) and subsurface drip-irrigated (SSDI) autumn potato were found 13.9-15.6, 11.2-12.6 and 8.63-9.70%; 15.4-16.98, 12.41-13.68 and 9.61-11.60%; 16.24-17.22, 13.06-14.19 and 10.09-11.27%, respectively, in FI100, DI60 and DI30 irrigation treatments (Figure 3). In spring season, soil moisture content in root zone area was averaged as 15.40-16.04, 15.02-15.93 and 13.74-14.31%; 16.30-17.02, 13.14-14.11 and 11.65-14.72%; 14.81-16.09, 11.12-12.77 and 8.74-9.81%, respectively, in treatments FI100, DI60 and DI30. In both cropping seasons, the fluctuation in moisture content in the soil profile for SDI and SSDI was in the order FI100 > DI60 > DI30, which can be attributed to irrigation amount.

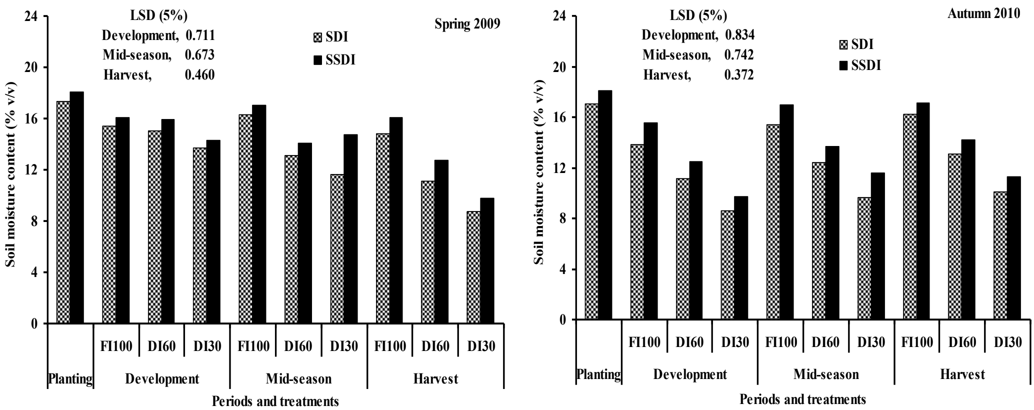

Figure 3 - Soil moisture content (%, v/v) under different irrigation treatments (FI100, DI-60 and DI30) for surface (SDI) and subsurface drip irrigation (SSDI) methods during the two cropping periods of potato. LSD (5%) indicates the least significant difference values at 5% level.

Soil salinity

Soil salinity values in the 0-60 cm soil layer, expressed by the ECe, under different irrigation treatments for surface and subsurface drip irrigation methods at planting, development, mid-season and harvest period of the spring and autumn potato are presented in Figure 4. Initial soil salinity values determined at planting were, respectively, 2.7 and 5.9 dS/m in the spring and autumn seasons. The results show that during the fall period, a decrease in ECe values measured at development, mid-season and harvest is observed under all irrigation treatments and methods compared to initial soil salinity. The decrease of ECe values is attributed to the leaching of soluble salts by fall rains (61.5 mm) (Figure 1) and the decrease in evaporative demand in autumn. However, in spring period, ECe values during development, mid-season and harvest were higher than the initial ECe for all irrigation treatments and methods despite spring rains (46 mm). This increase can be explained by sampling date which corresponds to period of high evaporation demand during the spring season.

The soil salinity also exhibits trends similar to that of the soil moisture content (Figure 4). The ECe values are lower in case of subsurface drip irrigation (SSDI) than the surface drip irrigation (SDI) for all irrigation treatments. The difference observed between irrigation methods is mainly due to the difference in soil moisture content since the irrigation water supplies were similar. These results are in close agreement with those of Oron et al. (1999) who indicated that soil salinity with subsurface drip irrigation is lower than that in the case of surface drip irrigation. According to the soil moisture content values for each irrigation method, we can conclude that the SSDI keeps higher soil water content in the root zone which may help to maintain a continuous leaching of accumulated salts and thus reduce the soil salinity values. Oron et al. (2002) reported that high moisture content in the root zone with SSDI could increase the leaching process of accumulated salts; whereas the conventional SDI facilitated sufficient leaching just below the emitter in the top soil layer, contributing to extra accumulation of salts in the active root zone of the crop and the soil salinity level remained high under the SDI system.

