Egypt. J. Soil Sci. **Vol. 63**, No. 4, pp: 553-569 (2023)

Egyptian Journal of Soil Science

http://ejss.journals.ekb.eg/

Assessment of Potato Growth and Yield under Smart Irrigation

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WATER scarcity is increasing in the world. There is a need to adopt irrigation management practices that can help to conserve water and sustain crop production in such water-limited areas. Potato productivity is generally influenced by irrigation water levels and irrigation systems, which depend on the soil type. In order to do so, the study aims to assess the vegetation and yield of potato varieties under a smart drip irrigation system to find out the best management of the irrigation scheduling for improving the growth and yield of potato crops. In this concern, two field experiments were conducted in two successive summer seasons of 2020 and 2021 at the experimental farm of the National Research Centre in El-Nubaria, El-Behira Governorate, Egypt, to investigate the effects of four irrigation levels (120, 100, 80 and 60% ETc) under two drip irrigation systems (surface drip irrigation (SDI) and subsurface drip irrigation (SSDI)) on three potato varieties (Spunta, Hermes and Cara). The results indicated that all the studied growth aspects were significantly increased with increasing the irrigation levels applied during both growing seasons, except water use efficiency (WUE) which significantly increased with decreasing irrigation level up to a certain limit. Also, the results showed that SSDI showed superior upon SDI with all vegetative, yield growth characteristics and WUE. Regarding the response of some potato varieties to irrigation systems and levels, results revealed that the highest value for an average tubers weight and yield /plant was recorded with Spunta followed by Cara and Hermes.

Keywords: Irrigation systems, Potato varieties, Smart irrigation.

1. Introduction

Shortage of water is considered the most important challenge that many countries are facing. Egypt is located in semiarid to arid climates regions. The total amount of available water in Egypt is about 55.5 milliard m^3 /year, and the agricultural sector consumes about 85% of the available water. However, in Egypt water availability for agriculture production is being reduced as a consequence of global climate change, and growing demand for other uses. Therefore, effective irrigation management is considered an important factor in increasing agricultural productivity, **(El-Sawy *et al.*, 2022; EL-Sayed at al., 2022).**

Potato (Solanum tuberosum L.) is a major food crop and vital source of nutrients for human populations is the potato, **(Eid *et al.*, 2020).** After rice and wheat, potatoes are the third most consumed crop worldwide. Potato is one of the most important crops grown in Egypt for local consumption, export and processing. It offers cheap carbohydrates and a range of vitamins and nutrients that are essential in a human diet, making it a substantial source of national income in Egypt. Also, potatoes are highly valued as an export good and are a significant source of revenue for the country, **(Abd El-Hady e al., 2023)**. The area cultivated with potatoes about 212,000 acres producing about 262.9 thousand hectares, and the total production of tubers reached about 6.91 million tons **(FAOSTAT 2021)**. It is a crop with a

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Received: 28/07/2023; Accepted: 26/08/2023
DOI: 10.21608/EJSS.2023.225688.1625
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short lifespan that is adaptable in usage, ideal for growing in a variety of conditions, and whose production is increasing quickly. It is rich in carbohydrates and has a large variety of nutrients and various bioactive compounds such as flavonoids, carotenoids, and phenolics **(Nasir and Toth, 2022).** Most potato varieties have shallower and less extended roots and, therefore, are more sensitive to water supply than most other crops. Therefore, it is essential for crops to have enough water available in the root zone throughout the entire growing season. In addition, there are specific problems in the management of sandy soils, including their excessive permeability, low water, and nutrient-holding capacities. Therefore, necessary to adopt irrigation strategies aimed at producing more ‘crop per drop’ and maximizing water use efficiency, **(Ghazouani *et al.*, 2019).**

Surface drib irrigation and SSDI is most efficient method of supplying nutrients and water to plants directly, which not only helps to conserve water but also boosts vegetable crop yields. An adequately managed SSDI system wets the root zone uniformly throughout the field while maintaining a dry soil surface; water losses due to evaporation and consequent growth of weeds are therefore reduced, and deep percolation is eliminated which can decrease groundwater pollution. A properly managed SSDI system evenly waters the root zone throughout the field while keeping the soil surface dry. water losses due to evaporation and consequent growth of weeds are therefore reduced, and deep percolation is eliminated which can decrease groundwater pollution, (**Çolak *et al.*, (2015**). In sandy loam textured soil, an SSDI could be utilized to apply water sparingly and save water compared to SDI, **(Badr *et al.*, 2010).** All of these advantages may help to improve water usage efficiency, which has significant implications for soil and water conservation and agricultural sustainability (**Çolak *et al., (*2015**). Overall, several studies have shown that the SSDI system will be a tool accessible to enhance water management and water production for sustainable agriculture in the future. Additionally, SSDI has led to higher yields, less water being applied, better crop quality, and lower expenses for other cultural practices, **(Sadik and Abd El-Aziz, 2018).**

Finding solutions to lower agricultural water usage while preserving or even improving crop yields is important as well **(Cheng *et al.*, 2021).** In areas where there is a lack of water, important irrigation management techniques like deficit irrigation (DI) and irrigation scheduling are gaining popularity to conserve water and maintain crop production. DI, a practice that supplies water below evapotranspiration demands, deliberately exposes plants to a certain level of moisture stress, The key to the regulated deficit irrigation strategy is the timing of the deficit and the degree of the deficit applied to achieve a desired effect on the plant. Regulated deficit irrigation is water saving technology that is relatively inexpensive and easy to implement **(Abdel-Aziz 2017; Parkash and Singh, 2020).** While excess water can also reduce yield below potential levels due to leaching of the applied nutrients, an increase in disease incidence, or failure to stimulate the growth of the commercially valuable parts of the plant, insufficient water results in high soil moisture tension, stressed plants, and reduced tuber yield **(Akkamis and Caliskan, 2021).**

On the other side, farmers could have a tendency to apply excessive amounts of water as "insurance" to reduce the hazards associated with potato production. However, excessive or insufficient irrigation can have a detrimental influence on tuber output, size, grade, and internal and exterior quality. Yield sensitivity to under deficit irrigation is attributed to the susceptibility of potato plants to water stress, particularly during the early tuber bulking stages, and their shallow roots, which can bring about restricted soil water capacity. Over-irrigation can reduce yields due to poor soil aeration, an increase in disease pressure, and nutrient loss from the shallow rooting zone. Therefore, both over- and under-irrigation should be avoided through effective irrigation management. where excessive or deficit soil water availableness throughout the season will adversely have an effect on tuber yield, quality, and storability, **(Crosby and Wang 2021).**

Additionally, smart irrigation systems have the potential to increase water consumption efficiency, particularly with the development of wireless communication technologies, monitoring systems, and sophisticated management algorithms for ideal irrigation scheduling **(Bwambale *et al.*, 2022).** Applying water to a field at the proper time, in the proper amount, and at the proper location is known as smart irrigation. As a result, monitoring and management tactics must be used to schedule irrigation in the best possible way, taking into account variations in soil moisture levels, shifting weather patterns, and the physiological needs of plants. Traditional irrigation methods use irrigation water without taking into account the spatiotemporal variation of soil properties and environmental factors that influence crop evapotranspiration **(Vories *et al.*, 2021).** As a result, the actual depth at which plants receive irrigation water varies spatially. Inadequate irrigation can cause plant stress, which can lower crop production and quality, while over-irrigation causes fertilizer leaching, deep percolation, surface ponding, and runoff. Smart irrigation systems require sensors to monitor soil, plant, and weather conditions in order to implement an optimal irrigation schedule, **(Bwambale *et al.*, 2022).** Smart irrigation methods have the potential to increase farm-level water application efficiencies, thereby assisting in the reduction of agriculture's impact on the environment and providing farmers with an economic advantage **(Hadi and Samer 2021).**

So, this work aims to find out the best management of the irrigation scheduling for improving the vegetative growth and tubers yield of potato crop grown under climate smart irrigation systems, by investigating the effects of four irrigation water levels (120, 100, 80 and 60% ETc) under two drip irrigation systems (surface drip irrigation) and subsurface drip irrigation on three potato varieties (Spunta, Hermes and Cara).

