



Enhancing Potato (*Solanum tuberosum* L.) Production in a Semi-arid Environment in Morocco Using Subsurface Drip Irrigation and Other Water-Saving Strategies

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Abstract

The Fès-Meknès region in Morocco is characterized by a typical Mediterranean climate and the cultivation of water-demanding, locally well-established cash crops, such as potato (*Solanum tuberosum* L.). Therefore, this region is likely to experience considerable water conservation benefits following implementation of Subsurface Drip Irrigation (SDI) technology alongside other water management strategies. To investigate this potential, we conducted a field trial comparing surface Drip Irrigation (DI) and SDI, combined with Regulated Deficit Irrigation and mulching as additional water-saving measures. Establishing potato crops solely with SDI proved challenging, leading to non-uniform germination and a 25% yield reduction at the plot level compared to DI. Tuber quality concerns, including disease infestation and malformations due to soil moisture fluctuations, may pose another drawback of SDI. However, plant measurements during the growing season and at harvest suggest that once established, potato plants benefited from the underground water and nutrient source, particularly later in the season, as indicated by (i) higher chlorophyll content; (ii) increased biomass at harvest; and (iii) 20% higher tuber yield from mature individual plants. Despite the initial establishment challenges, this highlights SDI's potential for improving late-season crop performance. Mulching did not result in any yield effects. Drawbacks for mulch application such as seed contamination and nitrogen immobilization were observed. While Regulated Deficit Irrigation increased plant water stress under hot and dry conditions, as shown by reduced stomatal conductance, it did not significantly impact yield. Thus, strategically reducing irrigation amounts saved 12% water without compromising productivity.

Keywords Deficit irrigation · Mulching · Water conservation · Mediterranean · Fès-Meknès Region

Introduction

Enhancing agricultural resilience through optimized management strategies is essential as environmental disturbances and resource scarcity intensify. This is particularly evident in Mediterranean agriculture, where irrigation has always played a pivotal role in food security, employment and economic development (Fader et al. 2016) and production systems are now increasingly threatened by climate change. Morocco exemplifies a country highly dependent on irrigation for plant production using approximately 90% of its freshwater withdrawals for irrigation. Despite only 17% of the cropping area being irrigated (FAO 2015), this sector contributes 45% to agricultural value-added and accounts for nearly 75% of agricultural exports (Bzioui 2004; Harbouze et al. 2019). At the same time, the Mediterranean is recognized as a Climate Change Hot Spot (Tuel and Eltahir 2020), and Morocco faces a high risk of failing to sustainably meet future irrigation water requirements (Fader et al. 2016). Despite these challenges, water intensive cash crops are extensively cultivated in Morocco.

Potato (*Solanum tuberosum* L.) is a major cash crop in Morocco, covering approximately 60,000 ha, with about 10,000 ha in the high-yielding Fès-Meknès region in the northeast (Blom-Zandstra et al. 2020). As a shallow-rooted crop, potato is particularly vulnerable to water stress (van Loon 1981; Wang et al. 2006; Shock et al. 2007; Cantore et al. 2014). In regions with low precipitation, effective water management is essential to maintain productivity and meet quality standards. Blom-Zandstra et al. (2020) highlight that improving irrigation water use efficiency could have the greatest impact on the sustainability of Morocco's potato value chain. Thus, noteworthy efforts have been made to implement water-saving technologies such as surface Drip Irrigation (Assouli et al. 2018; Blom-Zandstra et al. 2020). However, scaling up these technologies beyond pilot projects and field experiments is often hindered by a lack of adaptation to local conditions and integration into existing farming systems (Bekkar et al. 2009; Jobbins et al. 2015).

Subsurface Drip Irrigation (SDI) is a precision irrigation method defined as 'application of irrigation below the soil surface by microirrigation emitters' (ASABE 2019). It is often referred to as most sophisticated irrigation technique (Bordovsky et al. 2012; Mo et al. 2017) due to its ability to deliver water directly into the root zone, reducing evaporation and improving water-use efficiency. Additional reported advantages include improved plant health, weed suppression, enhanced fertilizer management, and automation possibilities that can lower labor and energy costs (Lamm and Camp 2007). Nevertheless, widespread adoption faces obstacles such as high initial investment costs (Onder et al. 2005; Payero 2005), which are only justified when the system remains in use for multiple years. For root crops, such as potato and onion, shallow SDI can interfere with harvest operations. Consequently, system design – particularly dripline depth, maintenance, and crop rotation choices are critical for long-term viability (Ayars et al. 1999; Lamm and Camp 2007; Lamm et al. 2021).

Beyond upgrading the irrigation system itself, optimizing irrigation scheduling is a key strategy for improving Water Use Efficiency (WUE) (Najafi and Tabatabaei 2007). Regulated Deficit Irrigation exposes crops to controlled water stress during non-critical growth stages and aims to restrict water use while minimizing yield losses (Kirda 2000; Karam et al. 2014). This measure is expected to be particularly effective in high-efficiency systems such as SDI.

Water-saving strategies in agriculture are not limited to the irrigation system and scheduling. Optimized cultural practices play a crucial role in a comprehensive water management approach. Mulching is a widely used technique that offers multiple benefits, including soil temperature regulation, enhanced soil fertility, and weed suppression (Oljača et al. 2016; Sekhon et al. 2020; Waheed et al. 2023; Biswal et al. 2025). In terms of water conservation, mulch creates a physical barrier that reduces evaporation, improves infiltration, and minimizes runoff, ultimately improving soil moisture retention (Ji and Unger 2001; Farrag et al. 2016; Biswal et al. 2022). These benefits are particularly relevant in potato cultivation, where soil moisture stability directly influences yield and tuber quality (Biswal et al. 2022; Waheed et al. 2023).

Previous studies have typically focused on only one or two of the factors affecting soil moisture – irrigation techniques, scheduling strategies, and mulching practices – despite clear interactions between these elements that may amplify or counteract each other (Chukalla et al. 2015; Farrag et al. 2016). In our opinion, isolated measures alone are not sufficient to address the challenges of plant production in Fès-Meknès and across the Mediterranean. Additionally, research on potato irrigated via SDI has been predominantly conducted in coarse soils with relatively shallow drip-line placement (Badr et al. 2010; El Mokh et al. 2014; Hamida et al. 2014; Mattar et al. 2021), often overlooking the role of tillage operations and long-term system usage. This contradicts the critical need for long-term SDI implementation to fully capitalize on its labor-saving and sustainability benefits—factors known to be of high concern for farmers’ irrigation investment decisions (van der Kooij et al. 2013).

Our experimental design explicitly accounts for these interactions by examining three key water management factors under silt–clay soil conditions with a relatively deep dripline placement (27 cm), closely reflecting practical farming conditions in the region. Furthermore, the inclusion of tuber quality parameters provides a more comprehensive evaluation of SDI’s potential for sustainable potato production.

Materials and Methods

Experimental Site

A field trial was conducted at the experimental site of the National School of Agriculture of Meknès (ENA Meknès) in the growing season 2023 from March to July. Geospatial coordinates for the site are 33°50′39″ N, 5°28′49″ W, with an elevation of 546 m above sea level. Climatic conditions in this region in northern central Morocco are semi-arid, with an annual precipitation of approximately 450 mm. Winters typically exhibit cool and humid conditions, while summers are hot and dry.

Table 1 Characteristics of the soil from the experimental field before trial start in 0 to 30 cm depth; Ferticonceil Lab, National School of Agriculture of Meknès 2023

Parameter (unit)	Value
Clay (%)	46.0
Silt (%)	40.5
Sand (%)	13.5
Electric conductivity (dS m^{-1})	0.107
pH	7.8
Total limestone (mg kg^{-1})	208
Organic matter (%)	3.72
Olsen P_2O_5 (mg kg^{-1})	24.0
Extractable K_2O (mg kg^{-1})	533.0

In the experimental field, a silt clay soil typical for the Saï's plain is found. Soil samples were collected to a depth of 30 cm, and physical and chemical characteristic analyzed (see Table 1). Prior to the onset of the experiment, the field was managed for several years with no-till cereal farming. A deep cultivation (up to 40 cm) with a share plough and a shallow cultivation with a rotary harrow (25 cm) were conducted before the installation of subsurface driplines. Post-installation, further two passes with the rotary harrow were performed in order to achieve a favorable soil structure for potato germination. Tubers of potato (*Solanum tuberosum* L.) cv. “Red Bullet” were hand planted on April 3rd in rows 80 cm apart with 30 cm spacing between tubers within the row and covered with loose soil in ridges. Agricultural practices for fertilization, weeding, disease and pest control were performed uniformly according to local recommendations. The same amount of nutrients was applied to all treatments, starting with 30 kg ha^{-1} diammonium phosphate solid fertilizer at the date of planting. Macronutrients were supplied later on through fertigation to meet plant requirements. Total