For both irrigation methods, FI100 resulted in a significantly lower ECe values than with deficit irrigation treatments (Figure 4). Higher soil salinity levels were observed for DI60 and DI30 deficit irrigation regimes. In autumn season, the ECe values under FI100 between development and harvest periods ranged from 3.8 to 5.1 and 2.7 to 3.8 dS/m, from 4.2 to 5.5 and 3.5 to 4.9 dS/m for DI60 and that under DI30 from 5.3 to 5.8 and 4.5 to 5.0 dS/m, respectively, for SDI and SSDI. The ECe values under FI100 between development and harvest of spring potato ranged from 4.2 to 5.4 and 3.7 and 4.5 dS/m, from 5.3 to 5.9 and 4.2 to 5.2 dS/m for DI60, and from 5.9 to 6.5 and 4.8 to 5.9 dS/m for DI30, respectively, for SDI and SSDI. ECe values were in order FI100 < DI60 < DI30. The reason for the higher soil salinity obtained for deficit irrigation treatments is attributed to absence of substantial leaching under

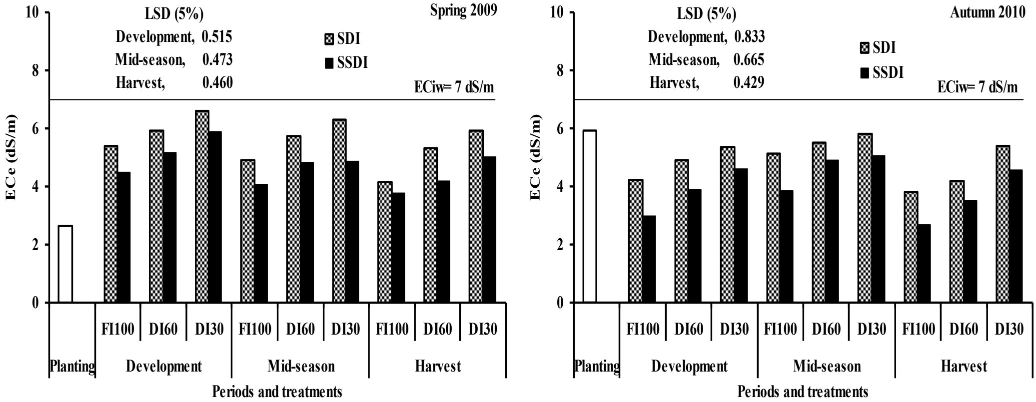

Figure 4 - Soil salinity (ECe, dS/m) under different irrigation treatments (FI100, DI-60 and DI30) for surface (SDI) and subsurface drip irrigation (SSDI) methods during the two cropping periods of potato. LSD (5%) indicates the least significant difference values at 5% level.

deficit irrigation conditions. Schoups *et al.* (2005), Kaman *et al.* (2006) and Geerts *et al.* (2008) reported that one consequence of reducing irrigation water use by deficit irrigation is the greater risk of increased soil salinity due to reduced leaching.

ECe values under the different irrigation treatments for both SDI and SSDI systems were lower than the EC of irrigation water used (7 dS/m). Singh and Bhumbla (1968) observed that the extent of salt accumulation depends on soil texture and reported that in soils containing less than 10% clay the ECe values remains lower than ECiw. Low values of ECe under the prevailing climatic conditions were due to the natural leaching of soluble salts by rainfall that occurred during fall and spring periods (spring: 46 mm and autumn: 61.5 mm) (Figure 1). Thus, under actual farming conditions, the use of high saline waters for irrigation of short-cycle crop during the rainy season seems to have relatively low impact on soil salinization as salts added by irrigation are removed from the root zone by natural leaching.

