

Efficiency of Subsurface Drip Irrigation for Potato Production Under Different Dry Stress Conditions

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Abstract Efficient water delivery systems such as drip irrigation can contribute towards increasing crop yield potential, improving crop water and fertilizer use efficiency. However, critical management considerations such as subsurface drip irrigation are necessary to attain improved irrigation efficiencies and production benefits particularly under arid regions. The objective of this study was to determine the effect of two irrigation methods, surface and subsurface drip irrigation combined with four irrigation levels, 100, 80, 60 and 40% of crop evapotranspiration on yield and yield components of potato grown on sandy soil. The field experiments were conducted in the years 2008 and 2009. In terms of soil water availability to plants, subsurface drip provided more favorable growth conditions for plant growth and maintained higher soil water content at the root zone, which resulted in a significant higher potato yield compared to surface drip irrigation. The difference between the two irrigation methods on yield components was concentrated on the mean tuber weight per plant, while no significant difference was found on the tuber number per plant. Reducing the amounts of applied water significantly decreased total potato yield and its components. Under subsurface drip irrigation, reducing amounts

of applied water to 80% ETC gave comparable yield and yield components to surface drip at full irrigation supply, indicating that 20% irrigation water can be saved without affecting the potato yield. At all irrigation levels, subsurface drip recorded higher water use efficiency (WUE) over surface drip. Maximum value was observed at 40% ETC. Fertilizer use efficiency (FUE) was also higher under subsurface drip and reduced significantly under both irrigation methods with increasing water deficit. These results suggested that subsurface drip offers the potential of better water management with respect to saving and distribution of water in the root zone and to obtain maximum yield accompanied by highest water and FUE.

Keywords Subsurface drip irrigation · Dry stress · Potato · Water use efficiency · Fertilizer use efficiency

Die Effizienz der Unterflur-Tropfbewässerung im Kartoffelanbau unter verschiedenen Trockenstressbedingungen

Zusammenfassung Effiziente Bewässerungssysteme, wie Tröpfchenbewässerung können zur Steigerung des Ertragspotenzials, sowie zur Verbesserung der Wasser- und Düngernutzungseffizienz beitragen. Allerdings sind kritische Erwägungen des Unterflur-Tröpfchenbewässerungs-Managements notwendig, um eine verbesserte Effizienz der Bewässerung und Produktionsvorteile, vor allem in ariden Regionen, zu erreichen. Ziel dieser Studie war es, die Wirkung von zwei Bewässerungsmethoden, eine oberflächliche und eine unterirdische Tropfbewässerung, kombiniert mit vier Bewässerungsstufen 100, 80, 60 und 40 % der Evapotranspiration, auf Ertrag und Ertragskomponenten der Kartoffel auf sandigen Böden zu untersuchen. Die Feldversuche

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fanden in den Jahren 2008 und 2009 statt. Bezüglich der Verfügbarkeit des Bodenwassers für die Pflanzen, wurden bei der Unterflur-Tröpfchenbewässerung günstigere Wachstumsbedingungen und höhere Wassergehalte in der Wurzelzone festgestellt. Diese bewirkten einen signifikant höheren Ernteertrag von Kartoffeln im Vergleich zur oberflächlichen Tröpfchenbewässerung. Der Unterschied zwischen den beiden Bewässerungsmethoden auf Ertragskomponenten bestand im Mittelgewicht der Kartoffelknollen pro Pflanze, während keine signifikanten Unterschiede auf die Anzahl der Knollen pro Pflanze gefunden wurden. Der Ertrag ging mit einer Reduzierung der Wassermengen deutlich zurück. Eine Verringerung der angewandten Wassermengen auf 80 % ETc bei Unterflur-Tröpfchenbewässerung, ergab einen vergleichbaren Ertrag wie mit Vollversorgung bei oberflächlicher Tröpfchenbewässerung. Somit zeigte sich, dass 20 % des Bewässerungswassers gespeichert werden können, ohne dass dies Auswirkungen auf die Ernteerträge hat. Durchgehend für alle Bewässerungsstufen hatte die Unterflur-Tröpfchenbewässerung eine höhere Wassernutzungseffizienz als die oberflächliche Tröpfchenbewässerung. Der maximale Wert wurde bei 40 % ETc festgestellt. Die Düngernutzungseffizienz war ebenfalls höher bei der Unterflur-Tröpfchenbewässerung und wurde deutlich in beiden Bewässerungsmethoden mit zunehmendem Wassermangel reduziert. Diese Ergebnisse verweisen darauf, dass eine Unterflur-Tröpfchenbewässerung das Potenzial eines besseren Wassermanagements hinsichtlich des Wassersparens sowie der Wasserverteilung in der Wurzelzone hatte. Mit diese Verfahren wurden maximale Erträge und eine höchste Wasser- und Düngernutzungseffizienz erreicht.