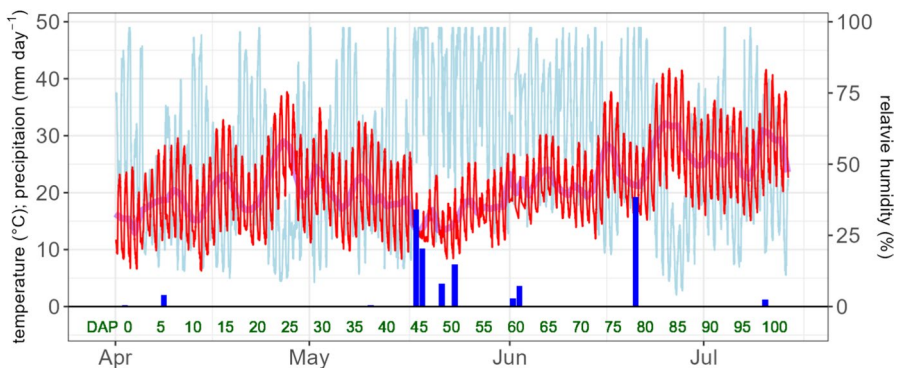


Fig. 1 Weather conditions during the potato growing period 2023 measured from a weather station directly beside the experimental field. Red line: hourly values of air temperature in °C; purple thick line: mean daily air temperature in °C; blue line: relative air humidity in %; blue columns: daily precipitation in mm. DAP: Days After Planting

nutrient supplied over the vegetation period summed up to 107 kg ha⁻¹ nitrogen, 36 kg ha⁻¹ phosphorus, and 14 kg ha⁻¹ potassium. No deficiency symptoms were observed.

Weather conditions recorded on site during the summer growing season from April to July 2023 are depicted in Fig. 1. Minimum and maximum temperature recorded were 6.26° C in April and 41.8° C measured in June, respectively. Air humidity levels fluctuated between 9 and 98%. Throughout the experimental period, total precipitation amounted to 61.4 mm, with rainfall events occurring mainly from mid-May to early June (Fig. 1).

Experimental Design

The field experiment was laid out as a tree factorial trial in Split-Plot design with four Blocks (Fig. 2). The first trial factor comprises the comparison of the two irrigation systems surface Drip Irrigation (DI) and Subsurface Drip Irrigation (SDI). Within the second trial factor, different irrigation schedules were tested. In the fully irrigated control variant, plants received 100% of Crop Evapotranspiration (ET_c), while plants suspected to Regulated Deficit Irrigation received only 75% of the full irrigation amount after plant establishment (details see Sect. 2.3). The level of deficit irrigation was based on previous work from the same site on potato by El Bergui et al. (2020). The combinations of the factors irrigation system and irrigation scheduling were randomly assigned to four main plots of the experiment and repeated in

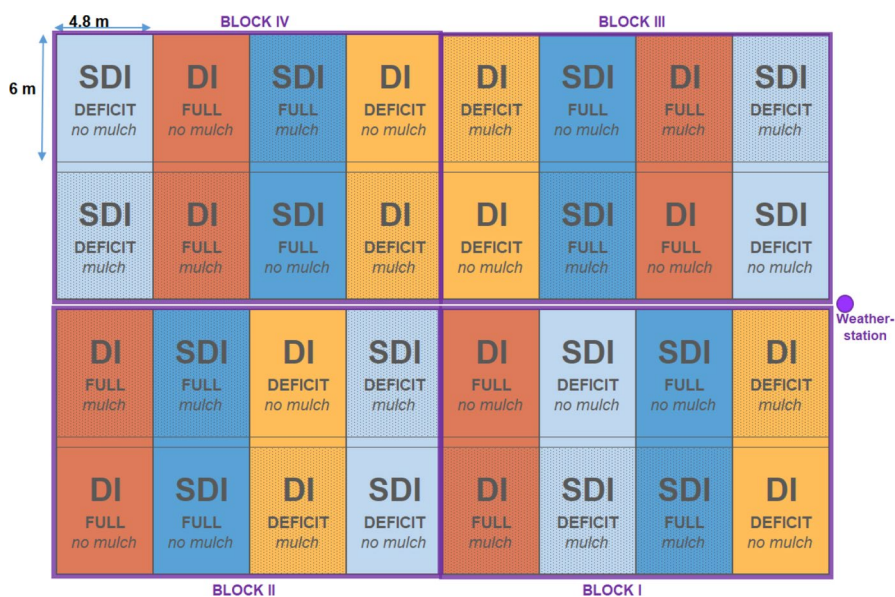


Fig. 2 Schematic of the field trial with four blocks and 8 treatments. DI: surface Drip Irrigation; SDI: Subsurface Drip Irrigation; FULL: full irrigation; DEFICIT: Regulated Deficit Irrigation; no mulch: without mulching; mulch: with mulching

four blocks. Each main plot was divided into two split plots comprising the third factor mulching, where one half was randomly selected to be covered by a 1:1 mixture of wheat and barley straw while the other half remained bare. The mulch amount was chosen to provide full cover of the soil surface with 5 t ha^{-1} . Dimensions of the 32 split plots were 4.8 m width, spanning six plant rows (respective six driplines), and 6 m length.

Irrigation Systems and Irrigation Scheduling

For both, DI and SDI, commercial pressure compensated driplines were used characterized by 16.2 mm outside diameter, 1 mm wall thickness, 1.0 L h^{-1} discharge rate and 30 cm distance between built-in emitters (DRIPNET, Netafilm®). Six driplines with a length of 12.4 m were installed per main plot, with one dripline allocated to each plant row. The driplines were connected with 20 mm diameter polyethylene (PE) pipes as the main and flushing pipes at the beginning and end of the plot, respectively. For DI, driplines were placed on the surface after potato planting and fixed with sticks. The SDI system was installed pre-planting by laying driplines in a depth of approximately 27 cm below the soil surface using a tractor-drawn machine. Main and flushing pipes at each end of SDI plots were installed in the same depth. This depth represents the shallowest feasible installation within the long-term crop rotation, keeping the driplines below the tillage layer required for field hygiene and seedbed preparation while still supplying water to the main rooting zone of varying crops and preventing mechanical damage of driplines during cultivation. Each main plot was connected with buried 35 mm diameter PE pipes to a valve station equipped with a manometer for system pressure control and air valves to release trapped air from the pipes. Thus, individual irrigation of each main plot was possible through the use of electromagnetic valves, enabling remote irrigation management via a web-based irrigation controller (GSI-DC, Galcon®). Real-time monitoring of the system was enabled by measurements from a digital flowmeter positioned at the head station. The water was pumped with a submersible pump powered by solar energy; hence, irrigation took place solely during daytimes with sufficient solar radiation.

During the first four Days After Planting (DAP) irrigation was run for one hour per day to ensure high soil humidity for plant germination, thereafter, daily irrigation

Table 2 Length and crop coefficient (k_c) values for potato growth stages (Allen et al. 1998) and total amount of water applied in treatments subjected to full (FULL) and Regulated Deficit Irrigation (DEFICIT). Means of irrigation amounts per main plot obtained from flowmeter data

Growth stage	Length of growth stage (days)	k_c value	Irrigation amount (mm)	
			FULL	DEFICIT
Initial	25	0.5	65	65
Development	30		88	88
Mid	20	1.15	90	74
Late	20	0.75 (end value)	100	71
Total	95		343	298

amounts were determined based on the water balance method. Therefore, the reference evapotranspiration (ET_0) was calculated in hourly steps using Penman–Monteith's semi empirical formula (Eq. 1) (Allen et al. 1998). Crop Evapotranspiration (ET_c) was determined by multiplying ET_0 with the crop factor k_c (Eq. 2, Table 2), with values specified for the crop, region, and development stage obtained from Allen et al. (1998). The lengths of development stages were adapted to local conditions based on field observations and meteorological data was collected by a station directly beside the field trial.

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e^0(T_{hr}) - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (1)$$

$$ET_c = ET_0 * k_c \quad (2)$$

where ET_0 reference evapotranspiration (mm day^{-1}); R_n net radiation at the crop surface (MJ m^{-2}); G soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$); T_{hr} mean hourly air temperature at 2 m height ($^{\circ}\text{C}$); u_2 wind speed at 2 m height (m s^{-1}); $e^0(T_{hr})$ saturation vapour pressure at air temperature T_{hr} (kPa); e_a actual vapor pressure (kPa); Δ slope vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$); γ psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$); ET_c crop evapotranspiration; k_c crop coefficient.