2. Material and Methods

The field experiment was carried out on potato plants (*Solanum tuberosum* L.) during two summer seasons of 10th Jun. 2020 and 15th Jun2021 at the experimental farm of the National Research Centre (NRC), El-Nubaria, El-Behira Governorate, north of Egypt. The experimental location is situated at latitude: 30°29'50"N, and longitude: 30°19'16"E. The research experiment was comprised of four irrigation levels (120, 100, 80, and 60% Etc) under two drip irrigation systems (Surface drip irrigation (SDI) and Subsurface drip irrigation (SSDI) were applied on three potato varieties (Spunta, Hermes, and Cara).

Where drip irrigation system (drip tubing GR type, 16 mm diameter with 30 cm emitter spacing built in (delivering 4 L/h at 1.5 bar) was used in the experiment for the surface and the subsurface drip irrigation treatments. The drip tubes were buried manually at depth of 20.0 cm in the middle of beds before cultivation.

The soil samples were collected at the beginning of the experiment. Mechanical, physical, and chemical properties of soil samples were determined at the standard soil-testing laboratory of NRC. The mechanical and physical analyses were carried out according to **Klute (1986),** while the chemical analyses were carried out according to the procedures outlined by **Page *et al.* (1982).** The mechanical, chemical and physical properties of the collected soils and water are given in Tables (1-2). Also, the monthly average weather data such as minimum temperature (Min. T.), maximum temperatures (Max. T.), relative humidity (RH), precipitation, wind speed (W.S.) and wind direction (W.D.), as shown in Table (3).

Table (1). Physical properties of experimental soil analyses.

Particle size distribution	Values (%)
Sand	94.17
Silt	4.17
Clay	1.66
Texture	**Sandy**

Table (2). Chemical properties of experimental soil and irrigation water analyses.

Chemical properties		Soil	water
pH		7.73	7.97
EC (dS m^{-1})		3.72	1.36
Soluble cations	Ca^{++}	11.70	6.35
($cmol_c$ kg^{-1} soil)	Mg^{++}	5.05	4.11
	Na^{+}	17.30	5.95
	K^{+}	3.13	0.23
Soluble anions	CO_3^{--}	Not detected	Not detected
($cmol_c$ kg^{-1} soil)	HCO_3^{-}	0.64	2.97
	Cl^{-}	25.15	4.36
	SO_4^{--}	11.35	5.12

Table (3). Metrological data of study area during seasons 2020 and 2021*.

Month	Min. T. ºC	Max. T. ºC	Relative Humidity (%)	Precipitation (mm)	Wind Speed (m/s)	Wind Direction (Degrees)
First season (2020)						
Jan.	8.16	18.30	70.15	0.93	2.98	239.02
Feb.	8.46	20.68	67.65	0.74	2.46	246.35
March	9.94	24.58	62.49	2.26	3.01	212.50
April	12.35	27.18	60.62	3.58	2.66	221.79
May	15.62	32.83	56.03	0.00	2.99	186.03
Second Season (2021)						
Jan.	9.21	21.80	63.98	0.15	2.58	169.74
Feb.	9.11	22.25	64.93	1.03	2.25	215.22
March	9.97	23.45	63.22	2.63	2.75	210.60
April	11.63	29.74	53.96	0.02	2.98	177.09
May	9.21	36.94	44.08	0.00	2.90	210.36

* Metrological data were obtained from Central Laboratory for Agricultural Climate (CLAC).

2.1. Irrigation requirements

The irrigation water requirement was calculated according to Food and Agricultural Organization (FAO) Penman- Monteith (PM) procedure, FAO 56 **(Allen et al., 1998)**, the results are showed in Table (4-6). The potential evapotranspiration was calculated as following equations (1).

$$\text{Eto} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34\,u_2)} \qquad (1)$$

where:

Eto = The daily reference evapotranspiration (mm day^{-1}),
Rn= Net radiation at the crop surface (MJ m-2 day^{-1}),
G = Soil heat flux density (MJ m-2 day^{-1}),
T = Mean daily air temperature at 2 m height (°C),
u2= Wind speed at 2 m height (m s-1),
es = Saturation vapor pressure (kPa),
ea = Actual vapor pressure (kPa),
Δ = The slope of vapor pressure curve (kPa °C^{-1})
γ = The psychometric constant (kPa °C-1).

The second step was to obtain values of water requirements (Etcrop) as following equations (2) (Doorenbos and Pruitt, 1977):

$$Etc = Eto \times kc \qquad (2)$$

Where:
Etc = Irrigation water requirement for crop [m3/fed./ day].
Eto = Reference crop evapotranspiration [mm/day].
Kc = Crop coefficient [dimensionless].

Tables (5-6) shows the irrigation requirements for potato plants under open field conditions during the 2020 and 2021 season

Table (4). Irrigation requirements for potato plants under open field conditions during both seasons of 2020 and 2021.

The irrigation water requirements							
				1st Season (2020)		**2nd season (2021)**	
Weeks	**Eto mm/day**	**Kc**	**Leaching req. Factor (20%)**	**Etc mm/day**	**Drip Irrigation water req. (m^3/fed/day)**	**Etc mm/day**	**Drip Irrigation water req. (m^3/fed/day)**
1	2.27	0.45	1.04	2.88	5.12	2.99	5.32
2	2.49	0.5	1.55	3.59	7.65	3.72	7.93
3	2.67	0.55	2.06	4.29	10.17	4.92	11.66
4	2.88	0.65	2.65	4.85	13.09	5.23	14.12
5	3.1	0.85	3.24	5.4	16.01	5.85	17.34
6	3.2	0.9	3.74	5.65	18.5	5.88	19.25
7	3.28	0.95	4.25	5.9	20.99	6.33	22.52
8	3.57	1.05	4.32	5.39	21.33	6.02	23.82
9	3.86	1.1	4.39	4.87	21.67	5.13	22.83
10	3.87	1.1	4.64	4.52	22.93	5.03	25.52
11	4.16	0.95	4.9	4.16	24.19	4.65	27.04
12	4.45	0.85	4.56	3.88	22.52	4.11	23.85
13	4.73	0.8	4.22	3.59	20.84	3.88	22.52
14	4.34	0.75	4.07	3.46	20.11	3.49	20.28
15	4.57	0.7	3.92	3.33	19.38	3.37	19.61

Table (5). Irrigation requirements (liter/plant/day) of irrigation levels for potato plants during both seasons of 2020 and 2021.

