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IMPACT OF DROUGHT ON POTATO YIELD QUALITY, WATER PRODUCTIVITY, AND PROFIT UNDER SURFACE VS. SUBSURFACE DRIP IRRIGATION

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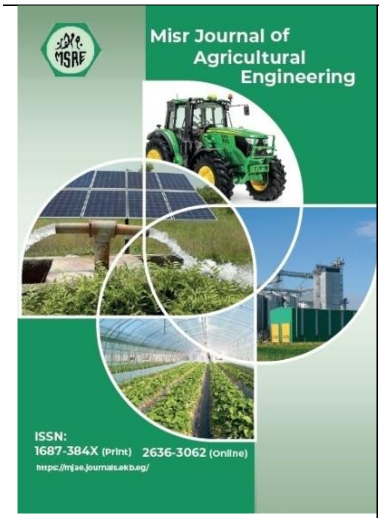


Keywords:
Deficit irrigation; Partial root zone drying; Yield quality water productivity; Profit net; Surface and subsurface drip irrigation.

ABSTRACT

Agriculture face challenges from water allocation and complications arising out of the climatic changes. Field experiments were conducted at Demo Farm, Faculty of Agriculture, Fayoum University. Potato seeds were planted in two seasons (2020 and 2021). The treatments are three deficit irrigations (DI) {I_1, I_2 and I_3 (100, 80 and 60% of ETc)}, two partial root zone drying (PRD) practices (single and double laterals), and three buried depth laterals {surface, and subsurface drip irrigation (SDI) with depths of 15 and 30 cm}. Tuber size and its physical properties, water productivity (WP), and profit net (PN) were determined. Results indicated the greater grade size of tubers was at 30-60 mm. At size 30-60 mm, the highest values of tuber yield, real density and PN were 31.942 t/ha, 1.087 g/cm^3, and 274906 L.E./ha, respectively, and they were recorded at I_1 under PRD and buried depth of 15 cm. The highest value of WP was 13.82 kg/m^3, and it was recorded with I_3, PRD under SDI with buried depth of 15 cm. When irrigation water applied (IWA) decreased by 20% and 40%, the potato yield decreased by 8.65% and 29.57%, respectively. When irrigation water is abundant, it could be using treatment I_1, PRD irrigation and SDI with buried depths of 15 cm to reach the highly significant yield and PN. While, under shortage of water resources, using treatment I_2, PRD irrigation, and SDI with buried depth of 15 cm to save 20% of IWA with a decrease of 8% in the potato yield.

INTRODUCTION

Using micro-irrigation techniques will be fundamental to the sustainability and conservation of water resources **(Kumar et al.,** 2023). Surface drip irrigation is considered the most efficient irrigation system due to its ability to control the irrigation water applied precisely, distribute water uniformly, reduce deep percolation and evaporation, and minimize salinity effects (**Karlberg and Frits, 2004**).

Subsurface drip irrigation (SDI) systems increase the water application efficiency, yield, water and energy savings, and decrease, i.e., labor requirements, water evaporation, deep percolation and runoff. They also, adapt well to fields of any shape and size as compared to other irrigation systems **(ASAE, 2005)**. Because of the shallow rooted nature of several vegetables, placement SDI laterals for these crops are regularly located at depths from 15 to 30 cm (Lamm and Camp, 2007). SDI systems lead to a greater yield and significant irrigation water saving of 23.2% than those in surface drip systems (Douh and Boujelben, 2011). SDI significantly increased the yield, water productivity (WP), and water use efficiency by 5.39, 6.75 and 3.97% as compared to drip irrigation, respectively (**Wang et al., 2022). Xiao et al. (2023)** have implemented the SDI system to ensure the secure use of unconventional water resources.

When drought tolerant genotypes are absence, agronomic management and practices could mitigate the drought stress **(Nasir and Toth, 2022)**. The important limiting factor for potato production is water, and it is possible to increase crop production by well scheduled irrigation water programs (Zhou **et al.**, 2020). The yield decreased as the deficit irrigation level increased; the highest values of the yield and WP would be at 90% of ETc **(Hassan et al., 2020).** Deficit irrigation with 50% of ETc had less water storage and the best water use efficiency (**Boutheina et al.,** 2022). The partial root-zone drying (PRD) irrigation practice gave the highest values of potato tubers (29.22 t ha^{-1}) as compared to the SDI system (26.14 t ha^{-1}) **(Al-Jabri and Al-Dulaimi, 2021).** Deficit irrigation and PRD irrigation are widely recognized water saving irrigation practices **(Hui et al., 2021).** PRD is the most popular and effective due to how many crops can save in the IWA up to 50% (Lamo et al., 2022). To use the irrigation water more efficiently, the PRD was recommended; this was an effective way to increase the WP (Demir **et al**., 2022).

The marketable tubers yield of size of 4 - 5 cm was 20% higher under PRD irrigation than in full irrigation (Shahnazari et al., 2007). Deficit irrigation in the late stage had a significant effect on tubers size and quality **(Ávila-Valdés et al., 2020).** Water deficit had an opposing effect on tubers size (Zhou **et al.**, 2020). Maximum medium sized tubers were achieved by applying irrigation of the potato crop at 60% management allowable depletion level (Ijaz-ul-Hassan et al., 2021). The potato tuber volume was 53.5, 113.0 and 135.1 cm^3 for small, medium, and large tubers, respectively (Abdalgawad et al., 2023).

The density of biomaterials had an important role in many applications, and is useful in the drying and storage of products, design of the storage bins **(Khater and Afify, 2021)**. The real density of potato tubers ranged from 1.125 to 1.190 g cm^{-3} for all treatments under study (Abdalgawad et al., 2023). Compression tests might be employed to obtain force deflection curves to check fruit firmness **(Khater et al., 2014)**. Tubers produced from soil supplemented by compost displayed higher firmness similarly under 100% of ETc and 75% of ETc **(Hajlaoui et al., 2024)**.

Potato is a very important food crop and rates 4th among the world's agricultural products in production volume, after wheat, rice, and corn (Majeed and Muhammad, 2018). In Egypt, potato is the second most important vegetable crop after tomato, and it is grown on 0.177 million hectares with production of about 5.2 million tons **(FAO-STAT, 2021).** The mean values of potato crop yield decreased by 13.39 and 30.04% at deficit irrigation 80 and 60% of ETc, respectively, as compared to irrigation treatment 100% of ETc **(Abd El-Wahed et al., 2020).** Potato plants are very sensitive to water stress because of their shallow root systems and are required to consume a plenty of water in the all-growing season (Akkamis and Caliskan, 2021). Full irrigation treatment (100% of water regime) and SDI system maximize potato tuber yield but decrease WP. While integration between SDI and deficit irrigation is effective in improving the WP due to less water being consumed **(Mattar et al., 2021).**

The water requirement of the potato crop was 4746.81 m^3 ha^{-1} in the summer season as compared with 4376.62 m^3 ha^{-1} in the Nili season **(Eid et al., 2017)**. The evapotranspiration values of potato varied between 18.5 and 67.3 cm under drip irrigation system **(Ayas, 2021).** SDI system resulted in an increase in the WP values as compared to other irrigation systems **(Najafi and Tabatabaei, 2007).** WP is projected to maximize crop yield and decrease in irrigation water. In order to meet these projections, irrigation systems will be optimized and modernized **(Fanish et al., 2011)**. Deficit irrigation treatments have a significantly higher WP as compared to full irrigation (Zin El-Abedin et al., 2017). The maximum water use efficiency tended to be lower for surface drip irrigation than for the SDI system. The greatest water use efficiency values were obtained from surface and SDI at 60% of full irrigation supply (18.3 kg m^{-3} and 19.7 kg m^{-3}), whereas the lowest water use efficiency values were those estimated at 100% of full irrigation (14.8 kg m^{-3} and 15.9 kg m^{-3}), respectively (Al-Ghobari and Dewidar, 2018). The treatment 100% of the irrigation regime was important for the highest WP **(Gültekin and Ertek, 2018).** Drip irrigation system is a solution of reduces water losses and allow higher water use efficiency **(Patel et al., 2023).** Irrigation with 80% of recommended irrigation water and nitrogen under SDI can be obtaining the higher values of WP and tubers yield as compared to surface drip irrigation with 80% of irrigation water and 100% recommended nitrogen (Kaur et al., **2023).**

Under adequate the deficit drip irrigation, the plants develop deep roots to reach the soil water, this resulting a significant water saving with a low decrease in crop yield and an increased profit net for farmers **(Chai et al. 2016).** To get economical crop yield and to increase WP, could be used SDI and spilled the amount of fertilizer to 9 or 12 doses as a fertigation **(Ahmed et al., 2017)**. The PRD technique facilitates 7-10 day's early harvest with high cash profit as compared to full irrigation **(Badr et al., 2018)**. The improvement in drip irrigation scheduling increased the farm income under the local condition (Ijaz-ul-Hassan et al., 2021).