Schlüsselwörter Unterflur-Tröpfchenbewässerung · Trockenstress · Kartoffel · Wassernutzungseffizienz · Düngernutzungseffizienz

Introduction

With increasing demands on limited water resources and the need to fulfill the requirements of increasing population, drip irrigation technology will undoubtedly play an important role in the future of the Egyptian agriculture. This method of irrigation provides many agronomic, water and energy conservation benefits that address many of the challenges facing irrigated lands. Consequently, the use of drip irrigation is rapidly increasing in arid and semi-arid regions with aim-amending plant water use efficiency (WUE) (Stikic et al. 2003) as well as improving nutrition supply in desert agro-systems (Badr et al. 2010).

Subsurface drip system is used to provide water to plant roots while maintaining a relatively dry soil surface, which ensures that applied water becomes available to a substan-

tial fraction of the plant root system (Camp 1998; Ayars et al. 1999). Moreover, subsurface drip system has the potential to save irrigation water by reducing soil surface wetting and thus reducing evaporation losses compared to other irrigation methods. According to Patel and Rajput (2007) a subsurface drip system could be used to apply water in small amounts and achieve water saving in comparison to surface drip irrigation in sandy loam textured soil. The use of subsurface drip offers many other advantages for crop production, including less nutrients leaching compared to surface irrigation, higher yields, a dry soil surface for improved weed control and crop health and the ability to apply water and nutrients to the most active part of the root zone (Enciso et al. 2005; Lamm and Camp 2007; Selim et al. 2009). Lamm and Trooien (2003), for instance, found that corn yield was the highest under subsurface drip at irrigation level of 75% crop water requirements. Hanson et al. (2006) studied the environmental impact of subsurface drip system placed 20 cm below the soil surface and observed that soil water remained at the root zone for utilization of plants and was not lost due to deep percolation. Water infiltration in the subsurface drip takes place in the region directly around the dripper, which is small compared with the total soil volume of irrigated field.

Drip line installation depth is commonly installed within 1030 cm below the soil surface. Determining the appropriate depth of lateral pipe placement for subsurface drip systems requires consideration of soil structure, texture and crop's root development pattern (Patel and Rajput 2008). Moreover, the wetted area with subsurface drip (radius of wetted perimeter, wetted distance above the drip line and wetted distance below the drip line) is a function of texture and soil hydraulic properties (Cook et al. 2003; Thorburn et al. 2003).

The effective use of subsurface technique of irrigation requires prior knowledge of specific crop yield water relations and water distribution pattern. Potato has a shallow root zone (85% of the root system is typically in the upper 40 cm of soil, but potato roots can extend beyond 1 m in depth) and has low tolerance for water stress (Wang et al. 2006). There have been many reports on the effects of water stress and irrigation regimes on potato crop in many parts of the world (Yuan et al. 2003; Onder et al. 2005; Kaur et al. 2005; Faberio et al. 2001). Drought severity, timing and duration of water stress during the different growth stages of potato crop influence the crop yield because it has a sparse root system (Opena and Porter 1999). Water stress causes reduction of yield by reducing growth of crop canopy and biomass. Scheduling water application is very critical to make the most efficient use of drip irrigation system, as excessive irrigation reduces yield, while inadequate irrigation causes water stress and reduces production (Yuan et al. 2003). However, little information is available about the

WUE, growth and yield of potato crop with on farm drip and subsurface drip irrigation.