Weeks	First season (2020)				Second season (2021)			
	120%	100%	80%	60%	120%	100%	80%	60%
1	0.392	0.327	0.261	0.196	0.407	0.339	0.271	0.204
2	0.585	0.488	0.390	0.293	0.607	0.506	0.405	0.303
3	0.778	0.649	0.519	0.389	0.892	0.744	0.595	0.446
4	1.002	0.835	0.668	0.501	1.081	0.901	0.720	0.540
5	1.225	1.021	0.817	0.613	1.327	1.106	0.885	0.664
6	1.416	1.180	0.944	0.708	1.473	1.228	0.982	0.737
7	1.606	1.339	1.071	0.803	1.723	1.436	1.149	0.862
8	1.632	1.360	1.088	0.816	1.823	1.519	1.215	0.911
9	1.658	1.382	1.106	0.829	1.747	1.456	1.165	0.874
10	1.755	1.462	1.170	0.877	1.953	1.628	1.302	0.977
11	1.851	1.543	1.234	0.926	2.069	1.724	1.380	1.035
12	1.723	1.436	1.149	0.862	1.825	1.521	1.217	0.913
13	1.595	1.329	1.063	0.797	1.723	1.436	1.149	0.862
14	1.539	1.283	1.026	0.770	1.552	1.293	1.035	0.776
15	1.483	1.236	0.989	0.742	1.501	1.251	1.001	0.750

2.2. Experimental design

The experiment was set up in a split-split plot design with three replicates. The irrigation levels were arranged in the main plots, the irrigation systems were randomly distributed in the sub-plots, and varieties were randomly assigned in the sub-subplots. The area of the experimental plot was 1080 m^2, consisting of 48 rows, as shown in Fig. (1).

Smart irrigation systems devices were used to control strategies of irrigation scheduling, which consist of A) HUNTER PRO-HC 6 station outdoor wi-fi controller with hydrawise software which makes it possible to control the system from any location and gain convenient access to it at any time from a smartphone, tablet, or web browser for a range of remote management capabilities. Also, web-based climate monitoring uses local forecast data, including temperature, precipitation, relative humidity, and wind speed, to adjust your irrigation system automatically, ensuring it helps in save water and improve plant's healthy, B) solenoid valve (PGV); C) Soil-Clik sensor for soil moisture sensing within the root zone. The probe will stop watering when it senses that the soil has attained the desired level of moisture, saving water. Soil-Clik consists of two components; A) moisture sensors probe (4), which is placed in the soil, and B) an electronic module, which communicates with the probe and the controller, as shown in Fig. (2).

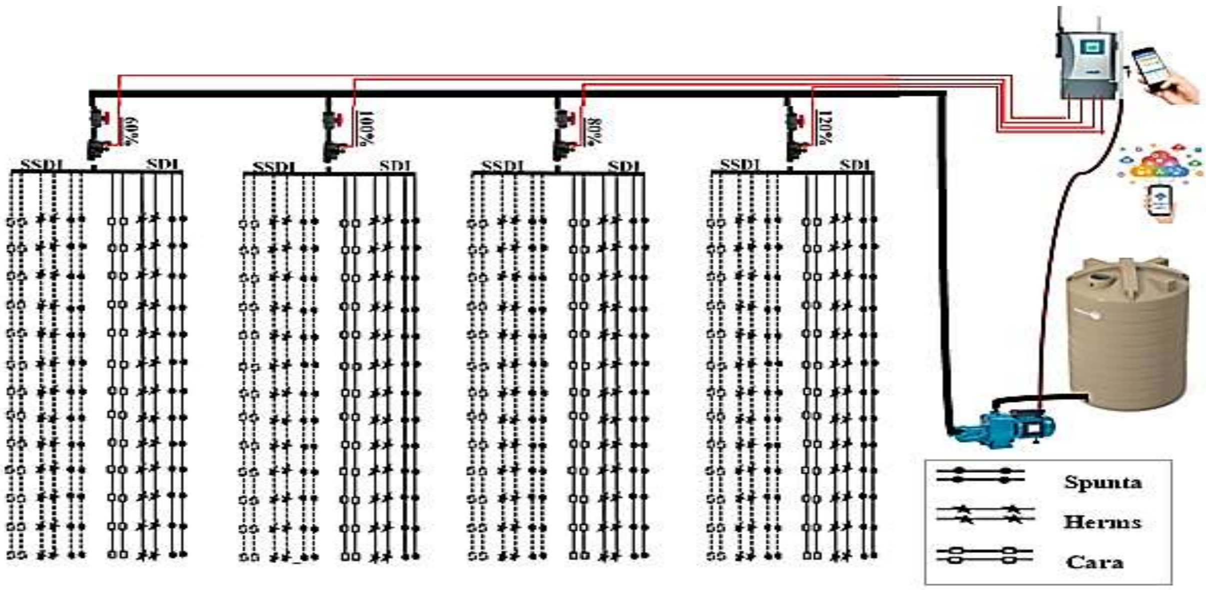

Fig. 1. The layout of the experiment.

Fig. 2. component of smart irrigation system.

2.3. Preparation of potato tubers and cultivation

Before planting, potato tubers were divided into around 35 g-sized pieces and allowed to cure for a week. To reduce soil-borne illnesses, the bio-fungicide Bio-health (containing Trichoderma sp. + Bacillus subtilis) was applied to all potato tuber seedlings at a rate of 150 ml per 100 L water. Potato tubers were manually planted on the 10^{th} and 15^{th} Jan. of 2020 and 2021, leaving 30 cm between plants and 90 cm between rows in all plots. The Egyptian Ministry of Agriculture and Land Reclamation's recommendations for potato cultivation in open fields were followed in all agricultural practices.

2.4. Measured characteristics and calculated

three plants were randomly chosen from three replications at 75 days from the sowing date to determine the following Vegetative growth characteristics: plant height (cm), number of leaves, number of main stems, shoot fresh weight(g), shoot dry weight (g) and total leaves area /plant (m^2). Using a 20-disc sampling per plant, each plant's total leaf area was calculated, dried, and weighed individually. A relationship between disk dry matter and disk area was applied to total leaf dry matter to find the total leaf area, according to **Koller (1972).** Also, five plants of each experimental plot were taken randomly, and their tubers were collected to estimate yield and yield components (number of tubers, average tuber weight, and yield /plant).

At final harvest, tubers were collected, and WUE (g/L) was calculated by dividing the fresh weight of tubers (g/plant) by the amount of water (L/plant) used during the treatment period (one month after planting to two weeks before physiological maturity**) (Elhani et al., 2019; Abd-Elrahmanm and Taha, 2018).**

Irrigation water use efficiency under deficit irrigation treatments was determined using the following equations given by Howell et al. (1990).

$$\text{WUE} = \frac{\text{Yield (g/plant)}}{\text{Applied irrigation water amount (L/plant)}}$$

2.5. Statistical analyses

Using the Minitab computer program, the variance of the data derived from each characteristic was analysed. The Duncan's New Multiple Range test at a 5% probability level was used to test the significance of differences among mean values of treatments, **(Steel and Torrie, 1980).**

3. Results

3.1. Effect of irrigation systems and levels on vegetative growth of potato crop

The influence of irrigation systems, irrigation levels, and their interactions on the vegetative growth characteristics of some potato plants varieties are shown in the data in Tables (6–11), i.e., plant height, number of leaves, number of main stems, shoot fresh and dry weights and total leaves area /plant.

The results a significantly increased with increasing the irrigation levels applied during both growing seasons in plant height, the number of leaves, shoot fresh weights, and total leaves area /plant. Whereas the number of main stems and dry weights of leaves /plant didn't record significant differences between 120 and 100% Etc. Also, results indicated that the highest significant values in all the studied growth aspects were recorded in the case of using the level of irrigation 120 and 100, followed by 80% ETc treatment, whereas 60% Etc obtained the lowest values, excluding shoot dry weight/plant the highest value was recorded in case of using the level of irrigation 100%, followed by 120, 80 and 60% Etc. Generally, deficit irrigation treatments significantly decreased all vegetative growth parameters compared to complete irrigation treatment.