Hourly values of ET_c were aggregated to calculate the crop's daily evapotranspiration, which served as the basis for determining the crop's net irrigation water requirement (NWR) by considering the available water from effective rainfall (P_e) and the soil's water reserve (Eq. 3, for all abbreviations see Table 3). Considering

Table 3 Parameters (incl. their abbreviation, unit, and value) used for the calculation of irrigation duration and number of irrigation events per day. Values are chosen based on expert knowledge and calculated according to Eqs. 3 to 8, respectively

Parameter	Abbreviation	Unit	Value
Net Water Requirement	<i>NWR</i>	mm per day	
Gross Water Requirement	<i>GWR</i>	mm per day	
Effective rainfall coefficient	<i>Pe</i>	%	80
Irrigation system efficiency	<i>e_i</i>	%	95
Uniformity of water distribution coefficient	<i>CU</i>	%	95
Readily Available Water	<i>RAW</i>	mm per day	1.25
Usable soil reserve	<i>RU</i>	mm	193
Threshold percentage of the useful reserve at which irrigation is triggered	<i>f</i>	%	2.7
Crop's rooting depth	<i>z_r</i>	m	0.3
Percentage of humidified soil	<i>Phs</i>	%	80
Field capacity after Saxton 1986	<i>W330</i>	mm	507
Wilting Point after Saxton 1986	<i>W15000</i>	mm	315
Irrigation amount applied by irrigation system	<i>Pf</i>	mm per hour	4.17

the estimated irrigation system efficiency (e_i) and the uniformity of water distribution in the field (CU) from field observations led to the daily gross water requirement (GWR , Eq. 4). This value, in turn, was utilized to ascertain the number of irrigations required on the following day (Eq. 5), through division with the Readily Available Water (RAW). RAW is equivalent to the Net Maximal Amount of irrigation and corresponds to the amount of water that a soil can hold in the effective root depth. Hence, it is influenced by soil and plant characteristics (Eq. 6) such as the usable soil reserve (RU , Eq. 7), the percentage of wetted surface (Phs), the crop's rooting depth (z_r), and a defined threshold value (f) representing the percentage of the available water at which irrigation is triggered. Additionally, the RAW , in conjunction with the irrigation system characteristics, determines the duration of each irrigation event. While certain parameters may indeed vary between the DI and the SDI system, standard values for the DI system were chosen to ensure the application of consistent irrigation amounts across both systems. The duration of one irrigation event was thus set to 18 min (Eq. 8). From June 1st on, ET_c was multiplied with 0.75 for the treatment of Regulated Deficit Irrigation and then processed in the same manner as described above to determine the number of irrigations per day.

$$NWR (mm) = ET_c - precipitation * P_e - reserve \quad (3)$$

$$GWR (mm) = \frac{NWR}{e_i * CU} \quad (4)$$

$$number\ of\ irrigation = GWR/RAW \quad (5)$$

$$RAW (mm) = RU * f * z_r * \frac{Phs}{100} \quad (6)$$

$$RU (mm) = W330 - W1500 \quad (7)$$

$$duration (h) = RAW/Pf \quad (8)$$

Data Collection

Data collection entailed various measurements conducted throughout the growing season and at the time of harvest. After plant emergence, the germination rate was assessed on the basis of digital imagery from two dates by counting emerging plants per row in each split plot. During the growth period, four plants from each split plot were chosen for repeated measurements of plant height (three times) and chlorophyll content (four times). The latter was determined using the hand clip measure device Dx4.5 (Dualex©). Stomatal conductance was assessed on two plants per split plot on four different dates using an AP4 Porometer (Delta-T Devices©). On July 6th and 7th (94 and 95 DAP), plants were sampled to ascertain aboveground fresh matter, aboveground dry matter (after oven

drying at 80° C until achieving constant weight) and the number of tubers. For this evaluation, four plants per split plot were randomly selected from the inner four plant rows, not considering immature plants in SDI plots. For each tuber, the weight and diameter were recorded. In order to gain further insights into yield formation, tubers were classified according to their diameter into three classes where < 35 mm was considered small, 35–70 mm moderate and > 70 mm large (Cantore et al. 2014). Afterwards, the weight fraction of tubers per class was calculated (Shahnazari et al., 2007; Mattar et al. 2021).

For plants from Regulated Deficit Irrigation treatment, a tuber quality analysis was performed. For the visual inspection, 30 tubers were randomly chosen from the four plants harvested per split plot, examined and rated regarding tuber diseases (symptoms of *Rhizoctonia solani* (dry core), *Sclerotinia sclerotiorum* or *Streptomyces scabiei*), pest infection (symptoms of *Agriotes* (wireworm)), skin and shape characteristics, damages, eye anomalies, as well as signs of sunburn and tuber germination. The indirect method of specific weight was used on four similar sized tubers per split plot to estimate starch content according to Gottschalk (2020). Brix content of tubers was determined for four to five randomly chosen tubers per split plot from all treatments with a digital refractometer (Silverado© PDR-20).

On July 13th and 14th (101 and 102 DAP), all plots were harvested and fresh tuber yield was determined. Furthermore, Irrigation Water Use Efficiency (IWUE) was calculated by dividing fresh tuber yield per plot by the amount of water used for irrigation throughout the growing period. The latter was obtained from data recorded per main plot by the digital flowmeter at the head station. For better comparison with published literature, Total Water Use Efficiency (TWUE) was calculated as tuber fresh matter per plot divided by total water applied, considering the irrigated amount plus water received by precipitation.

Data Analysis

All data analysis and graphical work were conducted using R (R Core Team 2024) with the “data.table” (Barrett et al. 2024) and “ggplot2” (Wickham 2016) packages. Data was transformed in order to obtain normal distribution in the cases of single plant yield, starch content, stomatal conductance, aboveground fresh and dry biomass by a logarithmic transformation, for tuber weight data by a cube root and for tuber diameter by a square root transformation. Linear Mixed Effect Models were fitted with lmer() or glmer() from lme4 (Bates et al. 2015), for numeric and integer data types, respectively. Irrigation system, irrigation schedule and mulching as well as their interactions were set as fixed factors, while block and main plot were set as random factors. In case of multiple observations, split plot was set as random factor as well. For the repeated measurement data of plant height and chlorophyll content, Plant ID was nested within main plot and defined as random factor. The p-values for Analysis of Variance (ANOVA) were obtained from “lmerTest” (Kuznetsova et al. 2017) or “car” (Fox and Weisberg 2019) for continuous and count data, respectively. For post-hoc tests of significant differences, the Tukey HSD test was used in the

“emmeans” (Lenth 2024) package. Regression analyses of yield formation parameters were performed by `lm()` R base function. Data in the text and tables is depicted as means $\pm$ standard deviation.

Results

Crop Establishment, Plot Yield, and Water Use Efficiency

The determination of germination rates from digital imagery revealed significant differences between irrigation systems, while mulching had no significant effect on germination rate (ANOVA, $\alpha=0.05$, Fig. 3). 31 Days After Planting (DAP) on May 4th, $97 \pm 4.7\%$ of tubers in DI plots were germinated, while germination rate in SDI plots did not exceed 45% with a very high variation ($\pm 33\%$). Within the following two weeks tubers in SDI plots kept germinating, reaching an average germination rate of $73 \pm 30.7\%$ on May 22nd (49 DAP). At that time plants in the DI variants had fully emerged ($99.6 \pm 1.4\%$).

Results from the harvest of whole plots on July 13th and 14th show a significant reduction of fresh tuber yield in subsurface ($30.7 \pm 10.5 \text{ t ha}^{-1}$) compared to surface-irrigated plots ($40.8 \pm 7.4 \text{ t ha}^{-1}$) by about 10 t ha^{-1} . The effect of irrigation schedule was not significant ($p=0.0625$) but there was a trend of lower yield in treatments of Regulated Deficit Irrigation for both, DI and SDI. Applying straw mulch in plots did not have a significant effect on potato yield (ANOVA, $\alpha=0.05$, Table 4). Calculated daily evapotranspiration and the resulting irrigation amounts for the complete growing season are depicted in Fig. 4.