The objectives of this study were to evaluate the performance of subsurface drip system on the basis of wetting pattern, water conservation and yield of potato grown on sandy soil under different water stress conditions in arid regions.

Materials and Methods

Location and Growth Conditions

The field experiments were conducted at Sarabuim, a desert region in east of Nile Delta of Egypt located at Ismailia province during the late summers (September–December) of 2008 and 2009. The research field is situated in an arid climate region (latitude of 32°23'N and longitude of 30°58'E).

The climate parameters during the growth period of potato are summarized in Table 1. During the two growing seasons, climate of the experimental site was dry as usual with ineffective rainfall amounts of 20 and 13 mm for 2008 and 2009, respectively. The mean monthly evaporation ranged from 5.5 to 2.3 mm and from 5.9 to 2.4 mm in the respective cropping season. The variations in mean maximum temperature in growing months were 21.7–33.2°C and 21.6–33.5°C, while the variations in mean minimum temperature were 9.7–19.6°C and 9.9–20.2°C in the years 2008 and 2009, respectively (Table 1).

The soil profile of the experimental site in the upper 0–40 cm soil was, well-drained sandy texture composing of 86.5% sand, 9.2% silt and 4.3% clay, with an alkaline pH 8.2, EC 0.85 dS m⁻¹, CaCO₃ 1.5%, O.M 0.27%. The available N, P and K were 14, 6 and 35 mg kg⁻¹ soil, respectively before the initiation of the experiment. The average soil water content at field capacity from surface soil layer down to 80 cm depth at 20 cm intervals was 11.7% and the permanent wilting point for the corresponding depths was 5.4% respectively.

Experimental Design and Treatments

The experiment was laid out in randomized block factorial design consisting of combinations of two irrigation methods combined with four irrigation levels and was replicated three times in 4.5 m wide × 10 m long plots of each

treatment. The irrigation methods were surface drip and subsurface drip irrigation systems as main factor and four irrigation levels included 100% (V 1.0), 80% (V 0.8), 60% (V 0.6) and 40% (V 0.4) of crop evapotranspiration as the sub main factor. Tubers of the late maturity potato (*Solanum tuberosum* L.) cultivar 'Cara' was hand planted on the early of September in 2008 and 2009. All plants were arranged into double rows with within-and between-row spacing of 25 and 40 cm, respectively parallel to the drip lines pre-furrowed to receive 30 t ha⁻¹ of organic manure as basic fertilizers. 300 kg N ha⁻¹ (ammonium nitrate), 150 kg P ha⁻¹ (phosphoric acid) and 250 kg K ha⁻¹ were applied during the crop growing season every year. All NPK fertilizers were injected directly into the irrigation water using venture-tube into the main line of drip systems at 6 days intervals in water soluble form. Fertigation was started two weeks after sowing and was stopped 30 days prior to the end of the crop period. Drip lines of 15 mm inner diameter (twin-wall, 40 cm dripper spacing, 2 l h⁻¹ discharge rate and 1.5 m apart) were either placed on soil surface or buried at 15 cm soil depth before planting under different irrigation levels. Subsurface drip system was placed at the shallowest soil depth possibly, consistent with lower capillary forces prevalent in sandy soil.