The data acquired on the impact of irrigation systems on potato crop vegetative development parameters revealed that SSDI outperformed SDI in terms of all vegetative growth traits. Whereas in both of the tested seasons, the SSDI system provided the greatest significant values for plant length, number of leaves, number of main stems, total leaf area, and shoot fresh and dry weights/plant when compared to the SDI system.

Regarding the potato varieties, the results revealed significant differences among all potato cultivars in all vegetative development parameters during both seasons. Cara cultivar exhibited the highest significant values for plant length, number of leaves, number of main stems, total leaves area, and shoot fresh weights of potato leaves/plant in both tested seasons, while the lowest values were noticed with the Spunta cultivar. On the contrary, the Spunta cultivar recorded the highest value for dry matter, followed by Cara, whereas the lowest values were obtained by the Hermes cultivar.

Regarding the first-order interactions, the combination between irrigation systems and levels showed that 120% Etc with SSDI irrigated plants produced the highest significant values for plant height, number of leaves, number of main stems, total leaves area, and shoot fresh weights /plant. While 60% Etc with SDI obtained the lowest values. For shoot dry weight /plant, 100% Etc with SSDI system had the highest significant values in the two growing seasons. As well as the combination between studied varieties and irrigation systems showed that Cara cultivar, which was irrigated by the SSDI system, produced the highest significant values for plant height, number of leaves, number of main stems, total leaves area, and shoot fresh weights /plant. At the same time, Spunta recorded the lowest values with SDI system in both growing seasons. For shoot dry weight, the Spunta cultivar with SSDI had the highest significant values. Whereas Hermes with the SDI system recorded the lowest values in the two growing seasons. Also, the combination between varieties and Irrigation levels showed that the Cara cultivar was irrigated with 120% Etc produced the highest significant values for plant length, number of leaves, number of main stems, total leaves area, and shoot fresh weights /plant. At the same time, Spunta recorded the lowest values with 60% Etc. For shoot dry weight, the Spunta cultivar with irrigation level of 100% Etc had the highest significant values. Whereas Hermes irrigated with 60% Etc recorded the lowest values in the two growing seasons.

Regarding the third interaction, the combination between irrigation levels, irrigation systems, and potato varieties, results showed that Cara, which was irrigated by 120% Etc with SSDI system, produced the highest significant values for plant height, number of leaves, number of main stems, total leaves area and shoot fresh weights /plant. While the lowest values were obtained by Spunta which irrigated with 60 % Etc under SDI. For shoot dry weight /plant, Spunta, which received 100% Etc under the SSDI system, had the highest significant values, while Hermes which received 60% Etc under the SDI system, recorded the lowest values in the two growing seasons.

Table 6. Effect of irrigation systems and levels on plant height of potatoes during two growing seasons, 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020) Varieties			2nd Season (2021) Varieties		
		Spunta	**Hermes**	**Cara**	**Spunta**	**Hermes**	**Cara**
120	**SDI**	39.30ghi	43.16def	51.11ab	42.33gh	45.67ef	53.67a
	SSDI	43.16def	46.66c	54.22a	46.11def	49.67bc	55.78a
100	**SDI**	37.72ijk	41.27fgh	48.33bc	40.67hi	41.56h	50.44b
	SSDI	43.22def	45.05cde	52.16a	46.44def	47.56cde	54.22a
80	**SDI**	31.11m	35.77jkl	42.44efg	34.11lm	38.22ijk	44.44fg
	SSDI	39.05hij	42.83df	46.16cd	42.11gh	45.33ef	48.56bcd
60	**SDI**	26.33n	31.22m	34.55kl	29.33n	33.78m	36.56jkl
	SSDI	32.50lm	35.83jk	38.50hij	35.56klm	38.56ij	41.67h

Table 7. Effect of irrigation systems and levels on the number of leaves /plants of potatoes during two growing seasons, 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020)			2nd Season (2021)		
		Varieties			Varieties		
		Spunta	**Hermes**	**Cara**	**Spunta**	**Hermes**	**Cara**
120	**SDI**	31.67hi	36.78d	43.44b	35.22ghi	40.00de	50.22b
	SSDI	35.11ef	40.89c	47.00a	37.78efg	42.56cd	53.89a
100	**SDI**	30.44ij	33.44g	40.00c	32.56ij	37.33efgh	45.33c
	SSDI	34.00fg	37.22d	42.89b	35.22ghi	39.56def	49.33b
80	**SDI**	23.78l	26.00k	29.67j	27.78lm	28.56l	36.67fgh
	SSDI	30.00j	33.22gh	36.44df	31.89jk	34.22hij	43.67c
60	**SDI**	15.89n	17.00n	21.00m	18.11o	18.33o	28.89kl
	SSDI	21.89m	24.22l	28.89j	23.56n	25.00mn	35.89gh

Table 8. Effect of irrigation systems and levels on shoot fresh weight of potato during two growing seasons, 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020)			2nd Season (2021)		
		Varieties			Varieties		
		Spunta	**Hermes**	**Cara**	**Spunta**	**Hermes**	**Cara**
120	**SDI**	154.7def	174.8bc	184.2ab	166.8fg	185.3bcde	198.3ab
	SSDI	164.9cd	179.8ab	192.0a	178.9def	194.0abc	206.0a
100	**SDI**	134.3ghi	156.4d	164.4cd	147.1jk	167.0fg	179.8cdef
	SSDI	143.1fgh	166.1cd	179.2ab	161.2ghi	178.1def	190.4bcd
80	**SDI**	102.9lm	132.7hij	143.0fgh	112.7n	146.2jk	158.3ghij
	SSDI	119.8jk	147.3efg	159.6de	138.4kl	161.7gh	170.9efg
60	**SDI**	67.2n	103.7l	113.9kl	83.2o	116.0mn	130.3
	SSDI	90.2m	123.2ijk	137.2gh	107.2n	137.3kl	150.8hijk

Table 9. Effect of irrigation systems and levels on shoot dry weight of potato during two growing seasons, 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020)			2nd Season (2021)		
		Varieties			Varieties		
		Spunta	**Hermes**	**Cara**	**Spunta**	**Hermes**	**Cara**
120	**SDI**	14.4^{abcde}	$13.6^{abcdefgh}$	$14.0^{abcdefg}$	19.0^{abcd}	15.2^{bcdef}	15.5^{abcde}
	SSDI	15.0^{ab}	$13.7^{abcdefgh}$	14.2^{abcdef}	16.7^{ab}	15.6^{abcde}	15.9^{abcd}
100	**SDI**	14.7^{abcd}	$14.0^{abcdefg}$	14.3^{abcdef}	16.3^{abc}	15.7^{abcde}	15.8^{abcd}
	SSDI	15.1^{a}	14.4^{abcdf}	14.8^{acb}	16.9^{a}	16.2^{abc}	16.2^{abc}
80	**SDI**	$13.8^{abcdefgh}$	12.9^{efgh}	$13.5^{abcdefgh}$	15.4^{abcde}	14.4^{def}	15.0^{cdef}
	SSDI	14.6^{abcd}	13.2^{cdefgh}	$13.9^{abcdefgh}$	16.3^{abc}	14.9^{cdef}	15.6^{abcde}
60	**SDI**	13.0^{defgh}	12.3^{h}	12.7^{fgh}	14.5^{def}	13.8^{f}	14.2^{ef}
	SSDI	$13.8^{abcdefgh}$	12.5^{gh}	$13.4^{bcdefgh}$	15.5^{abcde}	14.2^{ef}	15.1^{cdef}