The aim of the present work was to evaluate the effect of drought stress (deficit irrigation and partial root zone drying irrigation) on yield quality, water productivity and profit net of potato crop grown under surface and subsurface drip irrigation systems.

MATERIALS AND METHODS

Experiment site

Field experiments were conducted during the two growing seasons of 2021 and 2022 at the Experimental Demo Farm (7 km east of Fayoum city), Faculty of Agriculture, Fayoum University, Fayoum, Egypt, (Latitude: 29° 17̀ 34.1‶ N, Longitude: 30° 54̀ 57.3‶ E, and Altitude: +25 m. Disturbed and undisturbed soil samples were initially collected from the experimental soil at three depths: 0-20, 20-40 and 40-60 cm. Some initial physical characteristics of the experimental soil samples were determined and calculated according to the methods and procedures described by **Jury and Horton (2004).** The experimental site could be characterized a sandy loam in texture. Also, some initial soil chemical properties were determined according to the methods and procedures described by **Page et al. (1982)**. The chosen site was slightly salinity soil, EC values ranged from 4.66 to 6.45 dS m^{-1}. The experimental site was not alkaline and not calcareous soil. Soil physical and chemical properties data and irrigation water analysis were presented in Tables (1 and 2).

Experiment design

The experimental layout was a split split-plot design with three replicates. Drought stress is expressed as deficit irrigation and the partial root zone drying (PRD) irrigation. The main plots represented three deficit irrigation treatments, I_1 (100 % of ETc), I_2 (80 % of ETc) and I_3 (60 % of ETc). Each main plot was pounded with dikes (3 m in width) to avoid the horizontal movement of water from one treatment to another. Each main plot was divided into two sub-main plots, which received the PRD irrigation treatments, i.e., double and single lateral lines in the planting ridge.

The double laterals were spaced at 0.25 m on each planting ridge, and the space between both planting ridges is 0.7 m. Also, each the sub-main plot was divided into three sub-sub-main plots to received buried lateral depths treatments, i.e., zero, 15 and 30 cm. The total number of the experimental units = 3 (deficit irrigation) × 2 (PRD irrigation) × 3 lateral depths × 3 (replicates) = 54 experimental units, Fig. (1).

Table (1). Some soil physical properties of the experimental site (as mean values of two seasons).

Soil physical properties	Soil layer depth, cm		
	0-20	20-40	40-60
Particle size distribution, %			
Sand	74.6	74.0	73.5
Silt	11.0	11.2	11.4
Clay	14.4	14.8	15.1
Texture class	S.L.	S.L.	S.L.
Particle density, g cm^{-3}	2.65	2.65	2.66
Bulk density, g cm^{-3}	1.45	1.48	1.51
Field capacity, %	18.71	17.92	17.62
Wilting point, %	4.69	5.14	5.27
Available water content, %	14.02	12.78	12.35

Irrigation water requirement

Irrigation water requirements were calculated according to monthly mean weather data for two successive seasons 2021 and 2022 as shown in Table 3.

The daily evapotranspiration (ETo) values were computed by applying the following equation according to **Doorenbos and Pruitt (1992)**:

$$ETo = E_{pan} \times K_{pan}$$

Where: E_{pan} is evaporation from the Class A pan (mm d^{-1}), K_{pan} is pan evaporation coefficient, (K_{pan} = 0.8) **(Allen et al., 1998**).

The crop evapotranspiration (ETc) values were estimated using the reference evapotranspiration (ETo) and crop coefficient (Kc) values according to the following equation **(Doorenbos and Pruitt 1992)**:

$$ETc = ETo \times Kc$$

Table (2). Some soil chemical properties of the experimental site (as mean values of two seasons).

Soil chemical properties	Soil layer depth, cm 0-20	20-40	40-60	irrigation water
pH	7.32	7.41	7.55	7.12
EC, dS/m	4.66	5.73	6.45	0.47
Soluble cations (meq. L^{-1})				
Ca^{++}	10.36	13.72	15.56	1.13
Mg^{++}	6.67	8.91	9.17	0.89
Na^{+}	28.46	33.68	39.82	2.18
K^{+}	0.54	0.81	0.96	0.28
Soluble anions (meq. L^{-1})				
CO_3^{--}	--	--	--	--
HCO_3^{-}	1.13	1.36	1.55	0.67
Cl^{-}	18.19	22.31	24.71	1.83
SO_4^{--}	26.71	33.45	39.25	1.98
SAR	9.75	10.01	11.32	2.17

Table (3). Monthly mean weather data for two successive seasons 2021 and 2022 years, class A pan evaporation readings and ETo values.

Month	Year	Temperature C° $T_{MAX.}$	$T_{MIN.}$	MEAN	Relative humidity (RH %)	Wind speed (m sec^{-1})	No. hour of sunshine (h)	E_{pan} (mm/ day)	ETo (mm/ day)
FEB.	2021	23.4	9.7	16.6	41.0	2.0	9.46	2.36	1.89
	2022	22.0	8.3	15.2	42.0	1.9	9.44	2.22	1.78
MAR.	2021	29.4	12.7	21.1	37.0	2.1	10.19	3.47	2.78
	2022	26.7	12.7	19.7	36.0	2.2	10.21	3.93	3.14
APR.	2021	21.1	9.2	15.2	35.0	2.3	11.17	5.60	4.48
	2022	31.2	15.6	23.4	36.0	2.2	11.13	5.43	4.34
May	2021	36.0	19.8	27.9	51.6	4.2	11.70	6.58	5.26
	2022	36.1	19.7	27.9	51.8	5.6	11.83	6.85	5.48
June	2021	37.3	24.3	30.8	54.1	5.5	12.34	8.28	6.62
	2022	37.4	24.2	30.8	54.3	5.4	12.26	7.17	5.74