Estimation of Crop Water Requirement

The evaporation data was collected from Class "A" pan evaporimeter at weather station of east Delta region. Reference crop evapotranspiration (ET₀) was calculated on a daily basis by using PenmanMonteith's semi-empirical formula (Allen et al. 1998). The actual evapotranspiration was calculated by multiplying reference evapotranspiration with crop coefficient values (ET_c=ET₀×K_c) for different months based on crop growth stages. Potato is about 135 day's duration crop and may be divided into four stages namely initial: 25 days, developmental: 30 days, middle: 45 days and tuber maturity: 30 days. The crop coefficient during the crop season was adopted as 0.50, 0.65, 1.15 and 0.75 at initial, developmental, middle and tuber maturity stages, respectively (Allen et al. 1998). The total amount of water used during the 2008 and 2009 growing seasons were 322 and 327 mm, respectively at full irrigation supply for both surface and subsurface drip systems. During the initial

Table 1 Monthly mean of maximum (T_{\max}) and minimum (T_{\min}) air temperature, rainfall (mm) and references evapotranspiration (ET₀) during the growing season

Month	Year 2008				Year 2009			
	T_{\max}	T_{\min}	Rain fall (mm)	ET ₀ (mm d ⁻¹)	T_{\max}	T_{\min}	Rain fall (mm)	ET ₀ (mm d ⁻¹)
September	33.2	19.6	—	5.5	33.5	20.2	—	5.9
October	32.7	17.7	—	4.8	30.5	17.4	2.3	4.2
November	26.2	14.4	10.7	3.6	26.4	13.5	7.7	3.9
December	21.7	9.7	9.6	2.3	21.6	9.9	2.9	2.4

and developmental growth stages, irrigation frequency was running daily to encourage establishment, while during the tuber development and tuber maturity, irrigation frequency was reduced to be once every 3 days.

Soil Moisture Status and Yield Measurements

During the growing season, spatial soil moisture distribution in the soil was monitored by sampling, approximately one hour after terminating the irrigation shift. Soil samples were taken from the middle row of every plot below the dripper at depths of 10 cm down to 70 cm along with radial line originating at the point-source at distances of 5 cm up to 35 cm periodically throughout the different growth stages, using tube auger from the experimental area. Soil samples were dried in an oven for 24 h at 110°C and moisture content was determined gravimetrically. At harvest, plant development components were determined from 10 randomly selected plants in each subplot including total tuber yield per hectare, number of tubers per plant, mean tuber weight and tuber yield per plant. WUE was calculated as the ratio of total tuber yield and seasonal crop water applied for each irrigation level and expressed as $\text{kg yield}^{-1} \text{mm}^{-1}$. Fertilizer use efficiency (FUE) was calculated as a ratio of total tuber yield and quantity of total fertilizer applied and expressed as $\text{kg yield}^{-1} \text{kg}^{-1} \text{NPK}$.