In total, $343 \pm 7 \text{ mm}$ and $298 \pm 7 \text{ mm}$ were irrigated under full and deficit irrigated treatments, respectively (Table 2). Thus, the Regulated Deficit Irrigation amounted to 88% of the irrigation quantity in the fully irrigated variants, because the irrigation amount was reduced to 75% of ET_c only after potato establishment. These values of irrigation amounts, derived from flowmeter recordings over the whole vegetation

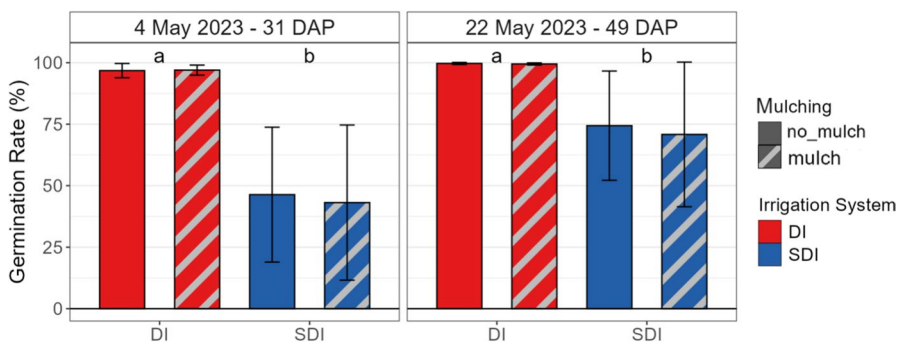


Fig. 3 Germination rate in percent on May 4th (31 DAP) and 22nd (49 DAP), means and standard deviation. No significant effect of mulching (ANOVA, $\alpha=0.05$). Significant differences between irrigation systems marked by lowercase letters (Tukey-test, $\alpha=0.05$). Irrigation scheduling is not considered as Regulated Deficit Irrigation treatment was not yet applied. DAP: Days After Planting

Table 4 Means $\pm$ standard deviation per treatment of plot yield, Irrigation and Total Water Use Efficiency (IWUE/TWUE), as well as single plant tuber yields, above-ground fresh and dry matter per single plant. Different lowercase letters in the same row indicate significant differences for irrigation system means (ANOVA, $\alpha=0.05$)

Irrigation system	DI		SDI			
	FULL		DEFICIT		FULL	
	No	Yes	No	Yes	No	Yes
Mulching						
Plot tuber yield (t ha ⁻¹)	44.1 $\pm$ 6.3	42.4 $\pm$ 9.5	39.2 $\pm$ 7.2	37.4 $\pm$ 7.4	34.1 $\pm$ 13.3	33.8 $\pm$ 13.0
Mean	40.8 $\pm$ 7.43a				30.7 $\pm$ 10.5 b	25.7 $\pm$ 5.6
Plot IWUE (kg m ⁻³)	12.5 $\pm$ 2.1	12.0 $\pm$ 3.0	12.7 $\pm$ 2.5	12.1 $\pm$ 2.4	9.7 $\pm$ 3.9	9.7 $\pm$ 3.9
Mean	12.3 $\pm$ 2.3a				9.4 $\pm$ 3.1 b	8.4 $\pm$ 2.1
Plot TWUE (kg m ⁻³)	10.5 $\pm$ 1.7	10.1 $\pm$ 2.4	10.4 $\pm$ 2.0	9.9 $\pm$ 2.0	8.1 $\pm$ 3.3	8.1 $\pm$ 3.2
Mean	10.2 $\pm$ 1.8 a				7.7 $\pm$ 2.6 b	6.9 $\pm$ 1.6
Single plant tuber yield (g plant ⁻¹)	1394 $\pm$ 300	1111 $\pm$ 282	1277 $\pm$ 244	1296 $\pm$ 302	1514 $\pm$ 397	1737 $\pm$ 610
Mean	1269 $\pm$ 294 a				1527 $\pm$ 442 b	1421 $\pm$ 358
Single plant aboveground fresh matter (g plant ⁻¹)	475.6 $\pm$ 86.0	304.2 $\pm$ 96.0	381.3 $\pm$ 77.9	377.9 $\pm$ 147.0	758.0 $\pm$ 250.6	927.2 $\pm$ 399.2
Mean	384.7 $\pm$ 119.0 a				801.4 $\pm$ 307.8 b	725.7 $\pm$ 203.4
Single plant aboveground dry matter (g plant ⁻¹)	60.0 $\pm$ 11.8	38.9 $\pm$ 13.1	49.5 $\pm$ 12.0	48.9 $\pm$ 20.1	99.4 $\pm$ 36.2	101.0 $\pm$ 47.2
Mean	49.3 $\pm$ 16.1 a				97.3 $\pm$ 36.8 b	93.2 $\pm$ 24.3
Number of tubers per plant (-)	11.6 $\pm$ 3.5	10.6 $\pm$ 3.4	12.0 $\pm$ 3.0	13.8 $\pm$ 3.8	13.8 $\pm$ 8.0	13.3 $\pm$ 6.3
Tuber weight (g tuber ⁻¹)	120.6 $\pm$ 85.5	105.2 $\pm$ 72.0	106.4 $\pm$ 76.4	94.3 $\pm$ 65.7	110.1 $\pm$ 108.8	130.5 $\pm$ 118.7
Tuber diameter (mm)	49.1 $\pm$ 14.5	46.5 $\pm$ 13.0	45.8 $\pm$ 12.9	44.6 $\pm$ 12.9	46.6 $\pm$ 16.2	48.8 $\pm$ 16.9
						46.1 $\pm$ 15.6
						47.2 $\pm$ 17.0

period, were used to calculate Irrigation Water Use Efficiency (IWUE, Table 4) per plot. Analysis of Variance ($\alpha=0.05$) revealed significant differences only between irrigation system treatments, with DI showing a higher IWUE than SDI, measuring $12.3 \pm 2.3 \text{ kg m}^{-3}$ and $9.4 \pm 3.1 \text{ kg m}^{-3}$, respectively. Total Water Use Efficiency (TWUE), which considers the amount of precipitation (66 mm during the potato growing period) as part of plant-available water, followed the same pattern as IWUE with a significant difference between irrigation systems. The DI treatment reached a mean value of $10.2 \pm 1.8 \text{ kg m}^{-3}$, while the SDI average for TWUE was $7.7 \pm 2.6 \text{ kg m}^{-3}$.

In-Season Measurements of Plant Development

Measurements of plant height were performed on three dates on marked plants (Fig. 5). On May 22nd (49 DAP), plants in SDI plots were significantly smaller than those in DI plots (Tukey HSD, $p=0.0018$). However, these differences were no longer significant on the two subsequent measurement dates in June. On the later measurement dates, plant height was significantly lower in mulched compared to non-mulched plots, with reductions of 4.2 cm and 4.7 cm on June 10th (68 DAP, $p=0.0333$) and June 30th (88 DAP, $p=0.0187$), respectively. Irrigation scheduling did not have a significant effect on plant height (ANOVA, $\alpha=0.05$).

Chlorophyll content was measured on four dates from late May to early July. Leaf chlorophyll content gradually decreasing over time in all treatments (Fig. 6) and consistently higher values occurred in SDI than DI variants. Significant differences between irrigation systems were observed on May 25th (52 DAP), June 13th (71 DAP) and July 4th (92 DAP), but not on June 22nd (88 DAP) (Tukey HSD, $\alpha=0.05$). Furthermore, a significant lower chlorophyll content was found in mulched compared to non-mulched plots on the last measurement date in early July.

Stomatal conductance was measured on four dates within the potato growing period. The most pronounced treatment differences occurred on June 26nd (84 DAP), which coincides with the highest temperatures and lowest relative humidity recorded during stomatal conductance measurements. On this date, Regulated Deficit Irrigation resulted in significantly lower stomatal conductance ($85.7 \pm 47.9 \text{ mmol m}^{-2} \text{ s}^{-1}$) compared to fully irrigated treatments ($125.9 \pm 52.4 \text{ mmol m}^{-2} \text{ s}^{-1}$) (Tukey HSD, $p < 0.0001$; data not shown).

Individual Plant Yield and Yield Formation

Irrigation system had a significant effect on aboveground fresh matter measured on individual plants, with two times higher fresh weight in SDI ($801.4 \pm 307.8 \text{ g plant}^{-1}$) than in DI plots ($384.7 \pm 119.0 \text{ g plant}^{-1}$). Neither mulching nor irrigation scheduling had a significant effect (ANOVA, $\alpha=0.05$). Water content of potato plants averaged at $87.2 \pm 1.6\%$, with no significant effect of any tested treatment. Consequently, aboveground dry biomass showed the same trend as fresh matter, with significantly higher values in SDI than DI plots (+97%) and no significant effect of mulching or irrigation schedule. Belowground parts of the harvested plants were not

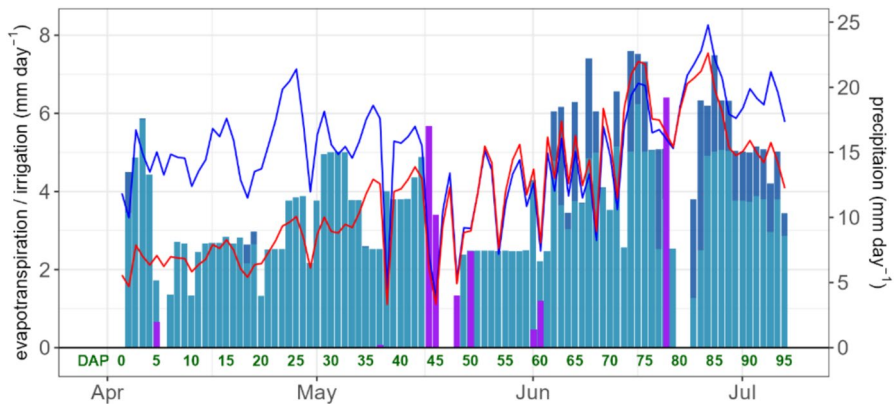


Fig. 4 Calculated evapotranspiration, measured precipitation and applied irrigation during the potato growing period 2023. Blue line: Reference evapotranspiration (ET_0); red line: Crop evapotranspiration (ET_c); purple bars: daily precipitation; light blue bars: irrigation amount per day in treatment of Regulated Deficit Irrigation; dark blue bars: additional irrigation under full irrigation. DAP: Days After Planting

quantitatively assessed, but pictures were taken to document qualitative differences observed in root architecture between SDI and DI treatments (Fig. 11).