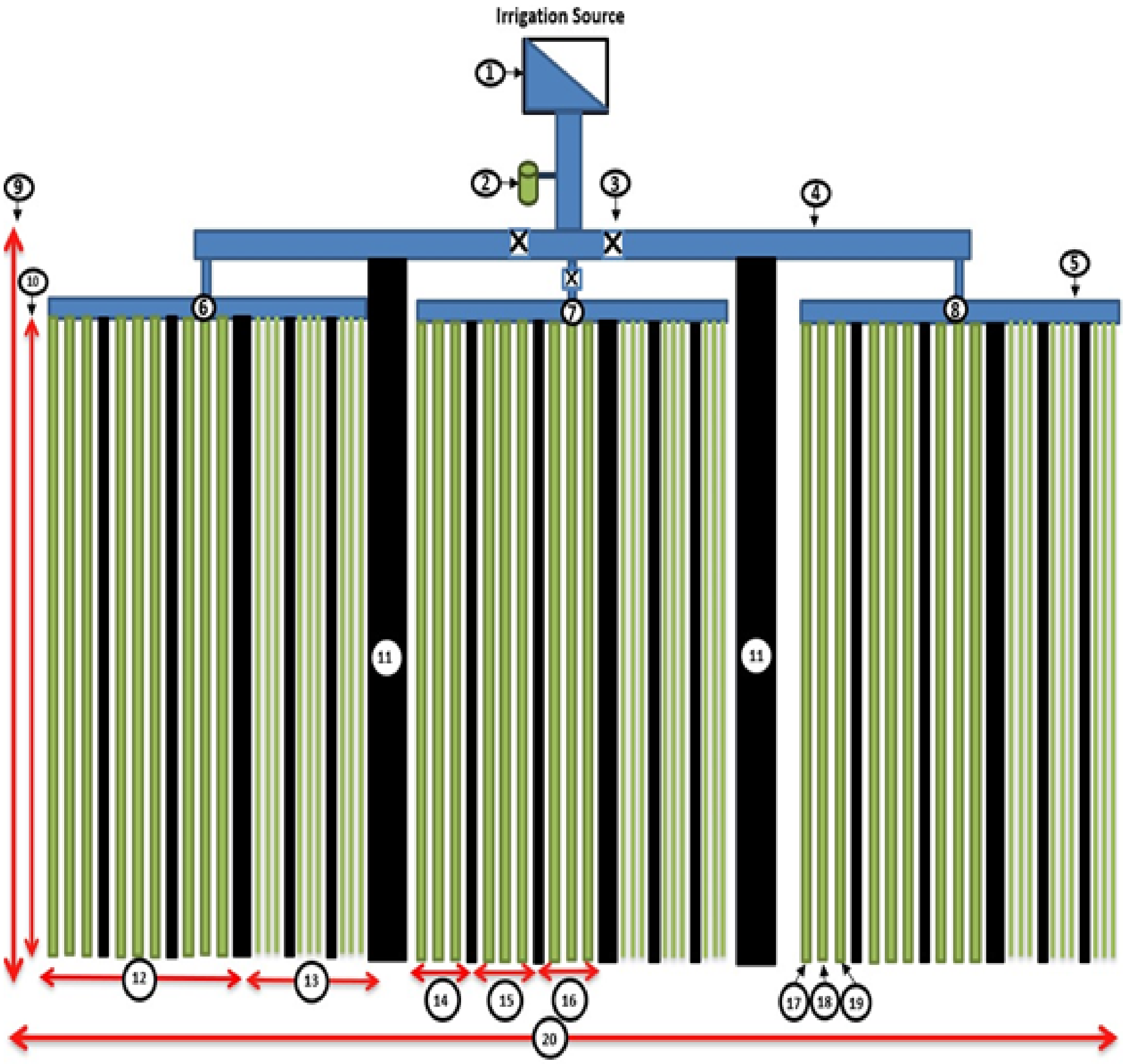
The amounts of irrigation water applied (IWA) ($m^3\ ha^{-1}$) of each treatment was determined by using the following equation according to **Keller and Karmeli (1975)**:

$$IWA = \frac{A \times ETc \times Ii \times Kr}{Ea \times 1000} \times \frac{1}{1 - LR}$$

Where: ETc is the crop evapotranspiration (mm day^{-1}), Ii is the irrigation intervals (day), Kr is the coverage coefficient ($Kr = (0.10 + G_C) \leq 1$) , G_C is the ground cover, Ea is application efficiency (%), (Ea = 90%), and LR is the leaching requirements.

Potato plants were irrigated at three days' intervals by different amounts of irrigation water. Potato plants received 39 irrigations, the total amounts of irrigation water applied values (as mean two seasons) were 4294.07, 3435.26, and 2576.45 $m^3\ ha^{-1}$ at irrigation treatments I_1, I_2 and I_3, respectively. Deficit irrigation treatments started directly after full germination of potato plants. The network of surface and subsurface drip irrigation systems was installed. In

Agriculture Faculty farm, the irrigation water is taken from Baher Wahby canal which take the irrigation water from Baher Yousef canal. The irrigation water conducted inside the faculty farm in a small well (3 m in length × 3 m in width × 2.5 m in depth) next to the experimental soil, the water pump placed on the edge of the well.



Where 1. Pump, 2. Fertilizer unit, 3. Valve, 4. Main lateral, 5. Sub-mean lateral, 6. I_1, 100%of ETc, 7. I_2, 80%of ETc, 8. I_3, 60%of ETc, 9. The experimental wide, 10. The lateral length, 11. Dike, 12. Double laterals treatment, 13. Single lateral treatment,14. Zero lateral depth, 15. 15 cm lateral depth, 16. 30 cm lateral depth, 17, 18 and 19 are the three replicates, and 20. The experimental length.

Fig. (1). Layout of the field experiment, shows the deficit irrigation, partial root zone drying irrigation and buried lateral depths treatments.

Irrigation system component

The drip irrigation system consists of a water pump (3 hp), fertilizer tank, mainline (made of PVC in 75 mm of diameter), sub-mainline (made of PE in 50 mm of diameter), dripper lines (laterals) made of PE in 16 mm of diameter, drippers and other accessories i.e., control valves, pressure gauges, water meters gauge, valves, connectors, and the end of dripper lines. Each main plot had one valve in the main irrigation line. The length of each lateral line was 15 m, and the drippers paced 0.3 m apart. Each dripper had flow rate of 4 l h^{-1} at 1.0 bar operation pressure. One valve has been placed in the beginning of each dripper line. PRD irrigation is used in the double laterals treatment (one lateral is open during irrigation and the other is off, and opposite that in the following irrigation).

Plant type

Potato (*Solanum tuberosum* L.) seeds tubers (Spunta variety) were planted in two successive springer seasons (2021 and 2022). Potato seeds were manually planted in the 10th February in the 1st and in the 12th February in the 2nd season, in hills 20 cm apart from each other. Potato plants were harvested after 120 days of planting. Compost was applied for all treatments in the experimental field (at rate 20 t ha^{-1}) before planting. Potato plants received NPK fertilizers requirements on the different doses as 285.71 kg N, 107.14 kg P_2O_5 and 114.29 kg K_2O units ha^{-1}, which in equal to 857 kg ha^{-1} of ammonium nitrate (33.5% N), 148 kg ha^{-1} of phosphoric acid (72.4% P_2O_5) and 238 kg ha^{-1} of potassium sulphate (48% K_2O), respectively. Before planting operation will be added 55.71 kg N, 35.14 kg P_2O_5 and 29.28 kg K_2O units of ammonium nitrate, superphosphate and potassium sulphate, respectively during land preparation. During plant growth season will be added 230 kg N, 72 kg P_2O_5 and 85 kg K_2O units of ammonium nitrate, phosphoric acid, and potassium sulphate, respectively, by fertigation.

Measurements and calculations

At the harvest time, seven plants were chosen randomly from each experimental unit and carried to the laboratory, the measurements were recorded as the follows:

1. Yield of potato tubers

Tuber's yield was estimated by weighing the total harvested tubers (t ha^{-1}). Potato tubers sizes were grading by sorted into three grade sizes based on tubers diameter: > 60 mm, 30 - 60 mm, and < 30 mm.

2. Yield quality of potato tubers

Some physical characteristics of potato tubers were measured as follows:

a. Real density of potato tubers

Mass of the potato tuber was measured by electric digital balance (Metler Model - Range 0-600 g ± 0.01 g, Japan). Measuring the tubers volume (cm^3) by water displacement method was used. The determination was replicated four times and the mean was considered. Real density (ρ_s) of tubers was calculated from the following Equation:

$$\rho_s = \frac{\text{Mass of potato tubers (g)}}{\text{Volume of potato tubers (cm}^3\text{)}}$$

b. Potato tuber firmness

A digital penetration resistance meter (FGN-50) with accuracy of 0.1 N was used for measuring both potato tubers firmness. Firmness was measured by pressing a flat end of appropriate plunger with diameter of 12.22 mm into each tuber of the concerned sample to a depth of 8 mm. The reading converted from Newton to kg cm^{-2}.