Statistical Analysis

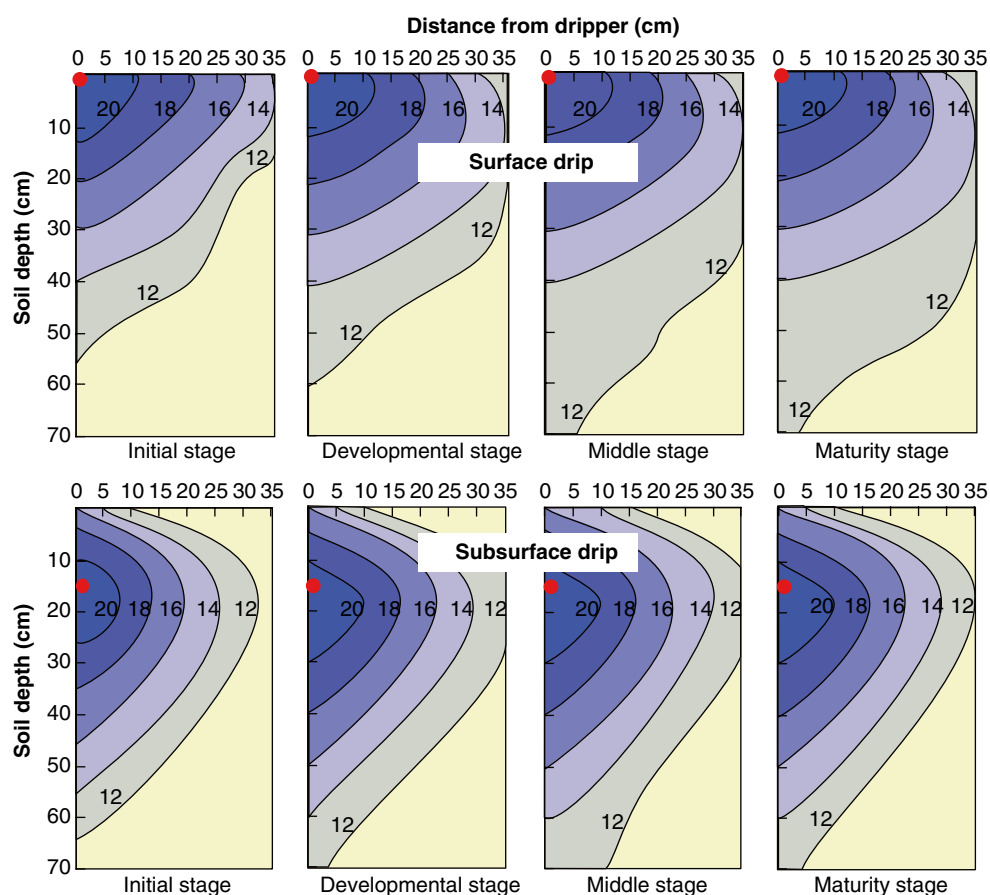
Trial data were subjected to the analysis of variance (ANOVA) appropriate to the experimental design to evaluate the effects of treatments on the yield and yield components of potato. CoStat (Version 6.303, CoHort, USA 1998–2004) was used to conduct the analysis of variance. Least significant differences (LSD) were used for means separation at 5% probability levels. Regression analysis was performed between total seasonal water use and total tuber yield of the crop.

Results and Discussions

Soil Water Distribution

Soil water distribution patterns varied significantly according to the method of drip irrigation system at different stages of crop growth. In both irrigation methods, soil water content increased up to middle stage of crop, but then it started decreasing at maturity stage (Fig. 1). Soil surface appeared moist with surface drip and remained relatively dry with subsurface drip at all growth stages of potato. In general, vertical movement of water was more pronounced than its

Fig. 1 Spatial distribution of water in soil for surface and subsurface drip irrigation systems during different growth stages of potato at full irrigation supply. The numbers labeling curves of contours lines indicate percentage of moisture content



lateral movement due to predominant of gravity force compared to capillary force in the sandy soil. The overall wetted area, delimited by the wetting front represented by the peripheral contour lines was larger for the subsurface drip and relatively smaller for the surface drip irrigation. However, surface drip allows water to move faster in horizontal direction and produced a greater radius to depth ratio than subsurface drip. Although subsurface drip was buried at 15 cm soil depth but a great deal amount of soil water remained at the root zone for plants utilization and was not lost due to deep percolation. The wetting pattern of elliptical shape was clearly obvious with subsurface drip; upward movement of water took place due to capillary forces and the wetted volume exhibited a vertically elongation pattern extended down to 70 cm soil depth around the dripper (Fig. 1).

Under surface drip at full irrigation supply, the soil water content up to 20 cm depth was ranged from 20 to 14%, while at 40 cm depth the soil water content was about 12% at different stages of potato growth. On the other hand, when drip lines were placed at 15 cm under soil surface, the upward capillary movement of water was not sufficient to reach top soil and soil water content at the surface decreased significantly to about 12% in comparison to surface drip. Under this depth of drip line placement, more than 16% soil water content was observed till the depth of 40 cm in all growth stages of crop. However, at the initial and developmental stage of crop, potato roots were confined up to 15 cm soil depth and thereafter they confined up to 40 cm soil depth where adequate soil water content was found at this depth, which was conducive for good growth and resulted in higher potato yield in subsurface drip system. This result confirm to the results of Wang et al. (2006) who found that potato roots had spread up to a radius of 25 cm from the water source (drip lines) and most were contained within 40 cm soil depth. Similarly, under water stressed treatments, subsurface drip method also showed higher water content in the soil profile especially at 40 cm depth and kept this difference until the end of the crop period (data not shown).