Crop yield

Potato yield and yield components under different irrigation treatments for SDI and SSDI methods in spring and fall growing seasons are presented in Tables 2 and 3. The data shows that the maximum potato yields for both SDI and SSDI methods occurred in the FI100 treatment in both seasons (Table 2). Yield values were 28.85 and 31.97 t/ha in spring season and 18.71 and 23.01 t/ha in fall one under SDI and SSDI methods, respectively. Although yield observed under FI100 under both irrigation methods is numerically higher than DI60 difference was not statistically different during the two cropping seasons. However, yields decreased significantly for DI30 treatment in comparison to FI100 in both irrigation methods. Potato yields of DI60 and DI30 treatments were also significantly different ($p<0.05$). Steyn *et al.* (1998) had reported significant potato yield reduction with the reduction of applied water. The reduction in potato yield was mainly attributed to reduction in tubers number, weight and size (Table 3) as a consequence of water supply shortage during tubers initiation and development. Previous studies have shown that adequate irrigation water supply before and during tubers initiation increases the number of tubers per plant (Cappaert *et al.*, 1992); whereas, after tubers initiation, it increases their individual sizes (Shock *et al.*, 1998). Deficit irrigation strategies results in higher salinity in the rooting zone than the FI100 treatment. The higher soil salinity levels associated with the deficit irrigation treatments induced important reductions in potato yield and its components.

In both seasons, SSDI increased yield compared with the SDI but the difference between both irrigation methods was not significant for all irrigation treatments (Table 2). Phene (1995), Weatherhead and Knox (1998) also reported no significant differences between surface and buried tape methods on potato yields. The low potato yields of SDI compared with SSDI were a result of reduced tubers number, weight and size (Table 3). In both seasons, tubers weight, number and size increased with SSDI under all irrigation treatment, although no significant differences were found between SDI and SSDI methods.

The differences in yields between SDI and SSDI are mainly due to the diverse soil moisture content and salinity in the root zone. Analyzing the data regarding soil-moisture content and soil salinity during the growing season revealed significant differences among the irrigation methods (Figures 3 and 4). Thus, the observed yield variation might be due to the combined effect of the moisture content and salinity in the soil. These results are in agreement with those of Oron *et al.* (1999) who reported that soil moisture content values under SSDI were higher and the ECe values were lower than those obtained with SDI.

The interaction effect between irrigation treatments and methods on potato tubers yield is presented in Table 2. In both cropping seasons, yield response to irrigation water is more pronounced under SSDI than that with SDI. Under both irrigation methods, maximum yield was obtained with treatment FI100. The yields decreased as the irrigation water amount decreased. Potato yield was enhanced under SSDI irrigation compared with SDI irrigation for each irrigation treatment. With DI30, tuber yields obtained in spring season were 19.70 and 22.34 t/ha for SDI and SSDI methods, respectively. However, the reduction in yields under SDI was counteracted by using the SSDI. The tubers yield obtained with SSDI and DI30 treatments (22.34 t/ha) was the similar as the yield obtained with SDI and DI60. The tubers yield attained 27.63 t/ha under irrigation treatment DI60 and SSDI. That yield is not

Table 2 - Potato yields under different irrigation methods (SDI and SSDI) and treatments (FI100, DI60 and DI30) during the two cropping periods of potato. LSD (5%) indicates the least significant difference values at 5% level.

IRRIGATION METHOD	SPRING				AUTUMN			
	IRRIGATION REGIMES				IRRIGATION REGIMES			
	DI30	DI60	FI100	MEAN	DI30	DI60	FI100	MEAN
SDI	19.70	24.48	28.85	24.34	9.78	13.90	18.71	14.13
SSDI	22.34	27.63	31.97	27.31	13.06	18.26	23.01	18.11
Mean	21.02	26.06	30.41			11.42	16.08 20.86	
LSD (5%)								
Irrigation method			3.271				4.474	
Irrigation regimes			4.440				4.902	
Irrigation method x Regime			4.233				3.635	

Table 3 - Yield components under different irrigation methods (SDI and SSDI) and treatments (FI100, DI60 and DI30) during the two cropping periods of potato. LSD (5%) indicates the least significant difference values at 5% level.

IRRIGATION METHOD	TUBERS NUMBER/m²		TUBER WEIGHT (g)		TUBER SIZE (mm)	
	SPRING	AUTUMN	SPRING	AUTUMN	SPRING	AUTUMN
SDI	15.21	13.41	86.14	82.77	49.8	43.4
SSDI	16.25	15.00	91.10	87.92	50.5	45.9
LSD (5%)	1.107	2.897	5.017	5.176	0.829	2.54
Irrigation regime						
DI30	16.33	12.40	86.02	76.70	46.9	40.4
DI60	19.9	13.90	92.77	87.31	50.2	45.6
FI100	21.31	15.35	97.40	90.20	52.1	47.7
LSD (5%)	1.413	1.456	5.077	2.957	2.071	2.173