3. Water productivity (WP) of potato crop

The WP values (kg m^{-3}) values were calculated after harvesting using the following Eq. according to **(Fessehazion et al., 2011).**

$$WP = \frac{\text{Potato tubers (kg ha}^{-1})}{\text{Irrigation water applied (m}^{3}\text{ ha}^{-1})}$$

4. Crop production functions

The potato crop production functions were calculated of the relations between the yield of potato crop and the irrigation water applied.

5. Profit net of potato crop

The prices of potato crop production (economic income), and agricultural requirements and management operations (total costs) values were calculated during the two years of cultivation. The total costs (L.E. ha^{-1}) = fixed costs + variable costs. The fixed costs = prices of the network of the drip irrigation (pump, main laterals lines, sub-main laterals lines, dripper lateral lines, valves, gauges, fertilizer unit and end of dripper lines). The variable costs = prices of the production requirements (Table, 4). The profit net values (L.E. ha^{-1}) were calculated as the following Eq.:

Profit net = Economic income - Total costs

6. Statistical and data analysis

All data were subjected to analysis of variance (ANOVA) according to **Gomez and Gomez (1984)** using InfoStat software estadistico. LSD values between treatments were calculated and compared at $P \leq 0.05$.

RESULTS AND DISCUSSIONS

1. Potato tubers quality

a). The size distribution of potato tubers yield

Table (4) showed that the effect of drought stress (deficit irrigation and PRD irrigation) on the size distribution of potato tubers yield values under surface and SDI systems. Results indicated that the grade size values of potato tubers yield as descending in the following order: (30-60 mm) > (> 60 mm) > (< 30 mm). The sizes of potato tubers yield values were significantly affected by deficit irrigation treatments. Full irrigation treatment (I_1) gave the highest values of grade size 30-60 mm of potato tuber yield under SDI with buried lateral depth at 15 cm. While, the deficit irrigation treatment (I_3) gave the highest potato tuber yield values at grade size < 30 mm under SDI with buried lateral depth at 30 cm. These results are in agreement with those reported by **Mattar et al. (2021),** who found that the irrigation water deficiency resulted in smaller potato tubers and lower crop yield. The mean values of the size potato tubers decreased by 12.23 and 27.96% when deficit irrigation increased from I_1 to I_2 and I_3, respectively, under PRD (double lateral) and SDI with buried lateral at 15 cm depth. These results are compatible with those reported by Abdalgawad et al. (2023).

The size of potato tubers yield values were significantly affected by the partial root zone drying irrigation. Under grade size 30-60 mm of potato tubers and PRD (double laterals), the values of the potato tubers yield were increased by 40.74, 2.03, and 13.75% for full irrigation treatment (I_1), and by 32.24, 10.67 and 9.19% for deficit irrigation (I_2), and by 30.71, 31.27 and 21.27% for deficit irrigation (I_3), at surface drip irrigation (0 cm of laterals), and SDI with buried lateral at 15 and 30 cm depths, respectively, as compared to single lateral treatments. These results are similar with those reported by **Singh and Changade (**2022). Under grade size 30-60 mm, the highest mean two seasons value of the potato tubers yield was 31.942 t ha^{-1}, and it was recorded when plants were irrigated with I_1 under PRD irrigation and SDI with buried lateral at 15 cm depth.

Table (4). Effect of drought stress (deficit irrigation and partial root zone drying irrigation) on the distribution size of potato tubers yield values (t ha^{-1}) under surface and subsurface drip irrigation systems (as mean values of two seasons).

Partial Root zone	Irrig. treat.	Surface drip irrigation system				Subsurface drip irrigation system							
		0 cm depth				15 cm depth				30 cm depth			
		> 60 mm	30-60 mm	< 30 mm	Mean	> 60 mm	30-60 mm	< 30 mm	Mean	> 60 mm	30-60 mm	< 30 mm	Mean
Single lateral	I_1	14.033	22.521	2.309	12.954	9.285	31.308	3.370	14.654	11.345	27.444	2.565	13.785
	I_2	13.210	21.318	1.794	12.107	10.827	26.941	3.399	13.722	9.417	26.249	2.319	12.662
	I_3	7.822	16.386	3.094	9.101	9.859	17.709	2.500	10.023	8.498	16.967	3.258	9.574
	Mean	11.688	20.075	2.399	11.387	9.990	25.319	3.090	12.800	9.753	23.553	2.714	12.007
Double laterals	I_1	9.070	31.696	2.600	14.455	12.917	31.942	4.583	16.481	12.484	31.217	1.145	14.949
	I_2	8.204	28.191	2.279	12.891	11.602	29.816	2.576	14.665	10.751	28.660	1.634	13.682
	I_3	6.609	21.418	2.395	10.141	9.512	23.246	2.862	11.873	9.661	20.609	2.001	10.757
	Mean	7.961	27.102	2.425	12.496	11.344	28.335	3.340	14.340	10.965	26.829	1.593	13.129

Where: Each value in this table is an average of 3 replications. I_1, I_2 and I_3 are the deficit irrigation treatments, 100%, 80% and 60% of crop evapotranspiration (ETc), respectively.

The lowest value (as mean two seasons) of the potato tubers yield was 16.386 t ha^{-1}, and it was recorded when potato plants were irrigated with I_3 under surface drip irrigation. These results are in agreement with those reported by **Badr et al.** (**2022)**.

b). Some physical properties of potato tubers

1. Real density of potato tubers

Table (5) and Figure (2) showed the effect of drought stress (deficit irrigation and PRD irrigation) on the real density values (g cm^{-3}) of potato tubers under surface drip and subsurface drip irrigation systems. The mean two-seasons values of the real density of potato tubers decreased by 0.55 and 1.30% when deficit irrigation increased from I_1 to I_2 and I_3, respectively. Changes in average tuber size in response to increasing the real density had a similar pattern to average plant yield or biomass.

Table (5). Effect of drought stress (deficit irrigation and partial root zone drying irrigation) treatment on the real density values (g cm^{-3}) of potato tubers under surface drip and subsurface drip irrigation systems (as mean values of two seasons).

Deficit irr. treat.	Depth of lateral (cm)	Real density, g cm^{-3}			Firmness of potato tubers, kg cm^{-2}			Water productivity (kg m^{-3})		
		Partial root zone			Partial root zone			Partial root zone		
		Single Lateral	Double laterals	Mean	Single lateral	Double laterals	Mean	Single lateral	Double laterals	Mean
I_1, 100% of ETc	0	1.074	1.077	1.076	3.02	2.91	2.97	9.05	10.10	9.58
	15	1.080	1.087	1.084	3.06	2.98	3.02	10.24	11.51	10.88
	30	1.078	1.083	1.081	3.12	3.07	3.10	9.63	10.44	10.04
	Mean	1.077	1.082	1.080	3.07	2.99	3.03	9.64	10.68	10.16
I_2, 80% of ETc	0	1.069	1.072	1.071	3.14	3.05	3.10	10.57	11.26	10.92
	15	1.074	1.081	1.078	3.20	3.11	3.16	11.98	12.81	12.40
	30	1.071	1.075	1.073	3.26	3.15	3.21	11.06	11.95	11.51
	Mean	1.071	1.076	1.074	3.20	3.10	3.15	11.20	12.01	11.61
I_3, 60% of ETc	0	1.062	1.065	1.064	3.17	3.10	3.14	10.60	11.81	11.21
	15	1.068	1.069	1.069	3.26	3.15	3.21	11.67	13.82	12.75
	30	1.064	1.067	1.066	3.29	3.19	3.24	11.15	12.52	11.84
	Mean	1.065	1.067	1.066	3.24	3.15	3.19	11.14	12.72	11.93

LSD values at 5%	DI	PRD	Depth	DI * PRD	DI * Depth	PRD* Depth	DI *PRD* Depth
Real density	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Firmness of tubers	0.012	0.010	0.012	0.016	0.020	0.017	0.029
Water productivity	0.012	0.009	0.012	0.016	0.020	0.016	0.028

Where: Each value in this Table is an average of 3 replications. I_1, I_2 and I_3 are the deficit irrigation treatments, 100%, 80% and 60% of crop evapotranspiration (ETc), respectively, DI is deficit irrigation, PRD is partial root zone drying.

