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Optimizing Water Productivity in potatoes crops through Comparative Irrigation Strategies under Scarce Water Conditions in Arid Environments

Mohammed Sadok Beggas*, Soumaia M'Nassri, El-Hadj Benkrid & Rajouene Majdoub

Department of Horticultural Systems Engineering and Natural Environment, Research Laboratory LR18AGR01, High Agronomic Institute of Chott Mariem, University of Sousse, Chott Mariem 4042, Sousse, Tunisia

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***Corresponding author**
sadek_hyd@yahoo.fr

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Abstract

The sustainability of potato production in arid regions can be significantly impacted by irrigation management decisions. In order to assess the effects of Subsurface Drip Irrigation (SDI) and standard pivot systems on soil properties, plant growth, yield components, IWUE, and WUE of two potato varieties, "Spunta" and "Arizona," a field study was carried out in 2023 and 2024. Our findings show that the SDI system increased the soil water content by 10.30% compared to the pivot one, which produced the highest biomass weights of 146.83 g/plant and 148.93 g/plant, respectively, during the vegetative growth and sprouting stages. However, in 2023, the pivot system increased this characteristic by 28% more than the SDI system. Additionally, those responded differently during the growth stage, with the Pivot * Arizona interaction showing a higher correlation than the pivot * Spunta interaction for each of the three phases. Regarding yield and yield components, SDI resulted in a 35.5% increase in tuber weight and a 29.5% rise in tuber number per m^2. Using SDI instead of the pivot resulted in a 21.56% increase in the marketable tuber size. Significant variations were noted between Spunta and Arizona varieties across all yield parameters during the two growing seasons. Notably, Arizona had the highest yield/ha (around 33t/ha), average tuber weight (61g), and marketable tuber C2 ($18.2/m^2$). Throughout the growing seasons, SDI-irrigated plants had a higher IWUE than the pivot system. WUE values ranged from 5.258 to 6.065 kg/m^3, while IWUE varied from 3.725 to 4.694 kg/m^3. According to these results, irrigation using the SDI system maximizes potato output and would increase water productivity because less water is needed, making these methods applicable in arid areas with limited water resources.

1. INTRODUCTION

The extreme climatic fluctuations during the last decade impact the Mediterranean climate region, particularly those in North Africa such as Algeria, which exacerbate water deficits (Vogel et al., 2019) and consequently affect agricultural production by lowering crop yields, especially for vegetable species that are more vulnerable to water stress (Parkash and Singh, 2020; Cafaro et al, 2026). Furthermore, the significant increase on global temperture in recent years may increase the probability and intensity of drought, possibly as a result of more evapotranspiration and less precipitation in some parts of the world (Kang et al., 2017). Consequently, groundwater levels in these regions are declining rapidly. According to several reports (Mattar et al., 2021; Noon et al., 2022; Tolba et al., 2023), improper management of water consumption in the agricultural sector will thereby enhance the negative effects of climate change by increasing water losses.

Water-saving techniques such as SDI and irrigation dose management are two essential strategies that are becoming more and more popular to conserve water and sustain agricultural productivity in water-deficient areas. Under DI, several crops, like onions (Wakchaure et al., 2018), eggplants (Mohawesh, 2018), peppers (Abdelkhalik et al.,2020), and potatoes (Teshome et al., 2024), receive less irrigation water than the full crop water requirements (ETc) over the growing season. However, plants can only withstand water stress up to a threshold level; after that, crop yield decreases drastically once the water stress threshold is exceeded (Parkash and Singh 2020). Drought, a prevalent abiotic stress, significantly affects plant growth and productivity, including that of potatoes (Djaman et al., 2021). According to several studies, a minimum of 50% soil moisture is necessary for sustainable potato crop production (Badr et al., 2012; Ahmadi et al., 2014). However, Cafaro et al. (2026) reported a higher irrigation requirement of up to 80–100% to ensure high tuber yield and high harvest index values. On the other hand, Attia et al.(2017) found that increasing irrigation water supply up to 125% of evapotranspiration enhanced tuber quality and yield by improving the dry matter and starch content of tubers

In Algeria's El Oued region, potatoes are the most widely grown vegetable. With a total area of 36,200 hectares and a total production of 136,500 tons in 2022 (Mancer et al. 2024), the El Oued region's production is dependent on groundwater, which is typically highly saline, especially in recent years due to climate change and temperature increases brought on by high seasonal evapotranspiration, where the potato requirements were estimated to be 400–800 mm (Beggas et al., 2026). Despite this, it contributes 40% of the local market. However, water availability is one of the main factors limiting potato production and quality because of its high sensitivity to water deficit (mostly due to its shallow root system, Opena and Porter, 1999), which causes a reduction in the number and size of leaves, delays tuber differentiation, slows subsequent growth, and has detrimental effects on tuber yields and earliness (Noun et al., 2022; Mostafa et al., 2024). In this regard, a number of studies have shown that effective irrigation water management increases irrigation water use efficiency (IWUE), lowers leaching losses of specific minerals like nitrogen, and supplies sufficient soil water for the roots of many species, including potatoes. It has been shown that drip irrigation (DI) uses less water than traditional sprinkler and furrow watering methods for this crop (Cafaro et al., 2026)..Nevertheless, pivot irrigation systems continue to be the most common in El Oued region , and there are still very few water-saving methods.

Regular sprinkler spraying may produce an inconsistent pattern of soil soaking when potatoes are grown on a slope; in contrast, DI provides water to the soil zones where plant root uptake takes place, significantly influencing the plant's water efficiency (Mora-Sanhueza et al., 2025) and keeps the soil wet around the roots and encourages the best possible biomass growth and tuberization processes. However, since the soil in arid areas is characterized by high leaching, rapid water infiltration, and low levels of moisture uptake by plant roots, spray or furrow irrigation is ineffective (Mattar et al., 2021). Additionally, because 85% of potatoes' roots develop between 0 and 30 cm of surface soil, even short-term water shortages can significantly reduce yield because potatoes have a high water use efficiency (WUE), ranging from 6 to 11.6 kg.ha-1.m-3(Zin ElAbedin et al., 2019). However, numerous factors, including variety, development stage, growing technique, and climate, affect the WUE (Djaman et al., 2021). The rate of evapotranspiration (ET) in millimeters per day or millimeters per cycle is frequently used to express crop water requirements (Matar et al., 2021). On the other hand, the late authors reported that the irrigation water use efficiency (IWUE) for potatoes under surface drip irrigation varied from 9.33 to 36.44 kg. ha-1.m-3 and from 9.05 to 30.12 kg. ha-1.m-3, while Onder et al. (2005) state that treating 33% of maximal evapotranspiration produced the highest IWUE and the overall water productivity ranged from 6.17 to 14.01 kg.ha-1.m-3. Furthermore, otato water requirements can vary greatly between genotypes and life cycle phases. In contrast to tuber formation and tuber bulking, the early development stage is the most sensitive to water stress among growth phases, making it the most responsive to irrigation. . According to Ierna et al. (2020), insufficient water can also decrease tuber size and significantly impact yield during tuber growth and bulking, but it can also delay growth and decrease earliness during tuber differentiation.

The effects of irrigation systems on potatoes cultivated in arid regions have been evaluated in some studies carried out in Tunisia (El Mokh et al., 2014; Nagaz et al., 2016), Egypt (Badr et al., 2012; Attia et al., 2017), Saudi Arabia (Zine El Abedin et al., 2019) and Algeria (Messahel et al., 2005; Amirouche et al., 2020). However, little is known about how irrigation practices affect the soil parameters and, in particular, how sensitive the three main stages of the potato plant's life cycle are. Furthermore, there is often disagreement on the type of varieties or water used in some studies. Therefore, this study aimed to assess the effects of two irrigation systems: SDI and pivot on sandy soil characteristics and evaluate the global responses of two potato varieties to determine the optimal combination variety and irrigation system. In addition, water use efficiency during the different stages of the plant life cycle , that is the main gap in El Oued's arid region, was investigated.

2. MATERIAL AND METHODS

2.1. Plant Material and experimental site

Certified (Class E) tuber seeds of two popular potatoes, "Spunta" and "Arizona," mid-early and mid-late cycle, respectively, were supplied by a local seed importer. Although they differ in terms of maturity and specific performance, Arizona and Spunta are both high-yielding, drought-tolerant potato types that are frequently used in El Oued region. Tuber seeds with a transverse diameter of around 45 to 55 mm and a weight of about 70 to 80 g were chosen for size uniformity. They were then allowed to sprout for 15 days at room temperature (23 ± 2 °C) in a vented environment.

The field experiment was conducted in the El Oued region of southeastern Algeria (33°21′40″ N, 6°51′38″ E) during the 2023 and 2024 growing seasons, from mid- February to mid-June in both years. The region has a hot, dry climate with average temperatures over 23,3°C, low and irregular precipitation (average of 29.71 mm annually), and high rates of evapotranspiration (Table 1). The soil at the experimental site was mostly sandy, had less than 1% organic matter, and had a minimal capacity to hold water (0.048 cm^3 g^{-1}). Its pH was slightly alkaline (7.03–7.12), its salinity was modest, and its electrical conductivity was about 2.05–2.07 dS m^{-1}. The soil was found to have low nutrient availability, with assimilable nitrogen between 0.06 and 0.07%, potassium between 70.40 and 119.30 mg kg^{-1}, and phosphorus between 18.12 and 58.22 mg kg^{-1} throughout the soil profile. The physical and chemical properties of the soil are listed in Table 2.