Table 10. Effect of irrigation systems and levels on the number of main stems of potatoes during two growing seasons, 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020) Varieties Spunta	Hermes	Cara	2nd Season (2021) Varieties Spunta	Hermes	Cara
120	SDI	3.6^{bcdef}	3.7^{bcdef}	4.4^{abc}	4.0^{bcdefg}	4.3^{abcdef}	5.0^{abc}
	SSDI	3.7^{bcdef}	4.2^{abcd}	5.2^{a}	4.4^{abcde}	4.9^{abcd}	5.7^{a}
100	SDI	3.3^{cdef}	3.6^{bcdef}	4.0^{bcde}	3.9^{bcdefg}	4.0^{bcdefg}	4.7^{abcd}
	SSDI	3.7^{bcdef}	4.0^{bcde}	4.7^{ab}	4.3^{abcdef}	4.7^{abcd}	5.3^{ab}
80	SDI	2.8^{f}	3.3^{cdef}	3.3^{cdef}	2.9^{fgh}	3.4^{defgh}	4.0^{bcdefg}
	SSDI	3.2^{def}	3.7^{bcdef}	4.2^{abcd}	3.6^{cdefgh}	4.0^{bcdefg}	4.6^{abcd}
60	SDI	2.6^{f}	2.6^{f}	3.0^{ef}	2.1^{h}	2.7^{gh}	3.0^{efgh}
	SSDI	2.7^{f}	$2.9e^{f}$	3.3^{cdef}	2.6^{cdefgh}	3.0^{efgh}	3.7^{cdefg}

Table 11. Effect of irrigation systems and levels on total leaf area of potatoes during two growing seasons, 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020) Varieties Spunta	Hermes	Cara	2nd Season (2021) Varieties Spunta	Hermes	Cara
120	SDI	0.34^{ijkl}	0.42^{bcdefg}	0.46^{bcd}	0.36^{hijk}	0.44^{bcdefg}	0.48^{bcd}
	SSDI	0.38^{fghij}	0.49^{ab}	0.54^{a}	0.40^{fghi}	0.51^{ab}	0.56^{a}
100	SDI	0.32^{jkl}	0.40^{defgh}	0.44^{bcde}	0.35^{ijk}	0.42^{defgh}	0.46^{bcde}
	SSDI	0.36^{ghijk}	0.47^{bc}	0.41^{cdefg}	0.38^{ghij}	0.49^{bc}	0.43^{cdefg}
80	SDI	0.25^{m}	0.34^{hijkl}	0.40^{dfghi}	0.27^{l}	0.36^{hijk}	0.42^{defgh}
	SSDI	0.28^{lm}	0.40^{efghi}	0.44^{bcdef}	0.30^{kl}	0.42^{defgh}	0.46^{bcdef}
60	SDI	0.15^{n}	0.30^{klm}	0.31^{klm}	0.17^{m}	0.32^{jkl}	0.33^{jkl}
	SSDI	0.27^{lm}	0.34^{hijkl}	0.38^{efghij}	0.29^{kl}	0.36^{hijk}	0.41^{fghi}

3.2. Effect of irrigation systems and levels on yield and yield components of the potato crop

Summer grown potato is increasingly affected by soil moisture deficit due to inadequate irrigation and high evaporative demand. Results indicated that increasing the amount of irrigation water from 60% Etc to 120% Etc significantly increased all yield characteristics during both growing seasons, excluding the number of tubers /plants that didn't notice significant differences between 120 and 100% Etc in both seasons. Also, the results revealed that the highest values for the number of tubers /plants, an average of tubers weight /plant, and yield/plant were obtained by 120% Etc, followed by 100% Etc treatment, while 60% Etc obtained the lowest values.
The data acquired on the impact of irrigation systems on potato crop yield characteristics revealed that SSDI significantly outperformed SDI in all yield parameters. Whereas, in both growing seasons, the SSDI system outperformed the SDI system in terms of yield/plant, average tuber weight/plant, and number of tubers/plant.

Also, results revealed significant differences among all potato cultivars in all yield characteristics during both growing seasons. Whereas Spunta recorded the highest values for the average tubers weight and yield/plant, followed by Cara and Hermes. In contrast, the Cara cultivar showed the highest significant value for the number of tubers /plants, while the lowest values were noticed with the Spunta cultivar.

Regarding the first-order interactions, the combination between irrigation systems and levels, the results showed that 120% Etc under SSDI irrigated plants produced the highest significant values for an average tubers weight and yield/plant. While the lowest values were obtained by 60% Etc with SDI in both tested seasons, as shown in Fig. (3).

As well as the combination between varieties and irrigation systems showed that the Cara cultivar is under SSDI, produced the highest significant values for the number of tubers /plants. While Spunta recorded the lowest values under SDI in both seasons. For the average tuber's weight and yield /plant, the Spunta cultivar under the SSDI system had the highest significant values. Whereas Hermes under the SDI system recorded the lowest values in the two growing seasons, as shown in Fig. (4).

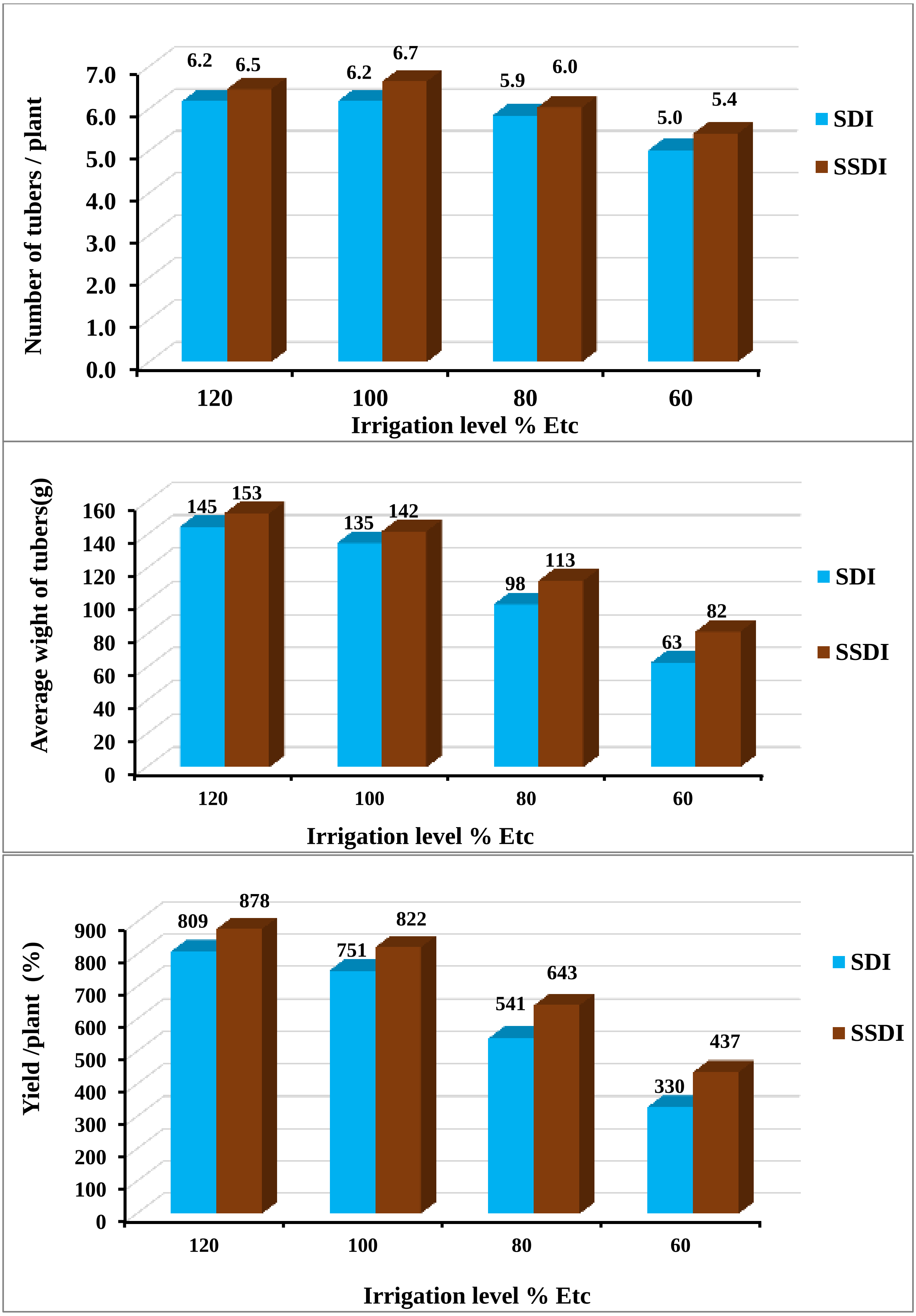

Fig.3. The interactions between irrigation levels and systems treatments on yield parameters.