These results are parallel with those reported by Knowles and Knowles (2006). The mean values of the real density were increased by 0.74 and 0.46% at full irrigation treatment (I_1), by 0.65 and 0.19% at the deficit irrigation treatment (I_2) and by 0.47 and 0.19% at the deficit irrigation treatment (I_3), when compared to surface drip irrigation (0 cm depth) to subsurface drip irrigation with buried lateral at 15 and 30 cm depths.

Under full irrigation treatment, PRD treatment led to increases in the mean values of the real density of potato tubers by 0.46%, 0.47%, and 0.19% as compared to single lateral treatments at deficit irrigation treatments I_1, I_2 and I_3, respectively. The highest value of the real density of potato tubers was 1.087 g cm^{-3}, and it was recorded at potato plants irrigated with I_1 under PRD irrigation and SDI with buried lateral at 15 cm depth.

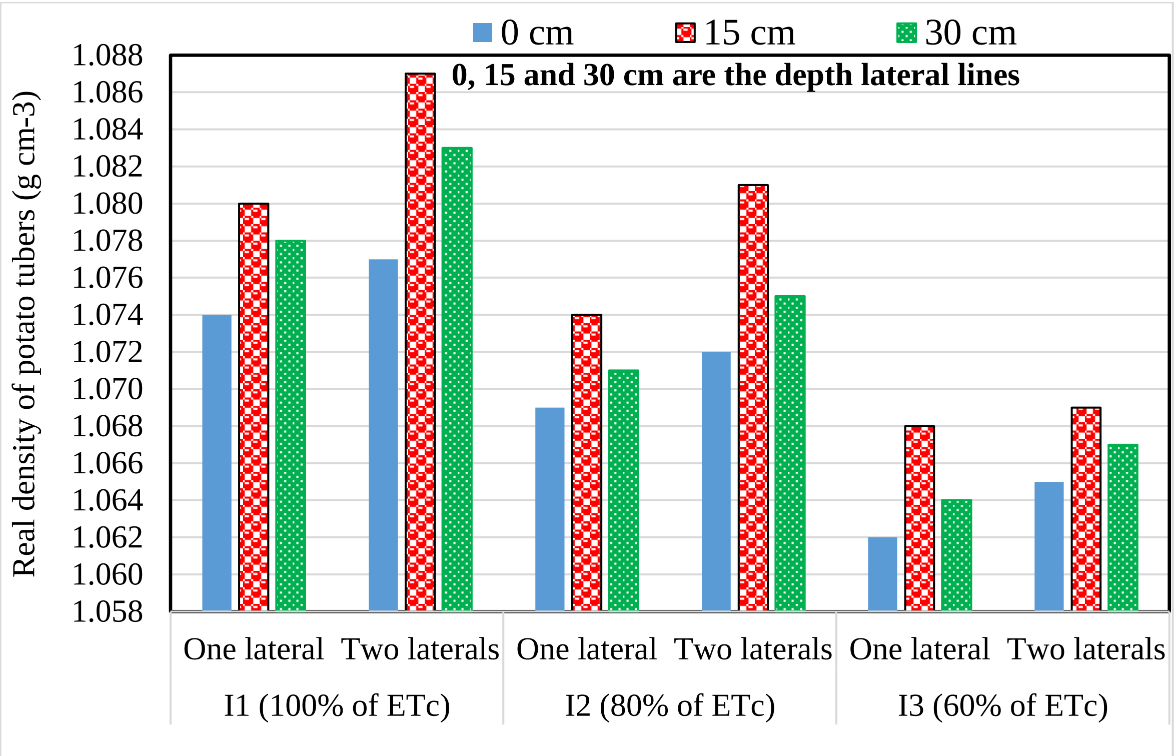


Fig. (2). Effect of drought stress (deficit irrigation and partial root zone drying irrigation) treatment on the real density values (g cm^{-3}) of potato tubers under surface and subsurface drip irrigation systems (as mean values of two seasons).

2. The firmness of potato tubers

Table (5) and Figure (3) showed the effect of drought stress (deficit irrigation and PRD irrigation) on the firmness values of potato tubers under surface drip and SDI systems. The mean values of the tuber firmness increased by 3.96 and 5.28% when deficit irrigation treatments increased from I_1 to I_2 and I_3, respectively. The percentage of increases in the firmness values of potato tubers under SDI with buried lateral at 30 cm depth are highly at deficit irrigation (I_3) as compared to other irrigation treatments I_1 and I_2.

PRD irrigation treatment led to decreases in the mean values of the tubers firmness by 2.61% at full irrigation treatment, by 3.13% at deficit irrigation treatment I_2 and by 2.78% at deficit irrigation treatment I_3 as compared to single lateral treatments. The mean values of the tuber firmness was increased by 1.68 and 4.38% at the full irrigation treatment I_1, by 1.94 and 3.55% at the deficit irrigation treatment I_2, and by 2.23 and 3.18% at the deficit irrigation treatment I_3, when the buried lateral depths changed from surface drip irrigation (zero cm depth) to subsurface drip irrigation at 15 and 30 cm depths, respectively. The highest value of tuber firmness was 3.29 kg cm^{-2}, and it was recorded when plants were irrigated with deficit irrigation treatment I_3 under PRD and subsurface drip irrigation with buried lateral at 30 cm depth. These results are parallel with those reported by **El-Sayed et al. (2022),** who found that there is an increasing significant effect on the average firmness values of tomato fruits when increasing the drought levels of different irrigation treatments.

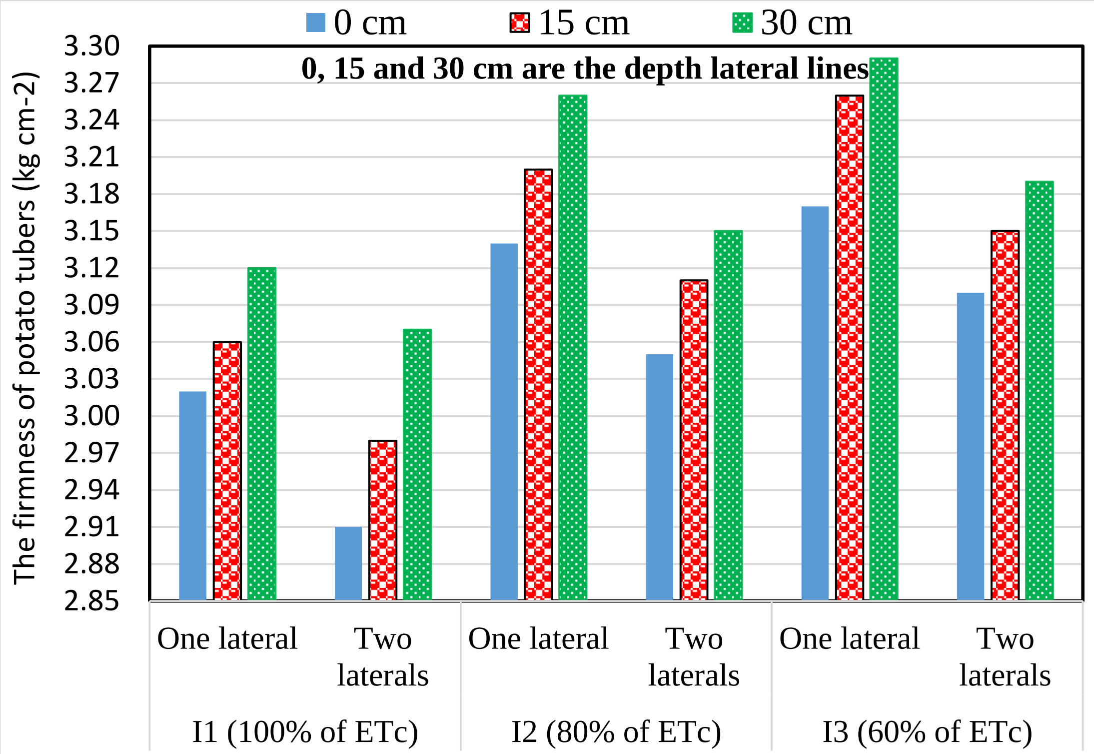


Fig. (3). Effect of drought stress (deficit irrigation and partial root zone drying irrigation) treatment on the firmness values (kg cm^{-2}) of potato tubers under surface and subsurface drip irrigation systems (as mean values of two seasons).