All the experimental plots received similar fertilization throughout the growing period as indicated in Table 3.

Table 1. Climatic conditions during the experimentation period during 2023 and 2024 growing season.

Year	Month	Air temp. (°C)		Relative humidity (%)		Precipi-tation (mm)	Avgerage solar radiation (W/m²)	Max wind speed (km/h)
		Max	Min	Max	Min			
2023	February	18.8	6.7	72	15	6.86	173	18.3
	March	25.5	12.2	51	17	0	207	20.2
	April	28.9	14.6	68	17	4.06	257	20.1
	May	31.1	18.6	60	15	10.16	287	25.5
	June	37.9	24.5	50	15	1.02	338	23.9
2024	February	21	9.5	62	20	2.03	172	22.7
	March	25.8	12.1	46	20	0.25	209	20.4
	April	27	15.7	80	15	31.74	248	27
	May	34.9	21.1	52	13	2.28	295	25.2
	June	40.4	25.8	42	11	0	345	25.4

Table 2. Soil physical and chemical properties of the experimental site.

Soil properties	Soil depth (cm)	
	0-20	20-40
Clay	0	0
Silt	2.34	1.98
Sand	97.66	98.02
Soil texture	Sandy	Sandy
pH	7.03	7.12
EC	2.07	2.05
Bulk density (g/cm^3)	1.58	1.53
Field Capacity (%)	12.50	11.32
Permanent wilting point (% vol)	7.10	7.08
Available water capacity (mm)	75.8	69.86
Organic matter (%)	0.83	0.62
Assimilable nitrogen (%)	0.06	0.07
Assimilable potassium (mg/kg)	70.40	119.30

2.2. Experimental Design

To evaluate the effects of two irrigation systems, Pivot and SDI, and two potato varieties, "Spunta" and "Arizona," in the El Oued arid region, this experiment was carried out on a large scale over the course of two consecutive years, 2023 and 2024. To ensure real agricultural production conditions, a whole macro-plot of one hectare was dedicated to each treatment. Throughout these plots, semi-automatic sensor-based control was applied consistently. Each plot was split up into elementary sub-plots (experimental units) that were around 1200 m² in size. Each variety was randomly assigned to three replications. The distribution of the variety, the particular location of the control sensors, and the exact spatial arrangement of these plots are depicted in Fig. 1.

The sensors controlled the various irrigation intervals and frequency. The SDI system's soil sensors started many high-frequency irrigations, or micro-irrigations, every day. By preventing water from descending below the root zone due to gravity, this technical technique aimed to instantly counteract El Oued sand's exceptionally high saturated hydraulic conductivity. Based on soil water conditions, time, and climate requirements, the Pivot system's automatic triggers rotated in cycles. Activation occurred as soon as the average of the sensors indicated that the wilting threshold was getting closer.

When the sensors detected that the field capacity had been reached across the researched root level, the automatic valves would precisely stop applying water volume; the volumes per

Table 3. Fertilization program throughout the growing period.

Application time	Fertilizer	Application rate (kg/ha)
Pre-planting	Humostar12% Humic acid (Nutagra, Béjia-Algeria)	50
	12.52.0 MAP mono ammonium phosphate (Nutagra, Béjia-Algeria)	200
	8-10-30 + 30 SO_3 (Nutagra, Béjia-Algeria)	500
From ridging to tuber maturity	Urea 46% (Asmidal, Annaba, Algeria)	216
	12.61.0 Soluble MAP Mono ammonium phosphate (Nutagra, Béjia-Algeria)	96
	Magnesium sulfate (16% MgO) (Nutagra, Béjia-Algeria)	25
	Potassium sulphate (50%) (Nutagra, Béjia-Algeria)	135
	Zn (EDTA) (Greenhas, Canal, Italy)	3

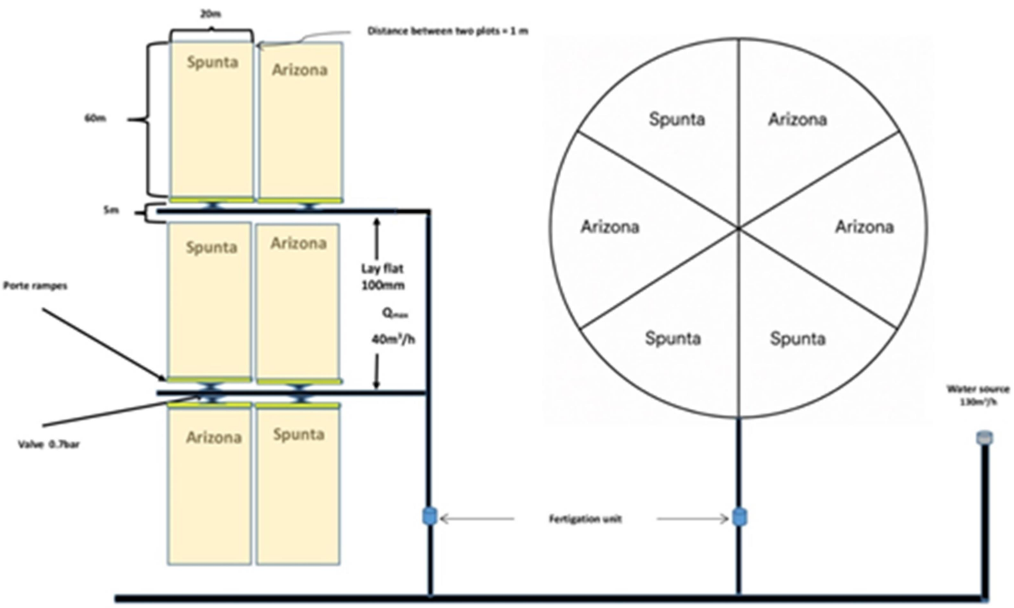

Fig. 1. Schematic layout of irrigation system.

occurrence were not predetermined. The volumes for each system during the three main stages of the plant cycle are listed in the supplementary Table. For the SDI system depth, the drip lines were placed at a fixed depth of 20 cm below the top of the planting mound, and the emitters were placed at the geometric center of the zone of maximal root activity.

2.3. Irrigation, soil water content measurement and actual crop evapotranspiration

In order to maintain ideal moisture conditions throughout the root zone, irrigation scheduling was based on crop water requirements and soil water status (Karizi et al., 2025). Equation 1 was used to determine the irrigation water depth applied at each irrigation event.

$$d = \sum_{i=1}^{n}(\theta_{Fc,i} - \theta_{v,i}) \times \Delta Z \qquad \text{Eq. 1}$$

Where d is the depth of irrigation (cm), $\theta FC,i$ is the volumetric soil water content at field capacity, $\theta v,i$ is the soil water content before irrigation, ΔZi is the thickness of soil layer i (cm), and n is the number of soil layers within the root zone.

In addition, during the crop season of 2023 and at a depth of 20-30 cm where potato roots grow, bulk soil density and available water capacity—which might vary depending on irrigation systems—were assessed using the techniques of Campbell and Henshall (2001) and Silva et al. (2014), respectively.

Soil volumtric water content (θv) was continuously monitored using capacitance probes installed at depths of 5–15 cm and 25 cm within the root zone. These measurements were used to adjust irrigation timing and applied water amounts throughout the growing season. Additionally, an automatic weather station was installed at the experimental site to continuously monitor local climatic conditions. The station recorded meteorological variables including air temperature (T), relative humidity (Hr), solar radiation (Rs), wind speed (W), and rainfall (R). The maximum, minimum, and average of climatic parameters during the experimentation period are reported in Table 3. Additionally, reference evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith equation based on daily meteorological data collected at the experimental site (Allen et al., 1998). Subsequently, crop evapotranspiration (ETc) was estimated following the equation 2. ETc values were used to estimate crop water requirements and to support irrigation scheduling throughout the growing seasons.

$$ET_C = K_C \times ET_0$$

Where ETc is the crop evapotranspiration (mm day^{-1}), ET0 is the reference evapotranspiration (mm day^{-1}), and Kc is the crop coefficient reflecting the crop growth stage. For potato, Kc values were adopted from FAO-56 guidelines and set to 0.5, 1.15, and 0.75 for the initial, mid-season, and late growth stages, respectively (Allen et al., 1998; Parkash and Singh, 2020).

2.4. Plant growth monitoring

Plant growth dynamics were monitored at three critical developmental stages such as vegetative growth (45 DAP), tuber initiation (65 DAP), and tuber bulking (90 DAP). At each stage, ten plants per replication were randomly selected and carefully excavated. The plants were separated into aerial biomass and roots (without tubers at the third stage), thoroughly cleaned, and weighed using a precision balance (±0.1 g). Fresh weights were recorded immediately, and root-to-shoot ratios were calculated, providing insight into the allocation of assimilates under varying water irrigation systems.

2.5. Yield and yield component

At harvest, potato plants were manually collected at the ground level, and tubers were separated from the plant biomass. Mature tubers for each plant, variety, and irrigation system (n = 30) were manually harvested at 110 DAP and 115 DAP for 2023 and 2024, respectively. After that, tubers were weighed, counted and classified into two size categories, such as C1 (< 40 mm) and C2 (> 40 mm).