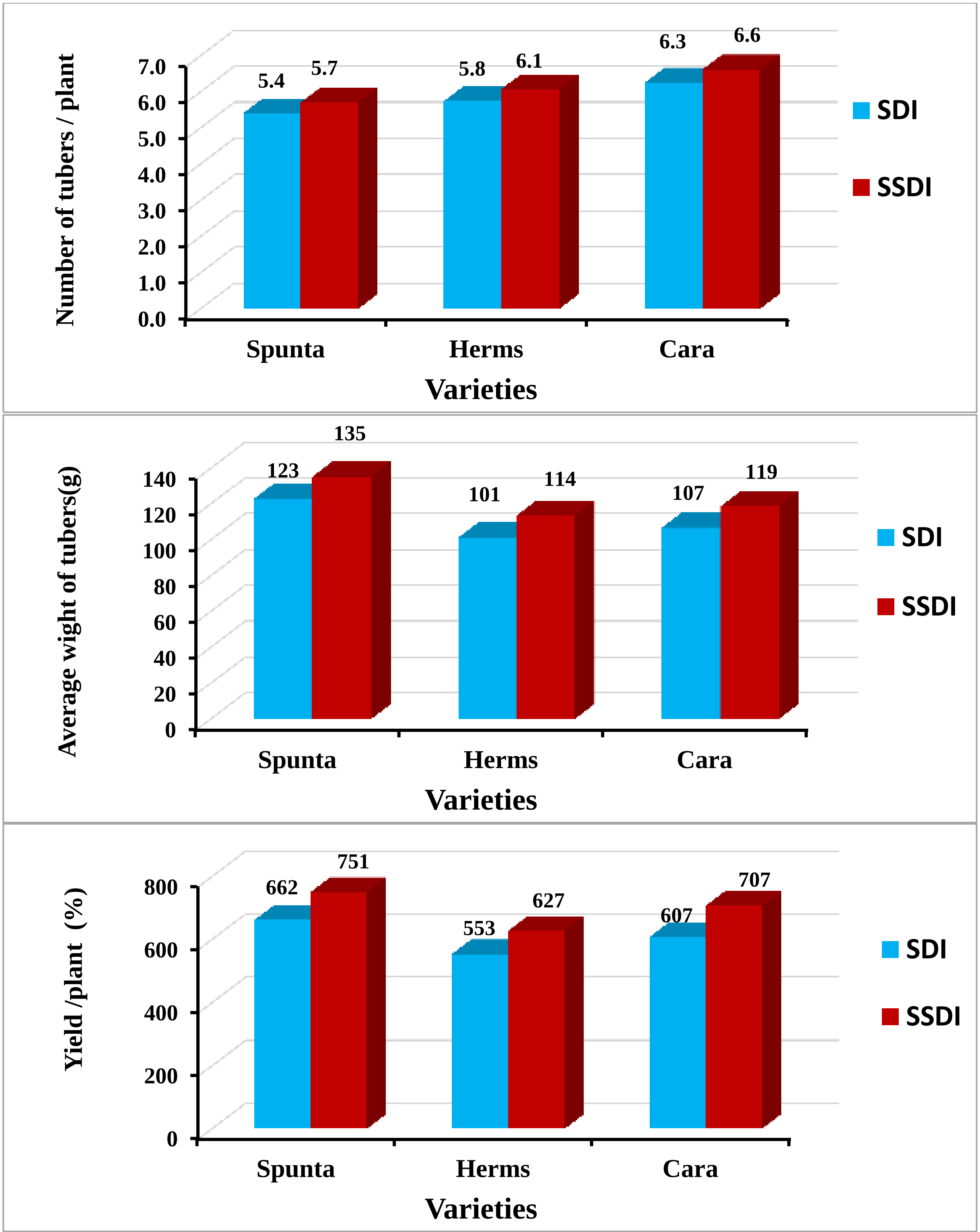

Fig.4. The interactions between irrigation levels and systems treatments on yield parameters.

Also, the combination between varieties and irrigation levels showed that the Cara cultivar irrigated with 120 % Etc produced the highest significant values for the number of tubers /plants. While Spunta recorded the lowest values with 60% Etc. For the average of tubers and yield/plant, Spunta cultivar with irrigation level 120% Etc had the highest significant values. Whereas Hermes with 60% Etc recorded the lowest values in the two growing seasons, as shown in Fig. (5).