The reason for reduction in evaporation loss under subsurface placement of drip lines is the less water availability on the soil surface for evaporation; the upwards movement of water was appreciably lower keeping adequate amount of water under soil surface for root uptake. Philip (1991) and Meshkat et al. (2000) also reported that moving of water through the soil to the surface becomes limiting as the soil surface dries, which resulted in smaller soil evaporation loss there by repressing the upward movement of water. In general, the position of the wetting front is commonly used to describe the extent of soil moisture distribution under different conditions. The depth of wetting front increased with buried lines beneath soil surface and helped to store a reasonable quantity of water below soil surface, which

reduces evaporation components. Previous studies have been reported that subsurface drip system reduced evaporation from the soil and increased the wetted soil volume and surface area more than surface systems allowing a deeper rooting pattern (Phene 1995; Oliveira et al. 1996; Patel and Rajpat 2008) Therefore, keeping the drip line within the crop root level below the soil surface replenishes water and nutrients effectively, which have positive effects on yield, tuber size and water savings and thus increase the irrigation efficiency.

Yield and Yield Components

Drip irrigation method (surface or subsurface) had significant effect on total potato yield and its entire components, except on the number of tuber per plant, which may be related to the cultivars and other environmental conditions (Table 2). The over all average yield resulted from subsurface drip system was significantly higher (36.32 t ha^{-1}) over surface drip (30.18 t ha^{-1}), which accounted to 20.4% yield increase. This yield increase can be attributed to significantly higher mean tuber weight and tuber yield per plant in subsurface drip over surface drip system. The better performance under subsurface drip can be explained to the maintenance of favorable soil water status in the root zone, which in turn helped the plants to utilize moisture as well as nutrients more efficiently from the limited wetted area (Hebbar et al. 2004; Zotarelli et al. 2008).

The irrigation levels had also significant effect on total yield and entire yield components in both years. Full irrigation supply resulted in the highest tuber yield values under both irrigation method and there were significant reductions on total yield and yield components when applying less amount of water. However, the overall average yield was generally more responsive to irrigation levels than to drip irrigation systems; yield reduced by about 9.3% with 20% reduction in amount of irrigation water, while on applying 40 and 60% less amount of water, potato yield decreased by 25.7 and 42.7%, respectively. Previous studies have also reported significant tuber yield and size reductions with the reduction of applied water (Yuan et al. 2003; Onder et al. 2005). Furthermore, genotypes showed significant differences in response to water stress (Steyn et al. 1998). Otherwise, reducing amounts of applied water to 80% ETc under subsurface drip gave comparable yield and yield components to surface drip at full irrigation supply. This fact indicate that 20% irrigation water can be saved without affecting the potato yield, which is similar to the results obtained by Patel and Rajput (2007). Most greatly affected was the mean tuber weight (fruit diameter is a significant quality factor for fresh market potato) and the higher values were obtained with subsurface drip at all irrigation levels. The effect of water on tuber size relies on the combination of deficits during the

Table 2 Yield and yield components of potato as affected by drip irrigation systems and levels of irrigation