2.6. Water productivity

Water productivity was evaluated with the goal to assess the efficiency of water use under different irrigation systems. Two complementary indicators, irrigation water use efficiency (IWUE) and water use efficiency (WUE), were considered in order to provide a comprehensive assessment of crop performance in relation to water inputs (Kirda et al., 2005). Water use efficiency was calculated using the ratio of tuber yield to crop evapotranspiration, which was calculated using the FAO-56 technique based on the Penman–Monteith reference evapotranspiration and crop-specific coefficients. The yield to total irrigation water applied is known as IWUE, which evaluates the effectiveness of irrigation methods independent of climatic demand. Thus, WUE and IWUE were determined using equations 3 and 4, respectively. All indices were calculated for each irrigation technique and variety, enabling a consistent and robust comparison of water use performance under arid conditions.

$$\boldsymbol{WUE} = \frac{\boldsymbol{Y}}{ETc} \qquad \text{Eq. 3}$$

$$\boldsymbol{IWUE} = \frac{\boldsymbol{Y}}{\boldsymbol{I}} \qquad \text{Eq. 4}$$

Where WUE is the Water Use Efficiency (kg m^{-3}), IWUE is the irrigation water use efficiency (kg m^{-3}), Y is the tuber yield (kg ha^{-1}) and ETc is the crop evapotranspiration (m^3 ha^{-1}), I is the irrigation water applied (m^3 ha^{-1}).

2.7. Statistical analyses

All measured variables, including soil properties, plant growth traits, yield and yield components, and water productivity indices, were statistically analyzed over the two growing seasons. Data were subjected to analysis of variance (ANOVA) using a split-plot design, with irrigation technique assigned to the main plots and potato variety to the subplots. The effects of irrigation technique (IS), variety (V), and their interaction were tested. Prior to analysis, data were examined for normality and homogeneity of variance to ensure compliance with ANOVA assumptions. Each treatment was replicated three times, and each experimental unit consisted of ten plants. Results are reported as mean values accompanied by their standard deviation (mean ± SD). When ANOVA indicated significant effects, mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a significance level of $p<0.05$. All statistical analyses were conducted using SAS software (version 9.2).

3. RESULTS AND DISCUSSION

Under two irrigation systems, two potato varieties Arizona and Spunta were investigated experimentally. The study's objectives were to: (i) evaluate the effects of irrigation systems on the volumetric soil water content and characteristics of the soil at different depths; and (ii) determine the optimal relationship that would enhance plant development parameters, yield components, and water use efficiency.

3.1. Effect of irrigation systems, growing seasons and sampling depth on soil characteristics

3.1.1. Impact of irrigation systems on soil bulk density and available water capacity

In contrast to the SDI system, pivot irrigation increased bulk density (compaction), illustrated in Fig. 2, which would alter the surface soil structure. We detected an average of 1.53±0.08 g/cm3 under the SDI system compared to 1.66±0.10 g/cm^3 for the pivot one, or a rise of 8.51%; this relative increase is related to the surface layer compaction index rather than the absolute density value. Simultaneously, for pivot system this effect is linked to a reduction in the available water capacity, which leads to poor root plant development; we found a value of 63.42± 1.46 mm at a soil depth of 20–30 cm. Conversely, the SDI system will enhance the root growth and tuberization process by lowering the bulk density (1.53 g/cm^3) and increasing the accessible water capacity by 70%. It is well known that the physical and chemical

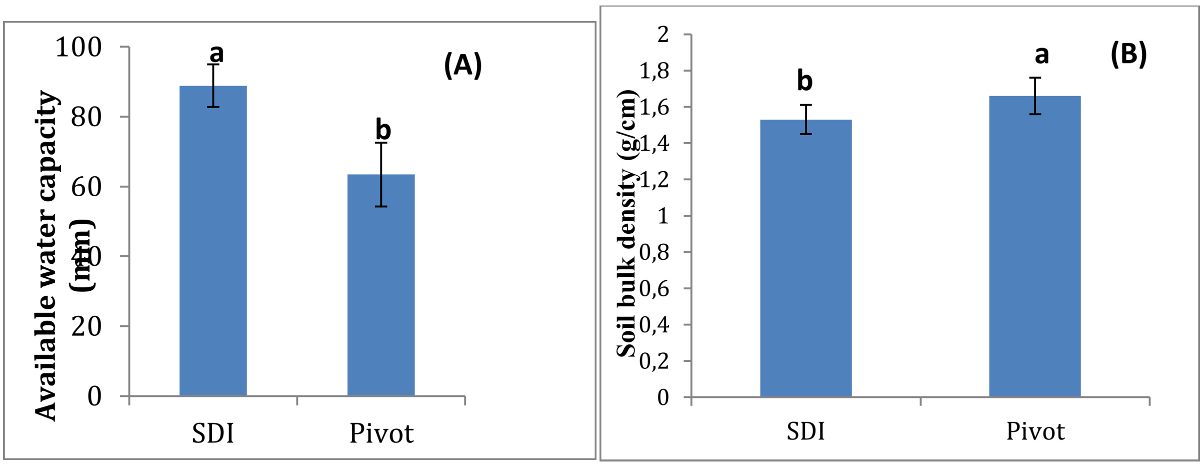

Fig. 2. Effect of irrigation system, SDI and pivot, on the available water capacity (A) and the bulk density of the soil at a depth of 20-30 cm.

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characteristics of soil are crucial for effective irrigation because they affect soil water storage, water availability to plants, water and air transmission through soil (Zhu et al., 2009), soil workability, drainage, and soil resilience to change, all of which have an impact on yield and production as well as the efficient use of nutrients (Horne and Scotter, 2016). Dry bulk density is a measure of the ratio of the mass of soil to the total volume of soil after oven drying (Campbell and Henshall, 2001). Increases in bulk density can reduce aeration and drainage, negatively impacting plant growth. In contrast, soils with low bulk density are loosely packed and often suffer from insufficient water reserves for good agricultural production (Horne and Scotter , 2016). Due to the highly sandy soil in the experimental area, an increase in soil evaporation associated with an increase in water penetration is the primary cause of the low available water capacity observed by using the pivot system. Drip irrigation has gained popularity because it effectively reduces soil surface evaporation and uniformly provides water throughout root zone development, despite its dependence on topography and the hydraulic design parameters of the drip system (Zhu et al., 2009).

3.1.2. Soil's physical characteristic as affected by irrigation system, season and depth sampling

Table 4 illustrates how the two irrigation methods during the 2023 and 2024 experimental years, as well as the various soil sampling depths, had a substantial ($p<0.02$) impact on soil physical properties such temperature (T), electrical conductivity (EC), relative humidity (RH), and water content. Specifically, pivot irrigation increased RH by 16% compared to SDI while lowering EC and soil temperature by 2.91 mS/cm versus 3.24 mS/cm and 18.43 versus 19.76°C, respectively. Relative humidity was lower under the SDI system than under the pivot system; values of 9.43% and 10.94% were noted. However, the SDI system decreased the soil water content, with values of 16.63% vs. 18.54% for the pivot system, while increasing the primary EC value by 11.73% and the temperature by 7.21%. Numerous studies have demonstrated that there is a strong relationship between soil moisture content and EC. According to a study by Hallouche et al. (2017), EC and soil water content have a linear relationship. Since soil water content is the primary determinant of current flow, numerous studies have verified that soil water content is, in fact, the most important factor influencing EC of all other components (Teffera et al., 2018). EC showed an increase in the depth layer, 3.44 mS/cm was recorded at 25 cm depth compared to 2.87 mS/cm at -15 cm, while at surface profile the EC was also higher, indicating the possibly salt accumulation in those depths, in spite of the soil drainage. This results would be attributed to the adjustment of the irrigation doses or the frequency of the irrigation as mentioned by Teffera et al. (2018). The greater EC in irrigated soils is caused by a number of variables, including the quality of the irrigation water, which may contain dissolved salts that over time may build up in the soil and raise the EC (Fadl et al. ,2024). However, these characteristics varied across the two growing seasons, with a greater relative humidity in 2023 and no appreciable change in 2024. As Table 2 illustrates, this led to differences in rainfall in April and May. Several authors (Teffera et al., 2018; Zahoor et al., 2019) reported similar results, showing significant differences in the soil physicochemical parameters across the experimental years dependent on the amounts and timing of rainfall.

3.1.3. The interaction effects of irrigation system, depth sampling and experimental year

Table 4. Mean RH, EC, temperature and soil water content (θv) as affected by irrigation systems, year and depth sampling.

Factor		RH (%)	EC(mS/cm)	T (°C)	Θv(%)
Irrigation systems (IS)	S.D.I.	9.43b	3.24a	19.76a	18.54a
	Pivot	10.94a	2.9b	18.43b	16.63b
Year	2023	10.15 a	3.07 b	18.92 b	17.36 a
	2024	10.05 a	3.28 a	19.54 a	15.24 b
Depth (m)	-5	9.53 b	3.00b	19.13b	15.64 c
	-15	9.15b	2.87c	19.10b	17.25a
	-25	11.56a	3.44a	19.41a	18.12a

The significant interaction effects ($p<0.02$) between the irrigation system, soil depth, and experimental years are displayed in Table 5. The SDI system induced the highest RH of 12.87% at a depth of 25 cm, where the maximum root expansion occurs, in comparison to the pivot system at the same depth, showing the buildup of water and bulb formation around plant roots. However, as Table 3 predicts, the pivot system produced a greater RH than the SDI one during the 2024 dry season.