2. The irrigation water applied

Table (6) illustrates the effect of drought stress (deficit irrigation and PRD irrigation) on the irrigation water applied (IWA) of potato tubers under surface and subsurface drip irrigation systems. The values mean two seasons of the total IWA were 4294.07, 3435.26, and 2576.45 m^3 ha^{-1} at the irrigation treatments I_1 to I_2 and I_3, respectively. The IWA values were the highest with the irrigation treatment I_1 as compared to other deficit irrigation treatments I_2, and I_3. The IWA values were low at the initial stage and increased at the development growth stage. The values reached their maximum during the mid-growth stage due to the plant roots and shoots being at maximum the maximum growth, after that, the values were decreased at the late growth stage under the 1st, 2nd, and the mean two seasons.

3. The water productivity of potato crop

Figure (4) showed the effect of drought stress (deficit irrigation and PRD irrigation) on the water productivity (WP) values of potato crops grown under surface and SDI systems. The results indicated that the values of the WP of the potato crop were significantly affected by deficit irrigation treatments.

Table (6). Irrigation water applied values (m^3 ha^{-1}) under different deficit irrigation treatments, different potato growth stages at the 1st, 2nd and the mean two seasons and surface and subsurface drip irrigation systems.

Season	Growth stage	I_1 100% of ETc	I_2 80% of ETc	I_3 60% of ETc
1st season	Initial	102.71	82.17	61.64
	Development	793.57	634.86	476.14
	Mid.	1837.55	1470.05	1102.52
	Late	1572.98	1258.38	943.79
	Total	4306.81	3445.45	2584.10
2nd season	Initial	107.29	85.83	64.38
	Development	806.55	645.24	483.93
	Mid.	1839.38	1471.50	1103.62
	Late	1528.12	1222.50	916.88
	Total	4281.33	3425.07	2568.81
Mean two seasons	Initial	105.00	84.00	63.01
	Development	800.06	640.05	480.04
	Mid.	1838.46	1470.77	1103.07
	Late	1550.55	1240.44	930.33
	Total	4294.07	3435.26	2576.45

The mean values of the WP increased by 14.27 and 17.42% when deficit irrigation increased from I_1 to I_2 and I_3, respectively. The maximum values of the WP of the potato crop were detected when the potato plants were irrigated with the highest deficit irrigation treatment (I_3). These results are in agreement with those found by **Mattar et al. (2020),** who concluded that deficit irrigation practice leads to an increase in WP values despite a reduction in crop yield as compared to full irrigation.

PRD irrigation treatment (double laterals) led to increases in the mean values of the WP by 10.79%, 7.23%, and 14.18% at irrigation treatments I_1, I_2, and I_3, respectively, as compared to single lateral lines treatments. The increases in the WP of potato crop values under PRD irrigation are attributed to the higher uniformity in the distribution of irrigation water along drip lines in the root zone, and to increasing the potato crop production (m^3 ha^{-1}). These results are in agreement with those found by **Akkamis and Caliskan (2023)**.

The mean values of the WP of potato crop were increased by 13.57 and 4.80% at the irrigation treatment I_1, and by 13.55 and 5.40% at the deficit irrigation treatment I_2, by 13.74 and 5.62% at the deficit irrigation treatment I_3, under SDI with buried lateral at 15 and 30 cm depths as compared to surface drip (0 cm lateral depth). In the sandy loam soil, the greater vertical water movement took place rather than that of capillary rise. These results are parallel with those reported by Dukes and Scholberg (2005), who found that drip laterals placed below 23 cm of soil depth failed to provide adequate water to corn grown in sandy soil. The highest value of the WP was 13.82 kg m^{-3}, and it was recorded when potato plants were irrigated with I_3 under PRD irrigation with buried lateral at 15 cm depth. While the lowest value of the WP was 9.05 kg m^{-3}, it was recorded when potato plants were irrigated with I_1 under single lateral conditions (0 cm lateral depth). These results are compatible with those reported by **Kanda et al. (2020),** who found that the highest WP was obtained under sub-surface drip irrigation system and 70 % of ETc.

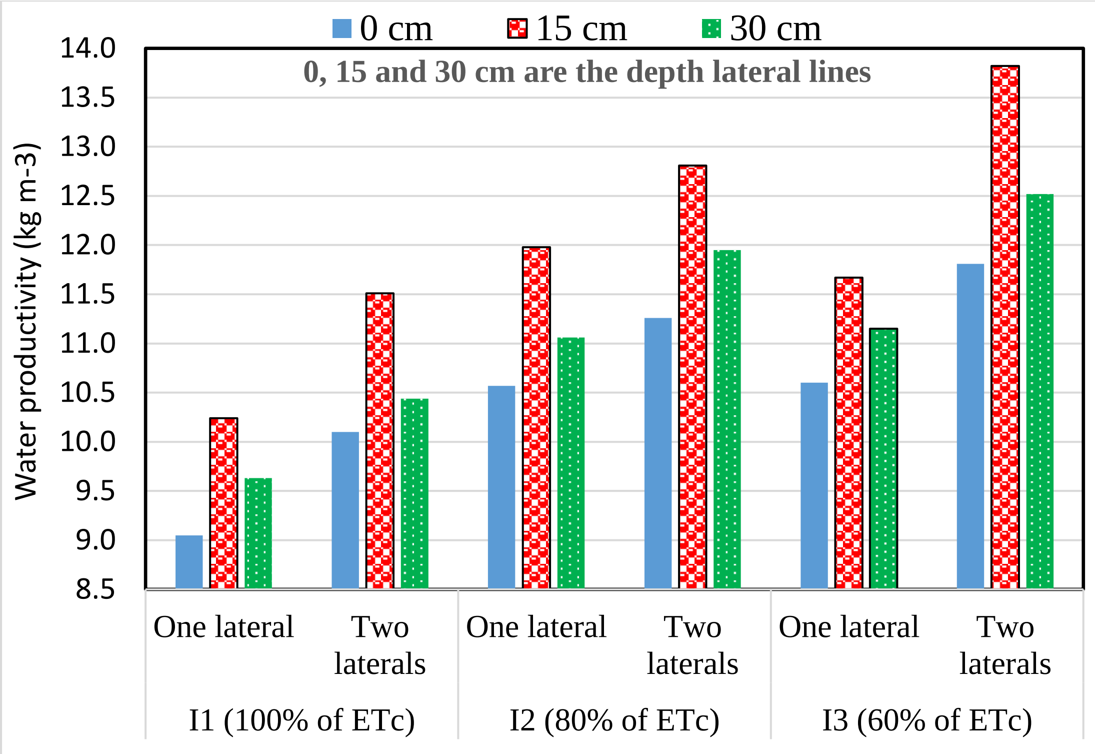


Fig. (4). Effect of drought stress (deficit irrigation and partial root zone drying irrigation) treatment on water productivity values (kg m^{-3}) of potato tubers under surface and subsurface drip irrigation systems (as mean values of two seasons).