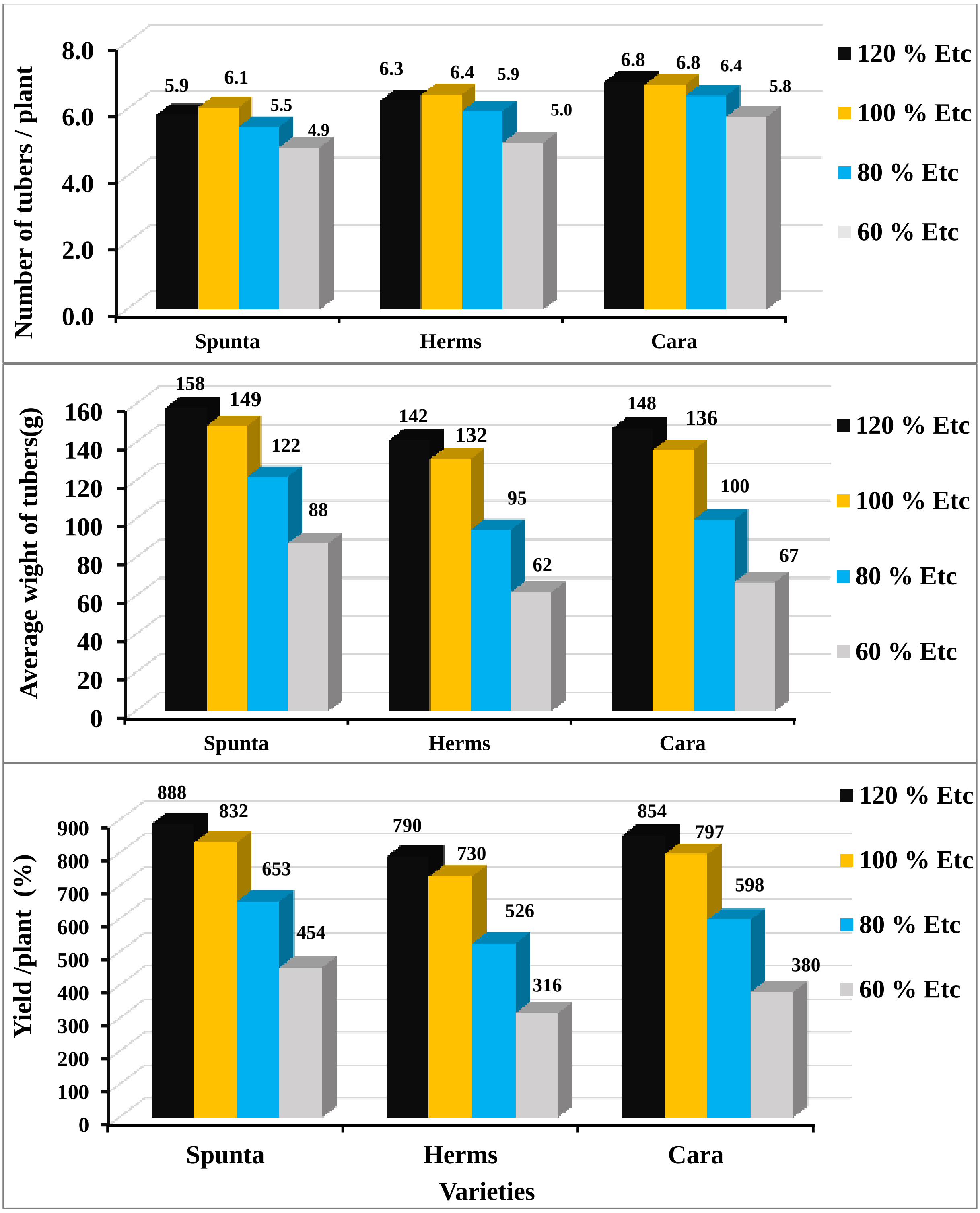

Fig.5. The interactions between Varieties (Spunta, Hermes and Cara) and irrigation levels treatments on yield parameters.

Regarding the third interaction, the combination between irrigation systems, levels, and varieties, results showed that Cara which was irrigated by 120% Etc under SSDI, produced the highest significant values for the number of tubers /plants in both growing seasons. While Spunta obtained the lowest values with 60% Etc under the SDI system in both seasons. For the average of tubers weight and yield /plant, the Spunta cultivar, which received 120% Etc under the SSDI system, had the highest significant values. Whereas Hermes, which received 60% Etc under the SDI system, recorded the lowest values in the two growing seasons, as shown in Fig. (6).

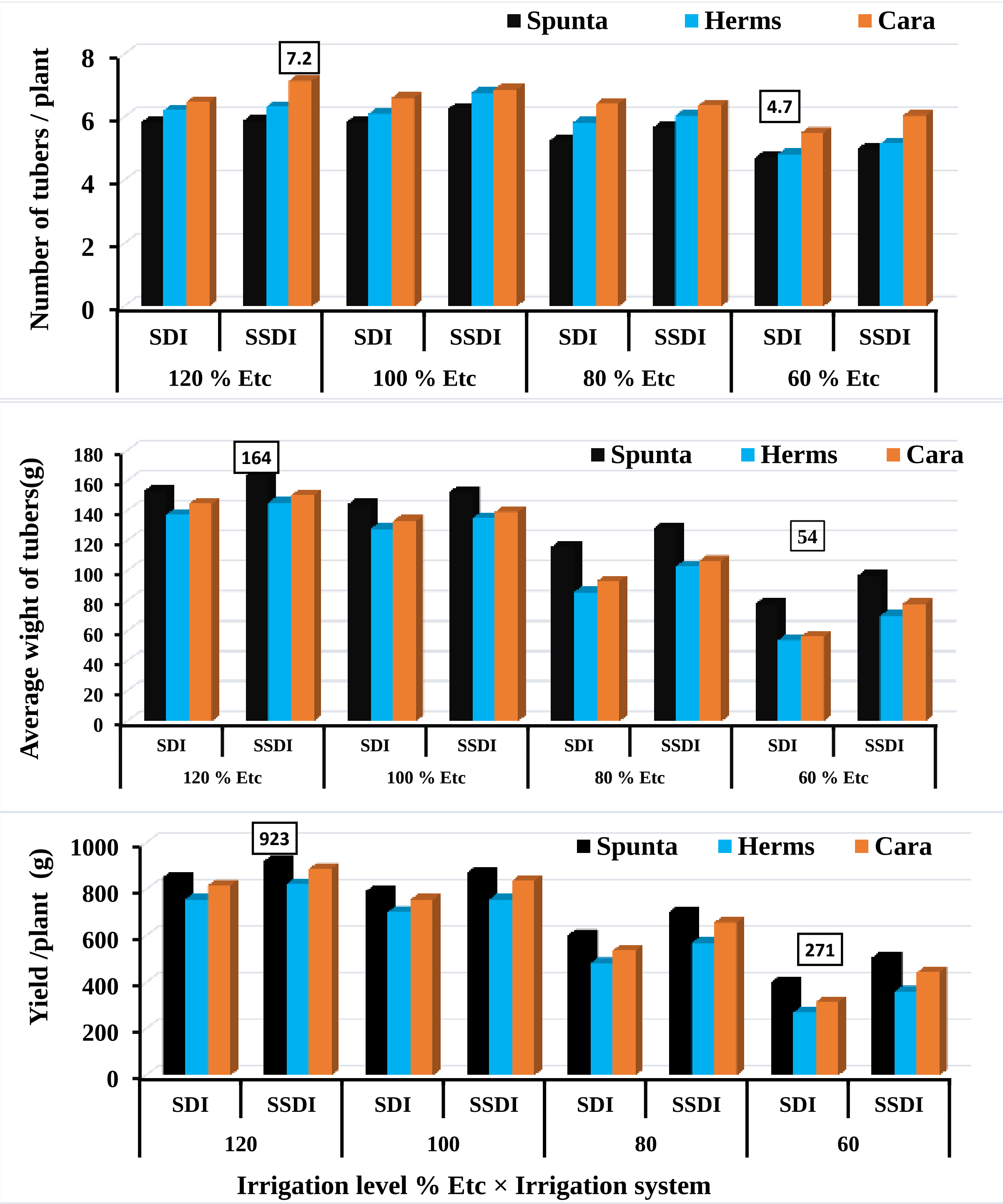

Fig.6. The third interactions (irrigation levels, irrigation systems and potato Varieties) on yield parameters.

3.3. Effect of irrigation systems and levels on water use efficiency of the potato crop

Data presented in Tables (12) reveal the effect of irrigation systems, levels, and their interactions on the water use efficiency (WUE) of the potato crop. Results revealed that WUE significantly increased with decreasing irrigation level up to a certain limit. Also, the results showed that increasing irrigation level over 80% led to decrease in WUE for all irrigation treatments. where the maximum values were observed with 80% followed by 100% and 120% ETc with significant differences between them. While, the lowest values were obtained by 60% ETc treatment the two studied seasons.

Respecting the effect of irrigation systems (surface and subsurface drip irrigation) on WUE of the potato crop, the obtained data revealed that SSDI showed significant superiority to SDI under field conditions in the both tested seasons. Also, the results revealed significant differences among all potato cultivars for water measurements during both growing seasons. Where, Spunta cultivar recorded the highest values for WUE, whereas the lowest values were obtained by Cara cultivar with significant differences with all cultivars in both growing seasons.

Regarding the first-order interactions, the combination between irrigation systems and levels, the results showed that 80 % ETc under SSDI irrigated plants produced the highest significant values. While the lowest values were obtained by 60% ETc with SDI in both tested seasons. As well as, the combination between varieties and irrigation systems showed that Spunta cultivar is under SSDI, produced the highest significant values. Whereas Cara cultivar under SDI system produced the lowest significant values in both tested seasons. Also, the combination between varieties and irrigation levels showed that the Spunta cultivar irrigated with 80% ETc produced the highest significant values. Whereas Cara cultivar with 60% produced the lowest significant values in both tested seasons.