Precision irrigation systems such as SDI have been suggested as the most eco-friendly ones for the sustainable use of natural resources with increased water and nutrient use efficiency when combined with fertigation practices (Trifonov et al., 2018; Elzner et al., 2018), consequently, potato plant growth and yield would be improved. The low EC was at -15 cm for both SDI and pivot systems, with SDI yielding the highest mean value (3.06 mS/cm) compared to pivot system's 2.61 mS/cm. When an SDI system is used for irrigation, salts can build up around a water bulb that forms in the 15–20 cm root zone, which can negatively impact plant growth. As various reports have noted (Crosby and Wang, 2021; Djaman et al., 2021), the frequency of irrigation might control this adverse effect. However, according to Demir and Sahin (2017), the pivot system may remove salts far from the root zone because we got the lowest EC value at -15 cm (2.61 mS/cm). Despite the EC ranging from 2.90 to 3.46 mS/cm in 20023 and 2024, respectively, there were no discernible differences between the two irrigation systems.

Throughout the 2023 and 2024 growing seasons, the average θv of three sampling points at depths of 5, 15, and 25 cm was calculated daily to assess the differences in soil water content between the two irrigation systems (SDI and Pivot). Table 5 displayed the effects of different irrigation systems at the three depths on the water content of the soil. The SDI system increased the soil water content by 11.5% in comparison to the pivot one . These findings corroborate those of Mattar et al. (2021), who found that potato plants irrigated with drip systems had a far high soil water content than those treated with pivot systems

Regarding the soil water content percentage significant variations were discovered, with the SDI systems improves this trait, a value of 18.97% was observed at a depth of 25 cm while the pivot induced 16.98% without significant differences. According to Djaman et al. (2021), this implies that the pivot increases soil evaporation and superficially moistens it, which prevents root development and stolon growth for better tuber production owing to nutrient infiltration through soil drainage. Our results, are in agreement to those of Mattar et al. (2021), who found that the maximum water content values were achieved by sub-drip irrigation. Additionally, SDI concentrated water content at a depth of 5 to 15 cm, which may be sufficient for root potato plants (Zin ElAbedin et al., 2019). The pivot system generated more optimum soil water content than the SDI system in 2024, with values ranging from 15.35% to 13.89%, despite weather-related temperature increases. In this context, Djaman et al. (2021) observed in their assessment of potato irrigation management that there is a noticeable variation in soil water

Table 5. Interaction effect of irrigation systems, year and soil depth sampling on relative humidity (RH), electrical conductivity (EC), temperature (T) and soil water content (θv).

Factor		RH (%)	EC(mS/cm)	T (°C)	Θv(%)
	SDI.(5cm)	8.88±0.94c	3.18±0.41a	19.59±2.58a	14.25±1.23b
	SDI(15cm)	8.83±0.26c	3.06±0.16b	19.69±2.44a	14.78±1.85b
IS x Depth	SDI(25cm)	12.87±0.32 a	3.50±0.31a	20.00±2.45a	18.97±2.06 a
	Pivot(5cm)	10.37±2.11b	2.76±0.18bc	18.52±1.99b	16.98±1.45ab
	Pivot(15cm)	9.57±0.36bc	2.61±0.06c	18.30±2.04b	15.58±1.23 b
	Pivot(25cm)	10.57±1.64b	3.35±0.03a	18.62±1.92b	16.87±2.08 ab
	SDI (2023)	9.43±1,04 b	3.24±0,35 a	19.76±1.42ab	15.45±1.32 b
IS*year	SDI (2024)	9.37±1,01 b	3.46±0,34 a	21.44±1.64 a	13.89 ±1.08 bc
	Pivot(2023)	11.88±1,41a	2.90±0,31 a	18.08±1.75b	17.65±1.12 a
	Pivot(2024)	10.73±1,35ab	3.10±0,32 a	18.64±1.26 b	15.35±1.04 b

content between growing seasons due to climate change, particularly the increase in temperature. Similarly, Tolba et al. (2023) investigated into the smart drip irrigation system in order to determine the best irrigation scheduling management to improve soil water content and potato crop growth and output. They concluded that the values fluctuated significantly depending on the climate throughout the two successive summer seasons of 2020 and 2021.

3.2. Vegetative growth traits as affected by irrigation system, varieties and experimental year

3.2.1. Main effect of irrigation system and variety through the cropping seasons

The fresh weights of the root and vegetative parts, as well as the root –to- shoot ratio which measured during the most crucial stages of the potato life cycle, were considerably impacted by the irrigation systems, the variety and the cropping season (Table 6). Because of the climate variance (Table 1), which had a different impact on the three cycle phases, the irrigation systems increased biomass growth more during the cropping season of 2023 than in 2024. SDI and pivot systems were found to differ significantly in the same year. The SDI system, which recorded values of 218.88g/plant and 201.26g/plant in 2023 and 2024, respectively, had a more favorable impact on the tuberization phase. The tuber yield would be impacted by this consequence. On the other hand, during the 2023 season, the pivot system enhanced both the vegetative and tuber bulking stages without significant differences. The pivot system promoted the increase of above-ground biomass throughout the 2023 season at the late tuber growth stage (tuber bulking) because the sprinklers maintain high leaf relative humidity, which is ideal for photosynthetic activity at the end of the cycle. In fact, this can increase stomatal performance and, as a result, efficient photosynthesis, preserving the high chlorophyll concentration (Grosby and Wang, 2021)); nonetheless, leaf expansion hinders the tuberization process in potato (Mattar et al., 2021). However, as shown below (Table 8), this vigorous vegetative growth under the pivot did not provide a higher tuber yield; instead, the SDI technique proved to be more successful in transferring assimilates (starch and sucrose) to

Table 6. Fresh weights of the vegetative and root parts, and root-to-shoot ratio at different growth stages (Vegetative growth and sprouting: VG, Tuberization:Tub and Tuber bulking:TubB) of two potato varieties, Spunta and Arizona submitted to two irrigation systems SDI and pivot.

Factor	Stage	Aerial Vegetative FW (g/plant)		Root part FW (g/plant)		Root/shoot ratio	
		2023	2024	2023	2024	2023	2024
Irrigation system							
	VG	146.83* c	139.27 c	23.46 a	21.74 a	0.16a	0.16a
SDI	Tub	218.88 a	201.26 a	18.65 b	17.22 b	0.09c	0.09c
	TubB	139.66 c	120.10 cd	18.07 b	16.38 b	0.13b	0.14b
	VG	148.93 c	143.75 c	22.12 a	20.08 a	0.15a	0.14b
Pivot	Tub	197.82b	187.23 b	16.37bc	15.1 c	0.08c	0.08c
	TubB	178.65 b	101.46 d	15.31 c	15.01 c	0.09c	0.15a
p-value		0.03*	0.03*	0.02*	0.04*	0.001*	0.001*
Variety							
	VG	152.26b	142.12 b	25.11a	22.15 a	0.16b	0.16a
Spunta	Tub	172.15ab	168.35 ab	20.19 c	18.37 b	0.12c	0.11b
	TubB	141.76 b	131.08 b	16.29 d	15.12c	0.11c	0.12b
	VG	141.65 b	135.98 b	26.17 a	19.78 ab	0.18a	0.15a
Arizona	Tub	186.75 a	175.11 a	22.75 b	16.18 c	0.12c	0.09bc
	TubB	147.16 b	138.67 b	18.19 c	15.29 c	0.12c	0.11b
p-value		0.01*	0.03*	0.004**	<0.001**	0.002*	0.001*

Values with the same letter in each column for each factor are similar according to Duncan's multiple range test (DMRT) at p< 0.05 the harvestable underground portion.

Similar trends with a significant impact were found for root fresh weight; the values varied from 23.46 to 22.12 and from 21.74 to 20.08g/plant in 2023 and 2024, respectively. Interestingly, SDI had a greater positive impact on root/shoot ration during the vegetative stage than pivot did in 2024, a year marked by high temperatures and hot winds, with values of 0.16g/plant compared to 0.14g/plant. In our recent research (Beggas et al.,2026) comparing the effects of irrigation methods, we found that all potato varieties had significantly more photosynthetic leaves per m2 under the SDI system, with Spunta having the highest results. Plant length also showed this beneficial effect, with the Spunta variety recording the greatest values. According to Darwish et al. (2003) N leaching increased when micro-sprinkler irrigation systems were used, however SDI systems guarantee that N is supplied close to the plant rhizosphere. This data shows that SDI leads to better water and nutrient availability, particularly N. Furthermore, Zhou et al. (2018) verified that, in comparison to pivot irrigation systems, drip irrigation in conjunction with fertilizer application produced greater N use efficiency and N recovery from tubers.

During the tuber bulking stage, the pivot system outperformed SDI in improving this trait. Our results are consistent with those of Wu et al. (2022), who measured plant growth, yield, and water productivity during field experiments to examine the dynamic distribution of potato roots in the soil as a basis for developing a new irrigation technique for potato production. Their findings indicated that there were significant differences in the root distribution of potato plants at various growth stages, indicating that the current water management technique of equal irrigation during potato production is ineffective and has a lot of room for improvement. During potato growth, varying the quantity of irrigation around the root distribution greatly boosted plant growth and tuber yield.