4. Water production functions

Data in Figure (5) indicated that the relationships between irrigation water applied (IWA) and productivity of potato crops grown under surface and SDI systems at the 1st, 2nd, and mean two seasons. There were significant increases in the productivity of potato crop values when the IWA increased. When the IWA decreased by 20% (I_2, 80% of ETc treatment), the productivity of potato crop decreased by 8.21, 9.08, and 8.65% at the 1st, 2nd, and mean two seasons, respectively. Also, when the IWA decreased by 40% (I_3, 60% of ETc treatment), the productivity of potato crop decreased by 30.77, 28.39, and 29.57% at the 1st, 2nd and mean values of two seasons, respectively. The correlation coefficient values between the productivity of potato crop and the IWA were 0.9324, 0.9586, and 0.9457 at the 1st, 2nd, and mean two seasons, respectively.

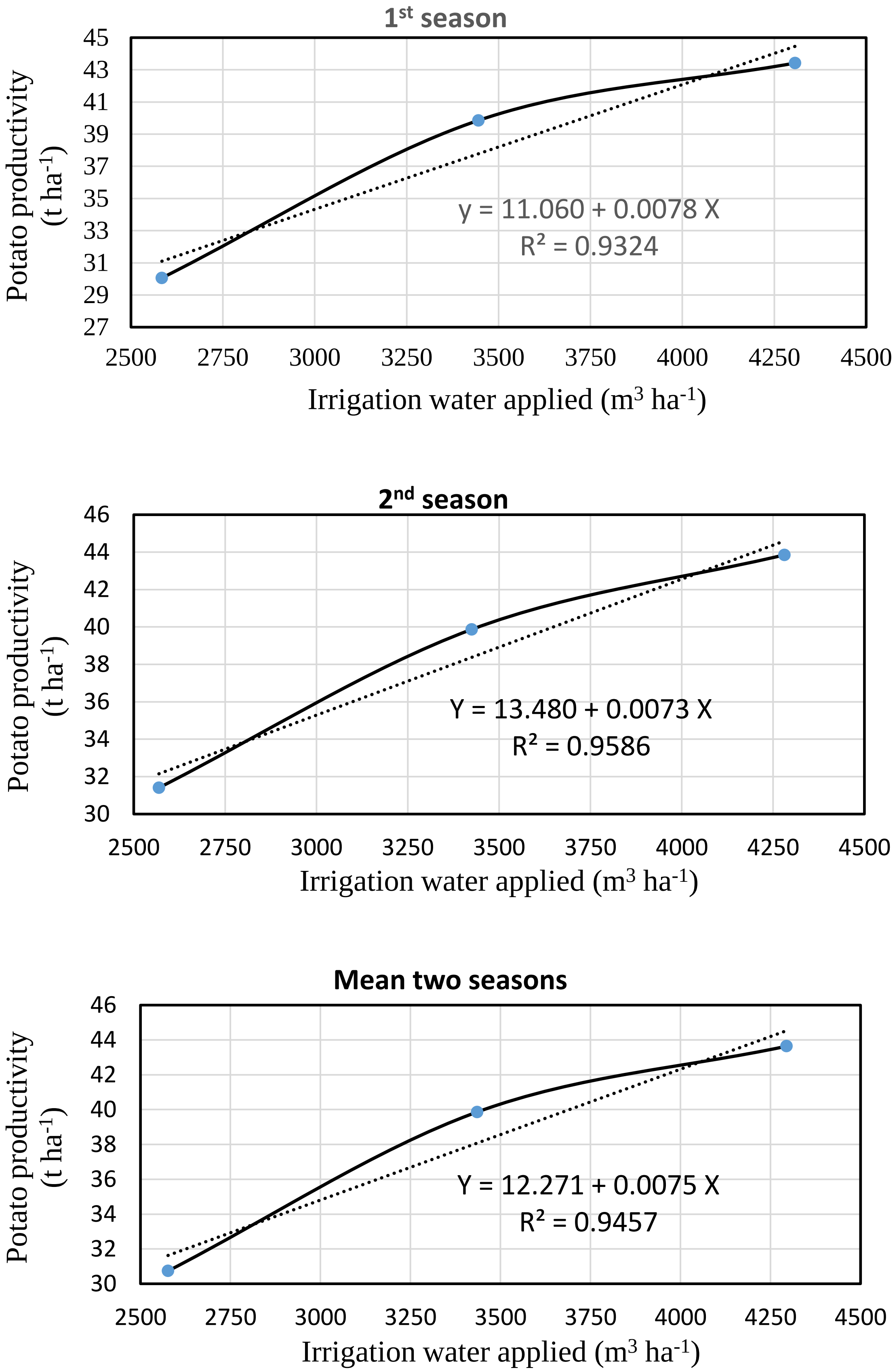


Fig. (5). The relationships between irrigation water applied and productivity of potato crop grown under surface and subsurface drip irrigation systems at the 1st, 2nd and mean values of two seasons.

The simple regression equations between the productivity of potato crop and the IWA are the following:

1st season	$Y = 11.060 + 0.0078\,X$
2nd season	$Y = 13.480 + 0.0073\,X$
Mean two seasons	$Y = 12.271 + 0.0075\,X$

Where: Y is the productivity of potato crop (t ha^{-1}), and X is the irrigation water applied (m^3 ha^{-1}).

From the previous equations, it could be predicted that the productivity of potato crop grown under surface and SDI systems decreased when decreases occurred in the irrigation water amounts, which resulted from climate changes or shortages in the irrigation water resources. This is a practice used to confront the challenges of the irrigation water scares required for agriculture in the future. These results are consistent with those obtained by **El Gindy and Abdel Aziz (2003).**

5. Profit net of potato crop

Table (7) showed the effect of (deficit irrigation and PRD irrigation) on the profit net of potato crops grown under surface and SDI systems. The highest value of the profit net of the potato crop was 274906 L.E. ha^{-1}, and it was recorded at irrigation treatment I_1, PRD, and subsurface drip irrigation with buried lateral at 15 cm depth. The lowest value of profit net of potato crop was 121436 L.E. ha^{-1}, and it was recorded at irrigation treatment I_3, and single laterals (zero cm depth). These results are in agreement with those concluded by **Shock et al. (2007),** who found that the increase in IWA of potatoes could return a greater in profit net. Increasing the deficit irrigation treatments from I_1 to I_2 and I_3 led to decreases in the mean values of profit net of potato crop by 10.96 and 37.91%. The highest values of profit net of potato crop at full irrigation treatment (I_1) attributed to the potato growth and yield were higher and the IWA is optimum as compared to other deficit irrigation treatments.

Table (7) showed that using the PRD irrigation (double lateral lines) led to an increase in the mean values of profit net by 14.39% at the I_1 treatment, by 9.66% at the I_2 treatment, and by 21.73% at the I_3 treatment as compared to using single lateral treatments. These increases might be attributed to the higher moisture distribution, which led to enhancing the roots and shoot growth of the plants and increasing the potato yield. These results are in agreement with those reported by **Topak et al.** (**2011),** who found that 25% saving in IWA caused 6.1% reduction in the profit net.

Under full irrigation treatment (I_1), the profit net values increased by 15.09 and 7.72% with single lateral conditions and by 15.47 and 11.70% with PRD irrigation (double lateral lines) with SDI and buried lateral at 15 and 30 cm depths, respectively, as compared to zero cm depth. Also, under irrigation treatment (I_2), the profit net values increased by 15.58 and 10.23% with single lateral treatments and by 15.67 and 8.69% with PRD irrigation with SDI and buried lateral at 15 and 30 cm depths, respectively, as compared to zero cm depth.

Table (7). Economic income (L.E. ha^{-1}) from potato crop as influenced by deficit irrigation treatments, partial root zone drying and soil lateral depths, under subsurface drip irrigation system (as average values of two seasons)*.