Single plant yield (Table 4), determined by the total fresh tuber weight per plant, was highest in the fully irrigated SDI treatment with mulch, including three outlier plants yielding 2802, 2801, and 3115 g plant⁻¹. Conversely, the lowest yields were observed in the fully irrigated DI treatment with mulch (minimum: 433 g plant⁻¹). Results show a clear impact of irrigation system on single plant yields. With 1527 ± 442 g plant⁻¹, SDI plants reached on average approximately 20% higher tuber yields than DI plants (1269 ± 294 g plant⁻¹). No significant effect was detected for mulching treatment or irrigation scheduling (ANOVA, $\alpha = 0.05$).

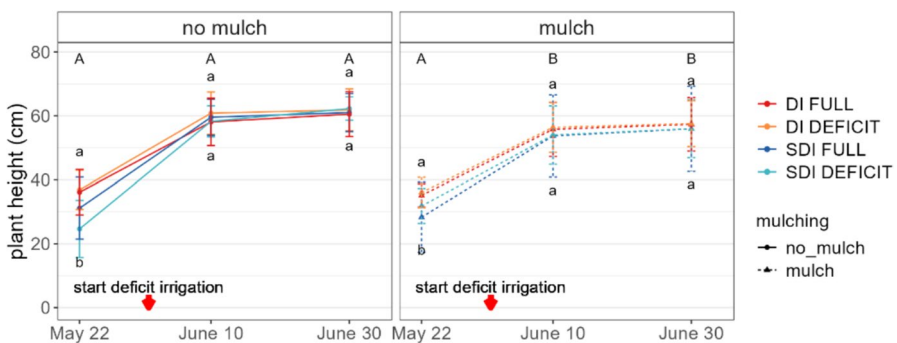


Fig. 5 Development of height of potato plants in the 8 experimental treatments. Means and standard deviation on tree measurement dates. Lowercase letters signify significant differences between irrigation schedules and uppercase letters between mulch treatments within one date (Tukey HSD, $\alpha = 0.05$)

The highest and lowest tuber counts (34 and 3 tubers per plant, respectively) were both found in the fully irrigated SDI treatment without mulch. None of the trial factors has a significant effect on tuber number per plant (ANOVA, $\alpha=0.05$). The maximum weight for a single tuber (796 g) was found on a plant from the fully irrigated SDI treatment with mulch, but neither this parameter nor tuber diameter was significantly affected by any treatment (ANOVA, $\alpha=0.05$).

For further analysis, tubers were classified into three size categories by diameter, and the fraction each group contributes to the plant fresh tuber yield was calculated (Fig. 7). No treatment had a significant effect on the occurrence of small tubers (< 35 mm). However, irrigation system significantly affected the proportion of moderately sized tubers (35–55 mm), with DI plots producing a greater share than SDI plots (ANOVA, $\alpha=0.05$). For large tubers (> 55 mm), a significant interaction between irrigation system and mulching was detected. In mulched variants, large tubers contributed significantly more to the fresh tuber yield in SDI than in DI, but this trend was not significant in non-mulched plots ($p=0.0515$, Fig. 7).

To explore relationships between yield components, multiple regression analyses were performed. A positive but non-significant linear relationship was found between single plant yield and mean tuber weight (adjusted $R^2=0.016$, Fig. 8A). In contrast, a significant positive correlation was observed between plant tuber yield and number of tubers per plant (adjusted $R^2=0.32$, Fig. 8B). A nonlinear logarithmic regression best described the relationship between mean tuber weight and tuber count per plant (adjusted $R^2=0.49$, Fig. 8C), outperforming a quadratic model.

Tuber Quality Parameters

Water availability and distribution in the soil as well as mulching are known to affect tuber quality. Thus, we selected a subset comprising potentially water stressed

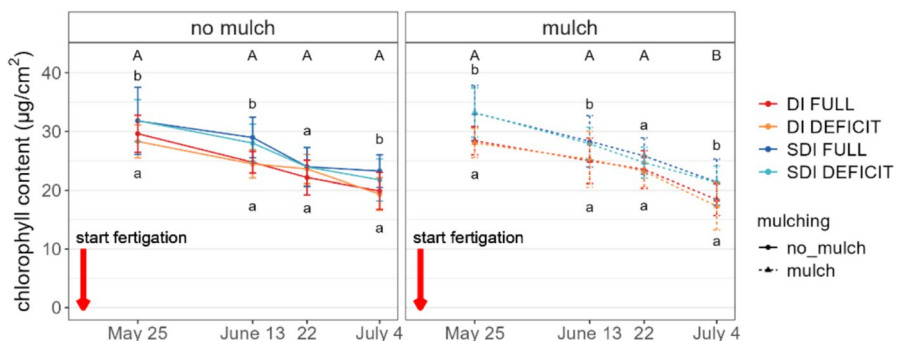


Fig. 6 Development of the chlorophyll content of potato leaves; means and standard deviation on four measurement dates. Lowercase letters signify significant differences between irrigation schedules and uppercase letters between mulch treatments within one date (Tukey HSD, $\alpha=0.05$)

potatoes of the Regulated Deficit Irrigation treatment to perform an inspection and analysis of tuber quality parameters. From each of the four plants used for single-plant analysis, 30 tubers of similar size were randomly selected and visually inspected for symptoms of pests, diseases, mechanical damage, and deformities (Fig. 9). Mulching compared to no mulching had no significant effect on any of the considered tuber quality parameters (ANOVA, $\alpha=0.05$). Unspecified damages, as well as tuber damage from mining insects, were more frequently found in SDI than DI treatments. Similarly, pitting tended to occur more often in SDI than in DI plots, although the difference was not statistically significant (ANOVA, $\alpha=0.05$). Mechanical damages were rare and equally distributed in the two irrigation systems. Unspecified deformations, secondary growth deformities, and eye anomalies occurred significantly more often in SDI than in DI treatments, whereas the higher incidence of stripe deformation in SDI was not statistically significant (ANOVA, $\alpha=0.05$). Early sprouting was more commonly observed in tubers from SDI-irrigated plants. Regarding skin characteristics, SDI tended to result in rougher skin texture, whereas DI was more often associated with smooth skin. The occurrence of cracked and netted skin was not influenced by the irrigation system. Approximately one-tenth of the tubers were affected by sunburn, with no significant differences between treatments. Disease incidence of dry core (caused by *Rhizoctonia solani* Kühn) and wireworm damage was not influenced by the irrigation system. *Streptomyces* infections were more frequently observed in SDI than in DI treatments, whereas the occurrence of patterned skin was similar across both systems.

Values for starch content showed a high variation ranging from 2.99 to 14.80% (Fig. 10). While starch content was not significantly affected by irrigation system or mulching (ANOVA, $\alpha=0.05$), tubers from SDI treatments tended to have slightly lower values. Brix content was measured on four to five tubers per treatment, where no significant differences were found between variants (ANOVA, $\alpha=0.05$, Fig. 10).