We observed a slight decline for both irrigation methods in 2024 for all growth parameters, especially when pivot was applied. The weather, as previously shown in Table 2, would account for this decline since the temperature was higher in May and June when the bulking stage was completed than it was in 2023. According to Djaman et al. (2021), a number of factors, including irrigation regimes, techniques, local climate, fertilizer management options, and other environmental and management factors, affect potato water use and evapotranspiration. Furthermore, our results align with those of Tolba et al. (2023), who investigated the impact of two drip irrigation systems on three potato varieties: subsurface drip irrigation and surface drip irrigation. They found that the irrigation system had a significant impact on all the growth aspects under study and that SDI outperformed sprinkler system in all vegetative growth. However, few research have examined how irrigation systems affect the various stages of the potato lifecycle.

With no discernible differences from Spunta, Arizona had the greatest biomass fresh weight throughout the tuberization phase in both 2023 and 2024 (186.75 g/plant and 175.11 g/plant, respectively). In 2023 and 2024, there was little difference between Spunta and Arizona in terms of root fresh weight and root/shoot ratio. However, during the tuber bulking phase, all growth characteristics are similar in Arizona and Spunta (Table 5).However, Arizona generally outperformed Spunta in this study, which is consistent with Tolba et al. (2023), who concluded a variable response of three potato varieties in all vegetative development parameters during both seasons of their experiment. The Cara cultivar demonstrated the highest significant values for shoot fresh weights of potato leaves/plant, number of leaves, number of main stems, total leaves area, and plant length, while the Spunta cultivar demonstrated the lowest values.

However, for every phase, the 2024 results were less significant than the 2023 values. According to Meligy et al. (2020), the difference is most likely due to the significant increase in temperature during the crucial months of 2024, which may restrict plant development and raise evapotranspiration. Additionally, in several Mediterranean nations, including Algeria and Tunisia, potatoes are cultivated in the autumn (late season) and particularly in the spring (seasonal cropping), when rising temperatures and severe soil water deficits cause evapotranspiration to rise and rainfall to decrease.For early and mid-early potato varieties like Arizona and Spunta, the tuber bulking stage occurs in March and April. During this time, irrigation should be used in terms of both quantity and methods. However, as this study points out, irrigation techniques and intervals might change from season to season based on the distribution of rainfall (Crosby and Wang, 2021).

3.2.2. Interaction effects analysis

Table 7 shows the interaction effect between irrigation system and variety through the two cropping seasons where significant differences were observed. Irrigation systems' effects vary greatly depending on the varieties tested; we discovered that SDI had greater impact on Spunta than the pivot system throughout the two experimental years, especially during the 2024 dry season, and at different stages of the potato cycle, especially the tuberization phase. a rise of 9% to 49% in the vegetative and tuberization phase in 2023 and 14% to 56% in 2024. Arizona, on the other hand, gained more from the pivot system; compared to the SDI, the vegetative and tuberization stages increased by 11% to 49% and 20% to 44%, respectively, in 2023 and 2024. The root fresh weights showed comparable trends in both experimental years, with a significant decrease from 2023 to 2024.

Arizona was more suited for the pivot method, but the Spunta plant, which was kept under the SDI system, had more developed root sections in both the 2023 and 2024 growth seasons. The root/shoot ratios were lower in 2024 than in 2023 at the most crucial phases, such as the vegetative and tuberization phases. These results align with those of El-Mohk et al. (2014), who examined the differences between drip and sub-drip irrigation for potato plants in a dry environment in Tunisia. Furthermore, Mattar et al. (2021) evaluated the impacts of drip and subsurface drip irrigation on potato development and yields in a desert location in Saudi Arabia and discovered comparable results. In this regard, Shalhevet et al. (1983) determined the water production functions of potatoes ('Desiree') under drip and sprinkler irrigation and found that Under drip irrigation the soil could dry to −40 J kg^{-1} without yield reduction, as long as the water supply was adequate. This was explained by the higher root concentration under drip than under sprinkler irrigation.

3.3. Yield and yield attributes

Except the number of tuber/m^2 with size less than 40mm, all other evaluated characteristics were significantly impacted ($p<0.001$) by the irrigation systems (Table 8), Plants under SDI system produced the highest yield, 31708.61 kg/ha, in contrast to the pivot method, which produced 27526.14 kg/ha. The SDI resulted in a 35.5% increase in tuber weight and a 29.5% rise in tuber quantity per m^2. Additionally, adopting

Table 7. Interaction effect of irrigation systems and variety on fresh weights of the vegetative and root parts as well as on root-to-shoot ratio at different growth stages (Vegetative growth and sprouting: VG, Tuberization:Tub and Tuber bulking:TubB) of two potato varieties, Spunta and Arizona submitted to two irrigation systems SDI and pivot.

Factor	**Stage**	**Aerial Vegetative FW (g/plant)**		**Root fresh weight (g/plant)**		**Root/shoot ratio**	
		2023	**2024**	**2023**	**2024**	**2023**	**2024**
	VG	140.93*±24.78 b	134.56±21.55c	33.76±4.98 a	25.85±2.56 b	0.24±0.02a	0.12±0.02 b
SDI *Spunta	Tub	225.85±41.15 a	215.89±34.12a	25.45±3.53 b	24.32±3.75 b	0.11±0.01b	0.11±0.01 b
	TubB	220.88±31.84 a	214.56±30.14a	23.46±4.10 b	17.89±1.45 c	0.10±0.01bc	0.08±0.01 c
	VG	129.24±26.56 c	118.22±19.01cd	17.86±2.12 c	13.84±2.17 c	0.14±0.02b	0.12±0.02 b
Pivot *Spunta	Tub	151.51±39.24 b	138.56±23.25 c	14.25±1.56 d	10.58±1.84 cd	0.09±0.01bc	0.07±0.01 c
	TubB	149.45±24.89 b	129.74±25.56	11.54±1.21 d	10.85±1.97	0.08±0.01c	0.08±0.01c
	VG	148.91±27.18 b	146.0±16.74 c	20.20±4.23 c	23.31±3.68 b	0.13±0.02b	0.16±0.02 a
SDI *Arizona	Tub	287.45±52.63 a	218.88±37.64 a	24.56±2.67 b	18.6±3.79 bc	0.08±0.01c	0.08±0.01 c
	TubB	178.4±22.87 ab	176.66±32.56 b	23.83±3.03 b	16.82±2.59	0.13±0.02b	0.09±0.02 c
	VG	143.91 ±24.85 b	142.85 ±27.54c	33.66±4.97 a	21.88±3.42 b	0.23±0.03a	0.15±0.03ab
Pivot *Arizona	Tub	225.95±65.39 a	199.58±21.75 b	25.47±2.58 b	20.84±2.65 b	0.12±0.01b	0.10±0.01 bc
	TubB	220.74±34.83 a	184.58±25.12 b	23.46±3.26 b	33.66±4.97 a	0.10±0.01bc	0.18±0.03 a
p-value		**0.032***	**0.002****	**0.001****	**0.041***	**0.002****	**0.003****

** Values with the same letter in each column for each factor are similar according to Duncan's multiple range test (DMRT) at p< 0.05*

Table 8. The impacts of growing season, varieties, and irrigation system on potato tuber production, yield components, irrigation and water use efficiency, and total water irrigation.

Factors	Yield (kg/ha)	Tub /m^2	TW(g)	C1: Tub<40mm	C2: Tub>40mm	IWUE	WUE	TW Irrig
Irrigation systems								
SDI	31708.61a	28.29 a	65.37 a	8.62 a	19.62 a	4.694 a	6.065 a	6763.90 b
Pivot	27526.14b	21.84 b	48.23 b	8.37 a	16.14 b	3.725 b	5.258 b	7352.54 a
p-value	<0.0001	<0.001	<0.001	<0.28	<0.0001	<0.001	<0.001	<0.001
Year								
2023	30137.98 a	26.55 a	60.07 a	9.03 a	18.93 a	4.285 a	5.76 a	7070.42 a
2024	29.096.77 b	23.58 b	53.54 b	7.97 b	16.83 b	4.126 b	5.56 b	7078.41 a
p-value	<0.0001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.08
Variety								
Spunta	26237.99 b	25.83 a	52.50 b	8.29 a	17.50 b	4.22 a	5.67 a	6300.48 b
Arizona	32996.76 a	24.30 b	61.11 a	8.70 a	18.27 a	4.18 b	5.64 a	7846.37 a
p-value	<0.0001	<0.001	<0.0001	<0.076	<0.0001	<0.001	<0.016	<0.001
CV(%)	1.06	6.67	6.19	16.47	7.16	1.02	1.09	0.23
Means	29617.37	25.07	56.80	8.50	17.89	4.20	5.66	7073.43

Tub/m^2: tubers number/m^2, TW: average of tuber weight, TWirrg: Total water irrigation.