Irrig. treat.	Partial root zone	Depth of lateral (cm)	No. of hour Irrig.	Price of applied irrigation L.E.	Fixed costs (L.E. ha^{-1})	Variable costs (L.E. ha^{-1})	Total costs (L.E. ha^{-1})	Mean potato yield (t ha^{-1})	Price of 1 ton of potato (L.E.)	Income of potato yield (L.E.)	Profit net of potato yield (L.E.)	Mean profit net of PRZ (L.E.)	Mean econ. income of irrig. treat. (L.E.)	Mean profit net of irrig. treatments (L.E.)
I_1 (100% of ETc)	One lateral	0	37.57	3757	5238	62186	71181	38.862	7000	272034	200853			
		15	37.57	3757	5238	62186	71181	43.961	7000	307727	236546	218563		
		30	37.57	3757	5238	62186	71181	41.353	7000	289471	218290		305465	234284
	Two laterals	0	37.57	3757	5238	62186	71181	43.365	7000	303555	232374			
		15	37.57	3757	5238	62186	71181	49.441	7000	346087	274906	250005		
		30	37.57	3757	5238	62186	71181	44.845	7000	313915	242734			
I_2 (80% of ETc)	One lateral	0	30.06	3006	5238	62186	70430	36.322	7000	254254	183824			
		15	30.06	3006	5238	62186	70430	41.167	7000	288169	217739	199007		
		30	30.06	3006	5238	62186	70430	37.984	7000	265888	195458		279048	208618
	Two laterals	0	30.06	3006	5238	62186	70430	38.675	7000	270725	200295			
		15	30.06	3006	5238	62186	70430	43.992	7000	307944	237514	218229		
		30	30.06	3006	5238	62186	70430	41.044	7000	287308	216878			
I_3 (60% of ETc)	One lateral	0	22.54	2254	5238	62186	69678	27.302	7000	191114	121436			
		15	22.54	2254	5238	62186	69678	30.067	7000	210469	140791	131201		
		30	22.54	2254	5238	62186	69678	28.722	7000	201054	131376		215135	145457
	Two laterals	0	22.54	2254	5238	62186	69678	30.421	7000	212947	143269			
		15	22.54	2254	5238	62186	69678	35.619	7000	249333	179655	159712		
		30	22.54	2254	5238	62186	69678	32.27	7000	225890	156212			

Where*, **The variable costs = 62186 L.E. ha^{-1}** = {15-ton compost × 700 L.E. = 10500 L.E. + 1800 L.E. preparing the soil + 1900 kg seeds × 14 L.E. = 26600 L.E. + 1400 L.E. planting + 1400 L.E. hoeing + 600 L.E. weeds protection + 800 L.E. insects protection + fertilizers (17 ammonium nitrate bags × 250 L.E. = 4250 L.E. + 150 L.E. superphosphate + 38 L phosphoric acid × 25 L.E. = 950 L.E. + 238 kg potassium sulphate × 32 L.E. = 7616 L.E. + 182 kg magnesium sulphate × 10 L.E. = 1820 L.E. + 500 L.E. calcium Nitrate + 5 kg humic × 120 L.E = 600 L.E.) + 1800 L.E. fuel + 1400 L.E. harvesting}. One hour irrigation = 100 L.E., Ton of potato yield = 7000 L.E., (PRZ = partial rot zone).

Under deficit irrigation treatment (I_3), the profit net values increased by 13.75 and 6.69% with single lateral treatments and by 20.25 and 13.05% with PRD irrigation, with subsurface drip irrigation and buried lateral at 15 and 30 cm depths, respectively, as compared to zero cm depth.

Under all deficit irrigation treatments, the profit net values of potato crops are highly subsurface drip irrigation as compared to surface drip irrigation when laterals are either single or double lines in the cultivated ridge. The increases in the values of profit net under PRD irrigation with subsurface drip irrigation and buried lateral 15 cm depth might be due to increasing the soil moisture around the potato roots. But at the zero cm depth of the lateral line, some of the soil moisture losses by evaporation, and at the 30 cm lateral depth some of the soil moisture losses to moving down by gravity. These results are in agreement with those reported by **(Kumar et al., 2007),** who concluded that the drip irrigation at 1.2 IW/CPE ratio significantly increased the net return as compared to 0.6, 0.8 and 1.0 IW/CPE ratio.

CONCLUSIONS

It could be recommended that, when irrigation water is abundant, it could be using the full irrigation treatment I_1, PRD irrigation with subsurface drip irrigation and lateral buried at 15 cm depth, to reach the highly significant increases in the growth, yield, yield quality, and profit net of potato crop. While, under shortage of the water resources, it could be using deficit irrigation treatment (I_2), PRD irrigation with SDI, and lateral buried at 15 cm depth; this will save about 20 % of the IWA (859 m^3 ha^{-1}) with a low decrease in the yield (about 8 %) of the potato crop.

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تأثير الجفاف على جودة المحصول وإنتاجية المياه والربح لمحصول البطاطس المنزرع تحت الري بالتنقيط السطحي مقابل الري بالتنقيط تحت السطحي

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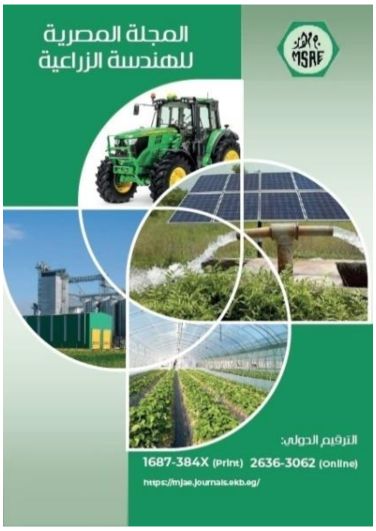

الكلمات المفتاحية:
الري المتناقص، الري بالتجفيف الجزئي لمنطقة الجذور، جودة وإنتاجية المياه، صافي الربح، الري بالتنقيط السطحي وتحت السطحي.

الملخص العربي

تواجه الزراعة تحديات في توزيعات المياه والمضاعفات الناجمة عن التغيرات المناخية، أجريت تجارب حقلية بمزرعة دمو، كلية الزراعة، جامعة الفيوم. تم زراعة درنات البطاطس في موسمين (٢٠٢١ و٢٠٢٢). استخدمت ثلاث معاملات من الري المتناقص (DI): I_1 و I_2 و I_3 (١٠٠و ٨٠ و ٦٠٪ من ETc). تم استخدام معاملتان من الري بالتجفيف الجزئي لمنطقة الجذور (PRD): خط واحد، خطان من خطوط المنقطات على خط الزراعة. تم استخدام ثلاثة أعماق لخطوط المنقطات: الري بالتنقيط السطحي، وتحت السطحي (١٥، ٣٠ سم). تم تقدير توزيع أحجام الدرنات وبعض الخصائص الفيزيائية لها وانتاجية المياه (WP) وصافي الربح لمحصول البطاطس. تشير النتائج إلى أن أعلى قيم لأقطار درنات البطاطس وجدت عند الحجم (٣٠-٦٠ مم)، ووجد أن أعلى قيمة لمحصول الدرنات والكثافة الحقيقية وصافي الربح كان ٣١,٩٤٢ طن/هكتار، ١,٠٨٧ جم/سم^3 و ٢٧٤٩٠٦ جنيه/هكتار على الترتيب عند المعاملة I_1 والري بأسلوب PRD ونظام SDI مع دفن الخطوط على عمق ١٥ سم. وجد أن أعلى قيمة ال WP للمحصول كان ١٣,٨٢ كجم/ م^3 عند المعاملة I_3 تحت نظام SDI مع دفن خطوط المنقطات على عمق ١٥ سم. عند انخفاض قيم مياه الري المضافة (IWA) بنسبة ٢٠٪ و٤٠٪ انخفضت قيم المحصول بنسبة ٨,٦٥٪ و٢٩,٥٧٪ على الترتيب. يمكن التوصية بأنه عند توفر مياه الري تستخدم معاملة الري I_1 والري PRD ونظام SDI مع دفن الخطوط على عمق ١٥ سم للوصول إلى زيادات معنوية في المحصول وصافي الربح. بينما تحت ظروف نقص مياه الري تستخدم المعاملة I_2 وتقنية الري PRD تحت نظام SDI مع دفن الخطوط على عمق ١٥ سم لتوفير ٢٠٪ من IWA مع انخفاض في المحصول بحوالي ٨٪.