Main effect	Tuber yield (t ha ⁻¹)		Tuber number plants ⁻¹		Mean tuber weight (g plant ⁻¹)		Plant yield (g plant ⁻¹)	
	2008	2009	2008	2009	2008	2009	2008	2009
<i>Drip system</i>								
SD	29.13	31.22	9.5	9.6	122	132	1,171	1,280
SSD	35.27	37.36	9.8	9.9	135	153	1,350	1,530
LSD (5%)	1.82	1.95	0.4	0.4	8	9	34	39
<i>Irrigation level</i>								
V 1.0	40.08	42.49	10.5	10.6	153	170	1,610	1,803
V 0.8	36.59	38.31	10.0	10.1	142	155	1,421	1,567
V 0.6	29.57	31.65	9.4	9.6	121	135	1,138	1,294
V 0.4	22.57	24.73	8.6	8.8	99	109	742	957
LSD (5%)	2.25	2.37	0.5	0.5	11	13	48	54
<i>Drip system × Irrigation level</i>								
SD								
V 1.0	38.42	40.82	10.3	10.4	148	165	1,524	1,716
V 0.8	34.32	36.24	9.8	9.9	139	147	1,362	1,455
V 0.6	25.95	27.56	9.2	9.4	115	123	1,058	1,156
V 0.4	17.82	20.27	8.5	8.6	85	92	740	792
SSD								
V 1.0	41.74	44.15	10.7	10.8	158	175	1,696	1,890
V 0.8	38.85	40.38	10.2	10.3	145	163	1,479	1,679
V 0.6	33.18	35.74	9.6	9.8	127	146	1,218	1,431
V 0.4	27.32	29.18	8.7	8.9	113	126	1,007	1,121
LSD (5%)	2.75	2.82	0.5	0.5	12	14	65	74

SD surface drip, SSD subsurface drip, LSD least significance difference

growth and the ripening stages, through the influence of the number of tubers per plant (Faberio et al. 2001).

The interaction effect of drip system × irrigation levels on potato yield and yield components was significant in all treatments except on the number of tuber per plant. Subsurface drip increased total yield over surface drip with more distinct effect under the water-stressed treatments. At full irrigation supply, subsurface drip increased yield by 8.3% with respect to the surface drip. However, under water deficit treatments, potato yield was 12.3, 28.8 and 48.3% higher by corresponding saving of 20, 40 and 60% of irrigation water, respectively. Similar results were reported by Shock and Feibert (2000), who observed that reduction in total yield of potato due to the progressive deficit irrigation treatments averaged 6.7, 10 and 14% with corresponding water savings of 25, 36 and 40%. Therefore, higher yield can be achieved by placing the drip line sufficiently below the soil surface, which ensures that applied water becomes available to the most active part of crop root zone and also cuts of evaporation losses due to restricted upward capillary flow.

Limited water supply, timing and duration of water stress during the different growth stages of potato crop influences the crop yield. According to Yuan et al. (2003) water stress reduced photosynthetic efficiency, but the drought during the periods of tuber initiation and bulking had the most drastic effect on the yield. However, in some circumstances, potato can tolerate limited deficit irrigation before tuber set without significant reductions in external and internal tuber

quality (Shock et al. 1992). These results suggest that, for drip-irrigated potato grown in sandy soil texture, subsurface drip system is a better management option affecting crop yields and their components. This could be an important consideration for growers who have system and management ability to overcome or restore some of yield losses under water deficit conditions.

Production Function

Total amount of applied water relative to tuber yield in ton per hectare was selected to show production functions through linear regression analysis. Drought stress during the growth stages had significantly affected tuber production, where the obtained mathematical function showed that a highly significant determination factor ($R^2=0.98$) under both drip irrigation systems (Fig. 2). Previous studies have also shown that potato yield responds linearly to the amount of applied water (Martin et al. 1992).