** Values with the same letter in each column for each factor are similar according to Duncan's multiple range test (DMRT) at p< 0.05.*

SDI instead of the pivot resulted in a 21.56% increase in marketable tube size (C2). Between the growing seasons, there were significant (p<0.001) differences in yield, with 2023 generating 30.137 t/ha and 2024 yielding 29.096 t/ha. Remarkably, yield components such as tuber size, weight, and tuber number/ m^2 were more important in 2023 than in 2024, with 18.93 tubers/m^2 (size C2), 60 g and 26.55 tubers/m^2. Additionally, the data showed that the two potato varieties differed significantly in every yield parameter during the course of the two growing seasons. Interestingly, Arizona recorded the highest values for marketable tubers C2 (18.2/m2), average tuber weight (61g), and yield/ha (around 33T/ha), followed by Spunta, indicating the best adaptability of Arizona in arid-region of El Oued. However, no significant differences were found for the smaller tubers generated (C1), although the Spunta had the greatest significant value for the number of tubers /m^2.

Ours findings are in accordance with those of Patel and Rajput (2007) and El-Mokh et al. (2014), who reported that SDI at a depth of 10 to 15 cm can increase tuber yield, and the SDI system significantly improved both the marketable tuber yield and yield components. Numerous research on vegetable production have used an SDI depth of 15–25 cm, and it has been demonstrated that SDI performs better than pivot systems in raising eggplant (Douh and Boujelben, 2010) and tomato (Lamm, 2016) yields. Reduced evaporation loss from the soil surface and maintenance of the ideal soil water content in the root zone, which leads to optimal crop production, are the reasons why the SDI system can increase tuber productivity (Selim et al., 2009).

These results are consistent with the findings of Cantore et al. (2014) and Ahmadi et al. (2014), as well as those of Çolak et al. (2017) for eggplant and Meligy et al. (2020) for potatoes, who found that crop yield is positively correlated with irrigation systems that supply varying amounts of water, which in turn affect vegetative growth and tuberization phases. In terms of the variation between the two growing seasons, the fresh tuber yield was higher in plants grown in 2023 than those grown in 2024. Low water surrounding the roots in the early stages of potato development, particularly during the sprouting period, may result in a decrease in the final fresh yield, according to Iqbal et al. (1999). In contrast, Onder et al. (2005) found that whereas irrigation levels had a considerable impact on potato tuber output, the irrigation system had no discernible influence; instead, variations were caused by soil properties and potato cultivars.

Due to their shallow root structure, which makes them extremely vulnerable to water stress, potato plants need to be properly watered in order to prevent drought conditions (Mokh et al., 2014). Fresh potato production is reported to rise with water availability (Wang et al., 2020).In their evaluation of various potato varieties, Zin ElAbedin et al. (2019) discovered that effective irrigation water management prior to and during tuber initiation enhances the number of tubers per plant and total yield, whereas proper irrigation management following tuber initiation increases the size of tubers. In addition, in a two-year experiment conducted in the Central Bekaa Valley of Lebanon in a semiarid climate, Karam et al. (2014) discovered that the full irrigation treatment overcame deficit irrigation at tuber bulking and tuber ripening by 12 and 43% in the first year and 11 and 39% in the second, respectively. Similar findings were reported by Fabeiro et al. (2001), who found that using deficit irrigation during the potato growth, tuber bulking, and ripening stages decreased potato yield. They also found that fully irrigated potatoes and the ripening stage deficit irrigation produced larger tubers, while applying deficit irrigation during the growth period with a high tuber number per plant produced the smallest tubers. Furthermore, Ierna & Mauromicale (2018) stated that irrigation, particularly when combined with N fertilizer, is favorably associated with higher yield and average tuber weight as well as fewer tubers that are discarded because of illnesses and unmarketable shape. In addition, Nagaz et al. (2016) indicated that low irrigation water quality and limited water availability are linked to lower yield and yield components (such as average tuber weight and tuber number), while scheduling irrigation according to soil water balance may also have a favorable effect on tuber yield and the potato crop's water use efficiency (El Mokh et al., 2014). Water, minerals, and carbohydrates particularly sucrose, which is transferred from leaves to tubers and transformed into starch accumulate in tubers during the tuberization stage, providing tubers a linear growth rate (Ahmadi et al., 2014). Thus, it could be hypothesized that the more even distribution of water under the SDI system as opposed to the pivot one may increase water availability in the root zone, leading to greater photosynthetic activity, better nutrient uptake, and ultimately improved crop production. Ierna and Mauromicale (2020)) found that the combination of high fertilization rates and high irrigation water supply led to significantly lower source-to-sink ratios (the ratio of biomass dry matter to dry tuber yield), indicating the significance of water and nutrient availability for attaining high tuber yields.

3.4. IWUE and WUE as affected by irrigation system, varieties and crop seasons

Table 8 displays also the water use efficiency (WUE) and irrigation water use efficiency (IWUE) data for every factor. Sub-drip-irrigated plants showed a greater IWUE than pivot-irrigated plants over the course of the two growth seasons ($P < 0.001$). While irrigation water use efficiency varied from 3.725 to 4.694 kg/m3, WUE values ranged from 5.258 to 6.065 kg/m3. Among the main food crops, potatoes have a high water use efficiency (WUE), ranging from 6 to 11.6 kg/ha/m^3, according to Yamaguchi and Tanaka (1990). However, the genetic material, management techniques, irrigation system, fertilizer rate, and other environmental factors all have a significant impact on potato WUE. Despite having a higher WUE than heritage potatoes, modern potatoes are not as economically productive when given the same amount of water (Fandika et al., 2016). Crop WUE can be maximized by using deficit irrigation systems (Badr et al, 2012). Ours results are in accordance with some authors. According to El-Mokh et al. (2014), plants treated with the SDI system—which is regarded as deficit irrigation—had the highest IWUE. Similarly, Liu et al. (2006), Ahmadi et al. (2014), and Ierna and Mauromicale (2018) demonstrated that the IWUE of potatoes was higher under deficit irrigation than under full irrigation, and El-Mokh et al. (2014) suggested that a higher IWUE could be achieved by applying the SDI system at a depth of 10–15 cm. Increased values of IWUE under deficit irrigation have also been observed for watermelon [*Citrullus lanatus* (Thunb) Matsum& Nakai] (Leskovar et al., 2004), tomato (Al-Qerem et al. 2012), red pepper (Sezen et al. 2014), bell pepper (Bladia and AbdArahman 2016), and eggplant (Colak et al. 2015, 2017), while Geets and Kirk (2009) confirmed that deficit irrigation successfully increased the IWUE of different crops without decreasing crop yield in dry regions.

IWUE also increased during the growing seasons, and WUE increased from 4.126 to 4.287 in 2024 and 2023, respectively. This would be explained by the climate variation between the two growing seasons affecting the water requirement for different varieties; Spunta had the highest IWUE (4.223 kg/m3) compared to Arizona (4.182 kg/m3), while WUE showed no discernible variations with values ranging from 5.642 and 5.674 kg/m3. The environmental conditions would affect IWUE because physiological processes that regulate the CO2 and H2O gradients between the plant's leaves and the surrounding air cause an increase in IWUE in plants under water stress. Water-stressed plants benefit from a high CO2 concentration around their leaves because partial stomatal closure increases photosynthesis and decreases transpiration, but well-watered plants are unaffected (Lopes et al., 2011; Hatfield and Dold, 2019). On the other hand, extreme water stress may result in total stomatal closure, which would lower IWUE and the yield of potato tubers (Zin El-Abedin et al., 2019).

3.5. Interaction effects of irrigation system, variety and growing season on yield and yield components as well as on IWUE and WUE of potato

The three-way interaction effects of the variables under investigation are displayed in Table 9, which shows a significant impact ($p<0.001$) on irrigation and water use efficiency as well as all yield indicators except tuber size <40mm. Additionally, the pivot system produced the lowest yield for both Spunta and Arizona varieties in 2023 and 2024, with Arizona's plants producing more than Spunta's. This suggests that potato genotypes respond differently to irrigation systems (Zin El-Abedin et al. 2017; 2019). It's interesting to note that in 2023 and 2024, the Arizona variety produced more than Spunta under both irrigation systems, with a notable decline in 2024.By using the SDI irrigation system, Arizona produced the greatest marketable yield of 35.63t/ha in 2023 and 34.45t/ha in 2024, while Spunta produced the lowest values of 23.46t/ha and 24.74t/ha via the pivot system. According to Patel and Rajput (2007) and El-Mokh et al. (2014), SDI at a depth of 10–15 cm can lead to a higher tuber production. The SDI system significantly increased the fresh tuber output. In numerous research on tomatoes (Lamm, 2016), an SDI depth of 15–25 cm has been often employed for crop production. It has been demonstrated that SDI performs better eggplant (Douh and Boujelben 2010) and tomato (Lamm 2016) yields. Because the SDI system maintains the ideal soil water content in the root zone and reduces evaporation loss from the soil surface, it can increase tuber productivity, leading to optimal crop output. In contrast, Patel and Rajput (2007) found that a 20% reduction in irrigation water using an SDI system had no noticeable effect on potato yield, while Onder et al. (2005) found that irrigation levels had a significant impact on potato tuber yield but the irrigation system had no apparent effect. The disagreements would result from the soil characteristics and the irrigation technique used.

The three-way interaction also had an impact on yield components, including tuber number/m^2, tuber weight, and tuber size, where the SDI system performed better with both varieties. When plants were handled using the SDI system, Arizona had the greatest tuber number in 2023 (31.33), followed by Spunta (28.66). Arizona continued to develop more tubers (28/m2) in 2024 than Spunta (25.16). However, this trait decreased under the pivot system; in 2023 and 2024, the Arizona variety produced low tuber numbers of 17.83 and 20.05, respectively. Although, regardless of the growing season and irrigation systems, the main tuber number/m^2 was more significant in Spunta (25.82) than in

Table 9. Three ways interaction effects of growing season, variety and irrigation system on yield, yield component, IWUE and WUE of potato grown in arid region.