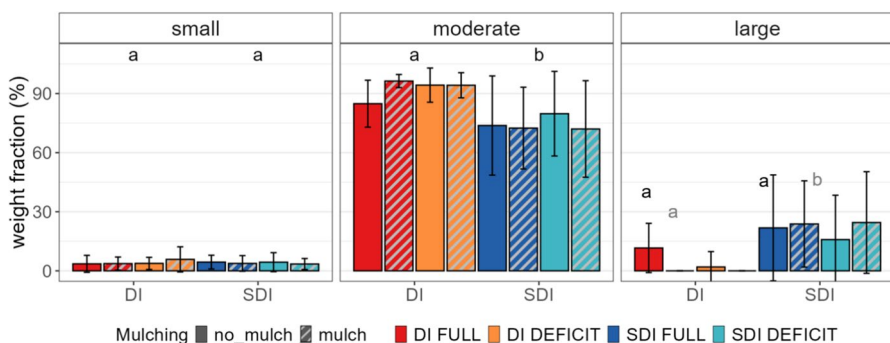


Fig. 7 Weight fraction in percent of tubers assigned to the diameter size classes small (< 35 mm), moderate (35–70 mm) and large (> 70 mm). Lowercase letters signify significant differences between irrigation systems (ANOVA, $\alpha=0.05$). For the large tuber size class, a significant interaction between irrigation system and mulching was found. Irrigation schedule treatment did not result in a significant effect

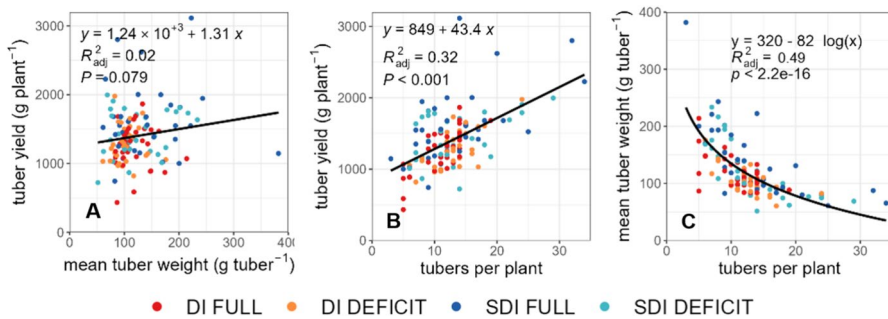


Fig. 8 Correlation between tuber yield of individual plants and mean tuber weight (A), and count of tubers per plant (B). Correlation between mean tuber weight and tubers per plant (C)

Discussion

Meteorological Conditions

Precipitation during the study period from April to mid-July 2023 largely aligned with the long-term monthly averages in the northern Fès-Meknès region (Kessabi et al. 2022). Typically, winter months (November – February) receive over 80 mm of precipitation, while rainfall decreases to below 20 mm during the hot summer months (June – September). In 2023, May's precipitation matched the long-term average of 40 mm, while slightly above-average rainfall (24 mm) was recorded for June. By the time of potato harvest in mid-July, almost no rainfall was observed for the month, as typical for the region. Notably, April 2023 stood out with an unusually low precipitation of 2.2 mm, far below the long-term average of 70 mm, following an already unusually dry March with almost no rainfall. These conditions reflect a broader trend of shifting rainfall patterns in the Mediterranean, where climate change is reducing the reliability of winter precipitation and significantly impacting agriculture (Tuel and Eltahir 2020).

Although this experiment was conducted in a single season at one location, the climatic conditions during the potato growing period (April to July) were representative for semi-arid climates and large parts of the Mediterranean, with very low in-season rainfall and high evaporative demand. In such environments, the main rainy period occurs from autumn to early spring, while precipitation from late spring to summer is minimal and highly consistent between years, so that crop water supply during most of the growing season depends almost entirely on irrigation and initial soil water storage (Zemzami and Elkadiri 2017; Kalimeris and Kolios 2019; Chakroun et al. 2023). Consequently, the late-season water balance and plant responses were largely governed by the imposed irrigation regimes, approximating semi-controlled conditions and supporting the broader relevance of the observed physiological and yield responses to other semi-arid and Mediterranean potato systems.

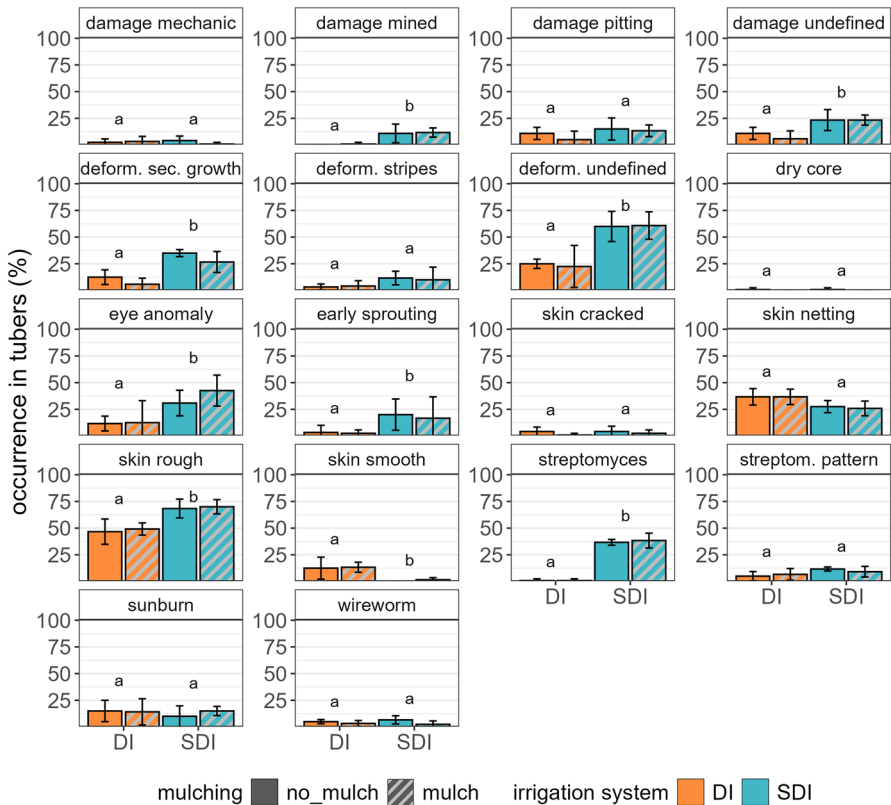


Fig. 9 Occurrence of symptoms of pests and diseases as well as other damages and deformations in tubers subjected to the treatment of Regulated Deficit Irrigation in percent. Lowercase letters signify significant differences between irrigation systems. Effect of mulching not significant for any parameter (ANOVA, $\alpha=0.05$)

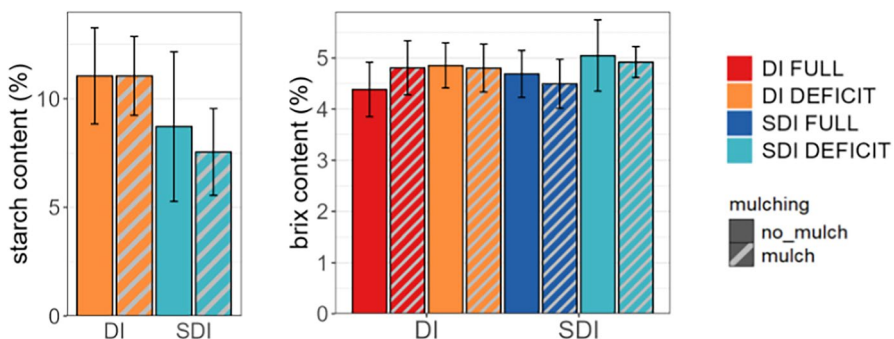


Fig. 10 Starch (left) and brix content (right) of potato tubers at harvest. Starch content was determined only for deficit irrigated treatments by specific weight, following the method of Gottschalk (2020). No significant effects for either parameter (ANOVA, $\alpha=0.05$)

Crop Establishment

Due to the absence of rainfall at the time of potato planting on April 3rd, tuber germination relied on water supplied by the irrigation systems. Ensuring uniform water availability to the tuber is one of the main challenges of SDI, especially when driplines are buried deep in the soil (Charlesworth and Muirhead 2003) and soil humidity around the tuber is determined by the complex interplay of soil, plant, and irrigation system characteristics (Thorburn et al. 2003; Patel and Rajput 2007; Elnesr and Alazba 2015). In our case, the main obstacle to water movement towards the tubers appeared to be the loose soil structure in the potato ridges (Bordovsky et al. 2012; Mo et al. 2023). Field observations confirmed that water from SDI rose to the soil surface between ridges but did not always penetrate the ridge centers (Fig. 11C). This resulted in a significantly lower germination rate in SDI compared to DI plots with a high spatial heterogeneity in tuber germination (Fig. 3), which influenced all subsequent measurements. The observed challenge is well documented in both research studies (Enciso et al. 2007; Patel and Rajput 2007; Bordovsky et al. 2012) and practical applications (Burt and Styles 1994; Mo et al. 2023).

Plot Yield

Mean fresh tuber yield for treatments ranged from 25.7 t ha⁻¹ to 44.1 t ha⁻¹. These values align well with the reported regional average yield of 32 t ha⁻¹ for the Fès-Meknès region (Blom-Zandstra et al. 2020). The highest yield recorded in a single plot was 56.3 t ha⁻¹ under the fully irrigated DI treatment with mulch, supporting Ferreira and Gonçalves's (2007) hypothesis of an upper tuber yield potential of 60 t ha⁻¹ in hot and dry environments for irrigated potato.

The delayed germination in SDI plots, which was only fully achieved after rainfall at the end of May, resulted in considerable heterogeneity in plant development. While plants that germinated concurrently with those in DI treatments reached maturity by the harvest date, later-germinated plants remained immature and exhibited poor tuber development. This disparity in plant development at harvest likely caused the significant yield reduction of 10 t ha⁻¹ (25%) in SDI compared to DI treatments.