significantly different from the yield obtained with FI100 and SDI. The tubers yield produced under SSDI with FI100 treatment was 31.97 t/ha which is higher than that obtained under SDI and FI100. For the fall period, the highest value (23.01 t/ha) was obtained with SSDI and FI100. The tubers yield showed its lowest value (9.78 t/ha) with SDI and DI30. However, under SSDI and irrigation treatments DI30 and DI60 the yields were similar to those obtained with SDI and DI60 and FI100 treatments. Thus, the yield reduction noted under SDI for all irrigation treatments can be overcome by applying saline water through a subsurface drip-irrigation (SSDI) system. The findings of Oron *et al.* (2002) and Al-Omran *et al.* (2006) also confirm these results. The high yields obtained with SSDI under the prevailing climatic conditions indicate its high potential to manage the irrigation of potato with saline water.

Successful use of saline waters for irrigation purposes will be linked to irrigation management that eliminates soil moisture deficit conditions (Bresler *et al.*, 1982; Shalhevet, 1994). Potato has been described as a relatively sensitive crop to salinity (Maas and Hoffman, 1977). Therefore, potato can be grown with acceptable yield using water that has a salinity level as high as 7 dS/m, if irrigation management practices maintain the fraction of ETc applied above the value of 60 % through a SSDI system.

Water use efficiency

The amounts of water applied under SDI and SSDI methods for the potato from planting to harvest over the two cropping periods are given in Table 4. Irrigation water applied before planting of spring and fall potato (74 mm) is not included in the total. Total rainfall amounts were 46 and 61.5 mm in spring and autumn seasons, respectively. The SDI and SSDI irrigation amounts were same for both cropping periods. For all treatments, irrigation water supply ranged from 109 to 363 in spring season and from 77 to 256 mm in autumn season for both SDI and SSDI methods. The amounts of irrigation water were similar to those reported by Singh *et al.* (1977), Waddell *et al.* (1999), Fabeiro *et al.* (2001), Onder *et al.* (2005) and Erdem *et al.* (2006).

The IWUE and TWUE of each treatment expressed as the ratio of potato yield to irrigation and total water received from planting to harvest are given in Table 5. The WUEs values obtained are comparable with those obtained in other field studies (Kang *et al.*, 2004; Onder *et al.*, 2005) and were affected by irrigation treatments. In saline conditions, the same amount of seasonal applied water did not provide the same water-use efficiencies. The highest water-use efficiencies (IWUE and TWUE)

Table 4 - Water supply from planting to harvest under different irrigation methods (SDI and SSDI) and treatments (FI100, DI60 and DI30) during the two cropping periods of potato.

Irrigation regimes	Irrigation* (mm)		Rainfall (mm)	Total water supply (mm)
	SDI	SSDI		
			Spring	
FI100	363	363	46	409
DI60	218	218	46	264
DI30	109	109	46	155
			Autumn	
FI100	256	256	61.5	317.5
DI60	154	154	61.5	215.5
DI30	77	77	61.5	138.5

* an irrigation of 74 mm supplied just before planting is not included in these totals

Table 5 - Irrigation and total water use efficiency (IWUE and TWUE) under different irrigation methods (SDI and SSDI) and treatments (FI100, DI60 and DI30) during the two cropping periods of potato. LSD (5 %) indicates the least significant difference values at 5 % level.

	IWUE (kg/ m^3)				TWUE (kg/m^3)			
Treatments	DI30	DI60	FI100	Mean	DI30	DI60	FI100	Mean
				Spring				
SDI	18.07	11.23	7.95	12.41	12.70	9.27	7.05	9.68
SSDI	20.49	12.67	8.80	13.99	14.41	10.46	7.81	10.90
Mean	19.28	11.95	8.37		13.56	9.87	7.44	
LSD (5%)								
Irrigation method			1.672				1.439	
Irrigation regimes			2.522				2.054	
Irrigation method x Regime			1.474				1.368	
				Autumn				
SDI	12.7	9.02	7.30	9.67	7.06	6.45	5.89	6.47
SSDI	16.96	11.85	8.98	12.60	9.42	8.47	7.24	8.38
Mean	14.83	10.44	8.14		8.24	7.46	6.57	
LSD (5%)								
Irrigation method			1.557				1.363	
Irrigation regimes			2.223				1.777	
Irrigation method x Regime			1.495				1.310	