Regarding the third interactions, the combination between irrigation systems, levels, and varieties, the results showed that Spunta cultivar irrigated with 80% ETc under SSDI system produced the highest significant values. While Cara obtained the lowest values with 60% ETc under the SDI system in both seasons.

Table 12: Effect of irrigation systems and levels on WUE for some potato cultivars during 2020 and 2021.

Irri. levels (% Etc)	Irri. systems	1st Season (2020) Varieties			2nd Season (2021) Varieties		
		Spunta	Hermes	Cara	Spunta	Hermes	Cara
120	SDI	8.77[def]	6.52[jk]	6.04[k]	8.16[def]	6.22[klm]	5.92[mn]
	SSDI	9.09[de]	6.97[ij]	6.83[jk]	8.94[bcd]	6.83[hijkl]	6.17[klmn]
100	SDI	9.29[de]	6.63[jk]	6.15[K]	8.58[cde]	6.46[jklm]	6.08[lmn]
	SSDI	10.76[ab]	7.64[hi]	7.04[ij]	9.65[ab]	7.24[ghij]	6.93[hijk]
80	SDI	10.11[bc]	7.87[h]	6.98[ij]	9.33[bc]	7.26[ghij]	6.52[ijklm]
	SSDI	11.07[a]	8.68[efg]	7.88[gh]	10.22[a]	8.01[efg]	7.36[fghi]
60	SDI	8.07[fgh]	5.21[l]	4.71[l]	7.45[fgh]	5.01[o]	4.74[o]
	SSDI	9.52[cd]	6.70[jk]	6.58[jk]	9.34[bc]	6.19[klmn]	5.38[no]

4. Discussion

The results showed the improvement of vegetation parameters and yield components with increased irrigation levels applied during the growing seasons, this might be as a result of the function that water plays in enhancing the absorption of minerals from the soil and the movement of photosynthetic assimilates, which would then show increases in leaf number and area as well as foliage weight per plant **(Leilah, 2009).** In addition, plants under drought stress have a variety of physiologic and biochemical consequences **(Zhang and Huang, 2013).** lowering transpiration rates, stomatal conductance, leaf area per plant, shoot length, fresh and dry biomass, and shot biomass in particular **(Mutava, *et al.* 2015).** In addition, **Bhardwaj and Yadav (2012)** reported that drought stress modifies photosynthetic rate, relative water content, leaf water potential, and stomata conductance. Ultimately, it destabilizes the membrane structure and permeability, protein structure, and function, leading to cell death.

Similar results were mentioned by **Osakabe *et al.* (2014)** found that drought significantly reduced the final area of potato leaves and explained that leaf expansion is the first morphological parameter that reduces when soil water potential increases. They stated that the impact of stress on cell enlargement is irreversible, and the leaf enlargement rate does not return to the rate of unstressed plants even after copious irrigation. The ratio of ABA to cytokinin rises in conditions of water stress, which inhibits plant development. Additionally, during periods of water stress, ABA is produced from carotenoids in the root and transported to other plant tissues, particularly the leaves, which in turn impacts the buildup of fresh shoot weight in the leaves and other organs (**Arafa *et al*. 2015).**

Also, the superiority of SSDI system is due to SDI system in all traits of vegetative and yield to the fact that the SSDI system is most effective in directly conveying water and nutrients to plants, where water is applied uniformly, allowing nearly all portions of the field to be irrigated efficiently. Additionally, irrigation water and injected fertilizers are given directly to the root zone, resulting in crop health and less nutrient loss than surface irrigation. They may also be applied to the most active region of the root zone. Additionally, the SSDI system lowers yearly weed development because it allows for regular, light irrigations that keep soil moisture levels at a level that promotes plant growth **(Çolak *et al.* 2015).** Moreover, the advantages of the SSDI system might be because of the making of additional appropriate circumstances in the root zone region, contrasted with surface drip irrigation system (**Al-Omran *et al.* 2010).** Additionally, the SSDI system in the sandy soil type had better salt distribution in the soil profile than the SDI system because the negative impacts of salt in the root zone and soil surface evaporation were diminished **(Elhindi 2012).**

In this respect, **Ibrahim and Aldesuquy (2003)** reported that yield results from the integration of metabolic reactions in plants; as a result, any stimulus that modifies this metabolic activity at any stage of plant development will have an impact on the yield. Furthermore, **Earl and Davis (2003)** hypothesized that three key processes, including I lower canopy absorption of photosynthetically active radiation, (ii) decreased radiation-use efficiency, and (iii) decreased harvest index, limit crop output when there is a soil water shortage. Additionally (**Aldesuquy *et al.* 2012)** said that the decline in photosynthetic pigments, carbohydrate buildup (polysaccharides), and nitrogenous substances might be responsible for the drop in yield (total nitrogen and protein).

Similar to **Selim *et al*. (2009),** it was stated that the capacity of subsurface drip irrigation systems to boost tubers output might be due to the reduced amount of water lost through evaporation from the soil surface, which produced the best crop yield. Furthermore, the SSDI system makes it possible to maintain the ideal level of soil moisture in the root zone, which increases the effectiveness of using fertilizer and water and results in a rise in vegetative growth and fruit output **(Thompson and Doerge, 1996).**

The superiority of the sub-surface drip irrigation system over the surface drip irrigation system (SDI) in the efficiency of irrigation water use for potato crops is due to all water utilized by plants with SSDI system compared to SDI system, where a part of irrigation water evaporated from soil surface layer. Also, bigger wetted volume in the root zone was observed with SSDI system. These results are in agreement with those obtained by **Mustafa *et al.* (2017),** who suggested that water use efficiency under SSDI system was much more than SDI system with cultivated potato plants. Also, the using of DI strategy is very important to increase crop water use efficiency (WUE), These results are in harmony with those obtained by **Patane *et al.* (2011)** concluded that the adoption of deficits irrigation strategies where a 30% reduction of ETc could be suggested in open-field processing tomato in South Italy, for increasing WUE, minimizing fruit losses and maintaining high fruit quality levels.

5. Conclusion

Water scarcity is increasing in the world, and the present agricultural systems throughout the world face enormous problems as a result. Therefore, necessary to adopt irrigation strategies aimed at producing more ‘crop per drop’ and maximizing water use efficiency. SSDI is the most efficient method of supplying nutrients and water to plants, and in addition to saving water, it also boosts vegetable crop yields. Additionally, smart irrigation systems have the potential to increase water consumption efficiency, particularly with the development of wireless communication technologies, monitoring systems, and sophisticated management algorithms for ideal irrigation scheduling. Applying water to a field at the proper time, in the proper amount, and at the proper location is known as smart irrigation. The results showed that the SSDI system outperformed the SDI system in terms of all vegetative and yield growth characteristics. Also, the results showed that irrigation levels significantly affected the growth and yield of potato varieties. Where results indicated that all the studied growth aspects were significantly increased with increasing the irrigation levels applied during both growing seasons.

Conflicts of interest: The author declares that he has no conflict of interest**.**

Formatting of funding sources: This research did not receive any specific funding.

Acknowledgments: The authors express sincere thanks to. Dr. Sameh Mohamed El-Sawy, Associate Professor of Vegetable Research, Agricultural and Biological Research Institute, National Research Centre, Cairo, Egypt, for his assistance and valuable guidance throughout the preparation and conduct of the field experiment and facilitating the accomplishment of this work.

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