Najafi and Tabatabaei (2007) similarly identified complications in early potato development with SDI systems when driplines were buried at a depth of 30 cm, reporting severe yield reductions of up to 74% compared to DI. In the same study, yield declines with deeply buried SDI systems were observed for tomato and eggplant, implying that challenges in crop establishment are not confined to potato. The authors attributed yield reductions to inadequate water content in the root zone early in the growing season, causing water stress and subsequent yield losses.

The 25% yield decline of fresh tuber yield in SDI compared to DI in our study contrasts with findings from global meta-analyses that highlight the yield advantages of subsurface over surface drip irrigation across various crops (Wang et al. 2022; Guo et al. 2023). For potato, Nawbahar et al. (2017) conducted research in Kurdistan-Iraq in a clay loam soil under conditions similar to those in our study.

They reported a significant yield increase with SDI buried at 25 cm depth, whereas yields for SDI in 10 cm and 40 cm depths did not significantly differ from DI. This work ensured uniform potato germination through consistent water application across treatments before emergence. Selim et al. (2009) provide comparative data from Egypt on DI and SDI at 25 cm burial depth. The SDI treatment significantly increased potato yield by 11.4%, attributed to improved water and nutrient use efficiency, reduced evaporation losses, and maintenance of optimal soil moisture in the root zone. Another study in Egypt by Badr et al. (2010), comparing DI and SDI buried at 15 cm, showed a significant tuber yield increase of 20.4% with SDI (averaged across years and irrigation levels). These benefits were more pronounced under water stress and explained by more favorable growth conditions under SDI due to higher soil water content in the root zone. However, yield response in the study was generally more sensitive to irrigation levels than to the type of irrigation systems, with a significant yield reduction at 80% ET_c deficit irrigation.

Deficit irrigation treatments similarly reduced potato yields significantly in the arid climate of Saudi Arabia, where a 30% irrigation reduction lead to a 17% yield decline, and a 50% reduction resulting in a 30% loss (Mattar et al. 2021). In contrast, the Regulated Deficit Irrigation treatment in our study did not result in a significant



Fig. 11 Pictures of potato roots from harvested individual plants grown under DI (a) and SDI (b) and photographs from the field trial: water distribution in the potato ridge of an SDI plot with mulch early after planting (c), fine roots of the potato crop concentrating close to the subsurface irrigation dripline after harvest (d)

yield response, likely due to the strategic water saving during less water-sensitive growth stages and the lower overall reduction of irrigation amounts by 12%. These results align with findings from a study conducted at the same location as our experiment, where yield stability was maintained at a 25% irrigation reduction (El Bergui et al. 2020), while a 50% reduction led to a 21 t ha⁻¹ yield loss. Similarly, a study in Tunisia reported that a 40% reduction in irrigation water did not significantly affect yields, with significant losses observed only at a 70% reduction from full irrigation (El Mokh et al. 2014). In that study, SDI resulted in higher tuber yields, although these differences were not statistically significant across irrigation levels. Non-significant differences in tuber yield between SDI and DI were equally reported by Onder et al. (2005) from Turkey, Samardžić et al. (2022) from Serbia, and Kaur et al. (2023) from India.

Water Use Efficiency

Irrigation Water Use Efficiency (IWUE) and Total Water Use Efficiency (TWUE) are two commonly used metrics to assess the efficiency of irrigation methods and facilitate comparisons between studies. In our study, IWUE was on average 12.31 kg m⁻³ for DI and 9.37 kg m⁻³ for SDI. These values are notably higher than those reported by Assouli et al. (2018) for farm-scale DI applications in the Fès-Meknès region (4.9 to 7.5 kg m⁻³, depending on farm size).

In the presented experiment, potato received equal water amounts through the DI and SDI system. Consequently, the observed yield reduction under SDI resulted in a significantly lower IWUE compared to DI. This contrasts with Mattar et al. (2021) who reported a significant increase of WUE (irrigation and precipitation considered) by 6 to 8% under SDI compared to DI. Nawbahar et al. (2017) observed a 55.5% increase in IWUE for sensor-based irrigated potato when using SDI compared to DI. Patel and Rajput (2007) reported a more pronounced benefit in IWUE for SDI compared to DI when irrigation amounts were reduced by 20 and 40%, but the deepest dripline depth of 20 cm resulted in low IWUE. Similarly, El Mokh et al. (2014) found higher IWUE and TWUE values for SDI than for DI, although these differences were not significant. Other studies, such as Samardžić et al. (2022), reported no differences between DI and SDI, regardless of the WUE metric used.

In our study, Regulated Deficit Irrigation did not significantly affect IWUE or TWUE. This contrasts with the widely observed trend of increased WUE with reduced water application in potato (Yuan et al. 2003; Patel and Rajput 2007; Badr et al. 2010; El Mokh et al. 2014; Mattar et al. 2021). Two factors might explain this discrepancy: firstly, modest water savings in our deficit irrigated treatment (12%), and secondly, these savings were counterbalanced by a slight, non-significant yield reduction compared to full irrigation (ANOVA, $p=0.062$). Contrary to expectations, Gültekin and Ertek (2018) reported the highest WUE in fully irrigated treatments compared to deficit irrigation, with TWUE values ranging between 8.5 and 11.5 kg m⁻³, similar to our findings. In their study too, the limited water savings (up to 25%) in deficit irrigation led to some yield reductions. Cantore et al. (2014) found

no significant effect of irrigation regime (100% ET_c , 50% ET_c , rainfed) on potato WUE in a mediterranean environment in Italy.

In-Season Plant Development and Field Observations

Early germinated potatoes in SDI treatments exhibited no visible or measured signs of water stress beyond the early development stage. For instance, at 49 Days After Planting (DAP), potato plants in SDI plots were shorter than those in DI. However, this difference in plant height had disappeared by 68 and 88 DAP. Other studies (Nawbahar et al. 2017; Mattar et al. 2021) found significantly taller potato plants under SDI compared to DI at harvest. Additionally, stomatal conductance did not significantly differ between irrigation systems at any of the four measurement dates during the growing period.

Regarding chlorophyll content in later development stages, SDI variants did outperform DI treatments. This suggests improved nutrient availability under SDI. After an initial period of growth, potato roots were likely able to reach the SDI wetting bulb and fully exploit the water and nutrients provided by the buried driplines. Adaptation of rooting patterns under SDI systems has been described in literature for tomatoes (Machadu and Oliveira 2005), winter wheat (Ma et al. 2022), melons (Sharma et al. 2014), bell pepper (Kong et al. 2012), and maize (Phene et al. 1991). Stalham and Allen (2001) demonstrated the capability of potato roots to access deeper soil layers for resource exploration, and Kaur et al. (2023) reported higher root mass densities of potato in the subsoil under SDI compared to DI. This downward root development under SDI is expected to enhance drought tolerance under limited irrigation amounts (Da Silva and Coolong 2019).

In the presented experiment morphological plasticity in root growth was observed during single plant harvest, indicating root adaptation to the differing water and nutrient patterns under DI and SDI. Images from single plant harvest (Fig. 11A, B) show fine root formation near the soil surface for plants grown under DI. In contrast, potato crops under SDI developed fewer but stronger roots extending into deeper soil layers. Clustering of potato fine roots near SDI emitters was also observed in the field (Fig. 11D).

Single Plant Observations

The observed adaptation of potato plants to SDI conditions, and the system's eventual advantage later in the season, is further supported by single plant data. By July, mature SDI plants had approximately double the total aboveground biomass compared to DI plants. This finding is consistent with observations from Mattar et al. (2021), who reported a 30 to 40% increase in fresh and dry matter weights of vegetative parts under SDI compared to DI. This greater biomass supports the hypothesis of improved nutrient availability via fertigation and increased plant-available water, particularly later in the season see chlorophyll content 4.5. These favorable conditions may have similarly led to the high tuber yield of individual plants grown under

SDI, significantly outperforming those in DI by 20%. Certainly, these individual plant measurements must be interpreted with caution. It is unclear to what extent the delayed germination in parts of SDI plots altered competition among potato plants, and thus impacted the resource availability for the randomly selected plants used in the individual yield assessment. This is particularly noteworthy because only plants that germinated simultaneously with DI potatoes were considered. This limitation should be kept in mind for the analysis of yield data from individual plants.