were observed for DI30 treatment in both irrigation methods. Islam *et al.* (1990), Kashyap and Panda (2003), and Yuan *et al.* (2003) also reported similar findings for potato. WUEs values decreased significantly from DI30 to FI100 with increase in water supply. The deficit irrigation treatment DI30 gave a higher WUE because yield reduction (31.7 % for SDI and 30 % for SSDI in spring and 48.3 % for SDI and 43.2 % for SSDI in autumn) was less than the irrigation (70 %) and total water supply (62 % in spring and 56 % in autumn). In this type of studies, generally, the lower the amount of water received, the higher the water use efficiency obtained (Fabeiro *et al.*, 2001).

The WUEs data showed also that for all irrigation treatments WUE was highest with SSDI and was lowest in case of SDI method. IWUE and TWUE of SSDI were higher and not differed significantly from SDI ($P<0.05$) for each irrigation treatment. Higher WUE in case SSDI method was obviously due to higher yield as compared to SDI as shown in Table 2.

Interaction effect of irrigation treatment x method showed that significantly higher WUE were observed with DI-30 treatment under both irrigation methods (Table 5). The WUE of potato decreased significantly as applied irrigation water increased. For each irrigation treatment, the WUE increased under SSDI irrigation as compared to

SDI system. However, the values of WUE with SSDI and treatments DI30 and DI60 were considerable higher than the WUE obtained with SDI and DI60 and FI100 treatments. These results demonstrate that SSDI method provides significant advantage on yield and WUE compared to SDI in potato production under experimental conditions especially with DI30 and DI60 deficit treatments and the potential of SSDI in saline water management and use.

Conclusions

Potato grown in spring and fall growing seasons was evaluated by applying different irrigation treatments under both surface and subsurface drip irrigation methods with saline water. Results showed that higher moisture content and lower salinity were maintained in the root zone with SSDI than SDI for all irrigation treatments. For both irrigation methods, the soil moisture content under FI100 was higher and the ECe was lower than those obtained with deficit irrigation treatments (DI60 and DI30).

In both seasons, potato yields were affected by irrigation treatments and methods. Potato yields of deficit irrigated treatments (DI30 and DI60) were significantly lower than those obtained under full irrigation (FI100) for both irrigation methods. Deficit irrigation treatments DI30 resulted in lower yields and in higher salinity in the root zone than full irrigation regime (FI100). As the salinity increased, there was a considerable reduction in potato yield and its components under deficit irrigation treatments. SSDI increased yield compared with the SDI but the difference between both irrigation methods was not significant for all irrigation treatments. The low potato yields of SDI compared with SSDI were a result of reduced tubers number, weight and size. In both seasons, tubers weight, number and size increased with SSDI under all irrigation treatment, although no significant differences were found between SDI and SSDI methods. The differences in yields between SDI and SSDI are mainly due to the diverse soil moisture content and salinity in the root zone.

The water use efficiency of spring and autumn potatoes irrigated with saline water was significantly affected by irrigation treatments and methods. The lowest values are observed for full irrigation treatment (FI100), while the highest values were obtained under DI30 deficit irrigation treatment in both irrigation methods. High efficiencies observed for the most severe restricted regime (DI30) is therefore counterbalanced by reduced yield and quality. The higher water use efficiency was obtained with SSDI as compared with SDI system for all irrigation treatments. The relatively high yields and water use efficiency values obtained under DI60 treatment indicate the high potential of the potato crop to valorize irrigation waters of limited quality under mild water deficit conditions. The yield and WUE reduction noted under SDI for all treatments can be overcome by applying saline water through a subsurface drip-irrigation (SSDI).

As a result of this field study, it can be concluded that the SSDI method offers considerable advantage for both yield and WUE and reduces the build-up of salinity in the root zone compared to the SDI in potato production. Subsurface drip (SSDI) and full irrigation (FI100) techniques could be recommended for irrigation of potato crop under the arid climate of southern Tunisia with the possibility to reduce supply up to 40% in case of limited water availability (DI60). Deficit irrigation offers a potential way to improve water use efficiency and to control soil salinity when it can benefit from the leaching capacity of rains. Investigation should focus on this issue and evaluate the efficiency of the rain that occur in fall-spring for natural leaching.

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