Factor	Y(kg/ha)	Tub/m^2	TW(g)	Tub<40mm	Tub>40mm	IWUE	WUE
2023*SDI*Spunta	29911.37*±170.38 c	28.66±2.95 a	59.83±5.32b	9.00±0.87a	19.67±2.49a	4.81±0.05a	6.25±0.09 a
2023*SDI*Arizona	35634.03±128.45 a	31.33±2.62 a	78.50±8.68 a	9.33±1.41a	22.00±3.20a	4.75±0.02b	6.09±0.03 b
2023*Pivot*Spunta	24747.56±152.03 e	26.16.2.87 ab	51.16±6.72b	8.66±1.40a	17.33±1.52b	3.76±0.05d	5.37±0.07 d
2023*Pivot*Arizona	31258.95±149.56 b	20.05±2.05bc	50.77±6.05b	9.11±1.07a	16.72±2.39b	3.82±0.06d	5.34±0.06 d
2024*SDI*Spunta	27830.70±171.07 d	25.16.2.47b	53.16±8.59b	7.83±1.61a	17.38±1.10b	4.62±0.05c	6.02±0.07 b
2024*SDI*Arizona	34458.33±227.70 a	28.00±2.24a	70.00±10.44ab	8.33±1.42a	19.51±2.69ab	4.58±0.06c	5.89±0.07 c
2024*Pivot*Spunta	23462.37±151.89 f	23.33±2.63b	45.83±6.64b	7.66±1.41a	15.67±1.34bc	3.56±0.04 e	5.08±0.05 f
2024*Pivot*Arizona	30635.7±204.07 c	17.83±2.71c	45.16±5.04b	8.05±0.99a	14.83±1.25c	3.74±0.03 d	5.24±0.04 e
Significance	<0.001	<0.001	<0.012	ns	<0.032	<0.01	<0.001

Arizona (24.30 tubers/m²). The pivot system had a similar detrimental impact on the tuber weight measurement, with the lowest values reported in 2024 and no noticeable distinction between the two varieties. Similar patterns occurred for tuber size, with values ranging from 19.51 to 22 for Arizona in 2024 and 2023, respectively, where the marketable number was more significant when using the SDI system than via pivot. According to Elhani et al. (2019), the marketable tuber weight, mean tuber weight, and number of tubers/m² were considerably greater under the SDI system than pivot in both seasons. The increased yield under the SDI system was associated with the increase of both the number and weight of formed tubers, while similar trends were observed for marketable tubers (C2 > 40 mm). This finding is partly in contrast with the study of Badr et al. (2005) who suggested that tuber weight is more sensitive to the irrigation regime than tuber number. On the other hand, Nagaz et al. (2016) discovered that water stress brought on by drip irrigation at various phases of growth decreases the number of tubers per plant in the arid region of Tunisia. Similarly, Zin El-Abedin et al. (2017) found that when squash (Cucurbita pepo L.) and potato plants were irrigated using the SDI technique, fewer fruit were produced. Marouelli and Silva (2007) noted that the number of commercially suitable tomato fruit per plant decreased with soil water tension during growth.

In terms of tuber size, Erdem et al. (2006) found the greatest number of tubers per plant with a low irrigation level by using drip irrigation, whereas Ahmadi et al. (2014) concluded that the number of potato tubers larger than 80 mm size class was highest with maximum water applied by sprinkler technique. This difference could result from variations in the plant species studied as well as additional environmental factors such air temperature and soil type (Rykaczewska 2013).

Data in Table 9 showed that IWUE varied significantly between the two growing seasons and was influenced by the irrigation system in both seasons and varieties ($p < 0.01$). For Spunta, plants grown under SDI had an IWUE that was 27.92% higher in 2023 and 29.77% higher in 2024 than those grown under the pivot system. In contrast to the pivot system, Arizona's IWUE increased by 24.34% in 2023 and 22.46% in 2024 when applying SDI.

WUE varied significantly between experimental years and irrigation systems, with values for Arizona and Spunta during the first growing season ranging from 6.09 and 6.25 kg/m3 with the SDI system to 5.37 and 5.34 kg/m3 with pivot irrigation, respectively. In 2024, plants under the pivot system had lower WUE values than those under the SDI, regardless of the variety. Kashyap and Ahmadi (2014) and Ierna and Mauromicale (2018) showed that the IWUE of potatoes was higher under deficit irrigation caused by the SDI system than under full irrigation, which is consistent with our findings. Additionally, Patel and Rajput (2007) and El-Mokh et al. (2014) proposed that using the SDI system at a depth of 10–15 cm could result in a greater IWUE.

Several authors have demonstrated improved IWUE values under deficit irrigation on some vegetable crops, proving that deficit irrigation was effective in arid areas. for red pepper (Bladia and AbdArahman, 2016), tomato (Al-Qerem et al., 2012), watermelon [Citrullus lanatus (Thunb) Matsum& Nakai] (Leskovar et al. 2004), and eggplant (Colak et al., 2015, 2017). In this context, physiological processes that regulate the CO_2 and H_2O gradients between the plant's leaves and the surrounding air cause an increase in IWUE in plants under water stress. Water-stressed plants benefit from a high CO_2 concentration around their leaves because partial stomatal closure increases photosynthesis and decreases transpiration, but well-watered plants are unaffected (Hatfield and Dold, 2019). However, according to Zin El-Abedin et al. (2019), extreme water stress may result in total stomatal closure, lower IWUE, and lower potato tuber production.

3.6. Irrigation doses and ETc during the main potato lifecycle phases

The functioning of the soil-plant-atmosphere system under the study's arid circumstances using two irrigation methods SDI and pivot, can be more clearly determined by combining the analysis of theoretical water requirements (ETc) and applied irrigation doses. Fig. 3 shows the changes in estimated crop evapotranspiration (ETc) values and the actual irrigation doses used throughout the period of the two experimental seasons. While the irrigation doses reflect the actual water amounts supplied within the context of semi-automatic irrigation management based on real-time monitoring of soil moisture and climatic conditions, ETc was calculated from in-situ measured climate data using the CROPWAT model.

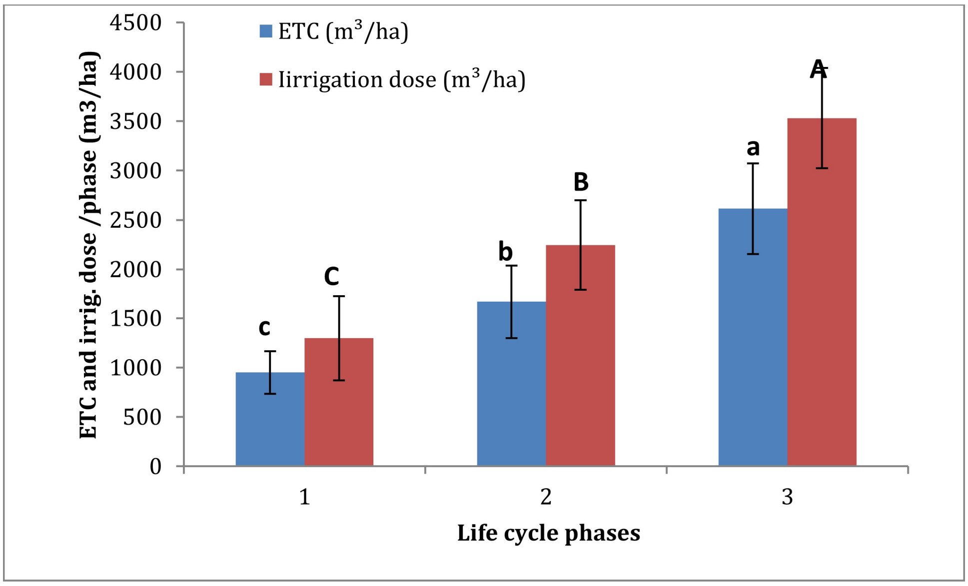

Fig. 3. Average evolution of the irrigation doses and ETc during the main lifecycle phases of potato plant (1: growth and sprouting (45DAP), 2: tuberization (65DAP), and 3: tuber bulking (90DAP)).

The average results for the two irrigation methods and varieties (Arizona and Spunta) at each stage of the life cycle are shown. The significant impact of annual climatic characteristics on these phases (45, 65, and 90 day after plantation: DAP) is explained by the evolution of irrigation doses and ETc values, which demonstrate how evapotranspiration increases as air temperature, solar radiation, and vapor pressure deficit gradually rise between planting in February and the growing cycle's completion in June (Table 2). Crop water requirements and actual irrigation doses significantly increase throughout the middle and end stages of the cycle, which correspond to the tuberization and tuber bulking stages, respectively, when atmospheric demand and plant canopy expansion are at their maximum. As a result, the crop water requirements vary from 950.8 m^3/ha during the first phase to 2615.33.5 m^3/ha during the last phase of the plant cycle, while the intermediate phase expressed a value of 1669.24 m^3/ha. ETc is influenced by the stage of crop growth; as crop cover increases, ETc rises and reaches its peak just before the crop achieves effective full cover, primarily due to the expansion of leaf area and increased transpiration. ETc varied from about 120 mm to around 280 mm, corresponding to a daily mean value at the maximum stage of growth (55 days after planting) from about 1.3 mm to around 5.6 mm for fully irrigated crops(Karam et al., 2014). For potato crops, which generally have a phenological cycle of 120–150 days, seasonal water requirements range from 350 to 625 mm, depending on climatic conditions (Karam et al., 2014). In addition Ferreira et al. (2002) stated that the cumulative Penman potential evapotranspiration (Etp) at the end of the season reached around 400 mm, and the total depth of water applied between planting and harvest through irrigation and rainfall varied from 68 mm in rain-fed treatments to 670 mm in the wettest treatment.