Several studies have examined the impact of water stress on potato yield formation (MacKerron and Jefferies 1986; Haverkort et al. 1990; Fabeiro et al. 2001; Djaman et al. 2021), consistently emphasizing the paramount role of the severity and timing of water stress in influencing plant growth and resource allocation. In the presented study, water availability for potato plants was expected to be influenced by irrigation system, scheduling and mulching. However, none of the tested treatments had significant effects on the number of tubers per plant, fresh weight per tuber, or tuber diameter, though high variability was observed in all parameters. Similarly, experimental results from Onder et al. (2005), El Mokh et al. (2014) and Samardžić et al. (2022) found no significant differences in yield components between SDI and DI. These results contrast with Mattar et al. (2021), who reported a significant increase in both mean tuber weight and number of tubers per plant in SDI compared to DI. Badr et al. (2010) found that higher yields in SDI were based on a significant increase of mean tuber weight, with no difference in tuber number. In contrast, Nawbahar et al. (2017) reported significantly lower mean tuber weights in SDI systems with dripline depths of 10 and 40 cm compared to DI, while there was no significant difference between SDI at 25 cm depth and DI.

The analysis of tuber size classes revealed that for mulched plots, larger tubers contributed significantly more to the total plant yield in SDI than in DI. According to the meta-analysis of Djaman et al. (2021), adequate water supply before and during tuber initiation promotes tuber number, while sufficient water availability during later stages increases tuber size. Thus, larger tubers in SDI support the theory of sufficient water and nutrient availability from the buried driplines in later development stages. The increased variance in tuber number per plant, observed in SDI compared to DI, supports the notion that early-stage water stress may have occurred under SDI. The lack of water for germination in parts of the SDI plots drastically reduced the plot tuber yield. However, for germinated SDI plants, moderate early-stage water deficit was likely compensated once roots accessed the wetting bulb (Fabeiro et al. 2001). The logarithmic increase of mean tuber weight with less tubers per plant (Fig. 8) provides further evidence for the compensation of low tuber formation through bigger tubers, especially under SDI.

Furthermore, a significant positive relationship between tuber number per plant and total yield (adj. $R^2=0.32$) was found, whereas the correlation between mean tuber weight and yield was weak (adj. $R^2=0.02$). Thus, across all treatments, a higher number of tubers per plant contributed more to high plant yields than bigger tubers in our study. In contrast, Mattar et al. (2021) and Badr et al. (2012) found a weaker correlation between potato plant yield and tuber number than for tuber weight, concluding that tuber number was not the primary reason for yield reduction under deficit irrigation. A recent study by Kaur et al. (2023) on SDI-irrigated potato

under various irrigation schedules and nitrogen levels found that high yields were closely associated with both number of tubers ($R^2=0.88$ and 0.90) and tuber weight ($R^2=0.94$ and 0.87).

Regulated Deficit Irrigation had no significant effect on any of the examined yield component parameters, contradicting several studies on deficit irrigation in potato (Fabeiro et al. 2001; Onder et al. 2005; Badr et al. 2010; Karam et al. 2014; Gültekin and Ertek 2018; Mattar et al. 2021). This supports the hypothesis that, in our experiment, strategically reduced irrigation did not induce relevant water stress. Only one of four stomatal conductance measurements showed a significant decrease under Regulated Deficit Irrigation. This contrasts with Liu et al. (2006), who observed persistently lower stomatal conductance and transpiration throughout the season under 50% deficit irrigation. Additionally, the lack of effect on tuber brix content, a common stress indicator, suggests that the reduced water amount applied in the treatment of Regulated Deficit Irrigation did not cause substantial stress. Badr et al. (2012) noted that potato crops are not very sensitive to moderate water deficit, showing clear yield reductions only when irrigated with less than 80% of crop ET_c .

Effect of Mulch Treatment

Although mulching is often reported to improve water retention and yield, particularly in dry environments (Oljača et al. 2016; Li et al. 2018; Biswal et al. 2022), these benefits were not observed in our study. Brar et al. (2019), for instance, documented a 44 mm reduction in soil evaporation and a 36 mm increase in transpiration due to mulch application, resulting in a 19% yield increase in potato. A similar yield benefit of 21.5% was reported when rice straw was applied in a semi-arid environment (Sekhon et al. 2020).

The lack of a positive yield effect in our study may be due to low water stress experienced by the potato plants, minimizing the impact of potential water conservation through straw mulch. Furthermore, evaporative losses may have been negligible during later growth stages when the canopy was fully developed, especially in plots with deep-buried SDI (Najafi and Tabatabaei 2007). As mulch was first applied in March 2023, long-term benefits, such as increased organic matter content and nutrient availability (Sekhon et al. 2020), were not yet realized. On the contrary, the observed lower chlorophyll content and plant height of mulched plants late in the growing season indicate a potential negative impact of nitrogen immobilization due to the high carbon to nitrogen ratio of cereal straw. Competition from germinated wheat and barley in the mulch may have further offset any benefits of mulching.

Tuber Quality

In Morocco, where potatoes are predominantly sold directly to consumers (Blom-Zandstra et al. 2020), tuber quality is a critical factor for marketability. Specific gravity, a key quality parameter closely linked to starch content, was not significantly affected by either irrigation system or mulching in our trial. Mean values of $1.06 \pm 0.01 \text{ g cm}^{-3}$ were consistent with those reported by Samardžić et al. (2022),

who likewise reported no significant effect of irrigation system (DI, SDI, non-irrigated). Selim et al. (2009) observed a slight but not significant increase in starch content in SDI compared to DI treatments.

Visual inspection of potatoes from deficit irrigated treatments showed no significant effect of mulching (ANOVA, $\alpha=0.05$) on quality parameters such as skin characteristics, malformations and damages. Increased pest damages in SDI has been previously reported by Djaman et al. (2021), including higher infestations of mites and potato tuber moth (*Phthorimaea operculella* Zeller). These observations are attributed to the changed microclimate and dry topsoil that can benefit certain potato pests. However, Olanya et al. (2007) found no significant effect of irrigation system (sprinkler, DI, SDI) on microclimate parameters such as relative humidity and canopy temperature, nor on the modelled infestation of late blight (*Phytophthora infestans* Mont) in potato. Subsurface irrigated tubers in our study showed increased damage from mining insects, more frequent potato scab (*Streptomyces spp.*), and higher occurrences of rough skin and deformities like secondary growth and eye anomalies. These deformities may result from greater soil moisture fluctuations in the tuber zone under the deep-buried SDI system. Under DI, tubers are developing in the continuously moist topsoil around the surface driplines, whereas for SDI this zone is on the upper edge of the wetting bulb where soil moisture varies more between irrigation events. Such fluctuations are known to cause malformations, particularly in the tuber's rose end and eye regions, due to irregular cell division and growth following re-watering events (Kumari 2011; Cantore et al. 2014; Amer et al. 2016).

Conclusion

This study evaluates water-saving strategies in potato farming under Mediterranean conditions, namely Regulated Deficit Irrigation, mulching, and Subsurface Drip irrigation (SDI), and assesses their potential to enhance potato production in semi-arid environments. Regulated Deficit Irrigation achieved 12% water savings without yield penalties, consistent with prior studies emphasizing the effectiveness of deficit irrigation during less drought-sensitive growth stages.

The application of straw mulch, in contrast, did not yield the anticipated positive effect on tuber yield, regardless of the irrigation system or scheduling. This discrepancy with existing literature may be attributed to its first-time application, limiting long-term benefits, and the minimized relevance of evaporation losses under full canopy cover.

Our findings on SDI identified three key factors to foster its successful implementation in arable cropping. *Firstly*, successful crop establishment and early plant development must be guaranteed. We consider uneven germination under SDI as the main reason for the 25% reduction in plot yield compared to DI. Thus, factors such as time of sowing, supplementary irrigation, dripline depth, and soil capillarity must be considered to ensure water availability during germination and early development. *Secondly*, a long vegetation period is required to fully exploit SDI benefits

during the late growing season. Physiological indicators like chlorophyll content and stomatal conductance, as well as higher aboveground biomass at harvest supported the hypothesis that SDI enhances plant growth later in the season, once roots have adapted to the subsurface water source. Yield formation analysis further suggests that early water limitation under SDI reduced tuber number per plant (due to constraints during tuber initiation), which was later compensated by increased tuber weight during the bulking phase when water and nutrient availability improved. *Lastly*, phytosanitary and quality effects must be considered. Our quality assessment revealed potential negative impacts of SDI, mainly due to fluctuations in soil moisture. These obstacles to the new technology should be further investigated, particularly given Morocco's strong reliance on irrigation, increasing disease pressures in the region and the already high pesticide use in potato cropping (Achbani et al. 2015; Berni et al. 2016; Blom-Zandstra et al. 2020).

The 20% yield increase under SDI, observed in mature single plants, demonstrates the system's potential under the tested conditions. However, it is crucial to acknowledge that this result may be influenced by competition effects. Despite being based on a single season, the clear physiological mechanisms observed under representative semi-arid Mediterranean conditions and the dominance of irrigation over in-season rainfall support the broader relevance of these findings for potato production systems in similar environments.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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