Water and Fertilizer Use Efficiency

Potato plants received the same amounts of irrigation water through surface or subsurface drip system during each season, which estimated as 322, 258, 193 and 129 mm at 100, 80, 60 and 40% ETc, in 2008, and 327, 262, 196 and 131 mm in 2009 at the corresponding values of ETc, respectively. However, the differences in the amounts of applied irriga-

Fig. 2 Linear regression relationship between total amount of applied water and total tuber yield (average of two seasons) under surface and subsurface drip systems

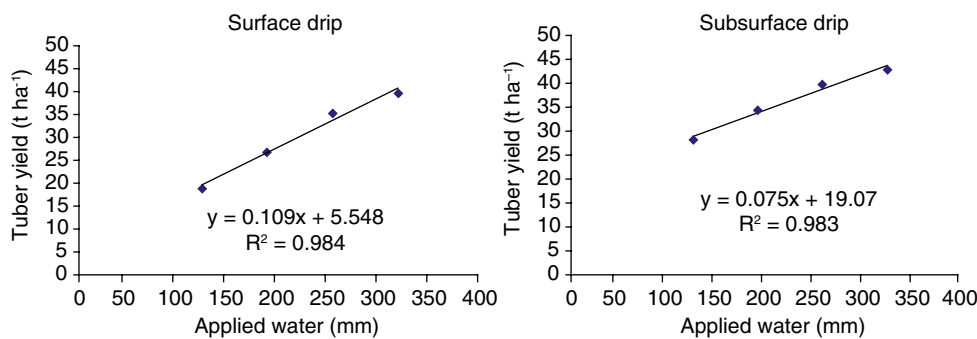


Table 3 Water use efficiency (WUE) and fertilizer use efficiency (FUE) by potato as affected drip irrigation systems and levels of irrigation

Main effect	WUE (kg ha ⁻¹ mm ⁻¹)		FUE (kg yield ⁻¹ kg NPK ⁻¹)	
	2008	2009	2008	2009
SD				
V 1.0	119	125	55	58
V 0.8	133	138	49	52
V 0.6	135	141	37	39
V 0.4	138	155	26	29
SSD				
V 1.0	130	135	60	63
V 0.8	151	154	56	58
V 0.6	172	182	47	51
V 0.4	212	215	39	42

SD surface drip, SSD subsurface drip

tion water in the four irrigation levels caused significant differences in the potato yield (Table 3). Lesser amount of applied irrigation water gave the higher WUE and subsurface drip method recorded superior values over surface drip especially under water deficit treatments. Since the source of water is at a certain depth when subsurface drip is used, the soil surface usually remains drier than for the surface drip irrigation. This leads to the reduction of evaporation from the soil surface and consequently to an increase in transpiration and overall WUE (Romero et al. 2004). However, the most deficit irrigation levels (40% ETc) gave maximum WUE of 138 and 155 kg ha⁻¹ mm⁻¹ in surface drip and 212 and 223 kg ha⁻¹ mm⁻¹ in subsurface drip during 2008 and 2009, respectively. Generally, in this type of water deficit studies, the lower the amount of water received, the higher the WUE obtained (Kashyap and Panda 2003; Yuan et al. 2003; Patel and Rajput 2007).

FUE was significantly higher in subsurface drip over surface drip irrigation under all irrigation levels. Maximum FUE was obtained by applying 100% ETc in 2008 and 2009, respectively. This was due to better availability of moisture and nutrients throughout the growth stages leading to better uptake of nutrients and production of potato.

Conclusions

Many new reclaimed areas of Egypt are facing a dramatic shortage of water resources for agriculture due to both scar-

city of rain fall and a considerable competition for water from new residential areas. Saving of water is a constant concern and new methods and irrigation strategies are urgent. Subsurface drip induces favorable soil moisture conditions in the active crop root zone, while conventional surface drip probably facilitates moisture losses primarily in the upper soil layer. The broadest water pattern is obtained under subsurface drip where most of root system had enclosed by relatively higher soil water content over surface drip, which was conducive for good growth of crop and tuber formation resulting in higher potato yields. At all irrigation levels, subsurface drip recorded higher WUE over surface drip and maximum value was observed at 40% ETc. FUE was also higher under subsurface drip and reduced significantly under both irrigation methods with increasing water deficit partly because of differences in total water inputs.

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