The controlled irrigation doses generally follow the same pattern as ETc, indicating that the semi-automatic irrigation control made it possible to adapt the water supply to soil water conditions and climate demand. However, the applied water volumes consistently above the theoretical ETc values. For instance, the applied irrigation doses range from 1297.28m^3/ha for an estimative ETc of 950.8 m^3/ha during the first phase, regardless of the irrigation technique and variety. Similar to this, the irrigation doses increases during the last phase with 3531.5 m^3/ha in the final phase when ETc reaches 2615.32 m^3/ha. Similar conclusion have been reported by Lascano et al. (2007) in their review of advancements in calculation and measurement methods made in soil-plant-atmosphere technology related to crop irrigation.

The increasing ETc during the growing cycle reflects both the crop's physiological growth and the gradual rise in ambient evaporative demand. When the plant canopy expands and biomass increases, particularly during the tuber growth phase when the plant's physiological activity increases, transpiration takes over as the main component of evapotranspiration (Noon et al., 2022, Tolba et al., 2022). Because semi-automatic irrigation management has made it possible to modify water inputs in response to climatic demand and soil moisture conditions, irrigation rates in this scenario usually follow the same pattern as ETc. However, the applied water quantities consistently above the theoretical ETc values.

This discrepancy can be explained by a variety of field water balance-related phenomena. Deep percolation outside of the active root zone, direct evaporation from the soil surface, or water redistribution within the soil profile all cause some of the applied water to be lost (Mattar et al., 2021). The water supply mechanism has additional losses. Furthermore, maintaining sufficient moisture levels in the root zone is still essential in arid conditions, where an unanticipated drop in soil water content can result in water stress and affect plant physiological systems (Teshome et al. 2024).

3.7. ETc and irrigation doses as impacted by Irrigation systems during the lifecycle

Significant variations in the irrigation system and varieties under investigation on ETc and irrigation doses across the main stages of the potato lifecycle were found by the three-way interaction analysis (Fig. 4). Due to the low biomass and water requirements, no notable changes were seen during the first phase. ETc values were approximately 950 m3/ha, while irrigation doses ranged from 1224 to 1228 m3/ha when using the SDI system and from 1312 to 1368 m3/ha when using the pivot system. However, notable variations were noted for ETc and irrigation doses in plants maintained by SDI and pivot as well as between varieties during the tuberization and tuber bulking stages (64 and 90 DAP). Interestingly, the pivot system produced the greatest values in Arizona plants when compared to the SDI system; throughout the second and third stages, there was a notable 33% increase in ETc. In terms of irrigation dosages, Arizona plants required more water than Spunta plants using a pivot system compared to SDI. The differences in irrigation systems demonstrate how soil moisture dynamics and irrigation requirements are impacted by the water application strategy. Subsurface irrigation (SDI) decreases surface

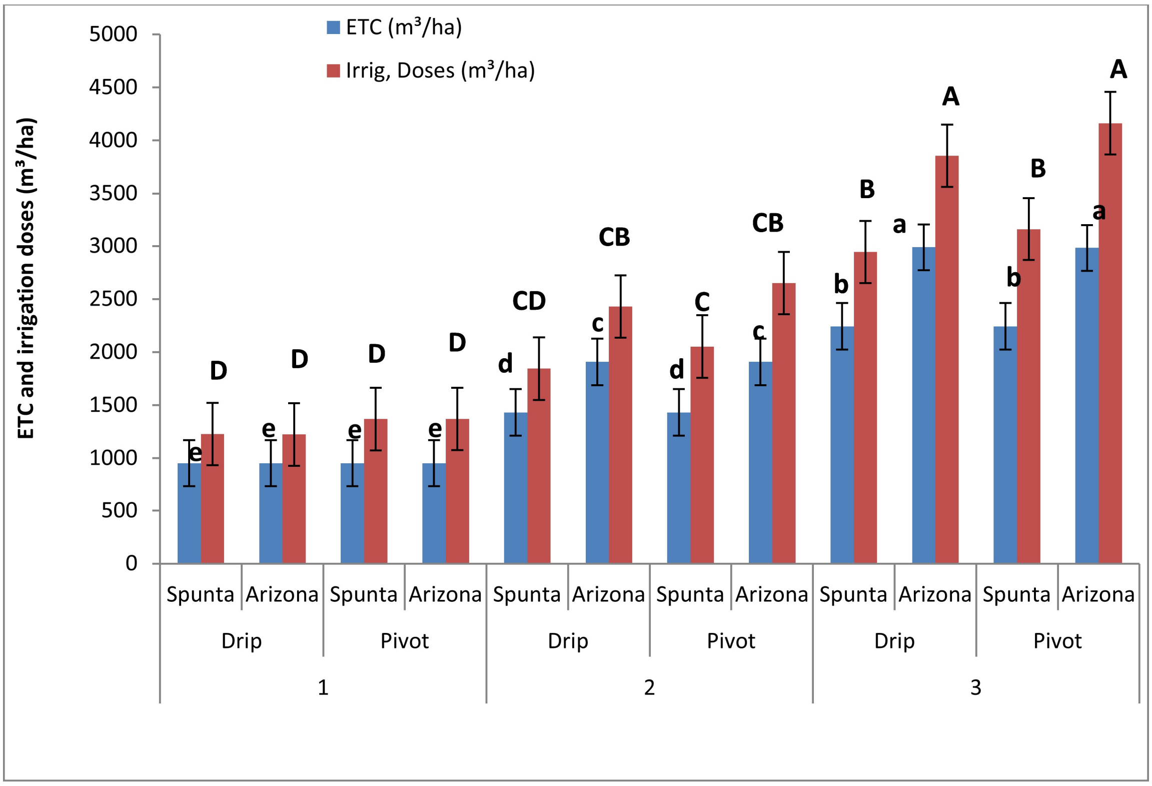

Fig. 4. Effects of SDI and pivot irrigation techniques on irrigation doses and ETc evolution over the three main phases of two potato varieties under study (1: growth and sprouting,45DAP, 2: tuberization, 65DAP and 3: tuber bulking, 90DAP).

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evaporation losses and improves more constant soil moisture by promoting localized soaking directly at the root zone. However, by saturating more of the soil surface area and exposing the applied water to more atmospheric conditions, center pivot irrigation increases evaporation losses and enhances the spatial variability of soil moisture (Abdelkhalik et al, 2020). Center pivot systems frequently need higher irrigation rates to maintain sufficient water availability in the root zone, which can be explained by these operational changes, as noted by various authors (Djaman et al. 2021, Mattar et al. 2021).

The length of the growing cycle and the phenological characteristics of each variety are the main causes of the observed variances. Compared to a Spunta variety, the Arizona typically shows greater irrigation rates and cumulative evapotranspiration (ETc) values. In particular, a longer vegetative cycle and longer canopy expansion account for this development. Overall, these findings demonstrate that the irrigation system employed, soil moisture dynamics, varietal traits, and the change in climatic demand during the growing season all have a significant impact on the irrigation needs of potatoes in arid environments as well as the actual water inputs.

4. CONCLUSION

Due to the scarcity of water and the growing need for food worldwide, minimizing water consumption while maintaining crop production levels has emerged as a major objective of experimental research in agriculture, especially in dry regions. Thus, during the 2023 and 2024 growing seasons in an arid region of El Oued, Algeria, the current study examined the effects of SDI and pivot system irrigation on the soil characteristics and water content, plant vegetative growth traits, tuber yield and its components, IWUE, and WUE of two potato varieties. Regardless of the varieties tested, it was discovered that while the pivot system increased the amount of water in the soil, the SDI system was more effective because it improved the distribution of water around plant roots and decreased evaporation, which had a positive impact on yield and its components as well as IWUE and WUE. However, in terms of yield and yield components, the pivot system performed better with Arizona than with Spunta. Therefore, it could be suggested that SDI system is a promising and sustainable irrigation practice that could be adopted in arid regions within strategies of climate change mitigation, the sustainable use of natural resources and the reduction of food security risks. As a result, the benefits of a particular irrigation strategy will be dependent on the irrigation technique employed, the quantity of water supplied to fulfill plant requirements, and the cost associated with it. Evaluating the effectiveness of water use in the production systems under study also requires a careful examination of the crop's water requirements and the actual irrigation volumes used. The observed difference between theoretical requirements and actual inputs reflects both the irrigation system's impact on the crop's efficient use of water as well as the water losses inherent in the soil-plant-atmosphere system processes. In this regard, evaluating the effectiveness of various irrigation systems in terms of water efficiency will be possible by investigating the link between water inputs and the yield achieved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.joasdjournal.org/index.php/joasd/article/view/357/300

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